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CHARACTERISING THE NAMAQUALAND MUDBELT: CHRONOLOGY, PALYNOLOGY AND PALAEOENVIRONMENTS

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ABSTRACT

Catherine Elizabeth Darnell Gray
CHARACTERISING THE NAMAQUALAND MUDBELT: CHRONOLOGY, PALYNOLOGY AND PALAEOENVIRONMENTS

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This multiproxy study explores the palaeoenvironmental record of two cores, H2 and H7, from the Namaqualand Mudbelt representing an arid and highly variable landscape. As bulk organic radiocarbon ages previously proved problematic, with anomalous reversals, the primary objective was to improve chronology and palaeoenvironmental reconstructions through high resolution $\delta^{13}C$, $\delta^{15}N$ and pollen analysis, with the aid of principal component analysis.

Bulk organic radiocarbon dating of the surface sediment had previously yielded older than expected ages. New ^{210}Pb analysis has established that these surface sediments are modern and radiocarbon ages are now recalibrated to yield an adjusted age of ±3 470 cal yr BP at the base of the more distal core, H7. Pollen spectra correlate well with stable isotopes and include recent disturbance indicators in the Succulent Karoo, Grassland, Karoo expansion, stock farming, impoundment, saltmarsh degradation and increase in domestic cereal cultivation. The proximal and distal mudbelt sites are, however, isotopically distinct, with $\delta^{13}C$, inverse nitrogen and C/N ratios characterising H2 as more terrestrial. The excursion towards C_3-rich values at around 6m depth in the proximal mudbelt suggests an increase in marine sources and C_3 vegetation, while associated pollen aridity indicators implicate reduced inland flooding. This is contrasted against more humid conditions at 420 cm. Stronger upwelling occurred in near-surface distal mudbelt sediment and an influx of the Buffels River sediment flooded the region at ±3 470 yr BP, indicating cooler, less arid conditions. $\delta^{13}C$ studies reveal the Lower Xobies palaeoflood deposit to be less C_4-rich than expected, possibly due to sediment source, and is strikingly isotopically similar to the distal mudbelt.

The palaeoenvironmental interpretation of the pollen assemblage, isotopes and chronology presents an improved understanding of the region represented in the mudbelt sediments. This corresponds well with established records of the last ±3 500 years and human induced land use change within the Orange River Catchment. Results also highlight the dynamics of the Orange River, which, combined with a highly variable climate, suggest that caution should be exercised to avoid over-interpreting the level at which environmental changes can meaningfully be reconstructed in arid landscapes, particularly those which are subject to sporadic and catastrophic flooding events.

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Preface

The need to understand the dynamics of soil erosion in southern Africa precipitated the formation of the South African - based HODSA (Holocene Denudation of South Africa) research group (Dingle et al. 1994). This multi-disciplinary research group incorporated a wide range of expertise from the fields of Archaeology, Geology, Botany and Environmental and Geographical Sciences from the University of Cape Town and affiliated institutions (Sea Fisheries Research Institute, now the Centre for Marine and Coastal Management and the South African Museum in Cape Town). This research group was subsequently renamed SELUCSA (Soil Erosion and Land Use Change in South Africa) and was dedicated to establishing the underlying factors and processes creating the phenomenon of recent increased erosion in South Africa. This prompted a west coast inner continental shelf marine exploration on the SAS Protea in 1994, in collaboration with the South African Navy and resulted in retrieval of the HODSA gravity and box cores. Two of the seven gravity cores, H2 and H7, retrieved during this cruise have been used in this project and are the focus of this thesis. An earlier pilot study, presented as an unpublished honours thesis (Gray 1996) also utilised these cores. Some of the material in this thesis were first published in part in Gray et al. 2000.

The idea for investigating the possibility of pollen in the mudbelt was first suggested by my supervisor, Professor Michael Meadows, who highlighted the need to establish the presence of pollen. This resulted in the aforementioned pilot study (Gray 1996) which established a viable presence of pollen in the mudbelt. As a result of my study receiving the SAAG (Southern African Association of Geomorphologists) award for best geomorphology honours thesis of 1996, I presented an invitational paper at the SAAG 1998 conference, which was then published in a special volume of the South African Geographical Journal (Gray et al. 2000). This publication has a number of co-authors, who made varied contributions to the research in terms of their supervisory, advisory and logistical capacity: Gray, C. E. D., Meadows, M. E., Lee-Thorp, J. A. and Rogers, J., 2000: Characterising the Namaqualand Mudbelt of Southern Africa: Chronology, Palynology and Palaeoenvironments, South African Geographical Journal, 82 (3): 137-142. This paper represented key findings from the

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honours thesis pollen study (Gray 1996) and also included some aspects of my subsequent original research presented in this thesis, namely preliminary observations from the ^{13}C and ^{15}N isotope analysis of cores H2 and H7 and initial ^{210}Pb analysis. Professor Julia Lee-Thorp, as my co-supervisor, contributed to the logistics and financial implications of running the isotope analysis and Dr John Rogers, having established foundational aspects of the sedimentology of the mudbelt in numerous earlier publications, contributed to assisting with the logistics of arranging ^{210}Pb analysis, along with Julia Lee-Thorp through their French-South African research agreement. Further to my findings in Gray (1996), my three co-authors had highlighted the possibility of using additional geochemical analyses to examine the mudbelt sediment (Meadows et al. 1997).

Preliminary parts of the analysis presented in this thesis have been dellivered at a variety of international and local conferences and workshops during the course of this research. These meetings have informed my research and presented an invaluable environment in which I could discuss and develop my thesis.

I received laboratory assistance from Ian Newton, Dr Jean-Marie Jouanneau and Rudy van Zyl with running the ^{13}C and ^{15}N isotope analysis (mass spectrometer at UCT, Cape Town), ^{210}Pb isotope (University of Bordeaux, Bordeaux) and Total organic carbon (Elsenberg Soil Science Laboratory) analyses respectively. During fieldwork in the Richtersveld, I received logistical and sampling assistance from Tim Hart and Dave Halkett.

Except where stated above and in my acknowledgements, all sampling, sample preparation, processing, counting of pollen and picking of foraminifera, general laboratory work and analysis are my own work.

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*Tales sunt aquae, qualis terra per quam fluunt**

*Waters take their nature from the strata through which they flow

Plinius

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1 INTRODUCTION

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1 INTRODUCTION

1.1 Introduction

Existing thinly distributed Quaternary palaeoenvironmental records of southern Africa are characterised by relatively short sediment sequences representative of small to medium sized regions. The subcontinent has a few scattered records of late Quaternary environmental change and this significant time period is particularly poorly understood. Due to the nature of the semi-aridity of the region, suitable continuous to near-continuous repositories of environmental change proxies do not commonly accumulate. It is necessary to resolve the Quaternary and indeed the Late Pleistocene and Holocene in particular, in order to understand past and future trends and dynamic features of environmental change. It is the very paucity of palaeoenvironmental proxy data of this time period in southern Africa that prompts further investigation of the terrestrial record; the relevance of studies that draw on an offshore accumulation of material from a large terrestrial expanse deposited over a significant period of time becomes apparent.

The Namaqualand mudbelt, situated off the south-western coast of southern Africa (Figure 1.1), represents a significant and unique opportunity to explore late Quaternary environmental change in the region, providing a broad range of proxy palaeoenvironmental evidence. This research must by nature be multidisciplinary in approach and methodology. The Namaqualand mudbelt certainly qualifies as a rich source of palaeoenvironmental potential in three key areas:

1. The mudbelt represents a record of runoff history which extends to the Late Holocene, postdating the last sea level rise when the continental slope was scoured of its unconsolidated sediment mantle. This record also spans the more recent arrival of significant numbers of African herders, pastoralists and European colonists and their recent human impact in the ORC.

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2. Until recently, interest in the mudbelt was limited to that of sedimentology as it had been largely ignored due to the inherent lack of diamondiferous alluvials and any other aspects of commercial importance. This potentially useful site is considered to be pristine which enhances the feasibility of this study.
3. The mudbelt is unique in terms of the catchments from which it collects sediment. There is no other similar palaeoenvironmentally significant focal point of such expanse in southern Africa. Although the challenges presented by the sheer diversity of ecologies and problems of source sediment and sediment pulses are recognised, the mudbelt provides an unrivalled record of Holocene palaeoenvironment. Palynology and stable isotope analysis are established palaeoenvironmental indicators and have been successfully applied to terrestrially derived marine sediment at other sites. By virtue of its vast source area, the ORC presents both a challenge and an opportunity to explore its unrivalled potential for southern Africa.

It is particularly pertinent that South Africa, as an emerging nation, increases its awareness of, and acts upon, a sustainable land-use management plan. This poses an enormous challenge as the economic welfare of southern Africa depends heavily on agricultural resources which are directly affected by erosion and an ever-present water scarcity. Erosional effects can greatly increase flood damage and thereby destroy agricultural land, disturb sensitive ecologies, encourage desertification and promoting deleterious run-off patterns and it is clear that research in these fields is both relevant and necessary.

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1.2 Continental margins, deltas and mudbelts in context

The Late Quaternary history of the inner continental shelf off southern Africa's west coast is not well known and an accumulation of sediments such as occur in the Namaqualand Mudbelt therefore represents an important opportunity to elucidate it further.

Erosion leaves a significant mark on the southern African landscape and the Orange River, which drains an extensive estimated 40% (Dingle *et al.* 1987) of the sub-

continent, carries much of this sediment as runoff from the land. Given its high mean annual runoff [1](MAR) of 11 $km^3.yr^{-1}$, the Orange River is considered a significant world river[2] (Bremner *et al.* 1990) and covers a catchment area of approximately 1 x 10^6 km^2 (Benade 1993), carrying a sediment load thought to exceed a mean annual 60.4 x 10^6 tonnes (Bremner *et al.* 1990); indeed, the river is ranked the most turbid on the continent and the fourth most turbid in the world (Bremner *et al.* 1990, Compton and Maake 2007).

The fine fraction of this suspended load is deposited into the Atlantic Ocean off the west coast of southern Africa on the inner shelf; a significant portion of the fine sediment fraction travels south by the poleward countercurrent and is trapped in the Namaqualand deltaic mudbelt. The sand fraction is dispersed northwards by longshore drift, driven by strong southerly winds (Rogers 1977). The mudbelt represents a significant portion of the mud fraction of flood event and erosional sediment load.

Here, the mudbelt represents a record of the inland sediment as a discontinuous body of clay-dominated sediment running some ±20 km north of the Orange River Mouth (ORM) and 600 km to the south as far as Cape Columbine (Birch *et al.* 1991). It lies unconformably on the inner continental shelf at a water depth of between 80 and 140 m (Meadows *et al.* 1997, 2002, Gray *et al.* 2000). The mudbelt is between ±15km and ±25km in width and situated on the inner margin of the shelf, some 1 -10km from the shoreline (Birch *et al.* 1991) and extends up to ±30 km from the west coast shoreline

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[1] This is the natural MAR, based on the widely used 1939-1960 values (Bremner *et al.* 1990). Although these values are the only MAR used in current literature for the Orange River, estimates indicate less than half of the annual natural runoff of the Orange reaches the ORM due to development along the river (Heath 2001, Huizinga 1997 after DWA 1990[1]).

[2] A table of major world rivers, is found in Appendix A. Compared to high volume rivers such as the Amazon, Mississippi and the Yangtze, the Orange River appears relatively insignificant. However, it is quickly evident that within southern Africa, the Orange River plays an important role by virtue of its situation and dominating influence on the interior of the southern African subcontinent and in draining roughly 40% of the southern African interior; it compares favourably with other major rivers in terms of its large catchment area and high turbidity ratio.

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(of southern Africa). Beyond this, the mudbelt drops off dramatically due to the combined effect of increased depth, increased slope of the continental shelf and the erosive effect of ocean currents. The internal structure of the mudbelt has posed something of a problem and early seismic profiles yielded little or no internal structure. The continental shelf offers a unique opportunity for evaluating inland palaeoenvironmental change, with potential for longer and more continuous sequences compared to the generally sparse ephemeral records presented inland. The mudbelt has been previously referred to as a semi-continuous record (Mabote *et. al.* 1997, Meadows *et al.* 1997, 2002) but this needed to be established and is therefore addressed in this thesis.

Although there is a clear winter and summer seasonality in terms of temperature in southern Africa, the semi arid sub-continent is especially characterised by marked extremes in moisture availability, i.e. seasonal aridity (Scott and Lee-Thorp 2004). Some areas of the catchment are considered to be "well watered"; although by world standards the catchment is classed as arid, the river passing through differing rainfall regimes with marked seasonal variation (Basson and Rossouw 2003). Evaporation levels are comparatively high and the seasonal and inter-annual variations are especially significant in the Orange River Catchment (ORC) (Tyson 1986).

Continental margins comprise a fraction of the total surface area of the oceans, yet the significance of these provenances belie their small area (Hall *et al.* 2003) and they are highly significant in the transfer of materials, including carbon, nitrogen and phosphorus from the terrestrial to the oceanic realm. These pathways are constantly in flux and therefore change in space and time, and, as a result the continental margins are of special palaeoenvironmental interest, more so where biological processes and productivity are high and accumulation of fossiliferous material may take place at a relatively rapid rate. According to Hall *et al.* (2003), sediment accumulation rates at the margins are usually significantly higher by comparison with the open ocean.

There is currently much interest around the continental margin material fluxes between ocean and land and also the sensitivity to climate change in various components and aspects of this interface as the sheer number of publications (Arnaud-Fassetta and Provansal 2003) and research groups in this area attest. This interest has

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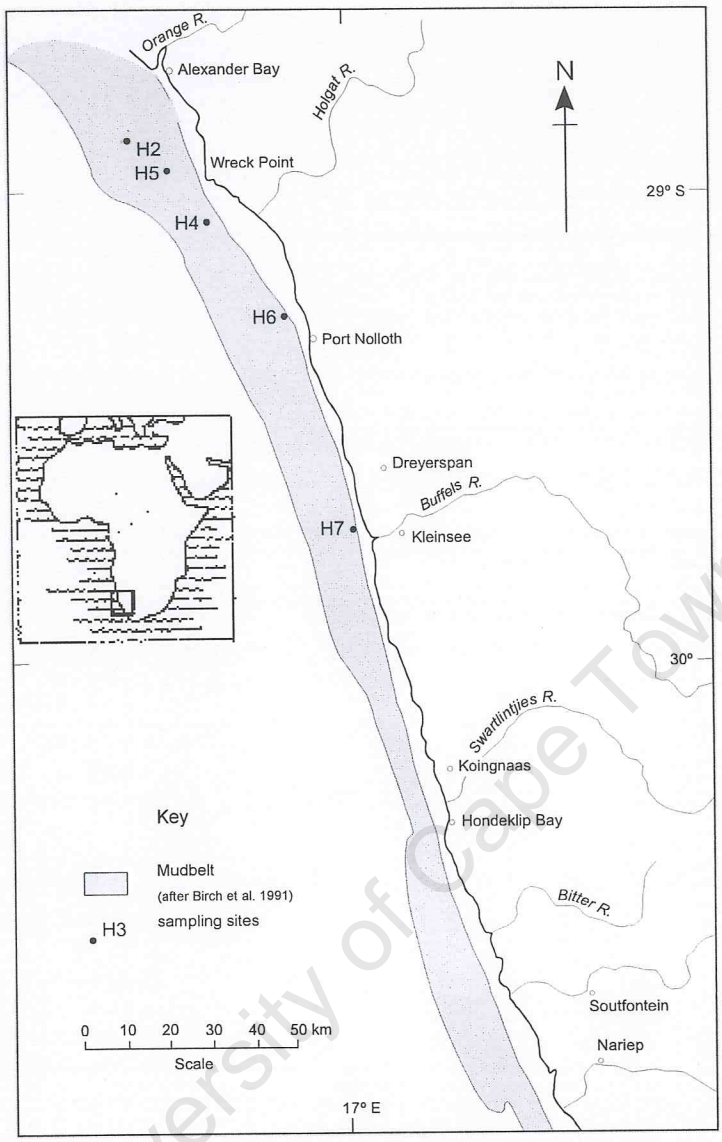

Figure 1.1 Location of the Namaqualand or Orange River Mudbelt, showing HODSA marine gravity cores, H2, H4, H5, H6, H7. Box cores are situated at the same co-ordinates as their gravity core counterpart (after Mabote *et al.* 1997, Birch *et al.* 1991 and Gray *et al.* 2000).

seeded various international collaborative research projects such as International Geosphere-Biosphere Programme or IGBP (http://www.igbp.kva.se/), International Geological Correlation Program or IGCP 396 Continental Shelves in the Quaternary (1996-2000) (http://www2.env.uea. ac.uk/gmmc/igcphome.html), subsequent IGCP 464 Continental Shelves during the Last Glacial Cycle (2000-2005) (http://tetide.geo.uniroma1.it/IGCP464/) and the Intercontinental Margins task team (ICMT).

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As rivers discharge their contents onto the adjacent shelf at the continental margin, the sudden change in hydrodynamics, geology and geomorphology, frequency of pulsing events, relatively low strength erosional vectors and other factors often contribute to the formation of a delta or fan at the mouth of the river (Cattaneo *et al.* 2004, Day *et al.* 1995). Deltas occur when streams or rivers open out into standing water of the sea or lake, where depositional forces outweigh erosional forces. The two primary force factors include eustatic variation and sediment yield (Arnaud-Fassetta and Provansal 2003). In doing so, the "competence and capacity" of the river is lost and deposition occurs as a delta. Here, the surface level of the water keeps the deposition layer in check. Rapid flood events result in sorted deposits with the bed load deposited first at the mouth then, in order of decreasing size (or weight) this embankment enlarges progressively in an outward fining sequence in an offshore direction. Three layers are typically identifiable: the foreset, bottomset and the topset layer. Deltas are inhibited where currents and wave action are very strong and may be classed according to either fluviatile dominated, swell dominated or macrotidal estuary dominated deltas (Arnaud-Fassetta and Provansal 2003). However, if the rate of sediment supplied by the river exceeds removal rate (erosion), then a delta is created. These features tend to postdate the Last Glacial Maximum (LGM) and decelerating sea-level rise with the result that significant deltas rarely pre-date beyond 8 500 BP and tend to have a modal age of 7 500 BP (Stanley and Warne 1994, Arnaud-Fassetta and Provansal 2003).

The world's largest drainage basins open out into deltas. Significant deltas, which open into the sea, include but are not limited to the Ganges-Brahmaputra, the Mackenzie and Mississippi (North America), Orinoco, Amazon and Paraná (South America), the Volga, Ob, Yenissi, Lena, Amur (Northern Eurasia), Indus and Ganges (Asia), the Tigris-Euphrates (Middle East), Huang-Ho, and Yangtze (China) and the Nile, Niger, Congo, Senegal, Zambezi and Orange deltas (Africa) and are discussed in Cattaneo *et al.* (2004), Törnqvist *et al.* (2004) and Stanley and Warne (1994). Relative to its size, Africa, as a continent, discharges relatively small amounts of sediment, compared with the island of Taiwan (which produces only slightly less sediment than the United States, not including Hawaii and Alaska) (Skinner and Porter 1997). It is therefore understandable that Africa (and similarly Australia) have such a low

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discharge output at the coastal margin due to their low altitude (on average) and arid climates. Each delta is unique; shaped by unique stream discharge, base level position, climatic variability, character and volume of load, coastline bedrock and offshore topography, intensity and direction of longshore waves and currents (Arnaud-Fassetta and Provansal 2003). For example, the delta of the Mississippi River, one of the largest in the world, opens into the Gulf of Mexico and possesses fingerlike bodies of sediment, which create a complex delta comprised of overlapping subdeltas of up to 7 000 BP in age (Cattaneo *et al.* 2004) due to high sediment load. The delta itself (with an estimated extent of 31 000 km^2), does not include the submarine portion. By comparison, the situation in the Namaqualand deltaic mudbelt is slightly different as the delta portion is submarine and the mudbelt portion of the delta is dominant. By way of further comparison, the Amazonas-Guianas Mudbelt possesses a considerable delta but is much larger than the Namaqualand Mudbelt, due to its relatively larger sediment load.

The term, "mudbelt" or "mud belt" is difficult to define other than that the loosely defined concept refers to a body of mud, usually deposited in a marine context at the terrestrial marine margin, beneath wave action, where it is allowed to build up some expanse. A relatively constant supply of fine clays and silts is required to facilitate mudbelt formation, usually originating from river sediment supply and is the case for deltas, mudbelts tend to be found at trailing edge continental margins. Further, these deposits tend to be of Quaternary age, post-dating the LGM where subsiding sea-level rise and progradation of the coast has facilitated accumulation. Although older deposits do occur, these tend to be found further offshore and their accumulation is dependent on a range of factors including the geology and hydrodynamics of the area. Despite the mudbelt concept escaping definition in most texts, it appears in a number of publications and an overview of some of the mudbelts found worldwide indicates why this is such a nebulous term – mudbelts seem to be as unique and varied as their location and environment suggests.

Inner shelf mud deposits occur on the Amazon inner continental shelf and also the East China Sea shelf off the Changjiang (Yangtze River) (Aller and Aller 1986). These deposits are mobile and have a variable presence of benthic fauna (benthic fauna may flourish in stable sediment and are reduced in areas of greatest sediment

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accumulation and reduced food availability). The Amazonas-Guianas Mudbelt is vast and is found off most of the South American inner shelf "downdrift" of the Amazon River (Aller *et al.* 2004a). This mudbelt is comprised of coastal mud waves, transported by trade wind-forced waves, diurnal tides and the North Brazil/Guiana Coastal Current (Aller *et al.* 2004a,b). The South Coast of Papua, New Guinea in the Gulf of Papua, where a series of rivers feed into the ocean, creating a fine grained, and organic-rich deltaic complex. A reworked mudbelt is found on the inner shelf at 10-20 m depth (Aller *et al.* 2004b). Mudbelts are clay-rich by definition and contrast with silt deposits, such as those found on the mid to outer continental shelf of the west coast of southern Africa, although there are elements of the mud in this part of the shelf, where muddy sands and sandy muds occur (Rogers 1977a,b) and very fine sand is found at the delta front (Bailey and Rogers 1997). Another significant silt deposit is situated off Cameroon, which is comprised of two sedimentary basins (the Rio Del Rey-Douala basin in the North and the Kribi-Campo basin in the South. The Rio Del Rey-Douala exhibits high sedimentation rates of terrigenous silts and sandy silts but no mudbelt is evident. The Congo deep-sea fan off the Congo River is situated at an upwelling region off West-Central Africa in the Northeast Angola Basin (Dale *et al.* 2002). Mud is found off many river-ocean interfaces but not always as a cohesive mudbelt, as is the case for mud found off the Peru-Chile continental margin (Munõz *et al.* 2004). The Huksan Mudbelt is found on the inner shelf of the southeastern Yellow Sea, Korea (Lee and Chu 2001). Two mud units of similar grain texture and clay mineralogy alternate with silt and clay-rich laminae; the two units differ in seismic profile. A suspended plume above the mudbelt, visible by satellite, originates from the Keum River on the west coast of Korea. This is enhanced by winter monsoon winds and increases the amount of particulate matter by the order of 1-2 times. Mudbelts generally present good proxies for Holocene palaeoenvironmental data and usually post-date stabilising sea-level of the last ±7 000 BP. It is unusual to find one such dating back as far as the Huksan Mudbelt, which is probably about 140 000 yrs in age (Lee and Chu 2001) and has not been scoured by LGM sea level change to the extent of that of the Namaqualand mudbelt.

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1.3 Review of existing research on the Orange River, its palaeoflood deposits, palynology and the mudbelt inner continental shelf sediments

The Orange River is unique in that it is the only river globally to receive its rainfall predominantly on the eastern side of a continent, yet deposit it on the "poleward side of a coastal desert" (Rogers 1977a and Gray 1996)[3]. The Orange River is perhaps one of the most studied rivers in southern Africa, with intensive study focusing especially on impoundment, related water abstraction, flooding (Bremner *et al.* 1990) and mining related activity at its mouth and estuary (Anderson 2006). However, despite intensive study of this significant river, palaeoenvironmental studies have been limited and restricted to localised sites or narrow fields of interest and few broad based studies exist. Sedimentology of the 1988 Orange River flood is documented by Bremner *et al.* (1990), where daily variations in sediment were analysed and the isotope value of some upper catchment sediments have been obtained by Compton and Maake (2007).

The relationship of the various hydrodynamic components governing the mudbelt accretion is complex and understanding of these components has tended to be limited. Interactions between temporal and spatial hydrodynamic components of differing intensities have facilitated the development of a discontinuous fine to clastic mudbelt in the Quaternary (Gray 1996, Meadows *et al.* 1997 and Dingle 1994).

Rogers and others have contributed towards the Orange River sedimentology literature and the inner continental shelf off the West Coast of southern Africa (Rogers 1977a,b, Rogers and Bremner 1991, Rogers & Li 2002, Bailey and Rogers 1997, Birch 1975, Birch *et al.* 1976, 1986 and 1991 and Tankard and Rogers (1978) and Compton and Maake 2007). Relatively little is known of changes in the Orange

[3] Poleward side: This describes the situation of the river compared to the desert and poles. The river and delta occur on the poleward side of the desert compared to the norm, where these tend to be found on the equatorward side of a desert.

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River flow during the Quaternary, but Zawada (1996, 2000), Zawada and Hattingh (n.d) and Zawada *et al.* (1996) have illuminated significant flood events of the mid- to late Holocene. As is the case of the mudbelt, there have been some problems with dating methods at these inland sites, in both age determination and limited sample size, therefore establishment of sediment accumulation rate, along with the uniformity of this deposition are not known. This is discussed in greater detail in chapter 2 (study site and sampling) and chapter 4 (chronology). Since the Pleistocene, the mouth of the Orange River is known to have moved from that of the Olifants River Mouth, to its present site at Oranjemund (Birch *et al.* 1991) and has existed *in situ* during the development of the current mudbelt for the postglacial period. Further, the majority of sediment is sourced above the Caledon/Orange River confluence in the upper Orange and the majority of fine mud is sourced in the Caledon River (Bremner *et al.* 1990, Compton and Maake 2007).

It is suggested that a large proportion of the Caledon River suspended load originates as topsoil (Upper Karoo sedimentary rock) compared with the bedrock above Aliwal North, which is basalt. Although the Buffels River is considered to have a limited contribution to the sedimentology of the mudbelt, recent publications consider the Orange River to have the most significant influence on sediment source, but more sedimentological and geochemical research needs to be done in this regard. Further, impoundment has contributed to the overall reduction in both sediment and discharge volume at the ORM (Bremner *et al.* 1990) by trapping sediment, abstraction and modulation of the flow.

Thus far comparative studies within various palaeoflood sites (Lower Orange vs. Prieska) have been disappointing as correlation of flood units presented difficulties due to reworking events (Zawada 1996, 2000 and Zawada *et al.* 1996).

Meadows *et al.* (1997) highlighted the need for improved understanding of the mudbelt chronology and in Mabote (1997) and in Mabote *et al.* (1997), examined additional aspects of its sediment in terms of sedimentology and geochemistry, identifying a fining upward sequence indicative of sea level rise (or shoreward transgression) in the mudbelt. Although the Orange River is the primary source of deltaic sediments, the input of marine sediments, berg winds and ephemeral rivers

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becomes progressively more significant further south from the Orange Delta off Kleinsee. This work by Mabote (Mabote 1996, 1997 and Mabote *et al.* 1997) updated the commonly held view, among other workers, of the Orange River being the sole source of mudbelt sediment (Rogers 1977a, Dingle *et al.* 1996 and Rogers & Bremner 1991).

The dating problem of establishing a chronology for the mudbelt sediments has been described in a number of publications including Meadows *et al.* (1997, 2002), Mabote *et al. (*1997), Gray (1996) and Gray *et al.* (2000).

In 1975 Davey and Rogers conducted a simple overview palynological study of offshore sediment from the Orange and other rivers, which indicated the presence of a limited number of plant families, as pollen in the mudbelt. Aside from this and another study on river mouth sediments between the Kunene and Gamtoos River by Coetzee and Rogers (1976) which had alluded to the potential for palynology studies of this area., no further work was done until the pollen pilot study in 1996 (Gray 1996). This study presented an opportunity to obtain vegetation indicators of change. Various dynamics affect pollen appearance in the record and these include bias to wind-borne pollen, varying source of flood material in a drainage catchment covering different microclimates, windblown pollen (prevailing wind dependent), reworking, small but potential contribution of marine-borne pollen, which may all represent bias and should be considered when interpreting the pollen results. As a result of aridity, pollen records are poor and scattered in extent across southern Africa, especially when compared to moist regions such as the northern hemisphere, are more conducive to pollen preservation and records are more prevalent. Palynology represented an intriguing opportunity to examine the erosional and flood events, thus a pilot study was conducted (Gray 1996) and published in Gray *et al.* (2000), to investigate the viability of further research offshore. This study provided conclusive evidence that there was in fact pollen in the mud, of sufficient quantities to show variations downcore (through various floods or depositional events). In addition, the available dating techniques had not, as yet, conclusively indicated whether surface material had been represented in the cores. Further investigation was necessary to establish whether surficial mudbelt sediment was recent in age (i.e. less than 150 years) and also whether any additional information could be gathered as to the flood events and

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palynology dynamics (source, deposition, environmental change).

This research responds to the need for drawing together the existing dataset along with additional analysis of the cores and utilising as yet unused avenues of proxy data in the mudbelt. These data include palynology and a number of chronological techniques, all of which may potentially contribute towards an understanding of palaeovegetation and environmental change.

1.4 Aims and objectives

Although the themes of soil erosion, flooding and land degradation underlie this research, it is comprised of a number of interlinking aims and objectives with two central directions of study: The first is the chronology of the Namaqualand mudbelt and the second is the vegetation record, represented through palynology and stable isotope analysis of the mudbelt. This research intends to examine the proxy data within the Namaqualand Mudbelt in its chronological and palaeoenvironmental context in order to improve understanding of the dynamics at work in the ORC over the time period represented by the mudbelt cores and correlated with existing inland data.

The specific aims of this research are listed as follows:

Chronology

1. To establish whether surficial sediments represent recent or modern material using ^{210}Pb analysis (and possibly ^{137}Cs) and resolve older than expected bulk organic radiocarbon dates. Attempt a higher resolution understanding of the chronology with the aid of ^{210}Pb analysis, if relevant.
2. To determine sedimentation rates based on the interpreted chronology, if feasible.
3. To examine the possibilities and viability of AMS radiocarbon foraminifera analysis of 4-6 selected samples, where bulk organic chronology is particularly confusing, in order to obtain a stronger chronology framework.
4. To collate chronology of key select known palaeoflood deposits and key events in the ORC.

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Lower Xobies and Jakkalsberg (Richtersveld) in context of the mudbelt

5. To draw on additional modern sample sites upriver (of the ORM) to correlate, if feasible, with the marine cores and thereby establish the timing and age of the sediment in the mudbelt using sediment feeding directly into that system. Compare results from within the ORC slack water deposits as a record of flood events: lower reaches of the Orange River identified by Zawada (1996), new analysis on sites identified by Webley (1997) and others identified by Hart and Halkett (1999 pers. comm.).

Vegetation (pollen)

6. To attempt a high resolution pollen analysis reconstruction of the changes in the vegetation assemblage by using the palynology sedimentation history and information with respect to existing and historical vegetation patterns. Detailed 15 cm intervals of gravity cores, box cores and selected inland sequences were sampled to reflect possible aspects of vegetation and vegetation change within the catchment area and ultimately assist in establishing a broader picture of the recent past environment and to reconstruct vegetation at the time of deposition.
7. To obtain some understanding of the dynamics of the environmental situation under which the pollen grains were transported and deposited in the mudbelt (windborne vs. riverborne pollen).
8. To establish whether palynological techniques could help resolve a detailed chronology through the identification of exotic biostratigraphic markers (non-indigenous pollen grains) by identifying exotic flora species introduced in recent times.

Stable isotope analysis

9. To conduct carbon stable light isotope analysis of the organic components of H2 and H7 in order to obtain a reflection of C_3 and C_4 plants from terrestrial as distinct from standard marine values of –21‰ supported by nitrogen stable isotope analysis if possible. This would presumably indicate the fluvial vs. terrigenous input, and also potentially give an indication of C_4 vs. C_3 vegetation from inland and shed light on the dynamics of the sediment source.

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Combined proxy data

10. To examine differences, if any, between the gravity and box cores and correlate data obtained from the above research and existing palaeoenvironmental data, with a view to syntheses of existing records we have for the catchment and southern Africa in general.

In short, the central objective of this thesis is to explore the pollen and stable isotope evidence of sediments from the southern African Namaqualand Mudbelt in order to provide a reconstruction of Holocene palaeoenvironments of the adjacent catchment.

1.6 Thesis outline

The fundamental basis of this research is focused on the Namaqualand Mudbelt to further explore its palaeoenvironmental potential. The study area, discussed in this chapter, includes a description of the diverse vegetation biomes and climate of the ORC, the surrounding region and existing palaeoenvironmental information. The methodologies used in this thesis are discussed in chapter 3. This chapter refers to the chronology, isotopes and palynology of chapters, 4, 5 and 6.

The problem of establishing chronology of the cores, fundamental to this research, is introduced in chapter 4. New research data are presented and discussed and results are provided.

Chapter 5 deals with carbon and nitrogen stable isotope analysis. This incorporates dynamics and distribution of vegetation such as that of the C_3 and C_4 photosynthetic pathways of terrestrial plants of the region and the marine influence on the mudbelt organic matter.

Chapter 6 is devoted to palynological work conducted on the mudbelt and associated inland Orange River terrestrial sites. This chapter builds on a pilot study (Gray *et al.* 1996 and 2000) and an earlier study by Coetzee and Rogers (1976).

The discussion and synthesis of findings of this research are discussed in chapter 7 and the conclusion with key findings and future recommendations are found in chapter 8.

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2 STUDY AREA

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2 STUDY AREA

This chapter examines the importance of the sediment record of the Orange River, which drains into the area and provides organic matter (OM) to the mudbelt, in the context of environmental and climatic change, flood events, vegetation history and historical land use in southern Africa. Existing knowledge about human influence in the ORC area is summarised. Vegetation biomes of the ORC and prevailing climatic conditions of the area are given as a background to interpretation of the palynological and palaeoenvironmental evidence. Sampling sites and strategy used in this study are outlined. The study area, including the Namaqualand mudbelt (the focus of attention in this thesis), selected Richtersveld slack water deposit sites and existing geological and palaeoenvironmental research of these sites is described.

The study area is comprised of two coring sites on the Namaqualand mudbelt (H2 and H7), a series of sample points along the lower reaches of the Orange River in the Richtersveld and three additional palaeoflood sites in the Richtersveld region. These additional sites are known as Lower Xobies, Jakkalsberg and Bloeddrift. Sampling and analysis of the mudbelt was intended to help characterise it as a means to shedding light on the inland palaeoenvironmental change, analysis of additional inland sites was required in order to contrast offshore with inland data. The ORC feeds directly into the mudbelt and so sampling of Orange River sediment was intended to provide clues as to the general pollen signal of the area during low flow discharge and palaeoflood deposits[1]. It was predicted that this Orange River material would yield pollen, even if the palaeoflood deposits proved inert due to the arid Richtersveld climate. A fundamental issue was establishing a better understanding of the chronology characteristics of the mudbelt as a basis of this investigation.

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[1] The scope of this project did not permit the extensive analysis of flood sediment required to fully examine the pollen signal during high flow and flooding. This should be a priority for future investigation.

The Orange River originates in the Lesotho Highlands of the Maluti-Drakensberg Mountains at an altitude of 3 300 m above sea level. Here the river is known as the Senqu River. Mean annual precipitation in the region often exceeds 1 800 mm and mean annual evaporation is about 1 100 mm (Zawada 2000). An estimated 40% of this originates in the Lesotho region, a region covering less than 4% of the total area of the drainage basin (Smook *et al.* 2002). The Orange River flows through a succession of landscape changes – varying geologies and biomes (Succulent Karoo, Grassland, Savanna, Nama Karoo and some forest elements) before finally opening into the sea at Alexander Bay, some 2 300 km west of its source. Here mean annual precipitation is below 50 mm but the mean annual evaporation potential can climb to over 3 000 mm (Smook *et al.* 2002). Indeed, less than 1% of river discharge is contributed in the Namaqualand (Heath 2001, after Department of Fisheries and Water, Windhoek, 1990). The major tributaries of the ORC (Figure 2.1) include those in the highlands of Lesotho which flow from the Senqu River, (source of the Orange), the Caledon River (eastern Provinces and Free State), the Vaal River (main tributary, incorporating the Vaal River Basin.), Modder River and Fish River (Namibia).

Much of southern Africa is characterised by severe water shortages, having no navigable rivers and no significant natural lakes, only artificial dams used for agricultural purposes. The MAR along the Orange River has been reduced by development such as irrigation, hydro-electric power and domestic and industrial abstraction of water in the Vaal River Basin. The Orange River is considered to be both currently and historically the primary contributor of sediment to the mudbelt, with other perennial rivers contributing to a lesser extent (Mabote 1997). For example

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Figure 2.1 Map of southern Africa showing the Orange River Catchment combined with the Buffels River Catchment, indicating main tributaries and extent of the catchment areas (adapted from Lange *et al.* 2007, Zawada *et al.* 1996, Zawada 1996, Bremner *et al.* 1990 and Marais 1972). Positions of the sample sites are illustrated in subsequent figures.

[Note: locations of the following points of interest: Oranjemund (1.), Kleinsee (2.), Olifants River Mouth (3.), Prieska (4.) and Aliwal North (5.).]

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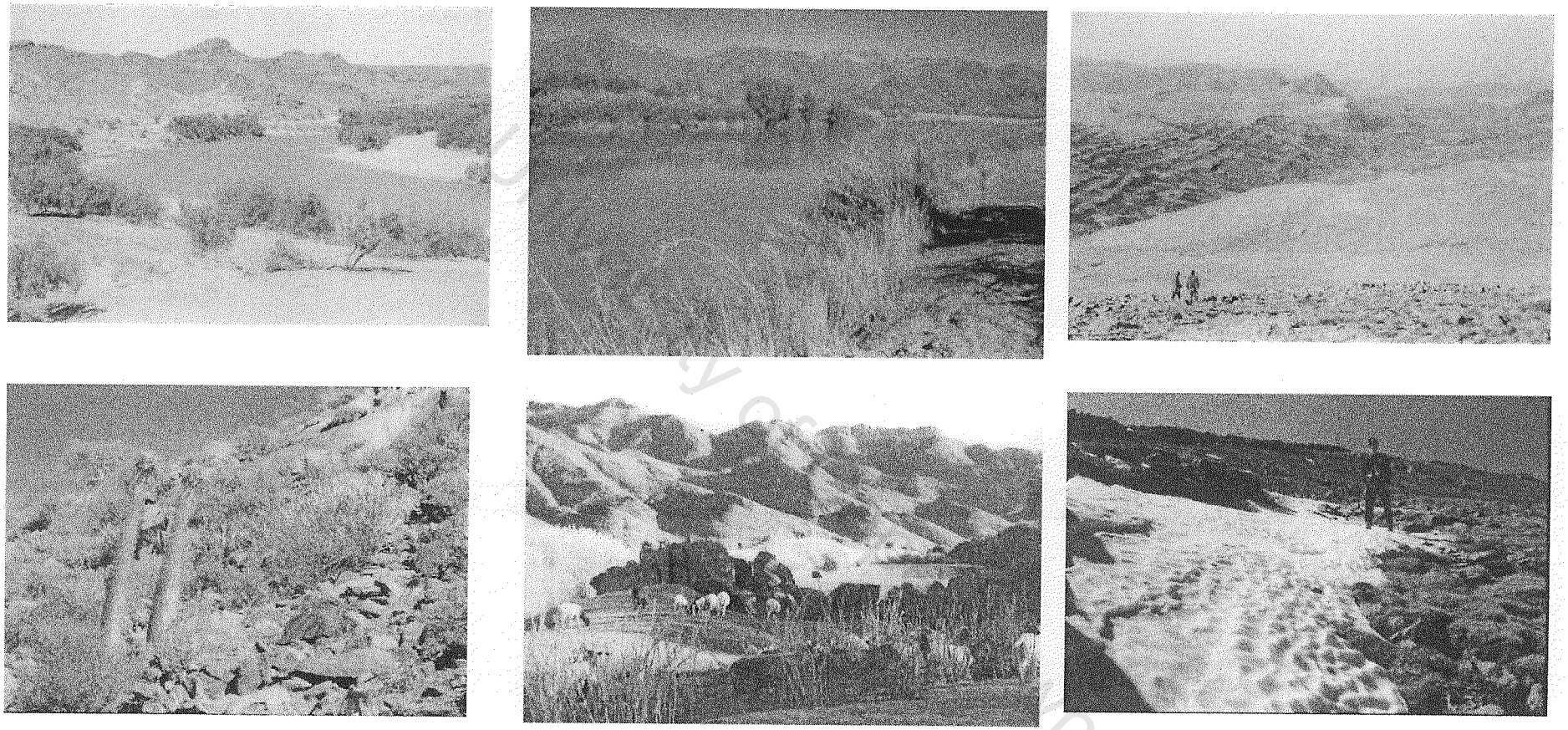

Plate 2.1 Photographs indicating the difference in climate within the Orange River Catchment from the moist Lesotho Highlands in the East (top and bottom right) to the arid Richtersveld in the Lower Orange River close in the West (top and bottom left). Centre photographs show vegetation on the banks of the Orange River in the Richtersveld region (photos: Catherine Gray).

the ephemeral West Coast Buffels River[2] contributes sediment periodically (although this has not been quantitatively assessed due to lack of long term monitoring in this restricted access diamond mining locale). The Buffels River is known to rarely open to the sea and only flows during exceptionally heavy rainfall in the region (Rogers 1977a). Due to the sensitive diamond mining nature of the region at the coastal mining town of Kleinsee, where the Buffels River reaches the sea, there is little in the way of flood recording (Herbert and Dewar pers. comm.). Change of management and other problems has led to a paucity of flood recording, a very poor understanding of the dynamics of this river and the frequency of significant flooding bringing sediment to the mudbelt. However, flooding does occur and results in flash floods carrying sediment, vegetation and water in significant quantities at irregular intervals and it follows that there should be a sediment input into the mudbelt from the Buffels River Catchment (Figure 2.1). The river has flooded in recent times, notably during 1986 and 1991 (Woodborne 1991).

The primary focus of this study is the Namaqualand Mudbelt but in order to understand the terrestrial dynamics and distinguish this from the marine context, it is also necessary to analyse terrestrial material feeding into the Orange River, particularly flood deposit material that would ultimately be incorporated within the mudbelt and palaeoflood deposits in the lower reaches of the Orange River. It is advantageous to try to understand the dynamics of a large catchment such as the ORC and the sediment at the distal end that may well contain information from both terrestrial and marine environments. It is therefore helpful to attempt to separate this information as far as possible.

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2.1 The Namaqualand Mudbelt

The Namaqualand deltaic mudbelt is also known as the Orange River or West Coast mudbelt (Birch *et al.* 1986, Meadows *et al.* 1997) and is situated on the inner continental shelf of southern Africa's West coast, extending south of the river under

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[2] There are two Buffels Rivers in South Africa. The river in question is not the Buffels River which is part of the Gouritz River system situated near Laingsburg, South Africa.

the influence of a poleward countercurrent (Nelson 1989). Here it is protected from wave action, being found below the influence of wave-induced currents (Meadows *et al.* 1997, Gray *et al.* 2000) and is known to be comprised of successive deposits of Holocene age (Rogers 1977a). The delta front is composed of sand up to a depth of 40 m, which corresponds to the wave base and below this is clayey-silt (40 – 120 m) (Bremner *et al.* 1990). The mudbelt is broadly cohesive, continuous and thicker in the Orange River prodelta, where the deposit is laminated and silt-rich (Gray *et al.* 2000). South of this area, the mudbelt tends to be more homogeneous and mud-rich. The mudbelt deposit has been restricted to the Holocene period; successive shoreline recessions/transgressions occur during each Glacial Maximum, thus increasing wave energy on the inner continental shelf and altering sea-level, resulting in scouring of sediments. Allied to this are the effects of inland and continental shelf subsidence. Thus, it is only during interglacials that records of terrestrial sediments such as the mudbelt tend to be cohesively retained on the inner continental shelf. According to recent sedimentology studies of the mudbelt (Mabote 1997 and Mabote *et al.* 1997), the sediment is considered largely terrigenous and mainly sourced in the ORC, although the ephemeral Buffels River and other perennial rivers make a less significant contribution. This sediment contribution is indicated by the increased width of the mudbelt where perennial rivers are found (Mabote *et al.* 1997), such as off the Orange, Olifant and Berg Rivers. Unfortunately no seismic profiles were successfully obtained.

Impoundments have had a significant influence on recent modern sediment load levels and indeed the river discharge in the Orange River since the 70's (Bremner *et al.* 1990). However, river damming first began in the early 20's and sediment load had already dropped from 60 million tons per year ($t.yr^{-1}$) between 1929 and 1969 to less than 17 million $t.yr^{-1}$after 1970, when damming began in earnest (Bremner *et al.* 1990, Compton and Maake 2007). This amounts to a post-dam reduction in sediment load of just over 70 % (Bremner *et al.* 1990, Compton and Maake 2007). The seasonality and amount of flooding has been reduced, resulting in not only significantly less sediment reaching the mouth, peak flooding has been reduced and flow has been moderated. Dams act as sediment reservoirs and reduce the down river catching effect of floods, unless the dam walls are breached (this occurred twice in 1988, resulting in extensive flooding and 40% over the annual sediment load being deposited over a 3

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month period). Indeed, prior to construction of the large dams, the mouth was seasonally closed a few months during low flow; the mouth opened in response to increased rainfall (towards the end of winter and early spring) where wave action and tidal flow also interacted (Huizinga 1997). Bremner *et al.* 1990 and others have cited that the most significant volumes of sediment are transported during flood events. The bulk of suspended sediment is silty clay (Bremner *et al.* 1990); between 40 and 60% of the pre-flood (year round) suspended sediment within the river in the upper catchment is composed of silty-clay. Since less than 1.8% of the total sediment is added below the Orange/Vaal confluence, this translates through to similar sediment size fraction of discharge volume during each flood event (Bremner *et al.* 1990). Damming is possibly the most probable reason for the increase in clay in suspended sediment at the ORM; also, recent decrease in suspended sediment possibly refers to the increase of farming and topsoil erosion since the 1930's (Bremner *et al.* 1990). A large proportion of the sediment is considered to be comprised of erosional sediment load, however, the exact relative proportions of bank to top soil erosion is not known, (Compton and Maake 2007).

The ORM represents a unique deposit in the southern African context and is comprised of terrigenous silts and clays, along with some marine organic components. Biogenic material from terrestrial and marine sources such as pollen and foraminifera respectively are entrained in the mudbelt and can be important palaeoecological tools to understanding palaeoenvironmental dynamics. Drawing on sediments from a very large catchment that comprises much of southern Africa, it is a potentially important repository for indicators of environmental changes in relation to, for example, climate, and vegetation under both natural and anthropogenic forcing mechanisms across southern Africa. The mudbelt is constructed from sediments derived from continental runoff, berg winds, channel erosion of older flood deposits and locally derived sediments– an array of vector variables which potentially indicate past erosion, recent land use patterns, soil residence time, climate, vegetation through proxies such as pollen spectra, stable carbon isotopes and ^{210}Pb.

2.2 Mudbelt core and grab samples

The so-called HODSA cores were retrieved from the Orange prodelta and inner shelf

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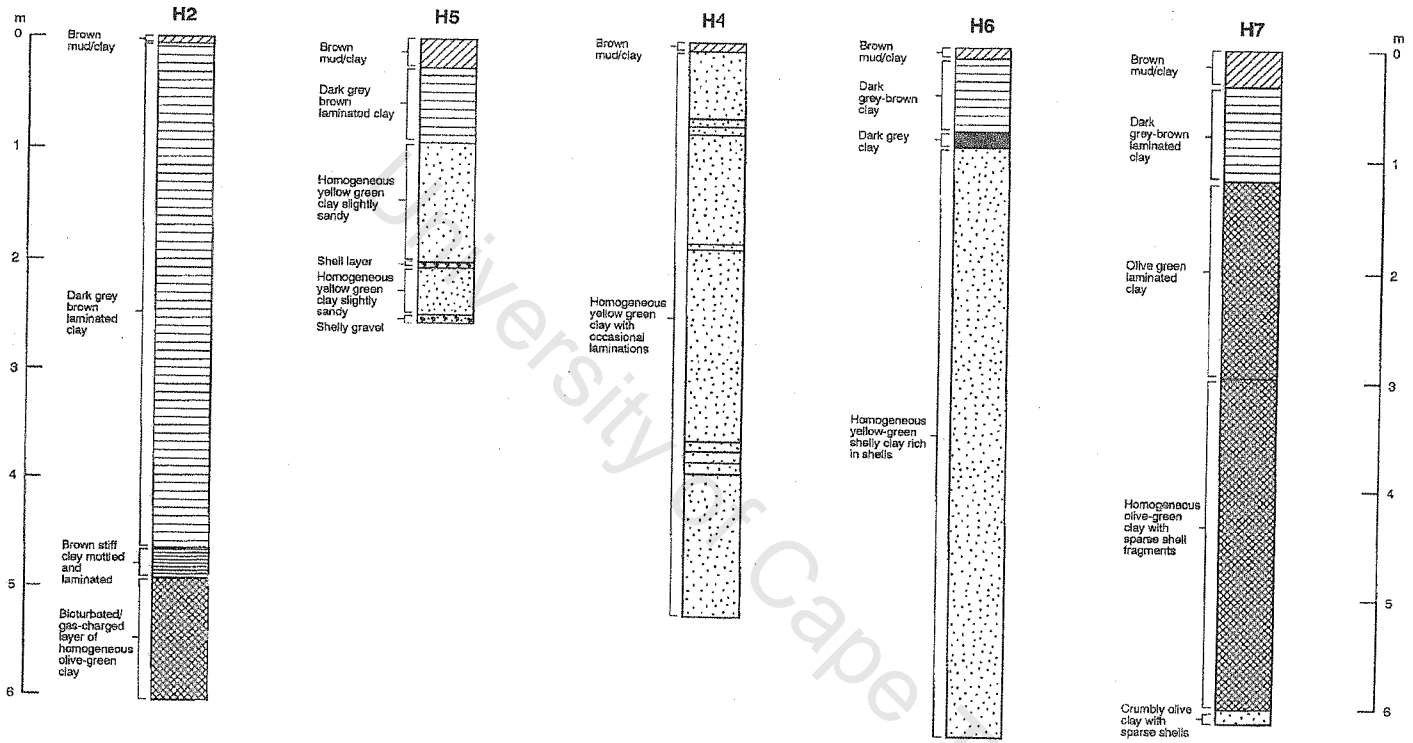

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Figure 2.2 Stratigraphy of mudbelt cores H2, H4, H5, H6 and H7 relevant to bulk organic radiocarbon ages. Note: box cores A 49, A37 and A 30 are stratigraphically identical to the gravity cores H2, H5 and H7 respectively and were retrieved at the same co-ordinates (After Meadows *et al.* 1997 and Gray *et al.* 2000).

sediments of the mudbelt in May of 1994 during a cruise of the *SAS Protea* (a South African naval hydrographic research) (Dingle 1994, Meadows *et al.* 1997). A gravity corer was used to extract seven cores from the mudbelt but was inexplicably lost overboard during the eighth coring attempt (Dingle 1994). These each extended up to 6 m in length (but some were shorter) and 300 mm in diameter (Figure 2.2). Ten grab-samples, relating to each gravity core, were taken from the surface sediments of the mudbelt using a Shipek Rotary grab sampler (Dingle 1994, Meadows *et al.* 1997) in order to optimize sampling of the potentially recent surface. Sample sites are located in Figure 1.1. off the Namaqualand coast between the Orange and Buffels Rivers. While seven gravity cores were retrieved, only cores H2 and H7 are of direct interest to this research.

H2, in the prodelta, was found at the following co-ordinates:

28° 52' 53" S, 16° 21' 30" E.

H7, the most southerly core, was retrieved off the Buffels River at the following co-ordinates:

29° 42' 12" S, 17° 00' 69" E.

An additional set of box cores were taken from the prodelta the following year during a cruise arranged by the then named Sea Fisheries Research Institute (now Marine & Coastal Management) on the South African Research vessel, *Africana*. The retrieval sites correspond to the sites of H2, H7 and H5 (situated between the two aforementioned sites) and can be located on Figure 1.1 (H5 being situated at 28° 00' 24" S 16° 28' 72" E). The samples were obtained using a box corer in order to evaluate whether the surface sediments had indeed been sampled during the gravity coring operation. These cores were labelled originally "A17930", "A17937" and "A17949" but were simplified to "A30", "A 37" and "A49", corresponding to H7, H5 and H2 respectively. [3]

[3] A further set of cores, not discussed here were obtained in 1988 during a Geological Survey cruise and data published by Meadows *et al.* (1997).

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The gravity cores were described by Rogers and reported in Dingle (1994) and later by Mabote according to laminated and unlaminated facies. These laminations can no longer be observed due to decay over time and it is evident that their subdivision was somewhat of a subjective exercise. These distinctions can be seen in Figure 2.2. Half the core was archived. The remaining working half was sampled at 5 cm intervals using a 1 cm long stainless steel core-divider and placed in 600 ml containers which were stored at ambient temperature without preservative. Sub-samples are labelled according to the depth of the core. The more northerly sites H1, 2, 3 and 4 are situated in the delta, whereas H5, 6 and 7 are more characteristic of the mudbelt on the shelf (Dingle 1994). The samples were originally assigned a complicated numbering system which has been simplified for convenience to depth measurements (Appendix B). HODSA samples used in this project were taken from these containers with a few removed from the archive half, although this proved a challenge due to subsequent water loss having caused shrinkage to occur. Six samples were initially analysed and their pollen described in a pilot study (Gray 1996, Gray *et al.* 2000).

2.3 The Richtersveld sites

Four Richtersveld sites on the lower Orange River were identified for the purposes of this research and are described here (Figure 2.3). Some of the sites (Lower Xobies, Bloeddrift, Jakkalsberg) had been previously described and analysed in terms of either palaeoflood hydrology or archaeological importance and thus offered an added advantage for this research. An initial sampling field trip was undertaken in the Richtersveld early in 1999, a period of low discharge in the lower ORC. This field trip was planned as a reconnaissance of the Richtersveld area as representative of the lower reaches of the Orange River and to obtain bulk sediment samples for modern pollen analysis. A second field excursion was conducted to the Richtersveld in September of 1999 with the assistance of contracts archaeologists Tim Hart and Dave Halkett.

However, the previously documented ages provided by Zawada (1996) and Zawada *et al.* (1996) were not entirely reliable given the mix of bone, IRSL (variable, contradictory results), ostrich egg shell (OES) and bulk organic ages obtained, which are prone to the ubiquitous issue of reworking. Thus, any additional bulk organic

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radiocarbon dating necessitated a careful choice of appropriate materials. Samples from all of these sites were used for various analyses including pollen, stable light isotopes and submitted select bulk organic samples for radiocarbon dating and total organic carbon (TOC).

2.3.1 Richtersveld bulk sediment

A select few modern sediment samples were retrieved from the bedload of the Orange River (Figure 2.3).

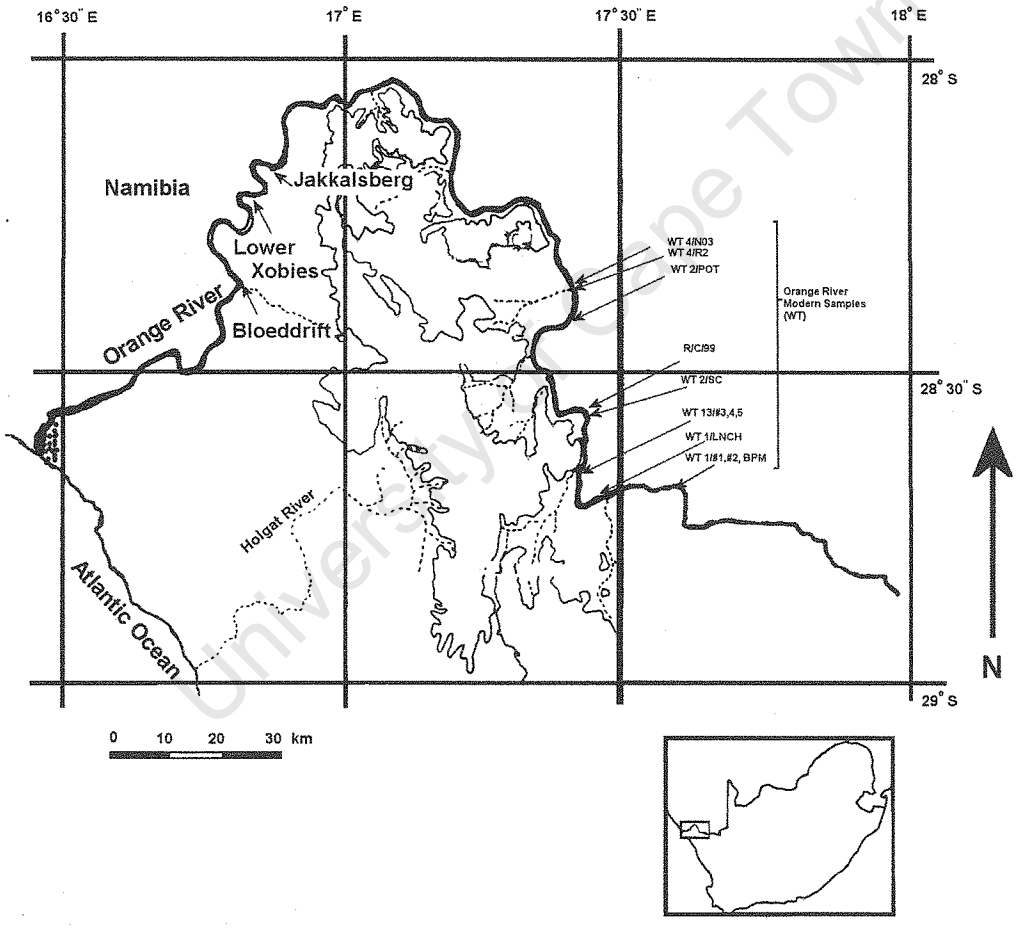

Figure 2.3 Map of the Richtersveld, indicating inland Richtersveld sites of the Orange River: Jakkalsberg (JKB), Lower Xobies (LX), Bloeddrift (BLD) and the Orange River (WT) sample sites (adapted from Webley 1997).

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2.3.2 Lower Xobies

The Lower Xobies Orange River palaeoflood site (slack water) deposit is situated in the Richtersveld at 28°13'20" S and 16°50'43" E. It is situated in an ephemeral tributary on the South African side of the Orange River, some 200 m from its confluence with the Orange (Figure 2.4) and has been extensively described by Zawada et al. (1996) as a high threshold flood slack water deposit. The Lower Xobies tributary joins the Orange River, where the Orange is single channeled, exhibits high sinuosity and is ±600 m wide (Zawada *et al.* 1996). The longitudinal profile of the river or thalweg gravel is composed of sub-angular dolomite and limestone clasts of between 0.5 and 15 cm long. The tributary flows along the strike of exposed rock, has a high gradient and decreases from a width of 150 m to 50 m or less at its mouth. The Lower Xobies Catchment is estimated to be about 5 km^2 in extent and therefore represents a small percentage fraction (less than 1%) of the total ORC drainage. However, the usefulness of using this site in this study is not so much its small representative drainage area, but its function as a repository of a high threshold flood event.

The units have been discussed in detail by Zawada 1991 and Zawada 1996 and a summary of the deposit follows:

The Lower Xobies site of exposure is 5.6 m in height and between 40 m and 150 m long; the exposure sequence is of interbedded fine sand and gravel (Figure 2.5).

Nine slack water deposits F1-F9 have been identified, varying between fine sand and sandy silt. These deposits or flood units are tabulated in Table 2.1. In general this deposit is slightly more coarse grained than the mudbelt which tends toward being clay-rich.

2.3.3 Jakkalsberg

Jakkalsberg (JKB) A (Figure 2.3) and B are open pastoralist midden and burial sites, located 40 m apart at coordinates 28°10'50" S, 16°53"15 E. These palaeoflood archaeologically-rich deposits were first located by a herdsman in 1992 and subsequently studied by Brink and Webley (1996). Adjacent to these sites at the same co-ordinates are JKB O (facing JKB A in Figure 2.4) and the open site JKB N.

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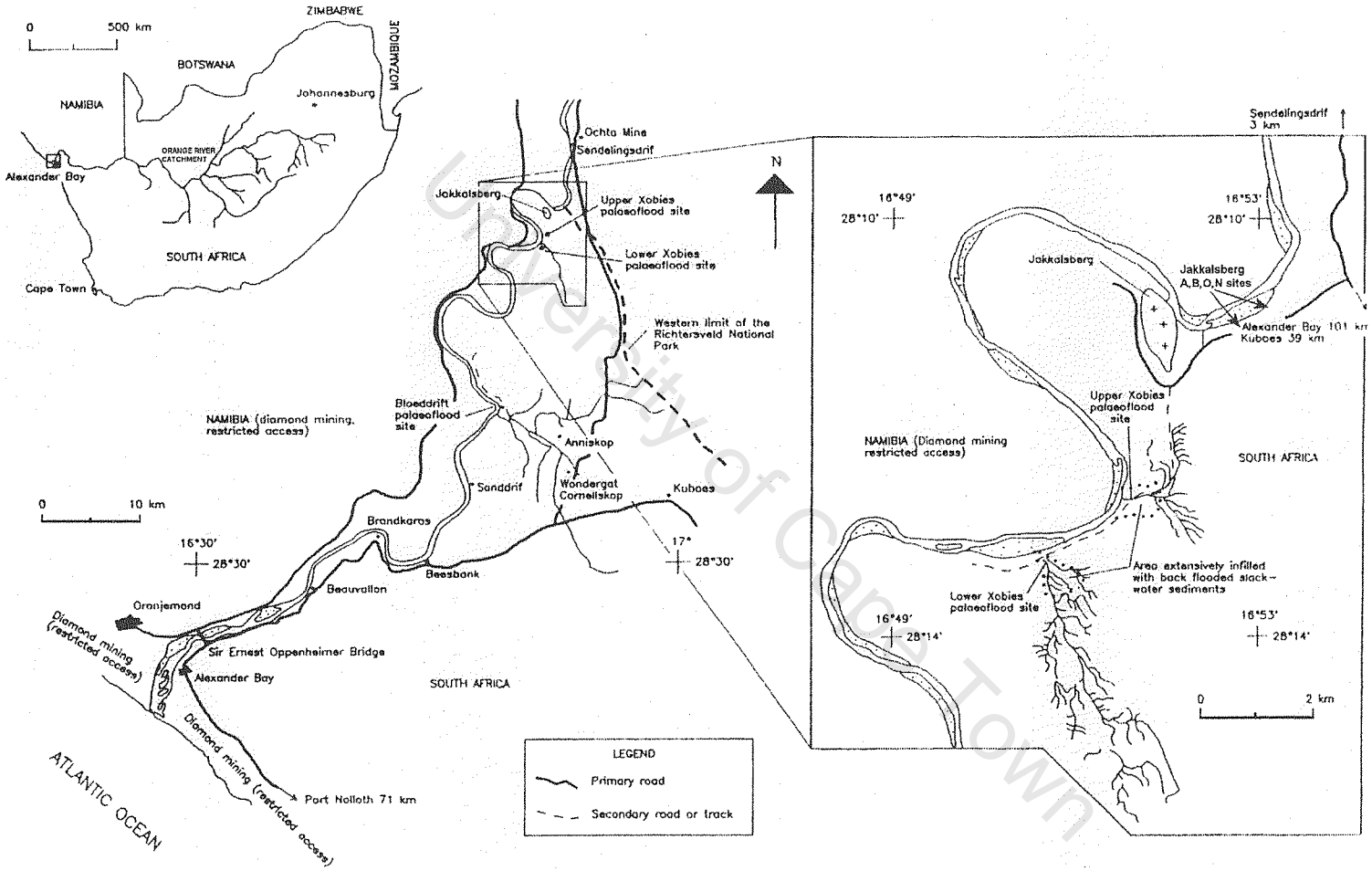

Figure 2.4 Richtersveld sites: Jakkalsberg (A, B, O, N), Bloeddrift (BLD 32), Lower Xobies (after Zawada *et al.* 1996).

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Flood Unit Level	Unit Description
F1	This unit is 66 cm thick and composed of very fine grained sand. It overlies the thalweg gravel. It is well laminated and bioturbated but interspersed with upward fining episodes and relates to back flooding sedimentation interspersed with periods of increased flow and quiet water (sedimentation) conditions.
F2	This unit varies between 80 and 170 cm in thickness and has an upward fining sedimentation of fine to very fine grained sand due to backflooding interspersed with increased flow regime and reworking of material.
F3	This unit is 5 cm thick and composed of very fine grained sand-silt with some laminations (slack water) and minimal signs of reworking.
F4	This unit is 50-78 cm thick and is composed of very fine grained sand, with some evidence of higher flood regime, indicated by planar surfaces on the base and surface of this unit. There is some indication of bioturbation. The unit is thought to have been deposited under back-flooding conditions but increased flow occurred at the start and end of this depositional event.
F5	This unit ranges from a thin gravel bed near the confluence to about 25 cm thickness. It is interspersed with a layer of very fine-grained sand which decreased in grain size further from the confluence. Two interflood hiatuses have been identified by their deposition of angular coarse-grained sand-gravel. Zawada hypothesizes that either the tributary back-flood incursions occurred or the material is weathered schists from the tributary mouth.
F6	38 cm thick very fine-grained sand with a sharp planar contact between Units 5 and 6. This deposit is slack water sedimentation during back-flooding of the tributary and alternating periods of slow and rapid flow and deposition.
F7	This unit is 34-90 cm thick with fine-grained sand and is incised from the overlying unit. Desiccation cracks 1-3 cm wide and 50 cm deep occur in the surface of this unit. Bioturbation is absent in this unit. This is a slack water deposit, deposited by back-flooding of the tributary. In palaeoflood hiatuses are represented twice in this unit and a high proportion of suspension settling is suggested.
F8	This very fine-grained sand unit is channel shaped being 35 cm deep by 206 cm wide. Some evidence of erosive incising, gravel deposits (higher energy conditions). This unit is also interpreted as a palaeoflood slack water deposit and there is evidence of interflood hiatuses at the base and upper contacts. The channel shaped deposit is interpreted as representing the maximum palaeoflood stage.
F9	This unit is 483 cm thick and composed of fine-grained sand. In this unit, desiccation cracks are evident and there is evidence of gravel deposition Again backflooding and hiatuses are interpreted.

Table 2.1 Unit description of the Lower Xobies palaeoflood unit F deposit (after Zawada *et al.* 1996).

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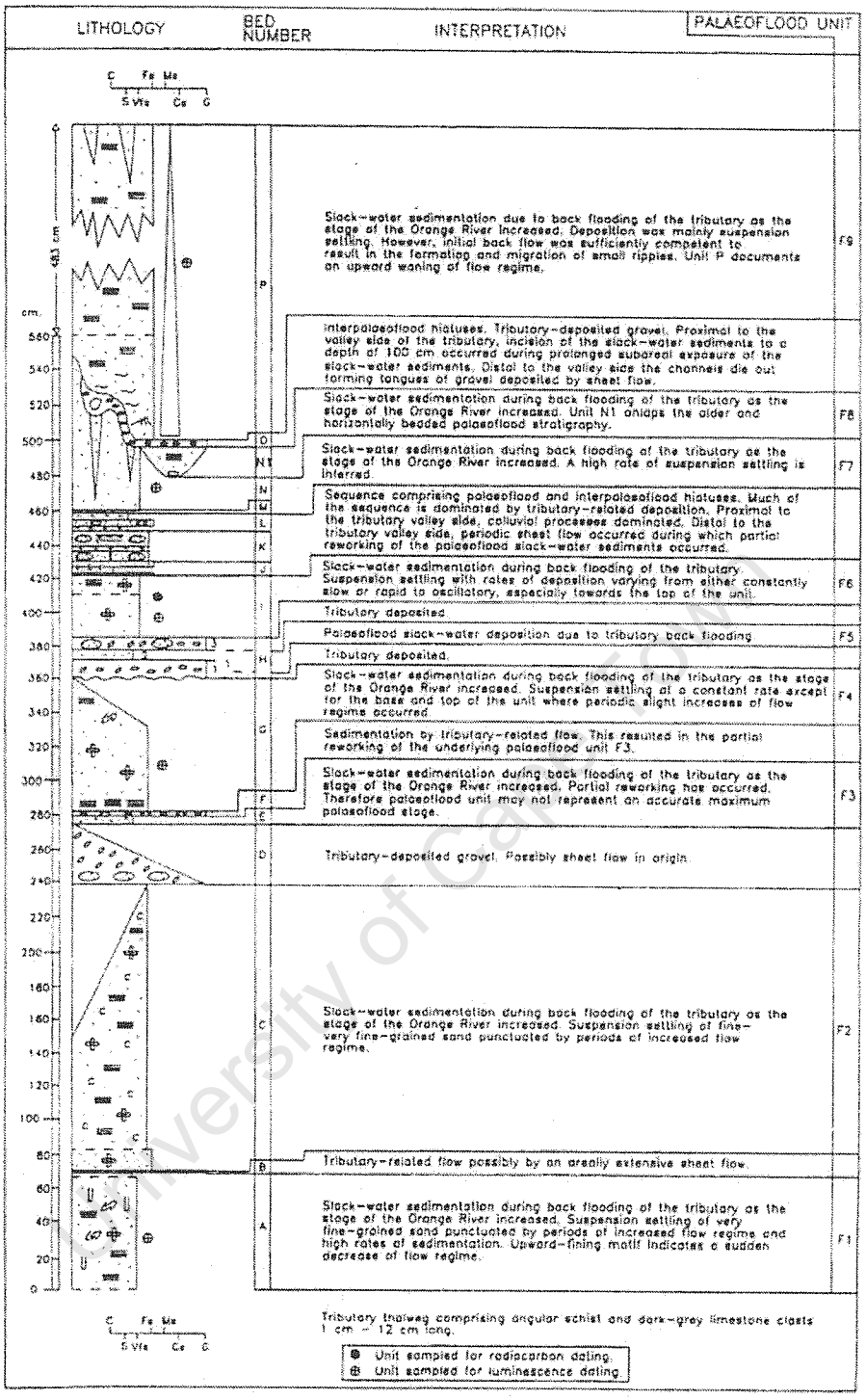

Figure 2.5 Lower Xobies palaeoflood stratigraphy (after Zawada *et al.* 1996).

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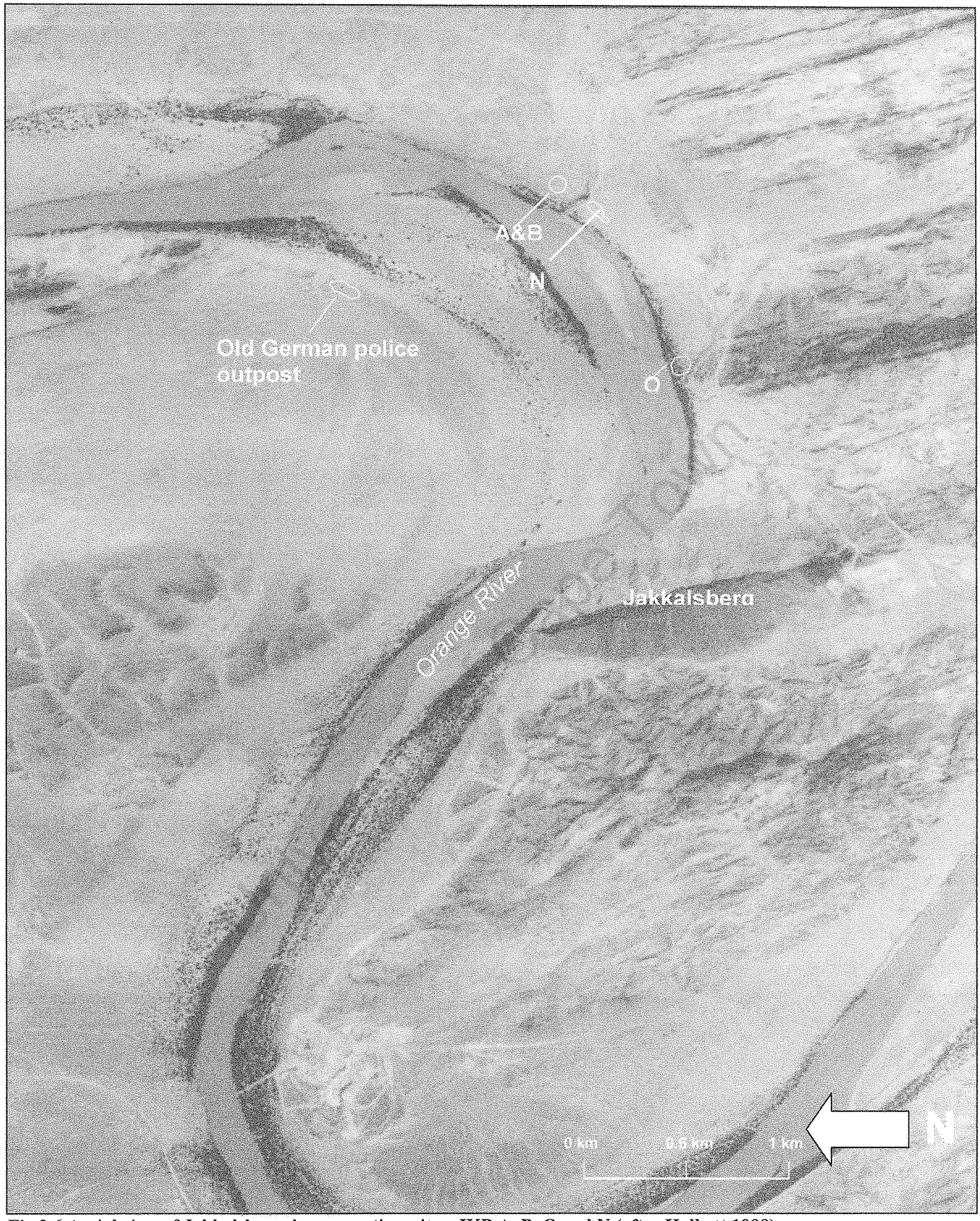

Fig 2.6 Aerial view of Jakkalsberg, incorporating sites, JKB A, B, O and N (after Halkett 1999).

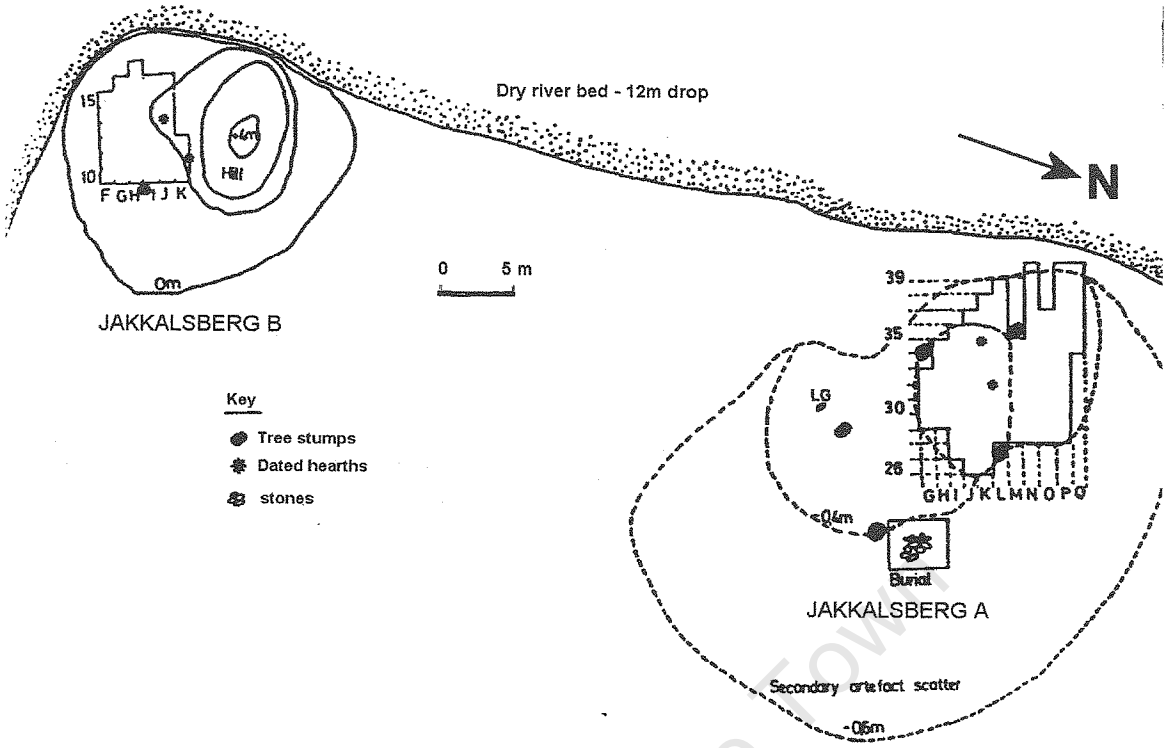

Figure 2.7 Map showing location of Jakkalsberg A and B on the banks of a dry tributary, 300 m to the south of the Orange River (after Webley 1997).

These deposits have been exposed and eroded and were situated at a bend in the Orange River. The fourth site, Jakkalsberg A and B was previously researched by Brink and Webley (1996) and Webley (1997), although an additional recent palaeoflood site in the vicinity, named for the purposes of clarity as Jakkalsberg O, was sampled. Additional analysis of scattered ostrich egg shell, located on the floodplain surface has been made by Hart (pers. comm.) on an open site known as Jakkalsberg N (Figure 2.6) and was situated in the vicinity about 30 m from the river. JKB N is described as a silt column with two layers of organic rich animal dung (sheep/goat) sandwiched between silt layers. Scattered OES beads located on the sediment surface were radiocarbon dated by Tim Hart. This information is useful given the choice of OES material that Zawada used and submitted for dating Lower Xobies' bed O. Jakkalsberg (JKB) sites A and B were located on the upstream plain of the Jakkalsberg Hill in the restricted mining area adjacent to the Richtersveld National Park (Figure 2.6). JKB A could be described as a small hillock

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(Brink and Webley 1996) that has been exposed (human and flooding influences) to reveal a cross section of silt flood deposits interspersed with two carbon (charcoal) rich hearths; JKB A is described as a more open site than JKB B, which is partially covered by a sandy hillock and situated 40 m south of JKBA (Brink and Webley 1996). JKB B is described as a partly covered hill exposure (also known as K11) comprised of silt deposits also interspersed with two charcoal hearths (Brink and Webley 1996). JKB O was situated in a sandy hillock, similar to that of JKB B, facing the JKB A site 10 m away from the river.

In Figure 2.7, the original Brink and Webley (1996) JKB site is mapped. Subsequent erosion has altered the original Brink and Webley site rendering it difficult to reconcile existing features with those of four years previously and the revised site map is illustrated in profile in Figure 2.10 for JKB A, and Figure 2.11 for JKB O. JKB B was not intact and therefore not analysed. Additional dates were required to verify the age of materials and these are reported in chapter 4 along with other analysis. These low-lying sites were situated on the floodplain and well below the perched 'threshold' palaeoflood deposits at Lower Xobies and Bloeddrift, first described by Zawada (1996).

The discovery of human remains at JKB A drove the initial focus of investigation by Webley. Due to the fragmentary nature of the remains however, it was not known if these were associated with occupation of the site and thus were not dated by Brink and Webley (1996). Other dates were obtained from archaeological deposits at JKB A and B, some 40 m apart and reported by Brink and Webley (1996) and Webley (1997).

Brink and Webley (1996) and Webley (1997) reported on two charcoal-rich hearth deposits found at JBK A which were interspersed with silt palaeoflood deposits. Situated 4 m apart and named "JKB A Hearth 1 and 2" Two additional hearths, also named Hearth 1 and 2 were dated at a site known as K11 at JKB B. These four sites (Figure 2.7) were dated at around 1 300 years BP and were considered to be related to 8th century occupation by herders (Brink and Webley 1996). Brink and Webley's 1996 dating results are discussed along with additional radiocarbon dating results in chapter 4.

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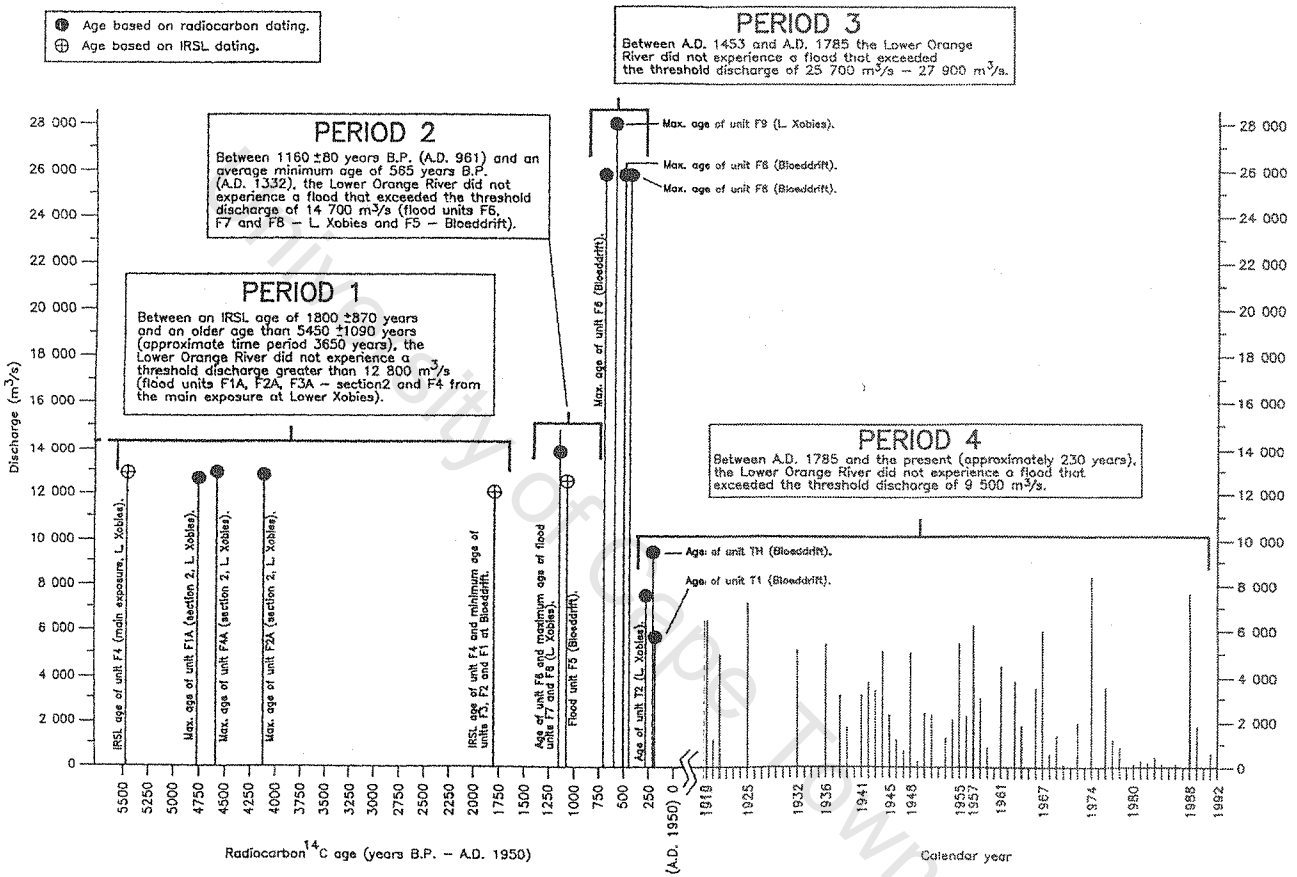

Figure 2.8 Compilation of palaeoflood records from Lower Xobies and Bloeddrift of the Orange River Catchment. Four palaeoflood periods identified by Zawada and represents major floods of the past 5 500 years (from Zawada 1996 and Zawada *et al.* 1996).

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2.3.4 Bloeddrift

Another sample slack water deposit site previously studied by Zawada (1996) and Zawada *et al.* (1996) used for dating and isotopic analysis was found at Bloeddrift (BLD), some 34 km downstream of the lower Xobies site at 28°21'50" S and 16°48'37" E. A small exposure, BLD 32 (Figure 2.3 and Figure 2.9), adjacent to the Zawada exposures was identified for analysis. This exhibited two archaeological lenses and was sampled and analysed.

This site consists of three cross-sections of flood deposits at 400 m, 450 m and 2 125 m respectively downstream of the Orange River Bloeddrift tributary confluence. The cross-sections were surveyed and described by Zawada (1996) and Zawada *et al.* (1996). Stratigraphic profiles (Figure 2.9) show various palaeoflood units revealing their maximum elevation above the channel (Zawada 1996). The top T1 unit corresponded to RB1 at Lower Xobies according to Zawada's palaeoflood discharge estimates of 5 580 $m^3.s^{-1}$and 5 580 $m^3.s^{-1}$respectively. These two records of discharge volume are both consistent with a measured flood discharge during the 1929 to 1950 period at Vioolsdrift. Figure 2.8 indicates Zawada's estimated flood discharge volumes for the lower reaches of the Orange River. The sample site identified for this research at Bloeddrift, BLD 32, is a site adjacent to the Zawada Bloeddrift exposures and proved both archaeologically rich but also provided useful evidence of palaeoflood deposits, which were well interspersed with archaeologically robust material for dating.

2.4 Richtersveld samples

2.4.1 Richtersveld bulk sediment

The first site described refers to a collection of sample points on the Lower Orange River, Richtersveld which were sampled during the low discharge period of April 1999. The sample sites from the Orange River are named WT and indicated in Figure 2.3 and are listed in Table 2.2. All samples were taken from shallow portions of the river where

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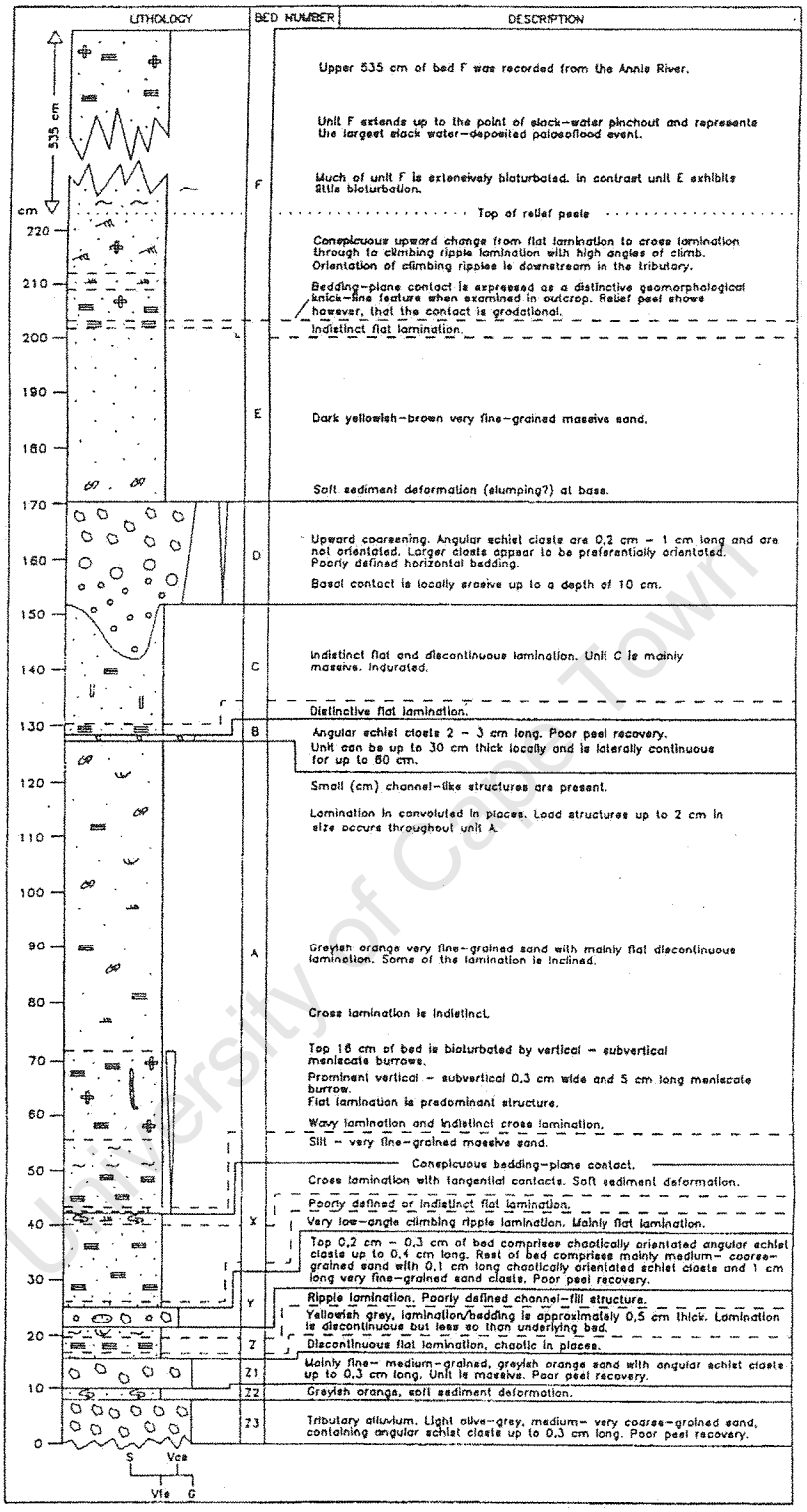

Figure 2.9 Bloeddrift palaeoflood stratigraphy (after Zawada *et al.* 1996).

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sediment would be removed during subsequent flood events further down the Orange River and possibly out into the mudbelt area. The river was lower than it is during flood events and therefore had left some areas of the river channel exposed for a few months of the year. Pothole sediment which had been exposed during this period was sampled. These samples were silt-rich (with coarse and fine grained silt elements) but had a small fine grained mud fraction. Being much more coarse grained than the mudbelt; they were therefore lithologically different from it by virtue of the predominant grain size.

The sampling field trip took the form of a canoe-based journey down a section of the Orange River, thus sampling was kept to a minimum. Sample sizes averaged ±500 ml each and clearly labelled in 500 ml plastic bags. Most samples were retrieved from shallow portions of the river and were obtained using a small trowel to lift sediment from the river sediments (up to 6 cm depth from the sediment surface) and placed in the plastic bag. Excess water was poured off until sufficient sediment had been collected. The pothole sample was much smaller with less than 200 ml being retrieved.

2.4.2 Lower Xobies

The Lower Xobies strata were well exposed due to the nature of the eroded river channel and sampling was a simple exercise. Therefore minimal cleaning of the exposed strata was necessary and samples were easily removed. The exposure was sampled at 10-15 cm intervals; all deposit layers were sampled, where 250 ml to 500 ml of material was sampled.

2.4.3 Jakkalsberg

A number of layers (midden, charcoal) were sampled for the purposes of dating by Brink and Webley (1996) and were re-sampled for the purposes of this research. JKB A, JKB O and JKB B have subsequently been removed by erosive flooding (Halkett pers. comm.).

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Orange River Modern sample	Latitude	Longitude
WT 4/NO3	28°22" S	17°24" E
WT 4/R2	28°22" S	17°24" E
WT 2/POT	28°23" S	17°25" E
RC /C/99	28°34" S	17°25" E
WT 2/SC	28°34" S	17°25" E
WT 13/#3/3	28°40" S	17°24" E
WT 13/#3/4	28°40" S	17°24" E
WT 13/#3/5	28°40" S	17°24" E
WT 1/LNCH	28°42" S	17°28" E
WT 1/#1	28°41" S	17°35" E
WT 1/#2	28°41" S	17°35" E
WT 1/BPM	28°41" S	17°35" E

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Table 2.2 Richtersveld Orange River bulk sediment sites and coordinates.

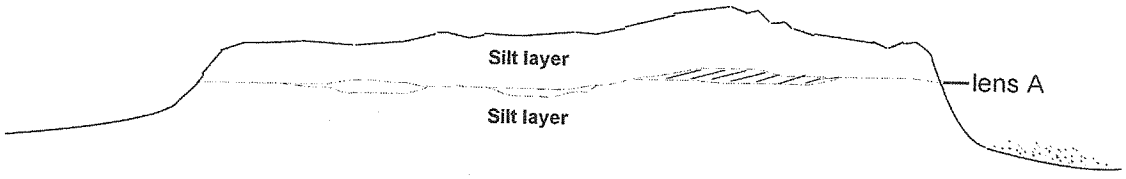

Figure 2.10 Jakkalsberg A (JKBA) in cross-section during 1999.

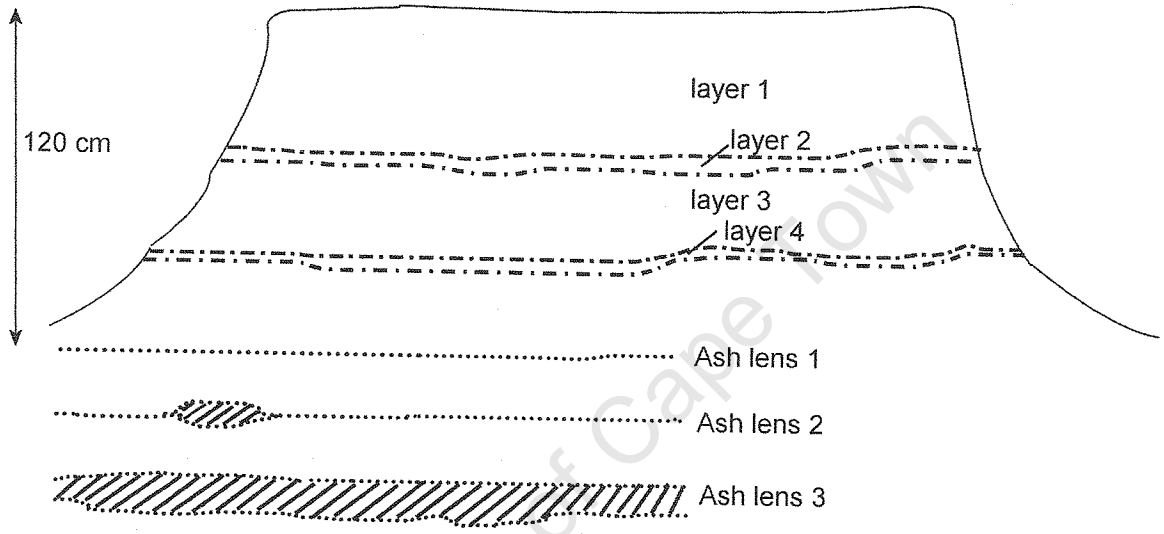

Figure 2.11 Jakkalsberg O (JKBO) in cross-section during 1999.

Samples at Jakkalsberg A and N were extracted during the September 1999 expedition. These were excavated and sampled and packed in plastic bags of ±2 000 ml, where dating analysis was necessary. About 500 ml of sediment was sampled when there was no need for bulk organic dates to be obtained. Jakkalsberg A and B were situated on the floodplain on the southern bank of the Orange River (Figure 2.3). However, there was difficulty in correlating sites with previous research by Brink and Webley (1996) as erosion had significantly affected the deposits and original maps were therefore open to interpretation.

A new sample, a charcoal lens, at Jakkalsberg A (JKB A CL), at a depth of 20 cm, was submitted for dating to provide correlation with previous research, as erosion had altered

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the site during the intervening years.

Two organic (dung) rich soil samples were also submitted for bulk radiocarbon dating. These were located at 900 mm (layer 4) and 700 mm (layer 2) below the hill surface. Other samples from JKB O which were submitted for dating included two ash lenses. These layers interspersed the flood deposits and were sub-sampled for possible pollen analysis (although these were expected to be palynologically clean/inert), TOC and stable light isotope analysis.

2.4.4 Bloeddrift

Bloeddrift BLD 32 surface samples were taken at a depth of 102 cm and 72 cm beneath the soil surface and submitted for analysis. The first sample (BLD 32 CL1) was a bone (sheep or goat) and charcoal rich and the second (BLD 32 CL) was a charcoal rich sample.

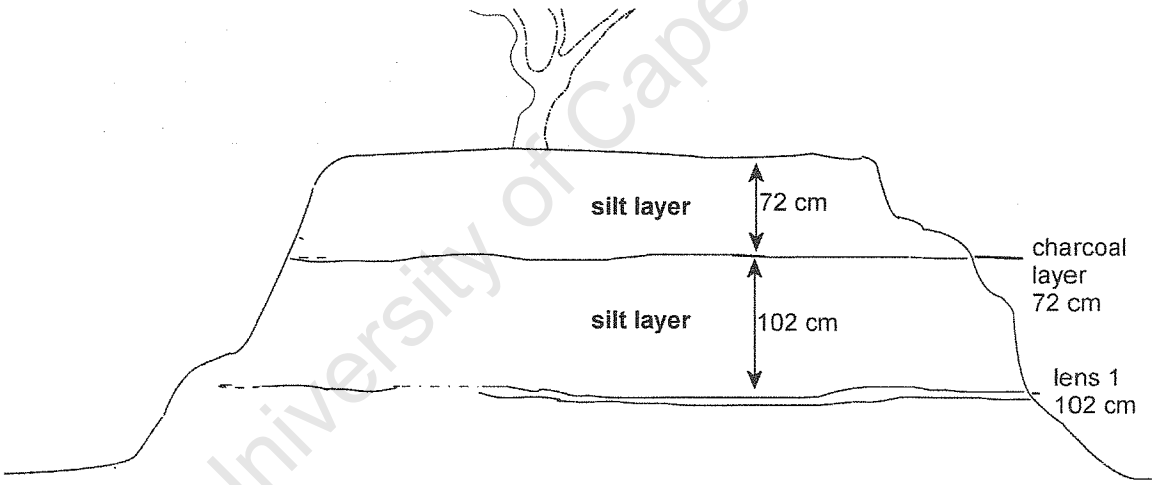

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Figure 2.12 Bloeddrift 32 (BLD32) in cross-section during 1999.

Sample sizes were similar to sediment sampled at Jakkalsberg. These samples were also sub-sampled for pollen analysis, TOC and stable light isotope analysis.

The description and interpretation of the age of sediment material at the study sites is

discussed in chapter 4.

2.5 Inner shelf and fluvial hydrodynamics and palaeoflood hydrology

The Late Quaternary has seen hugely varying contributions from both aeolian and riverine sources onto the continental shelf and forms the basis of work on offshore sediment cores of the Walvis Ridge by Stuut (2001). As mentioned in previous work (Gray *et al.* 2000 and Gray 1996), there is a complex array of factors controlling mudbelt sedimentation. These include but are not limited to climate, vegetation, land use patterns, erosion, soil residence time and ocean current conditions.

Nelson (1989) determined that deposition of sediment in the mudbelt is controlled by a southward-flowing countercurrent, which flows in an opposite direction to the prevailing cold northward flowing Benguela current. In a satellite image (Plate 2.2) taken during 2004, a fine sediment plume is visible which extends in an outward arc producing a thicker prodelta. However, the northward movement of sediment indicates that the bulk of the material and indeed the heavier fraction of sand and gravel are transferred to the north under the influence of wave-driven littoral drift (Rogers 1977b, after Hoyt *et al.* 1969). Fine sediment tends to be transported to the south where deposition is more gradual than initially might be anticipated.

Four hydrodynamic components can be identified on the inner shelf (Figure 2.13):

- The Fluvial component, namely the Orange River with smaller, erratic contributions from the ephemeral Buffels River.

  The Benguela Current. Northward flowing current carrying cold polar water. This is enhanced by baroclinic jets created on the shelf break and terrace edge which produces an area of upwelling (Nelson 1989). The nutrient rich polar water facilitates high biogenic productivity in the water and is considered to be the most powerfully sustained local wind-driven coastal upwelling of cold nutrient rich water world-wide (Sherman 1993).

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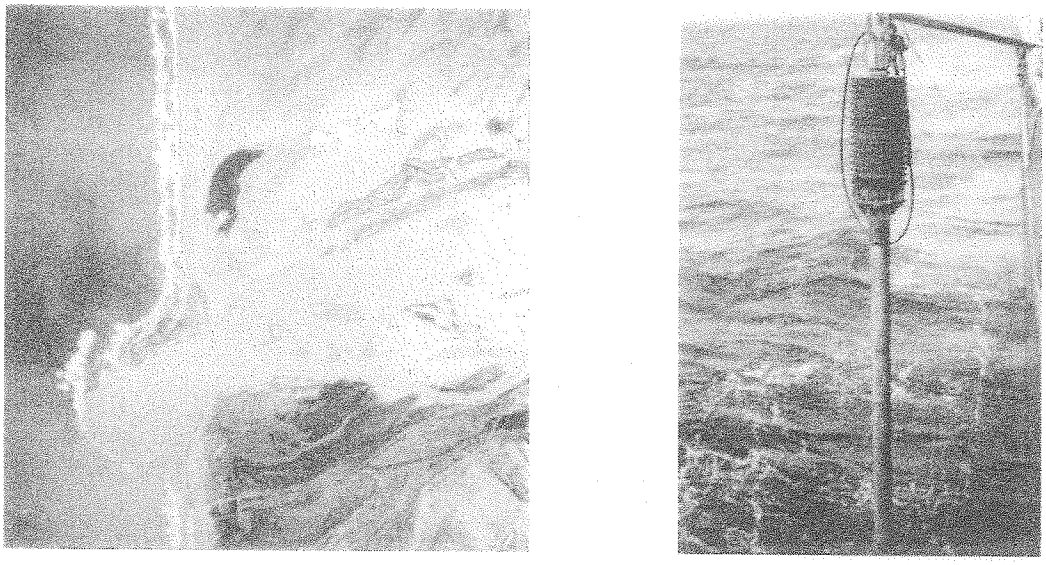

Plate 2.2 (L) Satellite image of the ORM sediment plume during flooding of 1988 (from Dingle 1994).Plate 2.3 (R) Gravity corer retrieving the OR Mudbelt HODSA cores (from Dingle 1994).

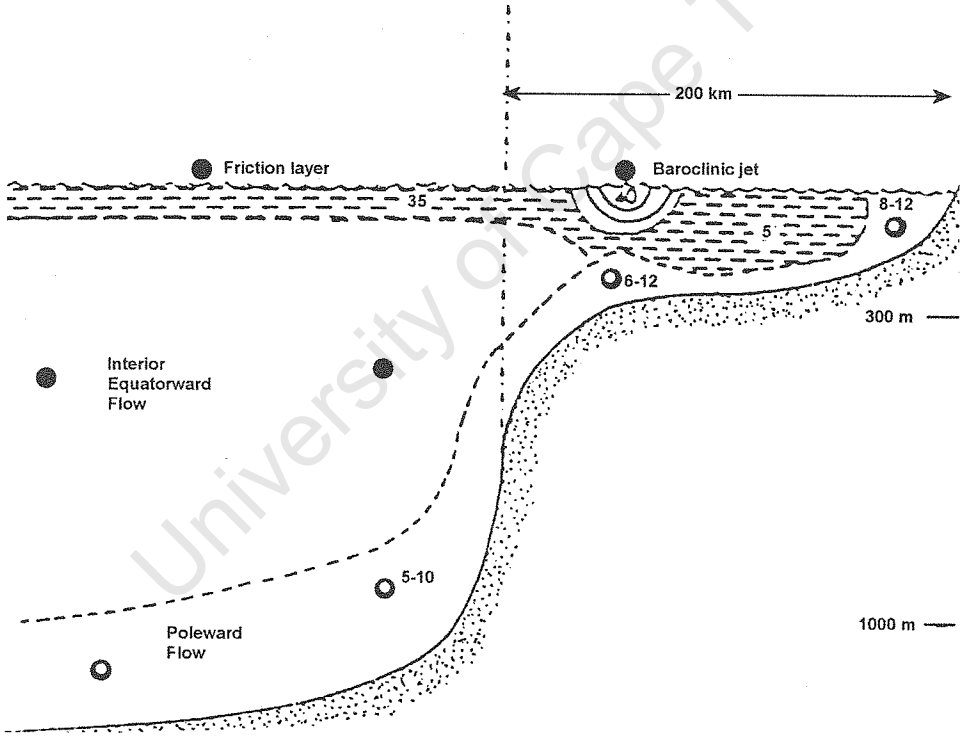

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Figure 2.13 Schematic of poleward and equatorward flow over the shelf and eastern Cape Basin with typical current speeds ($cm.s^{-1}$) (after Nelson 1989).

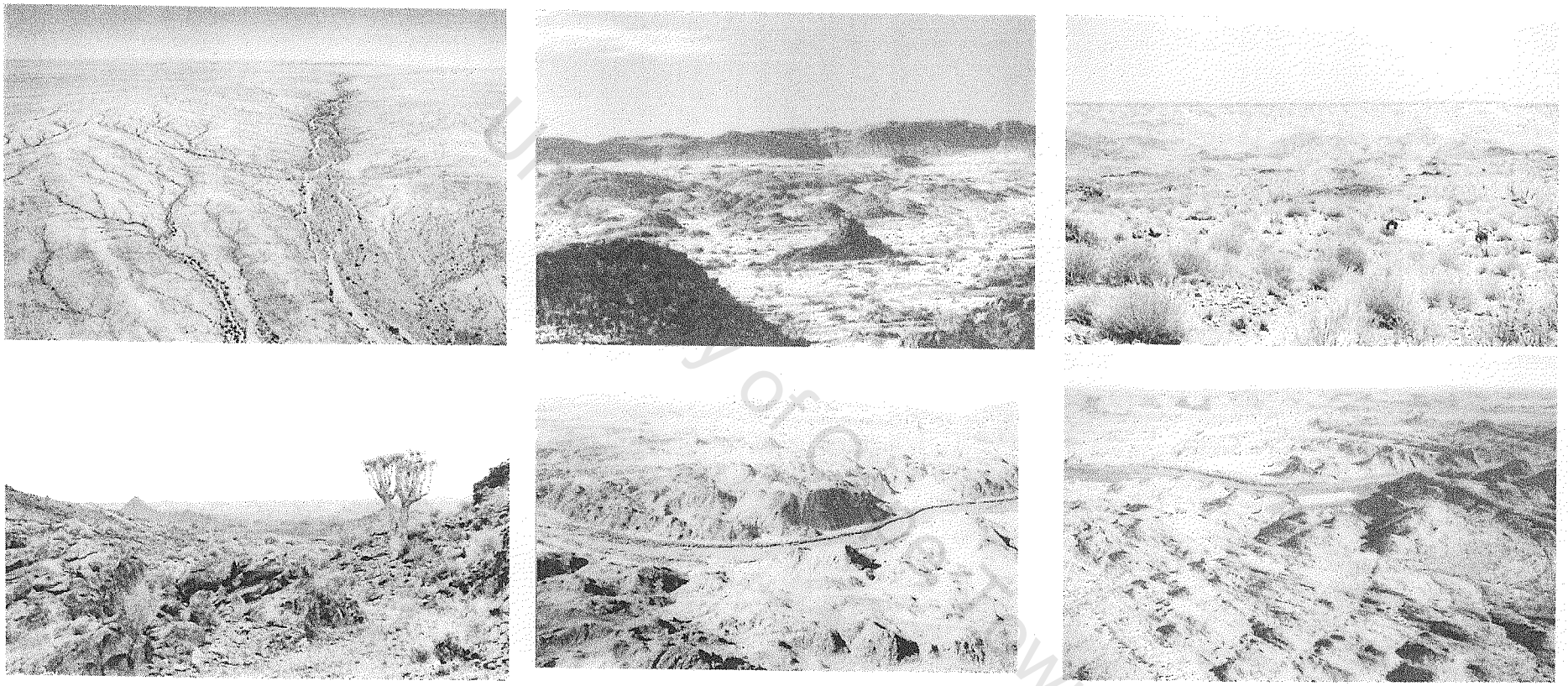

Plate 2.4 Photographs of the arid Richtersveld in the Lower Orange River. Vegetation is concentrated along the rivers and tributaries (bottom centre and right and top left), whereas it is more sparse further from the river. (photos: Tom Burgers).

- The poleward undercurrent, also known as the De Decker current (Nelson 1989) is thought to flow below the Benguela current, near the shelf bottom.

- Factors such as El Niño can account for semi-seasonal and occasional variations in the strength of the above components.

The Benguela upwelling system occurs off the west coast of southern Africa, as a result of Ekman transport (Jury and Brundrit 1992). This can be described as the effect of increasing coriolis deflection of currents with increasing depth, resulting in surface layers travelling in an opposite direction to lower layers. Strong along-shore currents interact with the edge of the continental shelf and are deflected away from the coastline, where they sink. Cold nutrient-rich water then rises to replace the surface water thus yielding exceptional levels of biogenic activity (Kennish 1989). This system is a typical feature of an open upwelling coast. Although the extent of the influence of upwelling on the mudbelt is not quantified and its intensity is variable, the centre of upwelling is however situated to the north of the mudbelt region. The influence should be considered in terms of the isotopic and reservoir age of the marine biogenic fraction of the mudbelt sediment and this is considered to be secondary as the vast majority of the organic matter, particularly that found in the prodelta closest to centre of upwelling, is probably terrestrially-sourced and the opal composition was therefore not considered.

The palaeoflood hydrology of a number of slack water deposits along the Orange River has been approached by Zawada and Hattingh (1993, 1994), Zawada (1996) Zawada *et al.* (1996) and a complex flooding history has begun to emerge.

Two sites that have been extensively used for this work are Bloeddrift and Lower Xobies. On the basis of palaeohydrology work on these sites, Zawada has identified 13 significant palaeofloods of the order of 10 000 to 15 000 $m^3.s^{-1}$ during the last 5 500 years. A "catastrophic" flood after AD 1450 would have measured approximately 28 000 $m^3.s^{-1}$.

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Recent flooding history includes the 1974 flood, measured as a gauged discharge of 8 330 $m^3.s^{-1}$, and the 1988 flood, measured as 7700 $m^3.s^{-1}$ (Bremner *et al.* 1990). An episodic flooding cycle of 11.8 years has been revealed in the OR during the last 200 years (Bremner *et al.* 1990, after Benade 1988). Also, the river is at times erratic and certain sections of it have ceased flowing from time to time (during the years, AD 1862, AD 1882, AD 1903, AD 1933, AD 1949, Bremner *et al.* 1990, after Warmelo 1927 and Kriel 1972). The record of palaeoflood hydrology (Zawada 1996, Zawada *et al.* 1996 and Zawada 2000) is detailed in chapter 4.

2.6 Vegetation

Six biomes are represented in the Orange River drainage basin, namely the Savanna, Grassland, Nama Karoo (semi-desert shrubland), Succulent Karoo, Fynbos and Forest. The Savanna Biome represents 46% of the interior of southern Africa (Low and Rebelo 1998) yet is not proportionally represented in the catchment. The Orange River is dominated by the Grassland Biome. Plant and animal biodiversity and endemism is high in these biomes, although not approaching that of the Fynbos Biome located far to the south of the area in the South Western Cape.

An estimated 13% of southern Africa is arable (Low and Rebelo 1998) and this arable portion of land is almost entirely used for agriculture. The current main issue related to agricultural land use includes loss of production capacity due to salinisation, erosion, acidification and compositional changes in rangelands. In addition, agriculture, forestry, conservation initiatives, mining and settlement requirements put greater pressure on the land. Much of the vegetation is therefore altered from its pre-colonisation format purely due to human management but the influence climate change has had on this, is yet to be quantified. Figure 2.15 indicates a vegetation map (Low and Rebelo 1998) of the "pre-colonial" vegetation of South Africa but this is not entirely representative of the present distribution of vegetation due to some of the above management issues.

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2.6.1 Biomes represented in the Orange River Catchment

The **Succulent Karoo** Biome is located in a thin band along the west coast for the first few kilometers of the lower reaches of the Orange River and north of the Cape Fold Mountains. More than 50% of this biome's over 5 000 plant species are endemic (Cowling *et al.* 1989, Cowling and Hilton-Taylor 1997, Milton *et al.* 1997) and over 60% of the plants are CAM species (Werger and Ellis 1981). Much of this biome is found on flat or undulating topography below 800 m (Low and Rebelo 1998) but some sections are found up to 1 500 m elevation. This biome is predominantly situated on weakly developed shallow lime-rich soil (Low and Rebelo 1998). A large proportion of

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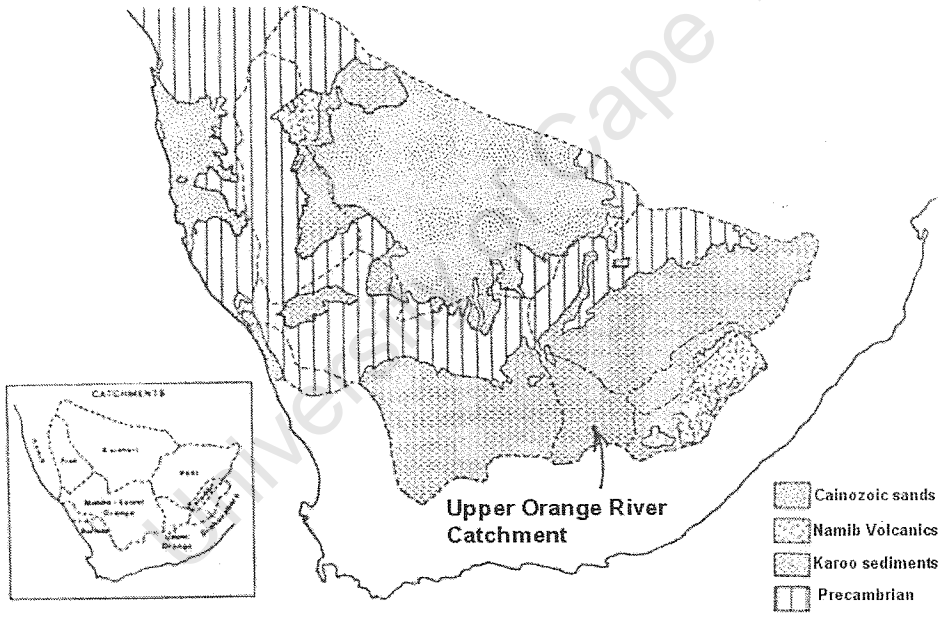

Figure 2.14 Simplified Geology of the Orange River Catchment and the Namib Desert (After Rogers 1977a).

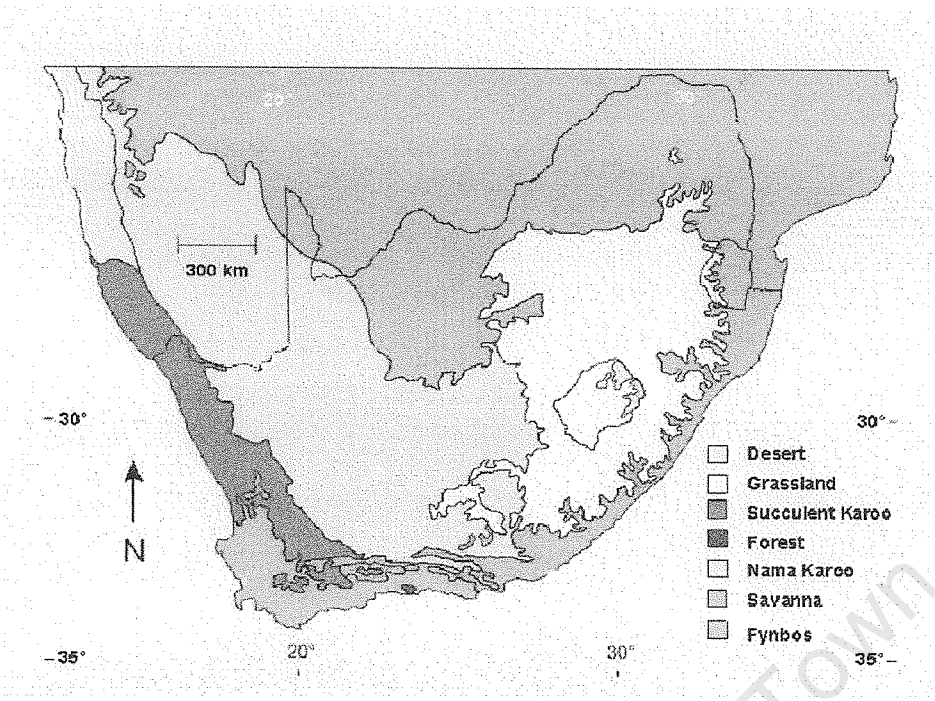

Figure 2.15 Vegetation biomes of southern Africa incorporating area covered by the Orange and Buffels River Catchments (after Scott and Lee Thorp 2004).

plants are dwarf leaf-succulents of the Mesembryanthemaceae and Crassulaceae families due to the intense aridity of the region, with limited rainfall of 20 - 290 mm.yr^{-1} occurring almost entirely during winter along with precipitation as coastal fog (Low and Rebelo 1998, Milton *et al.* 1997). The Crassulaceae family is the most species-rich in southern Africa and the succulent Karoo is a centre of African diversity for this family, with more than 2000 species (Milton *et al.* 1997 and Tőlken 1985).

The **Grassland** Biome is situated on the interior plateau. This high-altitude vegetation is considered to have attributes similar to the Fynbos Biome, in as much as it is the second most endemic biome after Fynbos, it is dominated by geophytes and herbaceous plants and grasses as trees are largely absent (Low and Rebelo 1998, O'Connor & Bredenkamp 1997). This biome dominates the catchment of the Orange River both spatially and by virtue of its C_4 photosynthetic pathways, although this changes to C_3 at high altitude (Low and Rebelo 1998, Scott and Lee Thorp 2004). The Grassland Biome is suited to a range of rainfall varying from 400 to 1 200 mm yr^{-1} and altitudes of sea level up to

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3 300m (O'Connor and Bredenkamp 1997). The grassland is largely uniform but possesses some floristic variation that can be attributed to the wide environmental range across which it is found (O'Connor and Bredenkamp 1997). This biome is commonly used for maize agriculture. Less important crops include sorghum (a traditional crop), wheat and sunflowers, which are less widely farmed (Low and Rebelo 1998). This biome tends to tolerate fire well and sweet grasses support stock during winter, whereas sour grasses do not and are more common above 625 mm annual rainfall. This biome has been heavily utilized for crops and urban development.

The **Savanna Biome** is the largest biome in southern Africa, occupying 46% of its area (Low and Rebelo 1998), predominantly across the Lowveld and the Kalahari, Botswana and Namibia. It extends broadly from sea level to 2 000 m and rainfall varies from 235 mm to 1 000 mm (Low and Rebelo 1998, Scholes *et al.* 1998). It is characterized by woody plants forming the upper layer and a grassy ground layer. There are three subtypes –shrubveld (upper layer is close to the ground), woodland (dense upper layer) and bushveld (intermediate upper layer) (Low and Rebelo 1998). The factors constraining development of the savanna are complex but a limited amount of rainfall is a prerequisite. This effectively limits the upper layer from developing further (Low and Rebelo 1998). Additional limiting factors include fires, grazing and summer rainfall which encourages grass dominance; most species are re-sprouters. Grass layers are dominated by C_4-type grasses, which are maximized areas of hot growing season. Winter rainfall areas are dominated by C_3-type grass (Low and Rebelo 1998).

Some patchy representations of the **Forest Biome** as Afromontane scrub are predominantly represented in the Lesotho Highlands.

The Nama Karoo, or semi-desert dwarf shrubland is found on the central plateau between 500 and 2 000m. It has a summer rainfall pattern that varies between 100 and 520 mm per year (Low and Rebelo 1998) and the grass is mainly C_4 type. Similar to the Succulent Karoo, it too is found on lime rich and weakly developed soils (Low and Rebelo 1998). Asteraceae, Poaceae, Aizoaceae, Mesembryanthemaceae, Liliaceae and Scrophulariaceae dominate the biome (Palmer and Hoffmann 1997). Overgrazing may

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lead to the proliferation of natural species, Threethorn *Rhigozym trichotomu*, *Chrysocoma ciliata* and Sweet Thorn *Acacia karroo*, with a proportional decrease in palatable grasses (Low and Rebelo 1998) and other species.

2.7 Southern Africa climate, wind pattern

The prevailing weather pattern influenced by the regional atmospheric circulation, along with its daily, seasonal and more long-term variations is incorporated into the "composite" term climate (Schulze 1997). The arid climate of the southern African subcontinent is influenced by an array of climatic factors, interacting to affect and produce seasonal and long-term climatic change at a range of different scales. The relationship with modern climate and vegetation and its changes, despite its complexity, is integral to the understanding of any palaeovegetation study.

The atmospheric circulation in southern Africa is based at an interface between two atmospheric systems, the tropical systems (the easterlies) to the north and the temperate atmospheric systems (the westerlies) to the south (Chase and Meadows 2007). These include the polar westerlies, anticyclones (both continental and subtropical anticyclones over the oceans) and the movement of these along with the Intertropical Convergence Zone (ITCZ) (Tyson and Preston-Whyte 2000, Chase and Meadows 2007). Along with three oceanic systems (the Atlantic, Indian and the Antarctic waters of the southern oceans), these atmospheric systems dominate the subcontinent. Perturbations within this create daily, seasonal and more long-term changes in weather and therefore precipitation patterns.

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The following atmospheric systems affect southern Africa:

- The polar westerlies, which migrate towards the equator during winter and influence the southern and western margins of southern Africa.

- The Intertropical Convergence Zone (ITCZ) migrates seasonally bringing monsoonal rain to the tropics which is fed by high sea surface temperatures and warming of the continent to create strong convective cells. It follows that this

system would be diminished in strength during glaciation.

- Temperate frontal systems embedded in the westerlies, and strengthened during the Last Glacial Maximum, result in the winter rainfall zone (WRZ) (Tyson and Preston-Whyte 2000). This zone is a feature of the southern and western coasts. Winter rainfall is directly produced by the development of temperate frontal systems in the polar westerlies, which move northward during the winter and are accompanied by a northward shift of the ITCZ (Tyson and Preston-Whyte 2000). Areas of transition on the other hand may be influenced by both winter and summer regimes from time to time and also appear to be affected by oceanic circulation and accompanying sea surface temperatures (SST) (Nicholson 2000).

- The seasonal interaction between subtropical high-pressure cells and migrations of the tropical easterlies, tied in with movement of the ITCZ and its more southerly position, result in the summer rainfall zone (SRZ). This zone affects rainfall in the north and east.

Oxygen–isotope analysis of deep-sea core sediments and cave deposits have identified glacial and interglacial periods until the Last Glacial Maximum (LGM) which had certainly ended by around 15 000 BP (Talma and Vogel 1992, Holmgren *et al.* 1999), although estimates vary from 23 000 cal yr BP to 19 000 cal yr BP (Chase and Meadows 2007). Water temperatures appear to have risen by about 5 °C since glacial times, although the majority of the land was considered to have had a periglacial climate at least during the LGM (Preston-White and Tyson 1988).

Climate change has varied in amplitude from mild to considerable during the late Quaternary (Holocene) (Meadows 2001, Deacon and Lancaster 1988). Scott and Lee-Thorp (2004) refer to the significant impact this has had on people, flora and fauna of the subcontinent. Generally, it is thought that the westerlies and the continental anticyclones strengthened during the late Quaternary and with their increase in intensity and frequency, most probably shifted equatorwards due to meridodonal shifts north in the atmospheric circulation system during the LGM accompanied by a northward expansion

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of the winter rainfall area (Dupont and Wyputta 2003); however, some sources argue for the westerlies being fixed in position at this time (Nicholson 2000) and certain GCM's suggest a poleward shift. However, it is considered that the Antarctic sea-ice expanded and winter storms became more intense, possibly explaining records of a more humid southwestern Africa (Stuut *et al.* 2004, van Zinderen Bakker 1976). Conditions are indicated to have been cooler, but not necessarily drier, as certain sites across a variety of biomes have indicated a much more complex moisture signal (Wonderkrater, Equus Cave); some areas point to increased aridity (e.g. Tswaing Crater, Scott 1999), while others point to possible increased moisture (Chase and Meadows 2007). Indeed, a situation of increased humidity during glacials and increased aridity during interglacials seems to be apparent on the west coast of southern Africa despite a more widespread trend towards aridity; this may be a direct result of increased Antarctic sea-ice which in turn may be driving the westerlies towards the equator. The northward shift of the winter rainfall area may have covered the entire ORC during the LGM, according to some sources, although more conservative models, such as Heine 1981 (after Chase and Meadows 2007), indicate a much smaller representation within the ORC amounting to little over 30% of its expanse. After the LGM, the late glacial period (18 000 to 11 500 cal yr BP) represented a period of transition between the glacial maximum and establishment of the Holocene (the last 11 500 cal yr BP). During this period, studies within southern Africa point to a warmer and more humid period under the banner of the African Humid Period (AHP) and occurring between about 14 800 up to and including the warmest period within southern Africa, the Holocene Altithermal (HA) period of between 8000 and 5500 cal years BP (De Menocal *et al.* 2000), temperatures may have increased between 2°C and 3°C in areas, but other regions suggest closer to about 1° C increase (Chase and Meadows 2007, after Heaton *et al.* 1983). This period may have been characterized by warm arid conditions, particularly in the western Cape section of the winter rainfall regions and increased rainfall in Namibia to the north and in the summer rainfall area, due to increased monsoonal rain (Chase and Meadows 2007). More moist conditions are reported at Klaarfontein and Cecilia Cave and might have indicated an increase in the activity of polar westerlies (Chase and Meadows, after Baxter 1989 and Cockcroft *et al.* 1987). After the AHP, cooling occurred and these same areas,

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mentioned above, experienced a reduction in temperature between 4000 and 2000 cal yr BP of 3° C and 0.5° C respectively, which corresponds with the 'Neoglacial period' (Talma and Vogel 1992). Evidence of the Medieval Warm Epoch (900 – 1300 AD) and the Little Ice Age (1300- 1850 AD) are found in some southern African records, but appear to be less widespread and of low amplitude compared to the AHP or HA (Chase and Meadows 2007). Evidence from Scholtz 1986 indicates an arid period occurred between 2700 and 1300 cal yr BP, during which forest development, located in a year round rainfall area in the southwestern Cape, was hampered.

As the chronology (chapter 4) suggests, the mudbelt material is of Late Holocene (Late Quaternary) time period. If we are interested in establishing the extent of climate change and its effects on biota in the interior, avenues of investigation are very limited. Records of Quaternary vegetation from glacial-interglacial periods in southern Africa are generally fragmented and characterized by short sequences (Scott *et al.* 1997) as the generally arid conditions tend not to be conducive to preservation of continuous 'traditional' proxy palaeoecological records (Chase and Meadows 2007). Modern biome patterns had already been established by the beginning of the Quaternary period but it is the shift in composition within this broader pattern in the period represented in the mudbelt sediments (specifically the HODSA cores), that is the focus of our interest and Pre-Quaternary palaeoclimate is not dealt with here.

The amount of solar radiation is rarely a vegetation-limiting factor in southern Africa, but topography may affect microclimates adversely. Generally mean annual temperature is low over elevated areas, such as the escarpment and higher over the northeastern coastal belt and the east coast of southern Africa, close to where the warm Mozambique current sweeps southwards; temperatures generally increase in a westerly direction. Temperatures are therefore lower in the Lesotho highlands, in the Orange River's headwaters and highest in the lower reaches. Frost conditions are typical in high altitude regions of the interior during the winter months.

Water, however, does limit vegetation in southern Africa and is mainly manifested as rain and fog (west coast). Snow occurs on the Drakensberg escarpment and in Lesotho but is

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often shortlived and melts within days. Generally, rainfall in southern Africa decreases from the escarpment east to west (Figure 2.16) with some increased rainfall sub-regions on the south coast and western Cape interior. Many factors are responsible for this including: altitude, ocean currents (warm Mozambique, cool Benguela), distance from the sea, aspect and topographic and physiographic "roughness" (Schulze 1997). Perhaps a more important aspect to be considered in light of the above, is annual variability in precipitation. Precipitation varies widely and is less than 25% in eastern southern Africa but it is up to 40% in the western half. In addition, rainfall is a seasonal phenomenon and although most of southern Africa experiences summer rainfall, the southern coastal area of the Western and Eastern Cape experience year round rainfall and much of the Western Cape experiences winter rainfall. Within this framework, areas tend to experience rainfall at a predictable time of season, for instance either late or early summer. The ORC primarily draws on summer rainfall regions in the upper catchment, where rains are primarily early summer (December), the rainfall seasonality pattern moves later in the season as the river draws closer to the mouth.

The above pattern is consistent until the river reaches the Succulent Karoo Biome, a reasonably wide coastal band, where winter rainfall predominates. Much of the precipitation is often fog-related, due to the dominating effect of the cool Benguela current and upwelling resulting in radiation and advection fog. Estimates of fog precipitation up to 3 km inland have been made by Nagel (Schultz 1997, after Nagel 1962) as being 300 mm per year in the Western Cape and 150 mm per year as far north as Swakopmund. Fog is correlated with the moisture content of air and is therefore more frequent in winter in winter rainfall areas (and summer fog in summer rainfall areas). Fog incidence correlates well with the presence of vascular epiphytes (Schulze 1997), where it plays an important role in the coastal Succulent Karoo Biome.

A 400 mm isohyet or rainfall line exists dividing southern Africa into distinct eastern and western halves. Although a large central area of the country receives an average of 400 mm rain, the isohyet divides the land into the eastern crop growing area and the western livestock grazing or irrigated land crop cultivation region.

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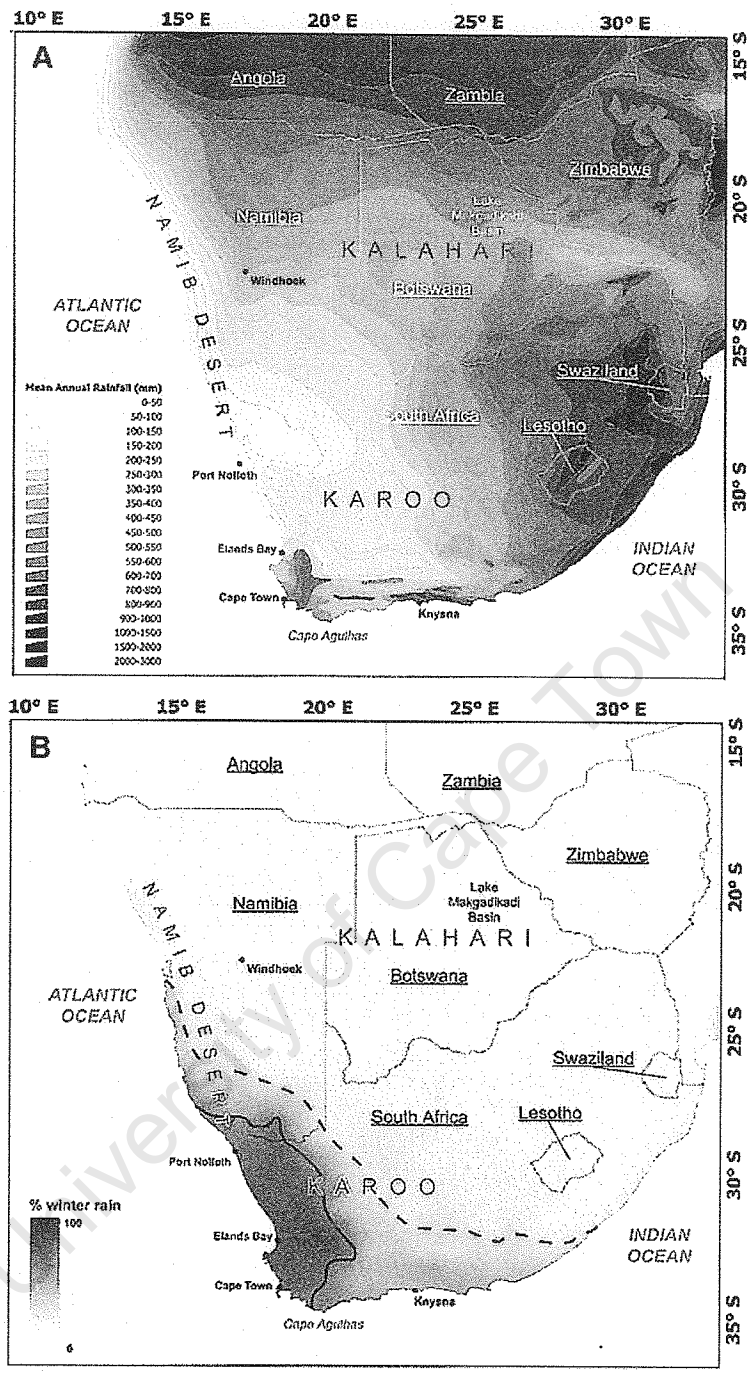

Figure 2.16 Current mean annual rainfall over southern Africa (A) and the current extent of the WRZ (winter rainfall zone), YRZ (year round rainfall zone) and SRZ (summer rainfall zone) indicated by solid and dashed boundary lines for the WRZ and ZRZ respectively. (B) (after Chase and Meadows 2007).

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The northwest has an annual rainfall below 200 mm but tremendous variation occurs along the coast, whereas much of the Eastern highveld experiences an average 500 to 900 mm, sometimes up to 2 000 mm rain per year. Potential evaporation is much higher, at 91%, in southern Africa than the global average of 65%. It is greatest in the lower reaches of the Orange River and decreases progressively higher up in the basin.

The atmospheric circulation in southern Africa is complex (Stuut and Lamy 2004, Nicholson 2000) and there is still much to be learnt as to the aspects, nature and intensity of driving forces of environmental change and General Circulation Models (GCM's) are as yet incomplete. The scattered, sparse nature of climate records within southern Africa is not entirely representative of the broader climate picture and some studies contradict each other (Barker and Gasse 2003, Chase 2006). Numerous subsequent perturbations and cyclical variations have occurred during glacial and interglacial times.

2.8 Historical land use

Hunter- gatherers were established in the subcontinent from at least early Stone Age times but human impact was minimal prior to the arrival of farmers and pastoralists in the last 2000 years or so (Deacon & Deacon 1999, Mitchell 2002). It is debatable whether either of these groups had any kind of long lasting influence on the landscape (Sealy pers. comm.) as it is hard to determine the impacts they had. Generally, researchers suggest that the influence was small enough to be balanced out by resilient vegetation due to overall low impact. They brought with them sheep and cattle (Scott and Lee Thorp 2004) and were reliant on the subtleties of the prevailing climate and seasonal changes, moving in response to societal needs. Thus, the so-called Iron Age agriculturalists settled in the moist eastern part of the country and the Stone Age pastoralists were found to occupy the drier west (Deacon & Deacon 1999, Mitchell 2002).

The pastoralists moved seasonally, in search of water and fresh pasture. Hunter-gatherers also tended to be found in the west and there is evidence to show they interacted with each other. It is difficult to categorise the mode of subsistence purely on the 'archaeological residue' (Maggs and Whitelaw 1991) and Shrire suggests that some

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classifications have been biased according to early European artistic impressions[4]. These two groups are currently known as the San (was 'Bushmen') and Khoi (was 'Hottentot') (Maggs & Whitelaw 1991, Deacon & Deacon 1999, Mitchell 2002). The Khoi, who were sometimes known to herd sheep and cattle, goats were mainly hunter-gatherers but many may have settled into a pastoralist mode. The San herded sheep, goats and cattle and were known as pastoralists (occupying a "hunting gathering niche"). The pastoralist 'economy' along with much of its oral history eventually declined due to heavy hunting by the colonial frontiersmen (Maggs & Whitelaw 1991).

Recent evidence from the Richtersveld Jakkalsberg site, originally researched by Webley (1986) and Brink & Webley (1996), indicates that Namaqua pastoralists have recently tended to congregate around permament waterholes during the dry hot summer and separated during winter into small herding units situated at so called stockposts (Maggs and Whitelaw 1991, Brink & Webley 1996). Records from the Bethelsklip site indicate this has been ongoing since at least the 12th century (800 years plus) (Maggs and Whitelaw 1991).

This has had a minimal effect on the environment when compared with the present scale of adjustment and response the vegetation of southern Africa and indeed the ORC has made in more recent times. European settlers arrived 400 years ago and subsequently have made their mark on the landscape with the last 45 years (Cunningham and Davis 1997, Hoffman 1997) having the most impact due to urbanization and population explosion. The first recorded arrival of European settlers in the Orange River was around 1777, although Europeans had visited the area as early as 1677, naming the river, Vigiti Magna (Williams 1902). Although disease and settler conflict resulted in decimation of the San population south of the Orange, the general population has grown significantly and has placed intense pressure on land resources in the ORC, resulting in extensive

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[4] For example, Burchell's 1812 illustrated 'View of a Bushman Kraal' (Cullinan 1992).

commercial agriculture and alteration of the landscape. Much of the cropland, now reflects little of its former indigenous vegetation.

Currently a few indigenous crop plants are grown and harvested. These include rooibos tea (*Aspalathus linearis*, Fabaceae), buchu (*Agathosma betulina*, Rutaceae), protea flowers, ferns, marula fruit and thatch reed (particularly on poor quality land) (Cunningham and Davis 1997). Staple food crops originating in South and Central America arrived in southern Africa with Iron Age farmers and Portuguese (arrival of ships on the east coast) during the last 400 years (Wells *et al.* 1986). These crops tended to be limited to summer rainfall areas and included sorghum (*Sorghum bicolor*, Poaceae), pearl millet (*Pennisetum glaucum*, Poaceae), finger millet (*Eleusine coacana*, Poaceae), Livingstone potato (*Plectranthus esculentus*, Lamiaceae), melon (*Citrullus lanatus* Cucurbitaceae) and have been used as subsistence and commercial crops but have mostly become less important, whereas sweet potato, tomatoes, cassava, potatoes, maize, wheat crops have become more prominent. Previously, only indigenous African cereals were present, with distribution limited to suitable summer rainfall areas.

2.9 Sedimentology, lithology, geochemistry and geology of the mudbelt and source sediment

Although the west coast continental shelf has experienced a series of scouring and mudbelt development during sea level low stands, high stand postglacial deposits are undoubtedly Quaternary in origin. These deposits sit unconformably on underlying Cretaceous sediments. The underlying continental shelf is comprised of much older Precambrian rock and gravels (De Decker 1987).

The inner shelf is late Precambrian in age (Rogers 1977a, De Decker 1987; Compton *et al.* 2002) and extends some 2 to 10 km offshore in places where the underlying Upper Cretaceous sediments of the middle shelf emerge (De Decker 1987, Woodborne 1991). Older deposits have a complex history as sea levels rose and fell during a series of polar glacial advance and retreat and associated ice volume changes. Sediment remnants are found in thin veneers (Rogers 1977a,b, Rogers and Bremner 1991) or packages below

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Quaternary sediments, where researchers, such as McMillan (1993) have been able to correlate episodes of sedimentation using benthic foraminiferal analysis. In addition phosphorite nodules made of reworked pebbles have been found in the mudbelt and are discussed in Compton *et al.* (2002). As the postglacial sea level has receded, the delta has prograded. During the Quaternary, sedimentation on the continental shelf has been limited and has also reflected a relatively stable period of uplift or subsidence, compared with a complex history of previous warping (McMillan 1993, Du Plessis *et al.* 1972). Despite fluctuations in sea level during the post glacial period (Jerardino 1995), which has resulted in some basal sand and gravel deposits on the shelf (Shackleton 1987 and Compton *et al.* 2002), conditions have been conducive to preserving a record of Late Holocene sedimentation on the inner shelf (Figure 2.17).

Both the sedimentological composition of the mudbelt and the development of the prodelta at the mouth of the Orange River testify to the terrigenous nature of the Holocene deposit (Meadows *et al.* 2002). The sediment is clay- (<2 μm) to silt- (2 to 63 μm) rich (Birch *et al.* 1986, Mabote 1997) and has been described by a number of authors as being a continuous and wedge-like "acoustically transparent" body (Birch 1975 after O' Shea 1971, Birch 1975, Birch *et al.* 1976, Rogers 1977a,b, Birch *et al.* 1986, De Decker 1987, Bremner *et al.* 1990, Rogers and Bremner 1991, Woodborne 1991 and Mabote 1997). Acoustic determination of units by De Beers Marine during 1999 have however, been unsuccessful due to acoustic scatter caused by the presence of gas bubbles within the mud.

Immediately after retrieval, the so-called HODSA gravity cores were split and described while the surface was still fresh (Dingle 1994). The cores measured a uniform 30 cm in diameter and varied between 1 and 6 m in length. Both H2 and H7 are 6 m in length. The cores are numbered in order of retrieval from north to south with the prefix "H" (H1 to H7). The highest rate of deposition is noted in H2, the core closest to the Orange River. This core is well laminated but displays the least logical chronology based on bulk organic dating (Meadows *et al.* 1997) where two age reversals are noted (Table 4.1, chapter 4). Preservation of laminations in the material closer to the Orange River Mouth or prodelta (H2) suggests higher sediment accumulation rate and minimal

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bioturbation (Dingle 1994, Mabote 1997, and Meadows *et al.* 1997). These laminations appear to decrease further away from the mouth.

The lithology in Figure 2.1 is described in Table B1 (Appendix B) in tabular format. The stratigraphy is poorly understood but two stratigraphic models have been put forward on the basis of stratigraphic descriptions of the HODSA cores. These models, A and B are found in Figure 2.18. The top layer of both H2 and H7 are composed of consolidated soft brown mud. In H2, below this mud layer, the stratigraphy is largely laminated soft brown to olive clay. Below the aforementioned brown mud layer common to both H2 and H7, H7 is composed of dark olive grey to dark brown clay near the surface and olive grey shelly clay at its base.

The upper catchment of the Orange River (in the Lesotho Highlands), is underlain by the Drakensberg basalts and erosion of this is related to illite (of the clay type smectite group) clay fraction (Zawada *et al.* 1996). Further along the Vaal to roughly 40 km upstream off the Vaal-Orange confluence, the river flows over the Karoo Supergroup, which encompasses the Drakensberg basalts and the younger strata of sandstone, siltstone, mudstone and shale of the Clarens, Elliot and Molteno formations. The river flows over the fine to medium gravel, sandstone, mudstone, dark shales and tillites of the Beaufort and Ecca group and the Dwyka Formation. Forty kilometers upstream from the confluence of the Vaal-Orange, the river flows over andesitic lava of the Ventersdorp Supergroup and dolomite, limestone, chert, banded iron formation and jaspilite of the Griqualand West sequence. Further along the river to approximately 75 km short of the mouth, the Orange flows through the Namaqua Metamorphic Province which consists of medium to high-grade metamorphosed gneiss (Tankard *et al.* 1982 and Zawada *et al.* 1996). The remainder of the river crosses a series of phyllite, quartz-chlorite schist, dolomite, basalts, andesitic lava, coarse grained quartzite and arkose of the Gariep Group or Richtersveld Sub-province (Zawada *et al.* 1996, Reid 1999). A simplified geology of the ORC and the Namib Desert is indicated in Figure 2.14.

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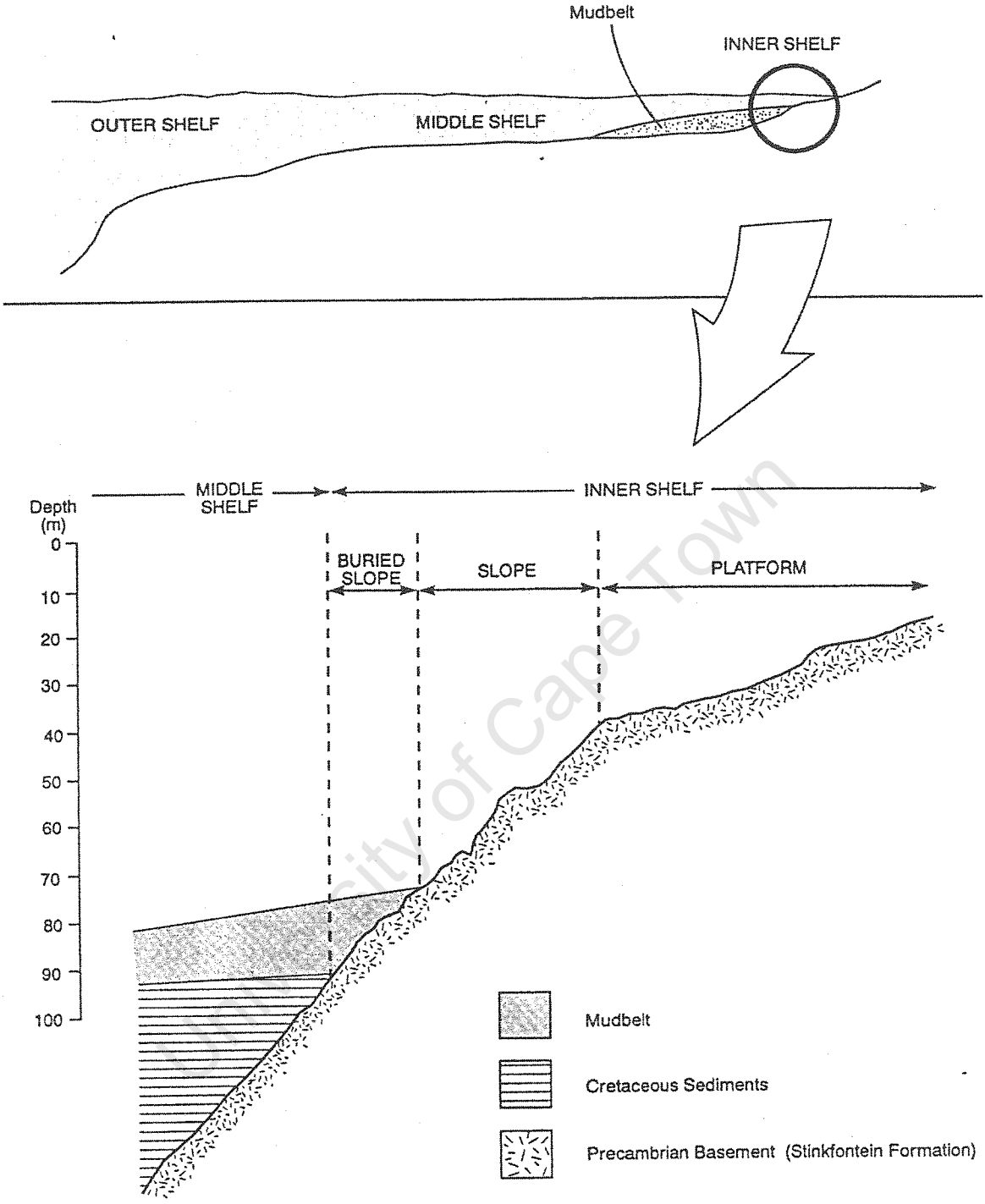

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Figure 2.17 Simplified bathymetry of the Namaqualand coast continental shelf (after Woodborne 1991 and Mabote 1997).

Mabote (1997) and Mabote *et al.* (1997) report on a detailed geochemical and

sedimentological analysis of the mudbelt material based on cores H2, H4, H6 and H7. This established grain size analysis of the mudbelt sediments as having a polymodal distribution which varies with depth; major modes generally fall within the fine-silt to very fine-silt (8μ-16 μ) range (Mabote 1997). Core H2 is characterised by medium to fine silt and H7 by a very fine to coarse clay range. Generally finer material was transported to the south of the mouth and coarser material to the north (Rogers 1977a,b). The polymodal nature of the sediments as pointing to mixing of more than one sediment source – possibly fluvial Orange River source material was mixed with berg wind aeolian material (Mabote 1997). The fining upward sequence on the delta suggested a rising sea-level during the Late Holocene (last ±1 000 years) (Mabote 1997; Dale and McMillan 1998; Compton *et al.* 2002). However, in general the Late Holocene (last 5 000 years) sea levels have been considered to be characterised by periods of relative stability (Compton *et al.* 2002) and current levels believed to have been reached between 7000 and 6000 years BP (Compton 2001). Herbert and Compton (in press) have observed that the mudbelt is characterised by much finer sediment to the south of core H7 and coarse grained sediment in the northern section of the mudbelt, although the prodelta tends towards finer sediment (Mabote *et al.* 1997).

Prodelta Cores H2, H1 and H3 were identified as dominated by terrigenous biogenic components such as plant fragments, but other non-biogenic components, including quartz sand mica from adiabatic berg winds and rock fragments from the ORC. Mabote (1997) observed samples to the south contained more marine biogenic components, such as sponge spicules, foraminifera, diatoms, shell fragments, fish scales and polychaete faecal pellets and this along with the polymodal grain size (signifying a mixing of sediment from two sources) suggests that the presence of greater quantities of marine biogenic components supports that the mudbelt off the Buffels River is not primarily derived from the Orange River. This assumption is not quantitative and only refers to the marine fraction, not the relative proportion of the inorganic fraction. Given the marine environment, a presence of marine biogenic components, it would be expected

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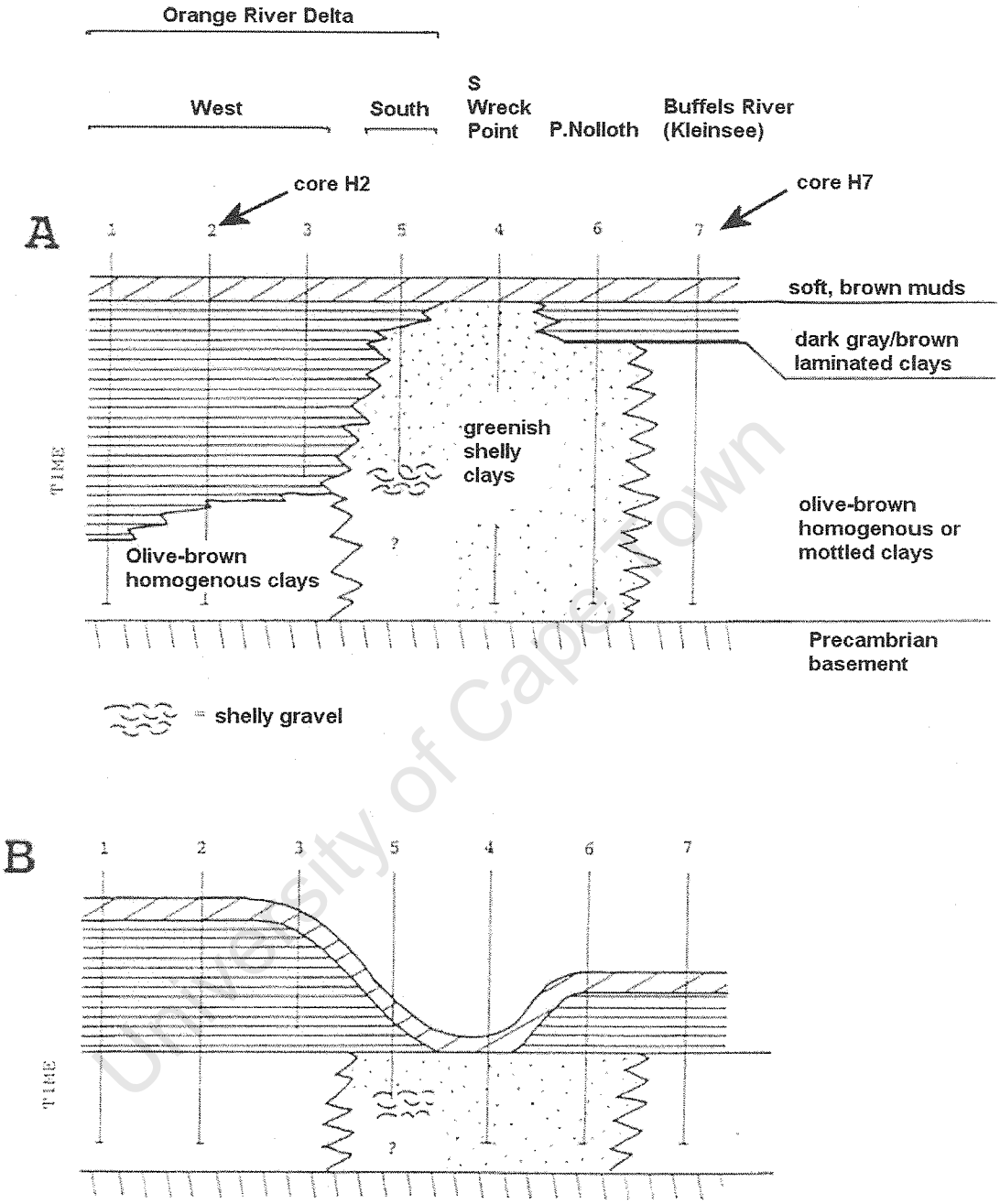

Figure 2.18 Two stratigraphic models, A and B used by Dingle (1994) to describe the possible stratigraphy of the mudbelt based on stratigraphic descriptions of the HODSA cores.

to be represented further from the ORM. Mabote concludes that analysis of the biogenic fraction points to the more terrestrial nature of the prodelta and the more

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marine nature of the rest of the mudbelt. These main conclusions were made on the basis of analysis of foraminifera and gypsum.The main conclusions of the Mabote (1997) study can be summarised as follows: The authigenic gypsum identified were associated with anaerobic conditions and its formation was related to sediment being primarily terrestrial on the prodelta and more marine elsewhere in the mudbelt. Gypsum was secondary and developed *in situ* as an authigenic component of the marine sediments and are neither reworked nor a product of post-sampling desiccation and preservation. The gypsum crystals are large unbroken tabular euhedral and were not consistently present throughout the core. Therefore, according to Briskin and Schreiber (1978) these crystals cannot be a product of desiccation. Gypsum-bearing layers are restricted to the bottom of Cores H4, H6 and H7 off Namaqualand, but not in cores H2 and H3 on the Orange Prodelta. Calcium concentrations were highest on the inner shelf (H7) and lowest at the prodelta relating directly to calcium carbonate originating from foraminiferal sources, suggesting terrestrial sediment is calcium poor. Cores H1, H2 and H3 contained no authigenic gypsum (Mabote 1997), which requires significant calcium levels in order to be produced and therefore appears to support Mabote's assertion, explaining the low presence of calcareous foraminifera in the gypsum–rich samples. It is however, possible for rapid authigenic production of gypsum to occur under lab conditions (Herbert pers. comm.) and sufficient gypsum produced after coring to introduce bias into the results. Authigenic gypsum is associated with anaerobic conditions and the presence of excess dissolved calcium is a prerequisite for production of gypsum. (Siesser and Rogers 1976). This is easily possible as H_2S and calcareous materials are present in varying degrees and possibly very low concentrations of these materials due to dissolution by H_2S (acidifying dissolved calcium and sulphate bond to form gypsum). Pyrite, which is present in many mudbelt samples is formed in similarly anoxic conditions and closely associated with this process.

Aeolian transport does play a role in sedimentation in the area, but it is difficult to determine even with detailed grain size analysis (Christensen *et al.* 2002 after Rea 1994). This dust is transported by berg winds for a few weeks each year and by year-round tradewinds (south easterlies). Aeolian transport has a seasonal pattern, reaching a maximum during the southern hemisphere winter. At this time, high pressure cells

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dominate the interior and adiabatic winds result. Grains are transported offshore in a westerly-southwesterly direction. Extensive sand and dust plumes are found some 150 to 200 km offshore (Shannon 1985, Stuut 2001) and can be detected by satellite. The presence of mica in the mudbelt sediment may be potentially useful providing a dominating component of the fine sand fraction from berg winds and from the upper Orange River and other contributing rivers such as the Caledon (Mabote 1997). Quartz is thought to have originated in Quaternary coastal dunes and was eroded and redistributed in the littoral zone during the Holocene. Mica probably originated in micaceous sedimentary rock in the Lesotho catchment of the Senqu (Mabote 1997, Woodborne 1991).

Aeolian dust from the Namib and Kalahari deserts dominate that carried by the southeastern tradewinds. Stuut and others have had no success in detecting the difference in such records at the Walvis ridge research site (Stuut 2001). However, a number of authors point to the presence of quartz and mica in the mudbelt sediment as being consistent with input from Berg Winds (adiabatic winds) blowing grains from the semi-arid Namaqualand interior (micaceous metamorphic rocks) (Shannon and Anderson 1982, after Whittaker 1984, Mabote 1997). Bryant *et al.* (in press) and others point to key ephemeral sources to the north of the ORC, in the Makgadikgadi Pan (Botswana), relating to factors such as water inundation, sediment inflow, surface wind speed and also ENSO and SST of the Indian Ocean which affect the supply of dust to the SE Atlantic.

Precise dating of the late Holocene mudbelt has been problematic but a combination of techniques has supported the original assumption that the sediment sampled during the HODSA coring operation was up to 1 700 BP in age (at least to the base of the retrieved cores). Depositional chronology of the mudbelt is detailed in the chronology, chapter 4.

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3 METHODOLOGY

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3 METHODOLOGY

The goal of this chapter is to detail the various methodologies used in this thesis. It serves as a preamble to the following three chapters, i.e. chronology of the Namaqualand Mudbelt cores in chapter 4, stable light isotope analysis in chapter 5 and pollen of the Namaqualand Mudbelt in chapter 6, in which the results are presented and discussed. Due to the widely differing methodologies of the three approaches employed, this chapter is therefore composed of three sections.

3.1 Introduction

Although this chapter does not and indeed can not synthesise the methods used in this project, it does aim to group the methods used together in one chapter and thus separate them from the data and the discussion of the following chapters. In doing so, it emphasises the results separately from the methodology and thereby provide some simplification and clarity to both methods and results.

The first of the three subdivisions of this chapter, **section 3.2**, deals with mudbelt **chronology** and involves the methodology used to obtain additional information about the age and deposition of the mudbelt sediments and related inland sites. This includes the principles, preparation and processing techniques required for radiocarbon dating and foraminiferal analysis (by Accelerator Mass Spectrometry or AMS dating), loss on ignition (LOI) and Walkley-Black titration methods to obtain total organic carbon (TOC), ^{210}Pb and ^{137}Cs dating techniques. Unfortunately, due to insufficient foraminiferal material in the sediment, this analysis was not successful; therefore, the only procedure regarding foraminifera in this chapter is that of picking of the foraminifera.

A discussion of the stable isotope methodology and sub-sampling protocol is found in **section 3.3**. This includes the rationale for analysing **carbon and nitrogen isotopes** of bulk organic components of the sediments, details the principles of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) light isotope analysis and incorporates the interpretive value of C/N ratios and 1/N against $\delta^{15}N$ graphs used in chapter 5.

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Section 3.4 details the preparation and **pollen** sample processing techniques used in this study, counting and preparation of pollen diagrams as well as the motivation for using particular methods and protocol strategies. The procedure developed from the initial pilot study, described in Gray (1996) and in Gray *et al.* (2000), where pollen counts for six mudbelt samples were processed and described.

3.2 Chronology of the Namaqualand Mudbelt and related sites

The problems of the mudbelt chronology have already been discussed in the early chapters of this thesis. These problems relate to the nature and timing of deposition in the mudbelt, as well as the nature of material and the nature and timing of the fluvial processes of the Orange River itself. The motivation for this analysis (along with a review of earlier work) aimed at establishing the chronology of the cores is dealt with in greater depth in chapter 3. This section describes existing and newer approaches designed to provide a better understanding of the Namaqualand mudbelt chronology through sediment dating.

3.2.1 Bulk radiocarbon dating, total carbon and total organic carbon

Bulk organic[1] radiocarbon dating was, until recently, the primary method used to interpret the age of the Namaqualand mudbelt. The 24 original bulk organic mudbelt sediment radiocarbon age determinations were obtained by Meadows *et al.* (1997). The results of these determinations were used during the pilot pollen study (Gray 1996, Gray *et al.* 2000) to complement isotope and pollen analysis conducted on the sediment as part of this project. Fresh analysis in this thesis using bulk organic radiocarbon dating has been useful in verifying the age of samples, such as at the Jakkalsberg sites (Brink and Webley 1996 and Webley 1996) together with other sediment sites in the vicinity as a base upon which palaeoenvironmental analysis (discussed in sections 2.3 and 2.4) could be interpreted. However, the bulk organic radiocarbon dating method is limited in terms of the nature of the material being dated (bulk organics) and also by virtue of its susceptibility to any sediment reworking within the ORC. Furthermore, the issue of residence time and addition of

[1] The term, 'bulk organic' refers to the organic fraction found in this instance in a particular unit weight of sediment.

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marine carbon has additional implications. Thus, the interpretation has until now, been clouded by results that are not well resolved in both time and space. In other words, these results refer more to an approximate or average age for an array of sediment events sourced over a wide area, where sediment reworking is a real but largely unpredictable characteristic of the area in question. Bulk radiocarbon ages are useful in providing an average age for a particular depositional event in the mudbelt. Given the possibility for sampling to span a succession of depositional layers, the results may prove variable if care is not taken in the sampling process and repeat samples are required.

3.2.1.1 **Principles of radiocarbon dating**

Radiocarbon dating, also known as carbon 14 (C-14) dating, is based on the premise that living organisms are largely composed of carbon. The carbon cycle is one of the most important geochemical cycles, along with nitrogen and phosphorus. Carbon, of which there are 3 isotopes (^{12}C, ^{13}C and ^{14}C), is a common element of the earth's lithosphere, hydrosphere and atmosphere as is its radioactive isotope. Only a portion (1×10^{-12}) of this carbon content is composed of the unstable radioactive isotope ^{14}C, which is in equilibrium with the atmosphere. The other two isotopes, ^{13}C and ^{12}C, are stable and represent the remaining 98.89% and 1.11% respectively (Lowe and Walker 1997). ^{14}C is produced in the upper atmosphere where nitrogen is bombarded with cosmic rays or neutrons (n), high energy particles from outside the solar system or solar energetic particles, producing a displacement of protons (p) in the nitrogen which then forms carbon atoms (Lowe and Walker 1997, after Mewaldt 1996):

$$^{14}N + n \rightarrow {}^{14}C + p$$

These carbon atoms, of which a small proportion may have a radioactive ^{14}C isotope nucleus, then form a bond with oxygen and CO_2 is produced and incorporated into the carbon cycle in the atmosphere, ocean and on land. Here, they may enter plants and animals through photosynthesis, resulting in all organic substances becoming weakly radioactive. Upon death of the organism, the equilibrium with the atmospheric ^{14}C is disrupted and the ^{14}C begins to decay at a half-life of 5730 ± 40 years (Lowe and

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Walker 1997). As the ^{14}C decays, it will then emit an electron (a weak beta particle, β) and become ^{14}N.

$$^{14}C \rightarrow {}^{14}N + \beta$$

Radiocarbon dating therefore, is based on this decay rate and its methodology lies in the identification of what proportion of ^{14}C remains in the item in question and how this compares to current atmospheric ^{14}C levels.

Beyond 40 000 years, the levels of ^{14}C are very low, not easily measured and may be regarded as infinitesimal, although theoretically the limit is 50 000 years (Lowe and Walker 1997). Younger samples may also give inaccurate results due to the influence of the post-industrial revolution circulation of unprecedented levels of CO_2 from fossil fuel carbon reservoirs. Calibration of dates is required to bring ^{14}C years in line with calendar years.

Conventional radiocarbon ages are determined through gas or liquid scintillation counting of the low energy β emissions of the ^{14}C over a period of time. However, Accelerator Mass Spectrometry (AMS) dating is a more direct method of detecting the actual number of ^{14}C atoms in a given sample and uses a particle accelerator as a mass spectrometer (Lowe and Walker 1997). AMS dating has the advantage of utilising a much smaller sample (a few milligrams), compared to bulk organic radiocarbon dating where significantly more sample is required (a few grams). It was for this reason that samples were prepared for foraminiferal picking and analysis with the intention of eventually establishing age using the AMS technique; discussed further in section 2.2.2. AMS radiocarbon analysis is conducted by acid hydrolysis of carbonates to yield CO_2, which is then reduced to a graphite (pure carbon) form at high temperatures in a vacuum. The graphite is then pressed into a target and analysed using the particle accelerator in the AMS facility.

Computed radiocarbon ages (conventional or AMS) are always accompanied by a standard error, which accommodates contamination-related statistical uncertainties associated with the ^{14}C decay curve, measurement errors and problems with targets or the ion beam used in the procedure (Lowe and Walker 1997).

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Generally, a number of statistical assumptions are made for radiocarbon dating and the following is assumed:

1) that ^{14}C production is constant over time,

2) ^{14}C:^{12}C ratio in the atmosphere is the same in the biosphere and hydrosphere,

3) decay rate is identifiable and

4) dead organisms exist in a vacuum upon death.

It is clear that these assumptions are not entirely valid. The ^{14}C content of the geosphere varies over time due to cosmic ray flux arising from geomagnetic field changes of earth and sun and impact of solar flares, changes in the distribution of CO_2 (carbon reservoirs) due to the excessive burning of carbon fuels in industry and thermonuclear reactions. Consequently, calibration curves have been derived in order to correct the dates from radiocarbon years (BP) to a calendar age range (Cal BC/AD) (Sewell 1998). The calibration is based on data obtained from organic materials that exhibit annual growth such as tree rings (bristlecone pine), lakes and marine varves. Despite this calibration, the resultant data are still "probabilistic" and do not represent absolute calendar dates (Sewell 1998). All published bulk organic radiocarbon ages for HODSA material are uncalibrated (Meadows *et al.* 1997, 2002, Gray *et al.* 2000).[2]

Isotopic fractionation, a concept discussed in chapter 5, may have a small effect on radiocarbon dates due to the preferential discrimination against ^{14}C being roughly twice as much as ^{13}C. This is particularly important to consider when an error less than 1% is required (Lowe and Walker 1997). Radiocarbon dating labs usually correct for fractionation on the basis of the laws of thermodynamics, in that the heavier isotope ^{14}C is twice as enriched as ^{13}C (Lowe and Walker 1997, after Olsson 1986), but often samples are "normalised" according to the value of -25‰, the mean isotopic value for wood.

3.2.1.2 Preparation of additional Richtersveld samples for bulk organic radiocarbon dating

Additional material from a variety of flood deposits in the Richtersveld (lower Orange Catchment), sampled in September 1999, was analysed in 2001. These flood deposit

[2] Just prior to submission of this thesis, Herbert and Compton (in press) submitted a paper which included the calibrated age of core H7 samples using previously published uncalibrated dates (Meadows *et al.* 1997, 2002).

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sites included Jakkalsberg (JKB) A and O, Bloeddrift 32 and Lower Xobies. The samples comprised of goat dung, animal bone, soil and charcoal. It was necessary for the goat dung to be picked from the dry sand sediment together with bone and charcoal. These were cleaned of extraneous sand and other material before being sent to the CSIR Quaternary Dating Research Unit (QUADRU) for radiocarbon dating. In some cases, existing radiocarbon age determinations were available, for example as at JKB. However, the JKB sites had changed since the 1999 field trip when bulk organic radiocarbon ages had been obtained and some erosion had taken place between the Brink and Webley (1996) field trip and the Richtersveld field trip in 1999. Erosion of these sites and poor GPS resolution at the time meant that existing literature and ages were not easily correlated with the sites. Thus problems associated with chronology and of mapping 'change', necessitated new bulk organic radiocarbon dating for some of the sites used in this research.

3.2.2 Macrofossils: Foraminifera

Ten samples were chosen for ^{14}C AMS dating of foraminifera. These sediment samples were duplicates of the 1996 samples dispatched for bulk organic AMS dating which had showed apparent inconsistencies in age (Meadows *et al.* 1997, Gray 1996). Successful dating of the foraminiferal material, although prone to some re-working and redeposition in certain environments (Lowe and Walker 1998), would in theory yield the age of the depositional event (flood) rather than the age of the potentially re-worked source material, and thus clarify the apparent inconsistencies. Benthic foraminifera are particularly relevant in this situation, since these foraminifera are less affected by currents and remain fixed to the sediment surface while alive. Ages based on foraminifera theoretically avoid the terrigenous sediment re-working issue and instead appear to date the "event" rather than the "material". However, some doubt has been cast on the extent of the effect that nutrient blooms have on the foraminiferal signal (Williams *et al.* 1993), although this should not be too significant a "contaminant".

In cases where it was impossible to duplicate samples of those successfully radiocarbon dated (where little or none of the original sample remained), samples for foraminiferal analysis were taken from either above or below the existing bulk ^{14}C

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AMS dated material. This highlights one of the limits of the study; large portions of material were already destroyed during the original sedimentological and geochemical analysis. Only a few select samples in Cores H2 and H7, repeat samples of those bulk organic radiocarbon dates, were prepared and intended for AMS analysis. It was hoped that if these samples were indeed successful, and time and finances permitting, further cores could be utilised to establish an even greater sample size and age of the mudbelt. This might have given some indication of spatial arrangement of the foraminiferal assemblage and the mudbelt depositional morphology.

Three abundant foraminifera of the West Coast were identified in terms of their palaeoecological niche importance and value for potential AMS dating within the water column in the mudbelt area. These three foraminifera species included *Discammina compressa*, *Ammonia japonica* and *Neogloboratalia pachyderma* were considered to have been deposited at the time of sedimentation and not re-worked therefore being useful for determining the age of mudbelt deposition (McMillan 1987, McMillan and Giradeau pers. comm.).

Scanning Electron Micrographs from McMillan's (1987) Late Quaternary Foraminifera from the Southern Part of Offshore South West Africa, were used as reference materials in this investigation.

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3.2.2.1 **Principles of foraminiferal analysis**

Foraminifera are single celled organisms or protists (prokaryotes) with calcareous shells or tests, where the shell is composed of calcite, aragonite minerals or agglutinated sediment (Murray 1991). The shell may have one or more chambers separated by septae; the cytoplasm from the soft protoplasmic body can move between the septae through small holes or foramina (Lowe and Walker 1997). Foraminifera occur as a variety of species (around 900 modern genera, 10 000 modern species) with a distinctive and attractive diversity of morphologies which can be likened to gastropods and cephalopods (Lowe and Walker 1997). They are found in a variety of environments with individual species favouring a particular environmental parameter or niche specific to a definite range of salinity, temperatures, water quality (sea water to brackwater to saltmarsh) and may occur in the marine environment as

benthic planktonic or to a lesser extent, pelagic varieties. Freshwater species occur in small numbers as thecamoebids or testate amoebae (Lowe and Walker 1997). Foraminifera vary in size from smaller than 0.4 mm (planktonic) to the larger tropical benthic species up to 10 cm in width. Individual species are identified in terms of a number of morphometric variables which relate in some way to the organism's mode of life (Williams *et al.* 1993) and include: skeletal material (pseudochitinous, arenaceous, siliceous or more commonly calcareous material), shell form, shape and arrangement of the chambers, position of the foramina (openings) and the detail of the shell.

Foraminifera are now a widely used proxy in marine micropalaeontology for palaeoclimatic reconstruction and palaeoceanography; they prove invaluable to numerous projects requiring information of the Quaternary and sediments from Cambrian times (Lowe and Walker 1997), and are widely used for oxygen and carbon stable isotope and trace element analysis (Murray and Alve 2002).

Calcareous foraminifera can be very effectively used for radiocarbon ^{14}C AMS dating as their constituents can be analysed as palaeoecological tracers. It was initially hoped that sufficient material would be obtained of the benthic type of foraminifera as these are restricted to surface sediment and do not move within the water column as in the case of the more plentiful planktonic species in the mudbelt (Mabote 1997). Nevertheless, the possibility of using planktonic species was considered as these species synthesise carbonate from water and much is known about the age of dissolved CO_2 in seawater (Jorissen *et al.* 1995). Benthic species are known to synthesise carbonate from the sediment surficial detritus and thus can produce a bias of results of any age analysis on the foraminifera. Correct protocol is required in order to avoid sample contamination and preparation mistakes (Giraudeau pers. comm.).

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3.2.2.2 **Method of extraction**

Samples were sieved with distilled water according to a standard protocol set out by Giraudeau and Elder (pers. comm.) through 160, 180 and 360 μm mesh sieves to separate the coarse foraminiferal fraction from the fine silt and mud fractions. This sieving also improved the picking process by separating similarly sized particles.

After thorough rinsing with distilled H_2O, the coarse fraction was washed into large glass beakers and dried at a low temperature (70°C) in a warming oven. The dried fraction was placed in small screw-cap glass vials in preparation for picking and separation of foraminifera according to planktonic and benthic morphological types and removal of detritus, especially faecal pellets. Unfortunately, due to insufficient sample, as discussed in chapter 4, the preparation process and standard AMS analysis could not be completed. After picking and sorting, the intention was to gently sonicate the relevant samples in order to remove extraneous material to the tests or filling the inner chambers. This was to be carried out in the vial in a DH20 medium, until the supernatant was clear, drawing it off with a syringe (with crimped needle) followed by rinsing in distilled H_2O and drying in an oven at 70°C. Insufficient material meant the procedures for subsequent counting and identification of foraminifera were not necessary and are therefore the subsequent procedures are not included.

3.2.3 Total organic carbon (TOC)

For most organic materials and sediments, the following equation applies:

$$\text{Total carbon} = \text{inorganic carbon} + \text{organic carbon}$$

Inorganic carbon is not quantifiably useful to the purposes of this project but organic carbon is important and is significant for interpretation of carbon stable isotope analysis and bulk organic radiocarbon dating (also referred in section 2.2.3.2 below and chapter 5).

Two methods, which both correlate to oxidizable organic carbon, are commonly used for analysis of sediment organic matter, weight loss on ignition (LOI) and the more costly modified Walkley-Black acid digestion (Schumacher 2002, after Mebius 1960). Their level of accuracy and suitability for sediments is often dependent on the (predicted) organic content: the Walkley-Black method (Abella and Zimmer 2007, after Walkley and Black 1932) which is usually suitable for sediments with a low organic matter content of <2%, whereas LOI is suitable for sediments with >6% organic matter. Organic carbon analyses were carried out on the mudbelt materials using both LOI and Walkley-Black methods. A few select samples had previously

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been analysed for inorganic carbon by Mabote (1997) using the LOI method had revealed low organic carbon content. Therefore, these organic carbon percentage values were expected to be particularly low in the mudbelt (Rogers 1977a, Mabote 1997).

The two methods are discussed in the following sections.

3.2.3.1 **Loss on ignition (LOI) method**

Weight loss on ignition (LOI) is a common method of approximating the organic matter and carbonate content of sediment (Heiri *et al.* 2001). Due to factors relating to ignition temperature, volatile salt content, loss of structural water and inorganic carbon (although inorganic carbon and structural water are typically lost at temperatures around 950°C according to Bengtsson and Enell (1986) and Heiri *et al.* (2001)), LOI is at best an approximation of sediment organic content. Heiri *et al.* (2001) have also reported other variations in results due to a non-uniformly profiled furnace leading to non-uniform combustion. This can produce discrepancies of about 0.42%. In addition, some researchers (Smith 2003) maintain that certain clays (particularly kaolinite) lose structural water at lower temperatures (<500°C) resulting in an artificially high LOI reading. This observation is particularly pertinent to the mudbelt sediment, given the large clay fraction compared to the small organic fraction.

3.2.3.2 **Weight loss on ignition (LOI)**

Total carbon analysis was initially carried out by combustion or loss on ignition (LOI) in order to expand on the small initial LOI analysis by Mabote (1997). A 5 g sub-sample of sediment was taken from the 500 ml core working halves, placed in a ceramic porcelain dish, transferred to a warming oven and then dried at 70°C for 24 hours, weighed for dry weight ($DW_{70°C}$) and then placed in a combustion chamber at 400°C for at least 4 hours ($DW_{400°C}$). After 4 hours, the samples were allowed to return to room temperature while still in the combustion chamber. No desiccation chamber was used at the initial drying stage or the post-combustion phase as moisture content of the samples would have added bias to the final dry weight. Other related calculations of LOI estimation of carbonate values, which can be obtained after

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further combustion at a temperature of about 950°C, were not obtained. The final weight was subtracted from the dry pre-ignition weight to give the total carbon and the final total (organic and inorganic) percentage carbon content calculated.

The difference in weight was calculated as equal to the carbon content as a proportion of the original dry weight and a total carbon percentage is calculated:

$$LOI_{400°C} = (DW_{70°C} - DW_{400°C}) / DW_{70°C} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

A more exact analysis of the organic carbon fraction was obtained by using Walkley-Black titrations.

3.2.3.3 **Walkley-Black method**

This method is based on the rapid dichromate oxidization of organic carbon in sediment by acid with titration. A modified version of this analysis follows the Mebius (1960) modification of the Walkley and Black (1932) analysis which involved heating of the sample during digestion; this method was adopted to avoid incomplete digestion of the organic matter (Schumacher 2002, after Mebius 1960).

At least 10 g of material was sub-sampled for the analysis of total organic carbon (TOC). The samples were first dried in a warming oven (50°C) and then finely ground by hand, using an agate pestle and mortar. The samples were then treated with HCl or H_2SO_4 acid (acid digestion) for removal of the inorganic carbon component.[3]

3.2.4 Scanning Electron Microscopy

Scanning Electron Microscopy or Energy Dispersive Using X-Ray analysis (SEM/EDX) was conducted at the University of Cape Town SEM laboratory on untreated mudbelt sediment with the aim of visually identifying the source of the organic carbon component of the clay-rich sediment using this high-resolution

[3] This TOC analysis was completed at the Elsenburg Soil, Water and Plant Tissue Laboratory (Western Cape Dept. Agriculture, Stellenbosch) using the Walkley-Black titration method with the assistance of Rudie van Zyl during October 2001.

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technique. A small amount of sediment from a single sample was sub-sampled as a thin mud-smear, which was then placed in a beaker and dried at 50°C. A very small flake of dried sediment was placed on the solid metal stub and then gold plated. For the purposes of observation, numerous SEM images of the sediment were taken for closer examination.

3.2.5 ^{210}Pb analysis

In this study, surface samples of box cores relating to gravity cores H2, H5 and H7 (along with a limited number of gravity core samples), were prepared according to the process described in 3.2.5.1 at the University of Cape Town sedimentology laboratories (Dept. Environmental and Geographical Science and the Geology Department). These samples were then analysed at the Geology Department, University of Bordeaux, France with the assistance of Dr Jean-Marie Jouanneau using a specialised mass spectrometer.

3.2.5.1 Principles of ^{210}Pb analysis

Naturally occurring radionuclides, such as ^{14}C and ^{210}Pb have proven useful in numerous applications relating to palaeoenvironmental work with the short-lived radioactive isotope ^{210}Pb being particularly useful in the field of sediment accumulation rates in water bodies, such as sea and lake sediments. The isotope ^{210}Pb is a natural product of the ^{238}U decay series and has a half-life of 22.3 years (Appleby and Oldfield 1983 and 1992, Muñoz *et al.* 2004). Because of this short half-life, it is possible to estimate accumulation rates and age estimates of sediment up to less than 150 years.

The parent element ^{238}U has a nearly infinite half-life of 4.5 x 10^9 years and is considered to be present in constant concentration over time in the earth's crust. However, its concentration may vary with location. The isotope ^{238}U decays through 15 successive radioactive daughter elements to the stable ^{210}Pb isotope.

The ^{238}U isotope decays slowly into ^{234}U (half-life of 248 000 years). This in turn decays into ^{230}Th (half-life of 80 000 years) and then ^{226}Ra (1 620 years) which behaves similarly to ^{238}U due to secular equilibrium. The isotope ^{226}Ra is found in low

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but constant concentrations world wide where it decays to the inert radioactive gas ^{222}Rn (half-life 3.8 days). This escapes into the atmosphere before decaying into ^{218}Po, which is a metallic (solid) radionuclide. The solid then falls to earth after a few days as dust and in rain, decaying within minutes to various radionuclides, eventually producing ^{210}Pb. This isotope has a strong affinity for sediment particles (van Hoof and Andren 1989, He and Walling 1997, 1999) and organic material. This is particularly true of clay and organic-rich sediments (He and Walling 1999). Soon ^{210}Po is produced, the granddaughter of ^{210}Pb in secular equilibrium with ^{210}Pb. As sediment is deposited, ^{210}Pb accumulates and successive sedimentation of ^{210}Pb isotope will ultimately give an approximation of how recently the sediment was laid down, up to an age of 150 years. The measured ^{210}Pb isotopes will then give an indication of the age of the material. However, statistically, this is only possible up to seven half-lives. Sediments older than about 150 years typically do not yield detectable levels of the isotope. The younger the material, the more radioactive lead isotopes will be present while the older material contains more stable lead. Thus the measurable ratio of ^{210}Pb: ^{206}Pb can give an indication of the depositional age of recent sediments (including peat, glaciers and ice sheets), assuming there is a constant atmospheric flux of ^{210}Pb (Appleby and Oldfield 1978, Lowe and Walker 1997, after Olsson 1986). This information is also central to calculating deposition rate, given sufficiently high resolution of ^{210}Pb data.

There are two components of ^{210}Pb activity – supported and unsupported lead. Supported lead is the fraction of lead that is derived from in situ decay of ^{226}Rn and therefore can generally be calculated as the measured activity of ^{226}Rn. Unsupported ^{210}Pb is derived from ^{210}Pb atmospheric fallout. This is produced within the atmosphere by ^{222}Rn decay, an intermediatary gas nuclide (French *et al.* 1994). It is the unsupported component of ^{210}Pb in sediment that is so useful in estimating floodplain sedimentation rates (He and Walling 1996). Thus the supported ^{210}Pb must be subtracted from the unsupported ^{210}Pb produced in the atmosphere.

The final product of the ^{238}U series is ^{206}Pb, a stable isotope. This isotope makes up 24.1% of natural lead, so excess ^{206}Pb is considered as an indicator of how much ^{238}U was originally present.

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3.2.5.2 Preparation of ^{210}Pb samples in South Africa

An adequate amount of dried, dialysed and ground sample is necessary in order for correct measurement of excess ^{210}Pb. A final dry weight of ±10 g was necessary for this analysis so more than 13 g of unprocessed, wet sediment was sub-sampled from the 500 ml tubs of working half core. This was then placed in a cellulose tube (tightly tied with string at both ends) and suspended in flowing water for at least 24 hours for the salts (e.g. NaCl, KCl) to be removed through the process of dialysis. Some samples were found to have dried during storage, thus requiring proper disaggregation and suspension in water prior to this step. After dialysis was complete, the tube was opened into a glass beaker and the contents washed from the tubing into the beaker. The beaker was labelled and placed in a warming oven (70°C) to dry. Drying took two to three days and a thin, dry mud crust formed in the beaker. This sediment was scraped from the beaker and manually ground into a very fine powder using an agate pestle and mortar. The samples were then re-weighed and packaged for transport to the research facility in France. Three separate ^{210}Pb analytical runs were conducted at the Geology laboratory of the University of Bordeaux, France i.e. 1998, 1999 and 2001.

3.2.5.3 Determination of ^{210}Pb analysis of samples in Bordeaux, France

The dry samples of between ±10 g were weighed, dried and placed in 6 cm diameter 0.5 ml cap-covered petri dishes and inserted into the spectrometer. (It was important to carry out this analysis at least longer than two months after sampling so as to ensure a secular equilibrium is established between ^{226}Ra and grand-daughters, ^{214}Pb and ^{214}Bi). Measurements more than five years after the cores were initially retrieved did not pose a problem. Here, radioisotopic measurements of ^{210}Pb were made using a semi-planar germanium detector coupled to a multichannel analyser (Jouanneau pers. comm.). Radioisotopic activity was counted over a 12 hour period, where the counts per minute are multiplied by a factor determined by gamma ray intensity and detector efficiency. The ^{210}Pb activity was measured by its gamma decay energies: 46.5 KeV (Jouanneau pers. comm.). Excess ^{210}Pb was calculated from ^{210}Pb activity minus the average of two ^{214}Pb energies (295 KeV and 352.0 KeV) and a ^{214}Bi peak at 609.3 KeV (which represents the ^{226}Ra and corresponds to the supported ^{210}Pb).

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3.2.6 ^{137}Cs analysis

At the time of the initial bulk organic dating work on the mudbelt, a sample of HODSA mudbelt material was analysed for ^{137}Cs levels which were found to be negligible (Meadows pers. comm.). However, it was possible for the ^{137}Cs analysis to be run on the spectrometer simultaneously with the ^{210}Pb analysis and therefore on a much larger sample using the same preparation techniques and spectrometer.

3.2.6.1 Principles of ^{137}Cs analysis

The ^{137}Cs isotope is an artificial radioactive nuclide produced as a direct result of thermonuclear activity (weapons testing and detonations) which began in 1945 (Lowe and Walker 1997) and peaked around 1963 (Huh and Su 1999). The half-life is 30 years and used mainly to establish the recency of sediments and to estimate rates of ground retreat (mining heaps) and has proved useful in sediment sourcing in catchments (Lowe and Walker 1997). Early work by Hardy *et al.* (1973) indicated that ^{137}Cs fallout is strongly dependent on latitudinal position. More recent studies indicate fallout is much reduced in the southern hemisphere (He and Walling 1997, 1999). This can be attributed to the fact that the most atomic detonations above ground or at ground level were conducted in the northern hemisphere and that the high level wind patterns are the only form of transfer available between north and south hemispheres.

Appleby and Oldfield (1992) report that ^{137}Cs values are much lower over oceans and tend to decrease in a west to easterly direction over continents due to the West-East circulation of air masses. In addition, ^{137}Cs fallout varies both temporally and spatially, given the timing and location of thermonuclear detonations. However, this fallout has been concentrated in the period between the late 1950's and early 1970's (He and Walling 1999). A final troubling aspect of ^{137}Cs detection is the current difficulty in making a distinction between the Chernobyl ^{137}Cs fallout of 1986 from the total ^{137}Cs input (He and Walling 1999).

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3.3 Stable light isotope analysis of the sediments of the Namaqualand mudbelt and related sites

This section details methods used for preparation and analysis of Namaqualand mudbelt and other inland sediment samples for both carbon and nitrogen stable light isotope analysis.

3.3.1 Principles of stable isotopes with reference to fluvial and marine sediments

The principles of stable isotopes are based on the kinetic isotope effect and fractionation of isotopes. The kinetic isotope effect describes the effect of one isotope reacting more rapidly than another isotope in an environment where the reaction is both non-reversible (unidirectional) and does not allow for a state of equilibrium. In this process, lighter molecules are involved in the faster reactions and result in the preferential assimilation of the lighter molecule or isotope through fractionation, whereby the ratio of stable isotopes is modified during assimilation into the organism, biochemical process or reaction. This occurs because atoms of isotopes react at different rates. The product of this variation, due to equilibrium, kinetic and physical effects such as evaporation, may be isotopically heavier or lighter than the original material as a result of fractionation. The heavy isotopes of carbon and nitrogen, analysed in this research are among the most useful of the biological tracers used in palaeoenvironmental studies and are invaluable to fluvial-marine analysis. Nitrogen and carbon isotopes yield potentially useful palaeoclimatic proxies, however, nitrogen isotopes should be used with some caution as nitrogen isotope data is complex and some results suggest a tendency towards mixed results in a marine setting (Holmes *et al.* 1999).

Carbon primarily occurs as two stable isotopes, ^{12}C and ^{13}C. On average the natural relative abundance of these two isotopes is 98.894% and 1.106% respectively. Biogenic materials are enriched in the lighter isotope (Killops and Killops 2005). The same principle is true of the isotopes, ^{15}N and ^{14}N. The radioactive isotope, ^{14}C, may make up the remainder of carbon isotopes, but this isotope is discussed in chapter 4.

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Stable isotope ratios are expressed in units relative to a standard in the delta (δ) notation in 1), as:

$$\delta x = [(Rx_{unknown}-Rx_{standard})/Rx_{standard}] \times 1000 \quad \ldots\ldots(2)$$

R is the isotopic ratio of ^{13}C to ^{12}C. $R_{unknown}$ is the unknown isotopic ratio of the sample being analysed and $R_{standard}$ is the isotopic ratio of the particular standard used. Units are expressed in parts *per mil* (or parts per thousand) units and abbreviated as the symbol ‰. Thus $\delta\ ^{13}C$ is expressed as follows:

$$\delta\ ^{13}C\ (‰) = [(^{13}C/^{12}C \text{ sample } -1)/ (^{13}C/^{12}C \text{ standard})] \times 1000 \quad \ldots\ldots(3)$$

When comparing values in carbon (and nitrogen) isotopes, the more positive the value, the more enriched with ^{13}C (or ^{15}N) the sample is. $\delta^{13}C$ data are expressed relative to PDB, otherwise known as the Pee Dee Belemnite Marine Carbonate Standard. This has a higher $^{13}C/^{12}C$ ratio than most other carbon substances. As PDB is by definition assigned a $\delta^{13}C$ value of zero, most organic samples have negative delta values (i.e. they contain less ^{13}C than the standard).

In nitrogen isotopes, $\delta\ ^{15}N$ is expressed relative to air:

$$\delta\ ^{15}N\ (‰) = [(^{15}N/^{14}N \text{ sample } -1)/(^{15}N/^{14}N \text{ standard})] \times 1000 \quad \ldots\ldots(4)$$

By definition, organic materials possess isotopes representative of differing photosynthetic systems (in the case of carbon stable light isotopes), rainfall abundance at time of "growth" or other aspects of nitrogen utilisation (with respect to nitrogen stable light isotopes). Isotope analysis can be useful in determining factors relating to environmental photosynthetic input, which in turn is indicative of vegetation structure. As this organic material decays and the isotopic signature is transferred, with some adjustment to become soil organic matter, the material along with its isotopic data may be carried as runoff, into rivers such as the Orange or Buffels River. Eventually this may be deposited in the marine environment. Additional isotope input from the marine systems may add to the isotopic assemblage.

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Some important aspects of $\delta^{15}N$ and $\delta^{13}C$ pertaining to their pathways and transference to the soil, fluvial and marine environment and set against a backdrop of existing isotope dynamics are discussed in sections 4.2 and 4.3.

3.3.2 Stable carbon ($\delta^{13}C$) isotopes in sediment

Bulk geochemical analysis of sedimentary organic matter (OM) has been widely used for palaeoclimatic studies (Wagner and Dupont 1999). There is significant variability in isotopic data of OM, as this is dependent on carbon source, composition, P_{CO2} (measure of carbon dioxide available), growth rate (in the case of marine plankton) and the metabolic pathway used during formation (Wagner & Dupont 1999). These issues need to be correctly addressed for interpretation of isotope data in both the terrigenous and marine environment. For the purposes of this study however, certain average marine values are considered in the interpretation.

3.3.2.1 Carbon isotopes, slack-water and changing vegetation

Plants are strongly fractionated by photosynthesis according to one of three photosynthetic pathways used to fix CO_2: namely, the Calvin-Benson (C_3), Hatch-Slack (C_4) and the Crassulacean Acid Metabolism (CAM) pathway (these are explained below). However, plants using the CAM pathway alternate between using either the C_3 or the C_4 photosynthetic pathway, depending on prevailing environmental conditions. It is the distinctive $\delta^{13}C$ values of C_3 or C_4 plants that enable them to be differentiated. These photosynthetic pathways result in the accumulation of distinct $^{13}C/^{12}C$ ratios within vegetation and decay products due to very different isotopic fractionation relating to these pathways. Upon decomposition of the plant matter, the isotopic ratio or isotopic signature is retained in the organic matter, but may experience further fractionation depending on various prevailing factors. Isotope analysis of bulk soil organic matter can provide valuable information about the overlying vegetation and the dominant photosynthetic pathway of the assemblage. Soil organic matter, occurring in sediments or paleosols, can provide information extending to pre-history and thus may be useful as a proxy for past vegetation change and palaeovegetation studies.

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C_4 plants are associated with warmer growing season temperature, are more water efficient than C_3 plants and are influenced by a variety of abiotic factors. These factors include light level, water and osmotic stress, temperature, nutrient availability and P_{CO2} (Koch 1998). CAM plants, however, will utilize C_4 pathways and exhibit associated isotopic values in arid conditions, but will indicate values between C_3 and C_4 value ranges in moist climates (Koch 1998). The Richtersveld, which includes the lower reaches of the Orange River, is associated with C_4 and CAM plants.

C_3 plants are defined by the Calvin-Benson photosynthetic pathway where a 3-carbon molecule is produced during photosynthesis. Here, CO_2 is fixed as a 3-carbon sugar by the enzyme RUBP (Ribulose-1,5-bisphosphate) carboxylase. The kinetic isotope effect that is associated with this enzyme, results in a global average $\delta^{13}C$ value of between -22‰ and -37‰ (average -27‰) relative to PDB, lower than that of atmospheric CO_2 (of about 7.7‰). Average $\delta\ ^{13}C$ values for C_3 plants extend from between -26‰ and -28‰. C_3 plants are therefore ^{13}C depleted (Koch 1998, O'Leary 1998 and Fogel & Cifuentes 1992). This category includes all trees, many shrubs (such as the non -succulent Karoo shrubs), small herbs and many temperate zone grass-types (Koch 1998) and plants using C_3 photosynthetic pathways are usually woody. This is the more globally common photosynthetic pathway (Koch 1998) i.e. terrestrial plants are dominantly C_3 and a large proportion of crop plants are C_3, so the range of isotopic values for this pathway is reasonably wide. However, many common southern African crops fall into the C_4 category, which includes maize, sorghum, millet and sugar cane.

Carbon isotope variation within C_3 plants is primarily influenced by such factors as temperature, aridity and water efficiency, but C_4 plants are less well affected by these as CO_2 is fixed much earlier in the C_4 photosynthetic process than in C_3. This and the fact that availability of nutrients and rainfall are inversely related to each other probably explains why Swap *et al* (2004) detected an inverse relationship between carbon stable isotope values of C_3 vegetation and rainfall and not with C_4 vegetation. Open C_3 systems are by definition nutrient-rich and thus not limited by nitrogen. ^{15}N is found to be higher in such systems (Swap *et al.* 2004), such as semi-arid and arid environments, contrasted against humid environments where water is not limited, but nitrogen and other nutrients are in short supply. This scale of understanding of C_3 is

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unprecedented, but difficult to apply to this study as the catchment is primarily dominated by C_4 vegetation. Aeolian transport is considered a possible source of excess nutrients due to the anticyclonic atmospheric circulation (Tyson 1996) and thus enhancing ^{15}N enrichment in moisture-limited areas.

C_4 plants using the Hatch-Slack photosynthetic pathway, on the other hand, have higher $\delta^{13}C$ values and are therefore enriched with ^{13}C. C_4 photosynthesis is often found in dry, warm climates in grasses (but include tropical grasses) and some sedges, as this is a more water efficient pathway. Initially, the CO_2 is fixed by PEP (phosphoenolpyruvate) carboxylase to a 4–carbon acid. The resulting $\delta\ ^{13}C$ values range globally from about -15‰ to -9‰ (average of about -12.5‰) which is much closer to that of the atmospheric CO_2 (Koch 1998). C_4 grasses dominate the interior of southern Africa and thus the drainage system of the Orange River. C_4 plants tend to fall between values of -37‰ and -22‰ (average around -27‰) with the C_4 -rich grassland tending to fall within this range (Hoffman *et al* 1995, Codron *et al* 2005a,b). Karoo shrubs and other C_3 plants fall between -26‰ and -30‰, whereas Karoo grasses and other C_4 plants fall between values of -10‰ and -14‰ (Hoffman *et al* 1995). Maize, sorghum, millet are some of the C_4 crop plants found in the Orange River Catchment. Maize has a $\delta^{13}C$ value of -14‰.

CAM or Crassulacean acid metabolism pathway plants, as mentioned above, alternate using either the C_3 or C_4 photosynthetic pathways. $\delta^{13}C$ values of CAM plants may therefore vary across the C_3 and C_4 value range (Ehleringer and Monson 1993). This photosynthetic pathway mechanism is much less common than the C_3 and C_4 pathways. Although a small proportion of plants use this pathway globally, it is a significant photosynthetic pathway within the Orange River Catchment, as the Succulent Karoo situated on the west coast of southern Africa is dominated by CAM plants. However, Compton and Maake (2007) study of the headwater sediment of the ORC show this region to be the primary contributor of sediment and therefore of the 13C contribution to the net outflow from the ORC thus limiting the CAM contribution.

Through fractionation, soil is generally considered to be about 2‰ enriched with $\delta^{13}C$ in relation to vegetation (Ambrose and Sikes 1991). In addition, atmospheric CO_2

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concentrations have become approximately 1.5‰ depleted ("Suess Effect") since the 1950's due to intense fossil fuel burning and therefore vegetation pre-dating this is slightly more enriched in $\delta^{13}C$ (Keeling 1979). The $\delta^{13}C$ Carbon isotope composition of paleosols reflects the isotopic signature of the overlying vegetation transferred to the sediment, although small isotopic shifts occur when components of the vegetation are lost during decomposition. These components, such as protein, lipid, lignin and cellulose macromolecules have distinct values, which tend to average out during bulk organic analysis. In addition, diagenesis is possible especially in harsh arid environments, such as the Richtersveld (Jakkalsberg and Lower Xobies). Here, high temperatures and low humidity for much of the year and the presence of young organic matter, such as root material on the soil surface can alter the isotopes within the lithology through contamination and leaching of soluble organics. Soils here typically have a low organic content and as such are particularly susceptible to contamination and leaching (Goodfriend 1999). Arid environments tend to produce plants with isotopically enriched $\delta^{13}C$ signatures (Swap *et al.* 2004); although this is not such an important aspect for riverbank and floodplain vegetation, which are not so much reflective of the climate, but rather of the proximity of the river and availability of water, as many plants are uncommon in that biome and instead relate to sources higher in the catchment. Riverborne muds and clays are more representative of upland soils, where conditions are not as harsh as the Richtersveld and the rainfall is conducive to vegetation. Thus the organic matter contained in the slack-water deposits (Jakkalsberg and Lower Xobies) is probably more isotopically representative of sediment organics higher up in the catchment than the larger Orange River Catchment itself.

Although vegetation is generally sparse in the Richtersveld, apart from a few trees, very little to no vegetation was evident at the surface of the Lower Xobies slack-water deposits, but it was in greater evidence at Jakkalsberg. It is possible that surface vegetation could affect post-depositional material, such as reworked floodplain and river bank material, which would later reappear in the mudbelt sediment material. Vegetation and organic matter is highly transient under these semi-arid conditions and therefore difficult to quantify. Due to the long period of time between sampling and processing, the protracted process of analysis, limited funding and access to suitable

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facilities, timeous analysis of individual molecular biomarkers was not viable and only bulk organic carbon analysis was carried out.

3.3.2.2 **Marine organic matter**

Bulk mudbelt $\delta^{13}C_{org}$ analysed for the purposes of this study is representative of a variety of organic carbon products of photosynthesis, sourced from terrigenous and marine materials (such as phytoplankton, coccolithophors and diatoms). The ocean receives terrestrial sediment and material from both abiotic and biotic sources, where much of the abiotic portion is a product of continental erosion and can be correlated with terrestrial plant vegetation. Values of $\delta^{13}C$ (dissolved inorganic carbon) however, vary widely in the ocean. The majority of marine organic matter is produced by phytoplankton in the photic zone and varies between -14‰ and-35‰ (Rau 2002, after Descolas-Gros and Fontugne 1990). Much of this variation is determined by sea surface temperature, species and growth rates (Fontugne and Duplessy 1981). Since oxidation often occurs at depth, photosynthesis uses ^{12}C preferentially and the isotopic signature of surface water tends to be enriched with ^{13}C, whereas ^{12}C is "preferentially transferred to deeper water" (Broeker and Peng 1982). Clearly this does not hold true for rapid mixing zones such as zones of upwelling and high latitude areas (Wefer *et al.* 1999), although the mudbelt is situated near to an upwelling zone, it is situated some distance from the intense zone of upwelling.

Fluvially derived terrestrial organic matter (soil and plant matter) is a significant portion of the terrestrial organic matter in sediments found off river mouths (Meyers 1997, Holtvoeth *et al* 2001) and an important, but overlooked contributor of organic matter found in these sediments are terrestrial rather than marine plants and soils (Holtvoeth *et al.* 2005). Marine sediment has an average isotopic value of around -20‰ (Wefer *et al.* 1999, Chester 2005) and therefore terrestrial-marine margins can be investigated for the terrestrial signature if the standard marine -20‰ value is assumed.

It is assumed that the $\delta^{13}C$ values from the sediment are a mixture of both C_3 and C_4 plants. C_4 vegetation is known to dominate the Orange River Catchment, whereas marine plants or phytoplankton are mainly C_3-rich and therefore produce low $^{13}C/^{12}C$

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ratios (Fontugne and Duplessy 1978, Wefer *et al.* 1999). Deep water particulate organic matter tends to be 2‰ to 3‰ more negative than the surface water (a detailed discussion of deep water isotope dynamics may be found in Fontugne and Duplessy 1981, Wefer *et al.* 1999 and others).

Bulk organic stable carbon isotopes have been used by a number of researchers to elucidate terrestrial signals of vegetation (Sweeny and Kaplan 1980, Wada *et al.* 1987). Potential bias can originate within the isotopic values of sediment in the marine context (at the continental margin) due to changes in water column productivity (growth conditions) (Bickert 2000). This potential for diagenesis of the sediment in the marine environment may be due to fractionation mechanisms within the water column, during or before deposition, but the isotopic signature is largely that of the original source material (Bickert 2000). It could be anticipated that within the Namaqualand mudbelt, the data might primarily reflect the terrestrial source material, with a smaller component from the marine organic matter and very little influence from diagenetic activity.

3.3.3 Stable nitrogen ($\delta^{15}N$) isotopes in sediment

Stable nitrogen isotopes are useful in examining aspects of nitrogen pathways and nutrient cycling, yet are not as well understood as carbon isotopes and appear complex due to the tremendous number of influences of the various pathways within the nitrogen cycle (Lee Thorp & Talma 2000). As a result, these continue to undergo revision in the literature. Indeed, Handley *et al.* (2001) were instrumental in debunking previously entrenched theory that $\delta^{15}N$ was transferred directly from atmospheric and other nitrogen sources. Instead, plant $\delta^{15}N$ is determined by an array of factors including soil type, climate, nitrogen availability and modes of isotopic fractionation (denitrification, demineralisation, nitrogen fixation, dissolution) and are not simply 'passive receptors' of external sources of nitrogen (Handley *et al.* 2001, Codron *et al.* 2005a). These processes of fractionation are modified by environmental stress, such as aridity, salinity and nitrogen soil deficiency (Handley and Scrimgeour 1997, Handley *et al.* 2001). In addition, the relationship between *mycorrhiza* and the above mentioned environmental stress is important to further understanding the nuances of nitrogen isotopes fractionation within plant matter and Handley *et al.*

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(1999) suggests soil has an additional important part in affecting plant isotopic values (Swap *et al.* 2004).

Plants take up nitrogen as nitrites and nitrates from the soil. In turn, these may be returned in a fractionated form to the soil during decomposition processes, whereas carbon isotopes are taken up from atmospheric sources and provide information on the photosynthetic pathways of carbon. Nitrogen isotopes are increasingly employed as a useful indicator of the source of nitrogen and the fate of nutrients in both inland and marine ecosystems in the water column (Bickert 2000). This isotopic proxy potentially provides additional information on the nature of the mudbelt and additional insight into aspects of inland palaeoenvironmental information represented therein that would otherwise not be possible to examine (Handley *et al.* 2000). Indeed, nitrogen isotope data is most useful when interpreted in tandem with other isotopic data such as carbon isotopes (Handley and Raven 1992, Codron *et al.* 2005a).

There is scope for much more research into these and other aspects of nitrogen isotope analysis within individual plant taxa of the terrestrial and marine ecosystem as catchment studies and broad scale nitrogen cycling studies are particularly lacking with respect to soil modelling and its interpretation. There are however, some useful inferences that can be made in the southern African context to assist in the interpretation of nitrogen isotope analysis of mudbelt material. (Some of these dynamics and measured data are discussed in section 5.3.1) and it is reasonable to assume that the fluvial nitrogen isotope values from the Orange River are likely to be high, given the arid nature of the inland region. It is important to note that a number of these complex factors (nitrification, loss of nitrogen due to heat, aridity or loss through runoff result in the conversion from plant material to soil organic matter) are difficult to quantify in open systems and only inferences of qualitative values are possible.

In this study, stable nitrogen isotope analysis of the mudbelt sediments was intended to further examine the mudbelt in terms of its isotopic proxies of palaeoproductivity and complement findings with respect to carbon isotope analysis.

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3.3.3.1 $\delta^{15}N$ in the terrestrial environment

Fractionation results in a wide variability of nitrogen isotope ratios in terrestrial plants (Bickert 2000). Soil is enriched with ^{15}N relative to atmospheric nitrogen due to dissolution, ammonia vitalisation and denitrification but it is difficult to quantify given these and other factors such as microbial action and reaction rates. Non- N-fixing plants are enriched in $\delta^{15}N$ compared to N_2-fixing plants. The lighter, more negative the delta (δ) value nitrogen produced, the better is the plant's ability to fix nitrogen. Thus, atmospheric nitrogen is isotopically lighter than plant tissue, which in turn is isotopically lighter than soil ^{15}N values. This $\delta^{15}N$ depletion is possibly due to microbes favouring the heavier isotope during decomposition and thus discriminating against the light isotope (Fogel and Cifuentes 1993).

A number of general studies of plant nitrogen isotopes have been made in southern Africa, but coverage is patchy and understanding of $\delta^{15}N$ of soil is limited (Heaton 1987, Sealy *et al.* 1987, Codron *et al.* 2005a and Swap *et al.* 2004). It is important to discern something of the nitrogen isotope values produced by the local vegetation in the Orange River and Buffels River Catchment in order to understand something of the $\delta^{15}N$ of the samples both inland and in the mudbelt. Some trends and observations relating to these papers are discussed in the following section.

An initial trend was observed in parts of the African continent where rainfall abundance and $\delta^{15}N$ of plants were correlated (Heaton 1987, after Heaton 1986), but although aridity (enrichment of soil with ^{15}N) is significant in dry soils, it is a less important factor (Heaton 1987) than climate, soil and availability of Nitrogen (Codron *et al.* 2005a). The $\delta^{15}N$ values of plants generally range from between -1‰ and 6‰ (Heaton 1987) but wide ranges within the terrestrial system have been recorded (Holmes *et al.* 1996). Recently, studies by Swap *et al.* (2004) and Codron *et al.* (2005a) have drawn together new results with existing data to show interesting variations within the nitrogen isotope data sets. Although the picture is complex, some trends have been identified and soil type in addition to climate are the most important factors affecting nitrogen in the Savanna region. Swap *et al.* (2004) have shown that stable nitrogen isotope values of C_3 vegetation in southern Africa can be explained by rainfall in more than half of recorded variance. This variance suggests that nutrients

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are inversely affected by the availability of water which has particular relevance to understanding of nutrient cycling in semi-arid and arid southern Africa (Swap *et al.* 2004) where soils and plants are relatively enriched in $\delta^{15}N$. C_4 vegetation on the other hand indicates no such correlation with rainfall. Swap *et al.* (2004) and others point out the East-West gradients of rainfall and other biophysical processes. Handley *et al.* (1999) describe semi-arid to arid regions as having a more open (nutrient-rich) nitrogen cycling than the more humid East due to water becoming more of a limiting factor here rather than nutrients. In the wetter system of the moist East, where water is widely available, but nutrients are limited, the system is 'tightly cycled' and $\delta^{15}N$ values are depleted. Codron *et al.* (2005a) have found significant environmentally and physiologically induced variability of up to 4‰ in the Savanna Biome, which is less than previous studies indicate. Indeed, as the Savanna covers the gradient extensively, it is easily subdivided into wet and dry halves, where water and nutrients play a primary role in productivity with dry soils and rainfall being more important issues in the wet Savanna (Swap *et al.* 2004). Dry and sandy environments of the west tend to be associated with high $\delta^{15}N$ values (Heaton 1987, Codron *et al.* 2005a), whereas the more moist conditions of the east have depleted $\delta^{15}N$ values (Swap *et al.* 2004), therefore this trend of $\delta^{15}N$ values correlates well with rainfall levels. Trees, forbs and grasses within the Savanna tend to have similar $\delta^{15}N$ values (Codron *et al.* 2005a). Within the Savanna, isotopic analysis of plants are also shown to be affected by soil type. Plants situated on sodic soils tend to have the highest $\delta^{15}N$ values (6.4‰ ± 2.2). Northern basaltic soils are not as high at (5.5‰ ± 1.6), whereas plants situated on the southern granitic and dry, sandy soils have slightly lower $\delta^{15}N$ values (5.1‰ ± 2.6). Plants situated on the dry sandy northern granites are low $\delta^{15}N$ (2.7‰ ± 1.4), whereas clay rich southern basaltic soils have lower $\delta^{15}N$ values (2.6‰ ± 1.9) (Codron *et al.* 2005a).

There are no published nitrogen data on the Succulent Karoo, but unpublished data suggests values very similar to those of the Savanna and the Kalahari. (William Stock pers. comm.). As an aside, Succulent Karoo has less rainfall than the Savanna and Kalahari biomes. It is however possible that $\delta^{15}N$ may be very slightly higher in the Succulent Karoo due to the coastal effect and increased aridity, but this kind of subtlety is probably not easy to discern in the mudbelt, given the diluting effect of other factors influencing OM in the region. Indeed, the CAM - dominated succulents

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(in the Savanna) tend to be enriched with $\delta^{15}N$ (Codron *et al.* 2005a). The nitrogen isotopic value of vegetation of the Savanna had been poorly studied until Codron *et al.* (2005a) published results investigating a broad selection of vegetation types in this biome for nitrogen and carbon isotope values. There is a smaller variation than previously measured for the Savanna biome. The $\delta^{13}C$ isotopic signature of plant values vary by up to 2 ‰ in C_3, or 1‰ in C_4–dominated vegetation, but $\delta^{15}N$ values vary up to 4 ‰ between various Savanna microclimates. Coastal and saline areas produced higher $\delta^{15}N$ values than other areas (the arid Namib coast was 10‰ higher than inland and saline soil found to be 4‰ higher than non-saline soils), but exceptions do occur and some sites have high values for no determinable reason. Namib values range from -1‰ to -6‰. Thus, factors other than simply aridity are responsible for variation of $\delta^{15}N$ values. However, coastal areas with high rainfall are found to reduce the coastal effect. Again, this is probably related to nutrient availability in the soil and the resulting isotopic fractionation by plants due to this.

3.3.3.2 $\delta^{15}N$ in the marine environment

The $\delta^{15}N$ values of the mudbelt sediment is composed of both terrestrial and marine organics and thus it is important to consider the deep-water marine environment as a contributor to our understanding of the mudbelt. The marine component of the nitrogen cycle consists of numerous organic and inorganic "pools" allied to biological activity. This activity includes nitrogen fixation, denitrification and nitrification and deamination and is complex given the number of variables at work in this environment. Indeed, the $\delta^{15}N$ values of marine sediment are further modified through the effects of kinetic fractionation (ammonification, nitrification and denitrification), as are terrestrial sediments. Therefore, nitrogen stable isotopes are useful in reconstructing the degree to which surface waters have utilised nitrates at the time of production (Bickert 2000). These aspects are detailed in Bickert 2000 (after Wada 1980), Altabet *et al.* 1991 and Voss *et al.* 1996.

Anoxic conditions result in marine organisms utilising alternatives to oxygen for their electron-receptor requirements. Nitrogen as nitrate is typically utilised by these organisms in the process of denitrification, where nitrogen gas is released as the by-product and is known to be a limiting nutrient in the Benguela upwelling region. It is

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also the most important source of nitrogen in the Benguela region (Rau 2002 after Probyn 1985) although it is generally considered that nitrogen limits the growth of phytoplankton in much of the ocean. This effectively alters the isotopic composition of the water column and results in fractionation of sediment pore waters. For discussion of this area, refer to Rau (2002) and Shannon and Pillar (1986).

Nitrogen fixation, nitrification and denitrification each involve biogenic use of N_2 and have slightly different fractionation factors. The release of ammonia gas has a significant isotopic effect and solutions of nitrogen gas have a small isotopic effect (Bickert 2000). Nitrogen (as nitrate) reaches the marine environment through precipitation, river discharge and nitrogen fixation and is effectively removed from the marine environment by sediment burial and denitrification. The entire nitrogen budget is difficult to quantify in such an open system. However, the important processes are the processes of denitrification within the water column and sediment. Denitrification is the primary process whereby marine nitrogen compounds are sustained at a higher $\delta^{15}N$ than atmospheric nitrogen and is also where significant fractionation may occur in the water column.

$\delta^{15}N$ of sediment surface tends to reflect the $\delta^{15}N$ signal produced by surface waters in the marine situation. However, this is true to a much smaller degree on the inner shelf where the influence of terrigenous material is much greater and the area of interest (the mudbelt) is also some distance from the Benguela upwelling, where the input of inland terrestrial sediment is significant. There is a much greater variation in $\delta^{15}N$ values than $\delta^{13}C$ values, as nitrogen is more rapidly lost during particulate organic matter (POM) degradation (Altabet and McCarthy 1985). Localised denitrification and remineralisation of sedimentary organic matter can create localised variation in the $\delta^{15}N$ isotopic signature. Deep-sea studies are not as useful for purposes of comparison in this study as they are heavily influenced by the marine signal or upwelling and not as concerned with the terrigenous component, as is the case on the inner-shelf mudbelt. On the inner shelf the marine and upwelling values are effectively diluted with terrigenous isotopic values. By comparison, sediment from the Angola Basin is rich in nitrogen from marine sources, rather than terrigenous, despite its proximity to the river mouth (Holmes *et al.* 1996).

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A combination of $\delta^{13}C$ and $\delta^{15}N$ isotope analysis draws together a better understanding of the terrestrial vs. marine data, as useful for investigating palaeoenvironmental clues of the mudbelt sediment.

3.3.4 Preparation of samples for stable light isotope analysis

Sub-samples of the H2 and H7 mudbelt core samples were extracted at 5 cm intervals for bulk sample isotope analysis. These samples were split for the purposes of preparing both carbon and nitrogen isotope analysis. The 5 cm resolution corresponds to a higher resolution than the 20 cm interval used for pollen analysis. Inland, Richtersveld palaeoflood sites (Lower Xobies, Bloeddrift and the Jakkalsberg site) were also sub-sampled for this purpose, although only certain layers were analysed in the case of the Bloeddrift (a single sample) and Jakkalsberg sites; a 5 cm sampling interval was used at Lower Xobies. Modern samples (WT#, WTPOT and R samples) were taken from the lower reaches of the Orange River. The same methodology was used to prepare modern river sediment samples, the Richtersveld deposits and the Lower Xobies slack-water deposit for stable carbon isotope analysis. The pre-treatment process for carbon isotope analysis involves the removal of inorganic carbon using HCl digestion. Nitrogen isotope analysis uses the same preparation as for carbon isotopes, with the omission of the HCl pre-treatment step (refer section 5.4.2).

Small amounts (about 300 mg) of mudbelt material were sub-sampled from the 500 ml containers of the gravity core working half. These sub-samples were either dried at 70°C in a warming oven overnight, or freeze dried for a few hours. After drying, the samples were then finely ground using a pestle and mortar to achieve isotopic homogeneity. A 5 mg sub-sample of this was then weighed and placed in 2 ml microfuge tubes. This was freeze-dried again to remove all traces of water. Any aggregates were broken up and ground to a fine powder using mortar and pestle. Due to the high clay content and high proportion of fines in the mudbelt material, there were few aggregates to slow the process.

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3.3.4.1 **Pre-treatment of samples**

Half the samples were destined for carbon isotope analysis; these were pre-treated with hydrochloric acid (HCl). HCl (10% or 1M) was added to the sample in the tube to remove the inorganic carbon (as carbonate) content. This is necessary as inorganic carbon alters the measurement of $\delta^{13}C$, unless carbonate is first removed from the sediment sample. (For more details refer to Harris *et al* 2001). The remaining samples, destined for nitrogen isotope analysis, were not treated with HCl, as this step is not necessary for nitrogen isotope analysis and tends to increase the $\delta^{15}N$ sediment values (Handley *et al.* 2000). The HCl treated samples were left for a twelve-hour period overnight and the following morning, the sample was then agitated in an ultrasonic bath for a few seconds in order to dissolve any remaining carbonate. Acid digestion of the carbonate results in an isotopic signature representing only the organic fraction in the sample remnant. After leaving the sample to settle for about 30 minutes, the samples were then thoroughly mixed, centrifuged, the supernatant poured off and the sample was washed twice with distilled water before being freeze dried and finely ground.

A 4-5 mg sub-sample of the remaining sample mass was then weighed in a small tin boat, carefully pressed closed and compressed into a spherical shape, with the use of forceps, then placed on a covered plastic cell-culture plate (to keep the sample dust-free). These samples were analysed on the Finnigan MAT 252 mass spectrometer at the Archaeometry laboratory, University of Cape Town, South Africa. The sample was combusted and the resulting CO_2 is measured for $\delta^{13}C$ or gaseous N_2 for $\delta^{15}N$ (or NH_4^+ or NO_3^-). A micro-analytical balance, with 3 decimal place accuracy was used to weigh samples. At least three additional representative samples were set aside as test samples that were analysed first, in order to ascertain whether sufficient material was prepared, before full analysis began. This ensured that samples prepared for carbon isotope analysis would have sufficient carbon in them in order to provide for the spectral analysis of the isotopes (and similarly for nitrogen) and interspersed with the samples during the analytical run. Merck Gel and sucrose were used as internal calibration standards for the stable carbon isotope analysis, whereas Valine, N1 and Merck Gel were the standards used for the nitrogen stable light isotope analyses.

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Raw isotopic data from each sample run were calibrated using a curve derived from the calibration standards and then corrected accordingly. Samples with extremely high or low values of amplitude, voltage or unexpected delta values, usually due to insufficient sample material, were discarded.

Results of $\delta^{15}N$ and $\delta^{13}C$ were calculated using equations 2 and 3 in section 5.1.1 and are tabulated in Tables E1- E5 in appendix E, illustrated in Figures 5.1- 5.6 and Tables 5.1 - 5.3 of chapter 5, where the carbon and nitrogen isotope results are detailed.

3.4 Pollen Analysis of the Namaqualand mudbelt

The basis of palynology lies in the assumption that the prevailing vegetation of a particular time period and area is represented by the "pollen rain" produced by the same vegetation of that area (Moore, Webb and Collinson 1991). Given appropriate preservation conditions, the resulting fossil pollen assemblage may be considered a useful index of that vegetation. Pollen is not, as is so often assumed, always produced in quantity and uniformly dispersed. Only a small proportion of pollen produced is effectively utilised for reproductive purposes (Faegri *et al.* 1989) and instead it is often difficult to predict the precise quantitative representation of pollen in the sediment record given the variety of factors affecting dispersal and production. By deduction, it is therefore also difficult to extrapolate past vegetation from the pollen record, given the potential ambiguity and variable nature of pollen preservation in sedimentary deposits.

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3.4.1 Principles of pollen analysis

Pollen is, by definition, produced by flowering plants in different quantities by various flowering species, but pollen morphology is specific to the taxon. Although the concept of pollen rain is complex, it can be assumed that the pollen rain represented in the Orange River sediment is representative to some degree of the taxa distributed throughout the catchment. Additional mudbelt pollen sources include airborne pollen from the interior, the Buffels River and potential ocean-borne pollen (less likely). This assumption incorporates some important concepts on which

palynology is based: fossil pollen represents the pollen rain of a particular period in time and thus provides a unique opportunity to explore the vegetation of that time period. The absence of a particular species or family of pollen grain from the record implies the species was absent from the catchment (Faegri *et al.* 1989). However, this assumption is not strictly true and can only point to an absence of evidence and not that a particular species is absent. The pollen assemblage of a sedimentary sequence such as the mudbelt may be examined at depth intervals and the contents can be used to construct a continuous record of vegetation through time. This can be helpful in assisting with understanding climate variations and the impact of human disturbance if the relevant mechanisms and causal relationships are adequately understood. However, variations in the pollen spectra are not necessarily proportionally reflected in the associated occurrence of vegetation. Instead, pollen spectra tend to reflect the greater abundant anemophilous pollen (wind transported) types; zoophilous (insect and animal-borne) and autogamous (self-fertilizing) pollen types are typically poorly represented. Pollen production and dispersal is subject to a number of climatic and environmental variables and short- to long-term climate change may be represented in the pollen record and preserved as a record of such an event. However, these short-term variables may be obscured by other variables, thus confusing the record (Moore 1989). Some variables which would affect the otherwise fine-resolution of the pollen spectra may include:

- variation in pollen source (catchment palynology), localised or widespread environmental change.
- local human effect on the environment, extreme events (major floods),
- geochemical variation.
- reworking and other lag responses (retarding movement of pollen from source to destination).
- aridity of the environment.
- climatic variation (rainfall, altitude, soil quality).
- lag in response by flowering plant taxa to climatic or other change.

Although it is possible to identify a small number of individual pollen grains within pollen-bearing sediment without chemical processing, it is expedient to process the sediment material and thereby clean the sample of extraneous material. (For detailed

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processing protocol refer to Appendix C). Clay-rich sample processing in the pilot study has shown that large variation in the physical and chemical characteristics of individual samples makes it difficult to predict the number of treatments each individual sample will ultimately require. Preliminary observations of this from the pilot study are presented in Gray (1996) and Gray *et al.* (2000). The palynology laboratory processing techniques used in this study are loosely based on standard procedures published by Moore *et al.* (1991), Faegri *et al.* (1989), Jansonius and McGregor (1996), a groundbreaking procedure for cleaning clay-rich samples by Bates *et al.* (1978), an unpublished Ph.D. thesis by Baxter (1996), together with input from a number of currently active palynologists. Despite these guidelines, processing of samples is at best an inexact technique and often relies on trial and error. However, refining of process capabilities and the reaction and effectiveness of various chemicals on preliminary samples does improve the situation. The processing of the samples for pollen, slide preparation and identification are detailed in Appendix C.

Preliminary work on the mudbelt, which had previously confirmed the presence of pollen in the mudbelt material (Gray 1996, Gray *et al.* 2000), is the basis on which this pollen study developed. An improved processing method and understanding of the pollen represented in the catchment facilitated an improved and more systematic identification process. These improvements and findings of new pollen data in the mudbelt and the Orange River are described in detail in the following sections.

3.4.2 Detrended correspondence analysis, principal component analysis and cluster analysis of pollen data

In order to understand some of the complexities underpinning the pollen spectra in and between core sequences H2 and H7, a selection of taxa pollen components was made for statistical ordination analysis. This was important, as the interpretation of the data rests heavily on whether the mudbelt pollen is indeed being governed by the primary source, the Orange River, or if it is more affected by airborne pollen or the episodic influence of the Buffels River, as in the case of the H7 core. Another important purpose of this analysis was to investigate palaeoenvironmental change potentially illustrated by the pollen, not immediately evident by examining the pollen diagrams. Even if the analysis confirmed the Orange River to be the primary factor, it was considered important to statistically exclude other possibilities. Although

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statistical analysis is useful, it should also be interpreted with caution, as it is, by definition, a means of interpreting data and is therefore subjective, governed by limitations and reductive in nature.

The data were prepared and processed for detrended correspondence analysis (DCA) and principal component analysis (PCA) computation according to a standard protocol (Grimm 1987 and Craigie and Sugden 2005); taxa with a presence below 5% for any of the samples from the data set were excluded, in addition to any Riparian elements, in order to clarify the analysis and reduce data noise. This effectively reduces the total amount of data and thus percentage variance, not co-variance, was calculated (see Table F9 – F11 Appendix F). As both H2 and H7 were used, taxa not common to both cores were excluded under these new limitations. There were originally more than 49 taxa, but the resulting dataset included only six: Asteraceae-Type1, Asteraceae-Type2, Caryophyllaceae, Euphorbiaceae, Poaceae and Restionaceae. These taxa are illustrated in a pollen diagram (Figure 6.7, chapter 6). Finally, the original raw count values were converted to a relative percentage. As the data had to be re-scaled in order to accommodate noise reduction, the data was analysed according to correlation matrices, instead of co-variance matrices (Bennet 2001). DCA, PCA and cluster analysis was applied using the palaeontological statistics package, PAST (version 1.38.) This package is well suited to palaeoenvironmental statistics, freely available and compatible with EXCEL.

Simple statistical interpretation was not possible because of the multivariate nature of the data and a simple XY plot was not possible. There are many multivariate statistical analytical methods, but it is common practice to use DCA, followed by PCA, if necessary. Both methods are aimed at establishing an understanding of the variance within a set of data, in terms of principal components. An additional method of interpretation of pollen data, cluster analysis, was available. Again, there are many possibilities and permutations of this type, but Grimm (1987) suggests using all available data in one analysis, so the samples may be associated with their nearest, not their most similar neighbour, therefore all samples were used from H2, H7 and modern Orange River samples in order to analyse this. The graphical output therefore shows sample association, rather than nearest neighbour similarities.

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DCA is a method of ordination, very similar to PCA, but is usually applied for comparison of associations of counted data. This method calculates eigenvalues and eigenvectors using a matrix of Chi-squared distance between data points (Jolliffe 1986). Only the four (or fewer) of the most important eigenvectors are included in the output. The detrended aspect of the analysis involves normalisation of the coordinates, by straightening plotted points, found in an arch (Hammer 2005), in order to assist interpretation.

PCA is a widely applicable technique based on eigenanalysis. This involves the stepwise treatment of data using subtraction of the mean value and calculation of the correlation (or covariance) matrix to find the eigenvectors and eigenvalues. Using the principal of data compression, the eigenvector with the highest eigenvalue is understood to be the principal component of the data set. Eigenvectors are important in terms of their ordered significance and are listed from highest value (explaining the most variance) to lowest value (explaining much less of the variance) (Smith 2002). Thus, any eigenvector that is above a specific value of one, is deemed valid, but those below that value are not considered significant. A crude, but effective method of analysis, known as 'factorial scree' establishes significant components by plotting eigenvalue against eigenvalue number and where the plot levels off, this denotes where factors may be deemed negligible. Principal component analysis is the most statistically significant explanation of the relationship between points in the data and analysing the standard deviation of points within the data result in calculated eigenvalues and eigenvectors (Hammer *et al.* 2007). Many statistical packages, such as Statistica, PAST will run these steps without any assistance, apart from proper pre-treatment of the data, to produce the results. PCA is a means of extracting the main factors affecting the data and enabling the plotting of this information graphically. Graphical representation of this data would not be otherwise possible. PCA should be interpreted in light of the original raw data and as a separate analysis. PCA's are therefore an analytical transformation of the original raw data into a new explanation that involves maximisation of the variance of the various PC vectors, which are graphically expressed as axes. This analysis involves extracting factors that account for the variance until the remaining variance is reduced to an insignificant value (MacLeod 2005).

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3.4.3 Pollen analysis in context

The source of mudbelt pollen has long been considered to be primarily fluvial and related to the Orange River Catchment (Dingle 1994, Gray 1996, Gray *et al.* 2000, Meadows *et al.* 1997, 2002). Additional flood event information has subsequently become available in both the Orange River and the ephemeral Buffels River. Although definitive records are not yet available on the Buffels River, evidence suggests this river contributes only erratically to the mudbelt. As mentioned in chapter 1, this evidence includes grey laminations (Mabote 1997). Additional factors include berg wind sand deposits, direct runoff (minimal) from the shoreline and pollen circulated in the oceans from other regions. Other evidence is detailed in chapters 3 and 5. The open nature of the mudbelt system is a major challenge with respect to understanding the source of the pollen and additional bias is created by a number of factors:

- The input of pollen taxa is difficult to quantify, given the overlap of various biome families in the main catchment area.
- The Orange River is still considered to be the primary source, but there is some confusion as to the relative proportions of other significant sources.
- This is further complicated by fluctuations of flood events.

A new flood research initiative by Hoffmann in the Buffels River Catchment will hopefully contribute to a better understanding in the near future and will enhance understanding of these dynamics.

In the following chapter (chronology chapter 4), results of the ^{210}Pb dating, the ^{137}Cs analysis and total organic carbon (TOC) are discussed, but no results were possible for the foraminifera due to insufficient sample in the mudbelt material. Chapter 5 details the stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes results for the mudbelt, inland sites and modern material and findings relating to this data. Pollen counts, analysis and a detailed analysis of variations within the pollen record are detailed in chapter 6.

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4 CHRONOLOGY OF THE NAMAQUALAND MUDBELT AND RELATED SITES

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4 CHRONOLOGY OF THE NAMAQUALAND MUDBELT AND RELATED SITES

This chapter concerns the results of a new attempt to obtain a better understanding of the chronology of the mudbelt represented by the HODSA core material. By reviewing earlier work aimed at establishing the chronology of the cores, a number of problems and challenges become apparent. As mentioned in chapter 3, these problems are related to the nature and timing of off-shore deposition in the mudbelt, as well as the nature and timing of material and the fluvial processes of the Orange River itself. This chapter presents results of new approaches to dating these sediments that were designed to overcome these challenges and closes with a synthesis of the new mudbelt chronology. It becomes apparent that some of these approaches were more successful than others. The overall dating of these mudbelt sediments at a reasonably high resolution, required for palaeoenvironmental reconstruction, remains inherently difficult. The methodologies used to produce the results in this chapter are detailed as part of chapter 3. In this chapter, the chronology of the cores as reported in recent literature is presented and this is followed by the strategy used in this thesis to obtain additional information about the age and deposition of the mudbelt sediments.

4.1 Introduction

The initial bulk organic radiocarbon age determinations (Meadows *et al.* 1997) provided results indicating apparent age reversals and inconsistencies in the cores. In addition, the surface sediment did not yield modern or recent radiocarbon ages, thus bringing into question whether or not the actual surface sediment of the mudbelt was sampled during the HODSA coring exercise (Gray 1996, Gray *et al.* 2000, Meadows *et al.* 1997). Resolving these apparent inconsistencies and uncertainties is the foundation on which this chapter is based. In addition, these radiocarbon ages are now calibrated, whereas previously these were presented uncalibrated. Some are, however presented uncalibrated when referring to previously published uncalibrated dates although the calibrated age is included where appropriate.

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Sites in the lower reaches of the Orange River, with known radiocarbon ages (section 4.4) were used to assist in improving understanding of the mudbelt sediment and its source material. Here, additional radiocarbon age determinations and associated review of published material was also necessary in some sites (Jakkalsberg and Bloeddrift) in order to verify sediment age and where change had occurred to the site in the interim (section 4.5). An attempt at extracting foraminifera for small sample AMS dating is also described here, along with TOC analysis for completeness of understanding the organic carbon, on which the majority of the previous dating analysis was based. In addition, ^{210}Pb and ^{137}Cs analyses were also conducted on the surface and near surface sediments.

4.2 Purpose of understanding the mudbelt chronology

It is necessary to understand the age and chronology of the Namaqualand mudbelt for a number of key reasons. Most importantly it is necessary to understand the timing and duration of sediment deposition as a basis for characterising the mudbelt. As such, it is fundamental for understanding the palaeoenvironmental proxy data within the mudbelt and therefore useful in the broadest understanding of inland erosion and environmental change as a basis on which to interpret and understand other palaeoecological data. Moreover, it is important to compare, contrast and interpret this information against the inland situation and this is only possible if the mudbelt chronology is understood at a reasonably high resolution. Indeed, understanding this mudbelt chronology is fundamental to obtaining the desired centennial-scale change in the proxy vegetation assemblage.

Some of the problems facing analysis of the mudbelt chronology include the nature of the dateable mudbelt organic material, portions of which do not appear to become deposited immediately. Instead, these may recirculate as particulate or dissolved organic material and along with inorganics may float on the surface or in the water column as flocculated, aggregated or adsorbed particles, where biogeochemical processes may occur (Dagg *et al.* 2004).

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This phenomenon is known as the reservoir effect[1]. These r e-circulated organics combine both terrestrial (which is potentially reworked, particularly given the expanse of the ORC) and marine sources (affected by the local marine reservoir age), before settling to the Mudbelt sediment deposit. In addition, the Orange River although perennial, has markedly varying flow rate and sediment load; flooding and erosion in the catchment occurs unexpectedly and with great magnitude (Zawada 1997). Thus the impact on the type and source of material washed into the catchment and flowing out of the mouth and potentially represented in the mudbelt is varied and of varying ages.

A recently manifested characteristic of the Orange River, which had a vast impact on flow rate (and therefore flow - onto the inner continental shelf and mudbelt) within the last 20 years, is the open mouth and deterioration of the estuary due to an altered flow regime in the catchment. This was primarily brought on through impounding of the river, mining activities and hydroelectricity installations in the ORC (Heath 2001).

There are several problems with the HODSA core chronology associated with the mudbelt in previously published work and these are addressed in the sections following (note: these following ages are presented below in uncalibrated form as published in Meadows *et al.* (1997, 2002) and Gray *et al.*(2000):

- Bulk organic radiocarbon ages yielded the near surface age of the mudbelt (5-10 cm depth) between 590 ± 41 and 865 ± 47 years BP (uncalibrated, Meadows *et al.* 1997), which is not modern and therefore appears to be at least 400 years older than the presumed most recent depositional events. Sediments just below this, at 13-15 cm in core H2, yield ages of

[1] The reservoir effect refers to the phenomenon whereby organic materials are circulated within a specific system (e.g. the marine system, as the ocean represents a major carbon reservoir but this may also occur in riparian and other systems) and result in an older than expected age when submitted to radiocarbon analysis. A correction of the resulting dates is required in order to produce an accurate radiocarbon date and thus facilitate an accurate comparison with other samples. Samples vary geographically within the ocean due to the complexities of oceanic circulation and older ages are usually found in areas of upwelling, such as on the West Coast of southern Africa.

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1 410 ± 61 years BP (uncalibrated, Meadows *et al.* 1997) and illustrate variation within just a small depth difference.

- Results of bulk organic radiocarbon analysis of 24 sediment samples from five core sites run in 1996 showed apparent age reversals in the mudbelt with the more obviously laminated sediments of the prodeltaic region, as represented by core H2, proving the most problematic in this regard (Meadows *et al.* 1997, Gray 1996, Gray *et al.* 2000, Meadows *et al.* 2002). This trend is particularly enigmatic since it would be expected that the more clearly laminated would be more chronologically consistent. Meadows *et al.* (2002), Gray (1996), Gray *et al.* (2000) indicate that dating of bulk organic carbon from this type of sediment in the mudbelt may be a problematic exercise due to issues of reworking, which is a well documented feature of mudbelts and similar environments. Related to this problem is the question of reworking of organics in the catchment prior to deposition in the mudbelt, which is in addition to the issue of *in situ* reworking.

- A single OSL date published in Meadows *et al.* 2002 yielded a similar age to that of the bulk organic uncalibrated radiocarbon date on a sample at the base of core H7. This lent more support for the radiocarbon age of core H7, yet did not resolve the issue of age reversals apparent elsewhere in the mudbelt.

An improved understanding of this chronology has necessitated a new approach to the analysis of age and depositional history of the mudbelt, and a new strategy was developed, part of which is referred to in Gray *et al.* 2000. Thus, in terms of problems of chronology and the gaps therein, which have now been identified, a number of strategies were applied with varying degrees of success. The following issues of chronology needed to be resolved and fully explored and are addressed in this chapter:

- Existing bulk organic radiocarbon ages obtained from the mudbelt were uncalibrated and therefore required calibration using a calibration curve suited to the southern hemisphere. Further, consideration needs to be made for a possible inclusion of an assumed correction for marine reservoir age. This was omitted from the calculation for reasons as laid out below.

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- The tops of the HODSA cores (surface to near surface of the mudbelt) yielded non-modern radiocarbon ages, but were expected to be representative of modern surface samples.

- Due to the above situation, it was not known if the surface sediments had actually been sampled during the gravity coring.

- Apparent age reversals exist in some of the bulk organic radiocarbon ages, especially in the more laminated core H2, although reversals are not restricted only to laminated sediment in core H2.

- The apparent age reversals in the bulk organic radiocarbon ages needed to be reconciled to establish time of sediment deposition as opposed to the age of organic material *per se*. Additional methods of establishing age were therefore required to address reworking of carbon.

- Techniques of chronology analysis using foraminifera and other dating techniques had not been fully explored in the mudbelt material.

- The age of organic material from inland sites at Jakkalsberg and Bloeddrift in the Richtersveld exhibited limited resemblance to published site data at the same geographical location.

These issues were addressed using the following strategies and techniques:

- The existing bulk organic radiocarbon ages obtained from the mudbelt were corrected using the southern hemisphere calibration curve, SHCAL04 (Stuiver and Reimer 1993), up to a calibrated age of 10 000 years BP and a single sample, outside this calibration curve, was corrected for the southern hemisphere offset of 56 ± 24 off the northern hemisphere data set (McCormac *et al.* 2004; Reimer pers comm); this is presented in section 4.4.1, along with the previously published uncalibrated dates. The remainder of the results of chronology issues addressed are presented in section 4.5.

- There are no known marine reservoir age corrections for the study area and only projected figures based on sample sites to the south and offshore. Given

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the presumably mixed nature of the mudbelt organics (i.e. opportunity for re-circulating sediment from both terrestrial and marine sources in varied and unknown proportions, any correction is at best an estimate (Reimer pers. comm.). These mixed sediments are by definition difficult to calibrate as a number of calibration options are available; however, various methods have been excluded. Therefore, it is reasonable, indeed logical, to present the calibrated data *without* correction for marine reservoir age given the potential for lag from both terrestrial and marine sources.

- Utilise ^{210}Pb analysis of the mudbelt surface sediment (core tops) to establish the age of surface sediments sampled and reconcile with the older than expected radiocarbon ages of surface samples.

- Attempt ^{137}Cs analysis for the same reason as above.

- Explore the potential of existing inland ORC flood deposits. This has the advantage of examining sediments which a re 'old' before they reach the mudbelt through actions of erosion and reworking.

- Obtain additional bulk organic radiocarbon dating of terrestrial inland lower catchment sites and slack water deposits to better utilise data from existing published sites for mudbelt chronology and palaeoecological characteristics comparison.

- Address the issue of bulk organic radiocarbon ages in the mudbelt cores and a single OSL date (Meadows *et al.* 2002), which appears to support an associated calibrated radiocarbon date in core H2, using results by the above techniques and strategies.

- Collection, picking and cleaning of foraminifera in relevant samples relating to existing bulk organic radiocarbon ages in order to run small sample AMS dating. Radiocarbon analysis of foraminifera would date the age of the marine deposition without using any terrestrial carbon reworked within the catchment. It was hoped to take this a step further from simply resolving existing chronology problems and fine tune some of the mudbelt depositional history. The foraminifera provide a more reliable organic material

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representative of the depositional event, compared to the previously analysed bulk organic sediment, which is sourced over a varied reworked inland source from a broad time-space continuum. The use of foraminifera was therefore aimed at eliminating the issue of reworked terrigenous organic matter in depositional events of the mudbelt.

4.3 Radiocarbon dating

Radiocarbon Accelerator Mass Spectrometry (or AMS) ^{14}C analysis is firmly established as an important means of chronometric dating of organic bearing material less than 40 000 years old and is the most widely used method for this time period (Lowe and Walker 1997). Both standard (or 'conventional') radiocarbon dating (using 10 mg) and AMS small sample dating of samples using only a few milligrams of carbon (< 5 mg) is now possible. However, a number of assumptions and problems associated with radiocarbon dating include, but are not limited, to the following: the reservoir effect of old carbon and other post-depositional or biogenic contamination (particularly in the marine environment), issues of reworking within fluvial and deltaic environments, temporal variations in production of ^{14}C, isotopic fractionation, circulation of older marine carbon and generally problematic deltaic depositional sequences for many of the aforementioned mechanisms. These mechanisms will be discussed in relation to published and new chronology data in this chapter.

Radiocarbon dating of sediment refers to the time of an organism's death and not necessarily to the depositional event due to transport, possible reworking and the reservoir effect. Soil is among the most difficult materials to date and there are many reasons for this. Soil is often comprised of organic matter deposited over a period of time and, therefore, ^{14}C isotopes do not refer to a single depositional event. Thus, bulk organic matter radiocarbon age determination estimates the mean residence time (Lowe and Walker 1997, after Geyh *et al.* 1971) of the soil organic matter. In addition, humic acids and roots induce turnover of carbon within the soil and it is often more useful to date specific items of material, for example charcoal, rather than bulk organic sediment. It is important to bear in mind that the mudbelt is situated in a marine environment and therefore is not only comprised of terrestrial but also marine -derived carbon typically yields ages much older than expected. Additional organic ^{14}C is introduced into the water only at the ocean surface and slowly mixed with

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deeper water. Therefore it is not surprising that the 24 bulk organic radiocarbon ages obtained from H2, H4, H5, H6 and H7 display inconsistencies. These ages are illustrated in Figure 4.8 and plotted as a graph in Figure 4.9, clearly showing problems of old and reworked carbon.

There are a number of factors determining carbon reworking at the marine-terrestrial margin. A number of sources point to the marine carbon artificial ageing effect due to the recirculation of old carbon in the oceans. The ^{14}C concentrations in surface water vary but studies show that surface waters of the North Atlantic approximate an average age of 400 years (Bard *et al.* 1987b; 1991). This is similarly true of the South Atlantic, where marine carbon from an upwelling zone can be 400 years or older (Vogel pers. comm.) and Stanley and Hait (2000) refer to a standard lag of between 400 and 800 years in parts of the Atlantic Ocean. Other mudbelt studies show much older radiocarbon ages (e.g. surface ages of over 2 000 years) for essentially 'modern' carbon in other parts of the world and some time-lags of 4 000 years have been recorded (Stanley and Hait 2000). However, problems arise in that this old marine age signal has not remained constant, simply due to variation in sources of ^{14}C production which may vary from place to place and time to time. Inclusion of such a correction in the data would be affected by the not insignificant input of terrestrial sediment and was deemed to be at best an estimate, so no correction for the marine carbon reservoir was made in the calibrations presented here.

4.4 Previously published chronologies of mudbelt and related inland catchment sites and additional supporting analyses

4.4.1 Bulk organic AMS radiocarbon dating of mudbelt (Meadows *et al.* 1997; Dingle 1994) and presentation of new calibration of these dates

Bulk organic AMS radiocarbon dating was previously carried out on 24 samples of HODSA core and grab samples (Meadows *et al.* 1997, Dingle 1994) of the Namaqualand mudbelt (see Table 4.1 and Figure 4.1). AMS analysis was conducted at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institute, USA. The uncalibrated results were reported in Dingle (1994) and Meadows *et al.* (1997) and subsequently discussed in Mabote 1997, Mabote *et al.* 1997, Gray 1996, Gray *et al.* 2000 and Meadows *et al.* 2002. New

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calibrations of these dates are now included in the table as previous publications have reported only uncalibrated dates. However, during preparation of this thesis, some additional calibrated ages from core H7 were published in Herbert and Compton (2007). The calibration protocol used by Herbert and Compton (2007) on the uncalibrated radiocarbon ages from core H7 (Meadows *et al.* 1997) differs markedly from that used here and is based on an assumed local reservoir age of 550 years (Tonner 2003, after Herbert and Compton 2007) and the Fairbanks calibration program (Fairbanks *et al.* 2005, http://radiocarbon.LDEO.columbia.edu/), version 0107. Herbert and Compton (2007) applied a local marine carbon reservoir correction of 550 years, obtained from a coastal site a few hundred kilometres to the south of the ORM, was applied to the dates, based on the work of Tonner[2] (2003 after Herbert and Compton 2007), Talma and Vogel (1993) and the Pretoria calibration program WC93. For the purposes of this thesis, the uncalibrated radiocarbon ages (Meadows *et al.* 1997) were calibrated using the CALIB Radiocarbon Calibration Program (Stuiver and Reimer 1993). The Fairbanks Calibration Curve was not used as it has come to my attention that this is not accurate for ages less than 26k years BP (Reimer pers. comm.) and is not accurate for the Southern Hemisphere. With the exception of one sample, ages here were calibrated using the Southern Hemisphere Calibration Curve dataset, SHCAL04.14c (McCormac *et al.* 2004). The remaining sample, found outside the 10 000 year BP range of the Southern Hemisphere Calibration Curve, was calibrated using the International INTCAL04.14c dataset (Reimer *et al.* 2004) and modified with the Southern Hemisphere offset of 56 ± 24 (McCormac *et al.* 2004, Reimer pers comm).

The calibrated bulk organic radiocarbon ages in cores H2, H4, H5, H6 and H7 are illustrated in Figure 4.1. The base of H2 (592 cm) has yielded a calibrated radiocarbon age of 858 ± 57 cal yr BP (OS 8871) yet at 472 cm, some 120 cm above this level, the sediment yielded an age of 1465 ± 51 cal yr BP (OS 8874).

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[2] This study was situated on the West Coast shelf, where a comparison of shell and charcoal samples yielded a marine carbon reservoir age of 550 years. This is slightly older than the global average of 400 years (Stuiver and Braziunas 1993).

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Site	Depth (cm)	Lab Number (NOSAMS)	AMS date (uncalibrated) years BP	CALIB calibrated (no correction) years BP Southern Hemisphere Calibration curve
H2	5-10	OS 8877	570 ± 35	536 ± 16
H2	13-15	OS 8876	1500 ± 45	1336 ± 34
H2	337-342	OS 8875	1350 ± 40	1231 ± 51
H2	472-477	OS 8874	1630 ± 40	1465 ± 51
H2	492-497	OS 8873	1290 ± 40	1164 ± 79
H2	557-562	OS 8872	1030 ± 35	873 ± 58
H2	592-597	OS 8871	990 ± 40	858 ± 57
H5	5-10	OS 8881	795 ± 40	693 ± 28
H5	32-37	OS 8880	1130 ± 50	993 ± 59
H5	222-227	OS 8879	2950 ± 30	3018 ± 59
H5	242-247	OS 8878	7890 ± 55	8630 ± 87
H4	5-8	OS 8885	950 ± 30	860 ±62
H4	95-100	OS 8884	6540 ± 35	7449 ± 23
H4	295-300	OS 8883	8850 ± 50	9900 ± 211
H4*	505-510	OS 8882	9750 ± 45	11255 ± 54 (Intcal04 with offset estimate of 56 ± 24 years BP)
H6	25-30	OS 8889	1250 ± 30	1120 ± 51
H6	85-90	OS 8888	1120 ± 35	990 ± 58
H6	105-110	OS 8887	1280 ± 35	1154 ± 74
H6	615-620	OS 8886	3340 ± 30	3513 ± 45
H7	10-15	OS 8894	880 ± 25	747 ± 23
H7	40-45	OS 8893	1170 ± 25	1015 ± 40
H7	180-185	OS 8892	2220 ± 40	2186 ± 118
H7	345-350	OS 8891	3020 ± 30	3143 ± 66
H7	595-600	OS 8890	3290 ± 35	3470 ± 78

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Table 4.1 **Bulk organic AMS radiocarbon ages of 24 core samples from the Namaqualand Mudbelt are indicated both uncalibrated (after Meadows *et al.* 1997) and calibrated; all but one of these ages (H4 505-510) have been calibrated using CALIB Radiocarbon Calibration Program (Stuiver and Reimer 1993) using the Southern Hemisphere Calibration Curve dataset and these calibrations are unpublished, SHCAL04.14c (McCormac *et al.* 2004). The remaining sample (*), found outside the 10 000 year BP range of the Southern Hemisphere Calibration Curve, was calibrated using the International INTCAL04.14c dataset (Reimer *et al.* 2004) and modified with the Southern Hemisphere offset of 56 ± 24 (McCormac *et al.* 2004, Reimer pers comm).**

These bulk organic radiocarbon ages have clearly established the mudbelt as being of Holocene age (Meadows *et al.* 1997 Dingle 1994). This was expected given that much of the area was terrestrial until the end of the LGM; existing sediment would have been scoured during post glacial sea level rise and re-deposited further offshore. The

bulk organic radiocarbon results also suggest, as expected, the mudbelt sediment closest to the mouth is younger in age than the mudbelt sediment found more distally, where deposition is more protracted.

From Table 4.1 (and Figure 4.1), the laminated sediment in H2, extending to 4.5 m is probably younger than the radiocarbon age of 1465 ± 51 cal yr BP, whereas the laminated sediment in H7 (also dark grey-brown clay) extends to just under 1 m depth and has a maximum radiocarbon age of 2186 ± 118 cal yr BP, a date relating to a depth of 180 cm. The base of H7 is dated at 3470 ± 78 cal yr BP. H4 and H5 seem to indicate very much older sediment below 100 cm, than at similar depths in H2, H6 and H7. The base of the laminations in core H2 (with a maximum age of 1465 ± 51 cal yr BP) may suggest that the base of laminated grey-brown clay, coinciding with the base of H7 is of similar age in the other cores, given that a bulk organic radiocarbon date of 2186 ± 118 cal yr BP, is found below this level. However, it is difficult to compare on the basis of lithology alone and depth appears to be more useful.

There is great variation between the radiocarbon ages of the base of the mudbelt cores. The base of H4, the oldest of the HODSA cores is dated at 11 255 ± 54 cal yr BP, whereas H5 is slightly younger at 8630 ± 87 cal yr BP at a depth of 242 cm and H6 is much younger at 3513 ± 45 cal yr BP. In H5, only 20 cm above the sediment dated at 8630 ± 87 cal yr BP, the sediment has a radiocarbon age of 3018 ± 59 cal yr BP, thus illustrating a tendency to variation in bulk organic radiocarbon age within a relatively small area and may even signify a series of hiatuses within the mudbelt sediment.

The bulk organic radiocarbon ages analysed from core H2 in the prodelta, yielded a more complex chronological picture than the less obviously laminated H7 core further to the south, but both H2 and H5 (closer to H7) also showed some apparent age reversals. This is particularly evident at the base of H2: Between depths of 337 cm and 597 cm, there are four reversals in calibrated radiocarbon age. A radiocarbon age of 1336 ± 34 cal yr BP occurs 324 cm above 1231 ± 51 cal yr BP, which in turn is found some 145 cm above 1465 ± 51 cal yr BP, a date which is only 20 cm above an age of 1164 ± 79 years BP, which is some 65 cm above 873 ± 58 cal yr BP, a date which is 35 cm above 858 ± 57 cal yr BP. Lithologically, H7 is more homogeneous

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and H2 is considered the least disturbed of the cores due to the presence of laminations and accompanied absence of bioturbation in much of the core. Although no actual evidence of bioturbation was recorded, the presence of fewer laminations in H7 indicates the possibility that bioturbation or reworking may have previously played more of a role in this more distal portion of the mudbelt.

Herbert and Compton (2007) provide new age data of the mudbelt using other gravity cores (not HODSA). This is referred to in chapter 7 in light of results presented here.

4.4.2 Mudbelt age by optically stimulated luminescence (OSL) from Meadows *et al.* 2002 and Gray *et al.* 2000

A single optically stimulated luminescence (OSL) date was obtained from a sample at the base of core H7 at a depth of between 560 and 580 cm (due to moisture loss shrinkage, the exact depth marker was difficult to define). This date was published in Meadows *et al.* 2002 and also in Gray *et al.* 2000 (after Meadows *et al.* 2002[3]). This single OSL date relies on the bleaching effects of sun on quartz grains (Meadows *et al.* 2002) and does not rely on organic material as in the case of radiocarbon dating, thus obviating issues of old carbon and sediment reworking in the catchment.

This OSL date of 2 189 ± 226 years BP (560-580 cm depth) corresponds somewhat with the bulk organic radiocarbon date of 3470 ± 78 cal yr BP, some 15 - 20 cm below it at 595 cm; this lends some support to the argument that the bulk organic ages are useful in that they offer a maximum age of the sediment and thus may be more reliable than previously thought (Gray *et al.* 2000, Meadows *et al.* 2002).

4.4.3 Additional radiocarbon dating at Jakkalsberg, Richtersveld (Brink and Webley 1996)

Of the inland sites available, those investigated by Webley (1996) and Brink and Webley (1996) were most useful for palaeoecological analysis for this research project. These sites had the advantage that radiocarbon ages for the area had previously been published and these dates related to some of the sites used in this

[3] Meadows *et al.* 2002 was in press at the time of Gray *et al.* 2000 publication.

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thesis. The chronology of these sites will be discussed in the following section. It was important that sediments used for palaeoenvironmental analysis were dated and this would therefore enable direct comparison with the age of the mudbelt sediment. However, some discrepancy became apparent due to site deterioration (erosion) at Webley's JKB A site. Therefore previously adequately dated sites required further dating in order to establish age and these analyses are presented in section 4.5. In addition, no dating analysis had been carried out at JKB O and JKB Q and new radiocarbon dating was required.

Two carbon-rich hearths, interspersed with silt flood deposit material, were located at Jakkalsberg, named site JKB A and reported in Brink and Webley (1996):

- Hearth 1 was analysed using radiocarbon dating and this yielded an age of 1 330 ± 60 years BP (Pta 5958) cal yr BP.
- Hearth 2 also analysed using radiocarbon dating yielded an age of 1 300 ± 25 years BP (Pta 6100) cal yr BP.

These closely associated hearths situated lying approximately 4 m apart are considered to be related to occupation by herders, known to have occurred between 1250 years BP and 1350 years BP (Brink and Webley 1996). Another of Webley's sites, JKB B appears to have been utilised around this time (Brink and Webley 1996). The JKB B site, known as K11 in Brink and Webley (1996), is partly covered by silt-capped hillside and two lenses were dated. These lenses yielded the following ages:

- Hearth 1 was dated at 1 429 ± 25 cal yr BP (Pta 6122).
- A second hearth was dated at 1 380 ± 50 cal yr BP (Pta 6101).

This means that these floodplain deposits both pre- and post-dated significant flood events and appear not to be of the magnitude recorded at Lower Xobies or Bloeddrift. The age of these deposits is included in Table 4.2 along with higher discharge events described in the following section.

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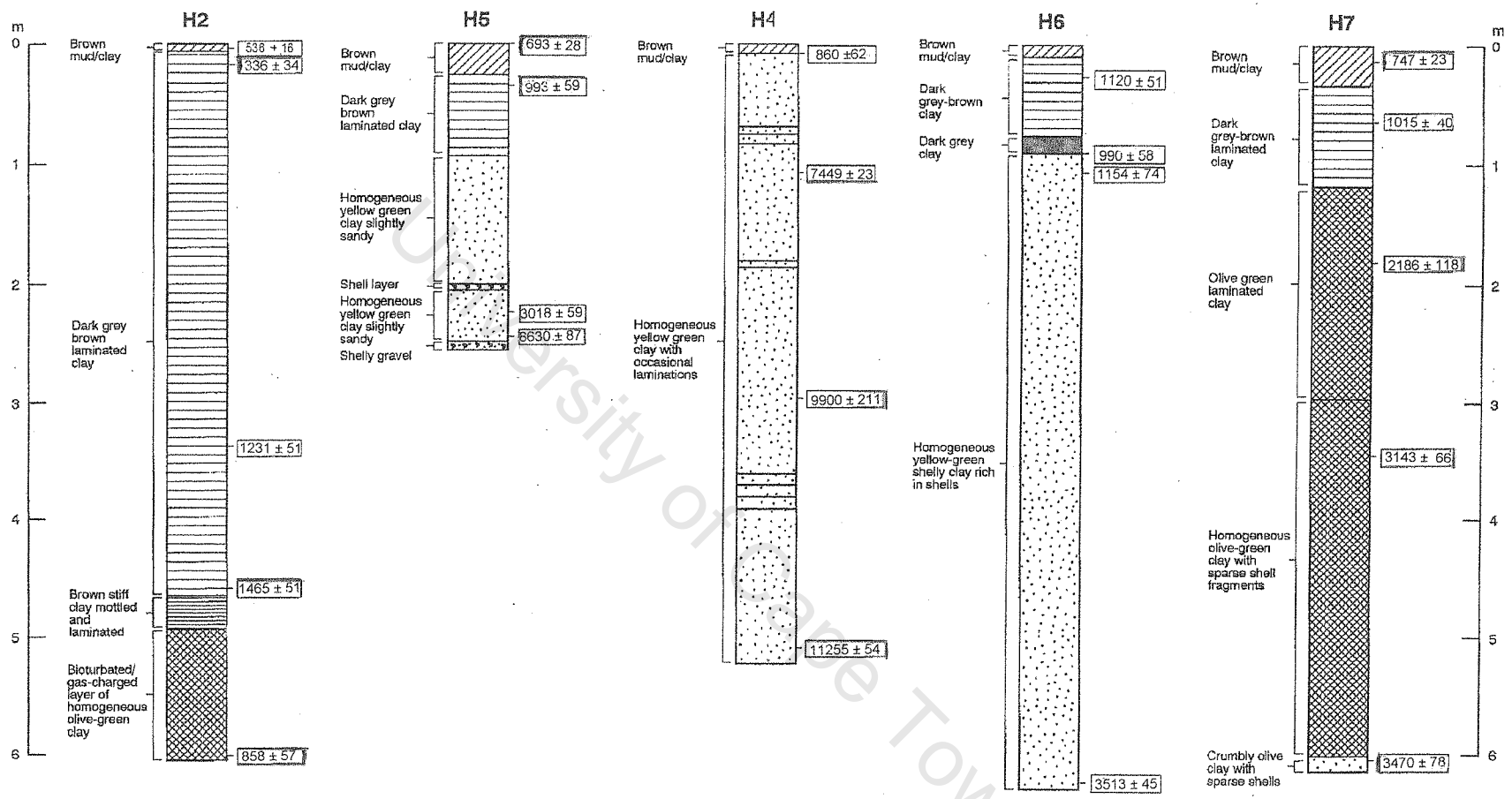

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Figure 4.1 Stratigraphy of Namaqualand mudbelt cores showing calibrated bulk organic radiocarbon dates (after Meadows *et al.* 1997 and 2002) .

Sample	Significant flood events	Date and flood discharge	Spans age	Year AD	Published	Description
LX (F1-F3)		F3, F2, F1 are possibly older than 5450 ± 1090 years BP.	5 450 ± 1090 years BP (possibly older)		Zawada (1996), Zawada et al (1997)	
Period 1-4	4 high threshold flood periods	13 palaeofloods of up to 14 660 $m^3.s^{-1}$ (range:10 000 $m^3.s^{-1}$ and 15 000 $m^3.s^{-1}$)	the past 5500 years		Zawada (1996)	
Period 1	5 major flood events	The threshold flood discharge: 12 800 $m^3.s^{-1}$. This period included 3 floods at Lower Xobies (between 4 700 ± 70 years BP and 4 120 ± 160 years BP).	approx. 3650 years.1800 ± 360 years – 5 450 ± 1090 years (IRSL).	Before AD 200	Zawada (1996)	
JKBA1; JKBA2; JKB B (K11) Hearth 1,2		JKBA1: 1330 ± 60 years BP (Pta 5958) ; JKBA2: 1300 ± 25 years BP (Pta 6100) ; 1429 ± 25 years BP (Pta 6122) and 1380 ± 50 years BP (6101)	between 1300 ± 25 years BP and 1 429 ± 25 years BP	AD 691; AD 762; AD 652 AD 668	(Brink and Webley 1996).	hearths
LX (F4A-I)	1 single event	single flood event with a discharge of about 13 130 $m^3.s^{-1}$	between 4770 ± 70 years BP (F4A) and 1 160 ± 80 years BP (I)		(Zawada et al. 1996).	
LX (C - C4: section 2; H)	1 of three major events	discharge volume was around 12 740 m^3s^{-1}; representative of 3 major events of this Period	between 4120 ± 160 years BP and 4 770 ± 70 years BP		(Zawada et al. 1996)	charcoal
LX (I)	1 single event	zebra lower jaw bone in flood deposit	1660 ± 80 years BP	AD 961	(Zawada et al. 1996)	bone
LX (F6)			1100 years BP		(Zawada et al. 1996)	
Period 2	4 major floods	threshold discharge volume for this period was about 14 700 $m^3.s^{-1}$.	400 years. approx. 1025 years BP - 685 years BP (estimated from AD)	AD 961 - AD 1332	(Zawada et al. 1996)	
LX	F7 and F8		between 1160 ± 80 years BP and 610 ± 50 years BP		(Zawada et al. 1996)	
Period 3	1 catastrophic event	includes a single catastrophic flood event (LX, BlD). Approx. threshold discharge between 25 700 $m^3.s^{-1}$ and 27 900 $m^3.s^{-1}$.	after 535 years BP (estimate)	probably after AD 1450	(Zawada et al. 1996)	
LX (O, F9)		Bed O and above and including bed F9	<610 ± 50 years BP, thus F9 probably deposited after this		(Zawada et al. 1996)	OES
Period 4	4+ major floods	Between 1919 and 1992 the three largest floods occurred in the Lower Orange. Discharge volumes did not exceed 9 500 $m^3.s^{-1}$: 8 330 $m^3.s^{-1}$ (1974); 7 700 $m^3.s^{-1}$ (1988) and 7 200 $m^3.s^{-1}$ (1925).	after 200 years BP	AD 1785 to the present	(van Bladeren 1995, Zawada 1996, 2000)	
BLD; LX (O)			Min. age: 710 ± 40 years BP (IRSL, RC)	AD 1785	(Zawada et al. 1996)	
LX (surface)		termite nest, leaf and sheep or goat dung, together with overlying slack water sediments		AD 1956 -AD 1958	(Zawada et al. 1996)	

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Table 4.2 Significant high threshold flood events and other residual flood evidence recorded in the Orange River Catchment sites (after Zawada (1996) and Zawada *et al.* (1996) [Age spans based on uncalibrated radiocarbon ages].

4.4.4 Existing palaeoflood analysis of the Lower Orange River (Zawada and Zawada *et al.* 1997)

Zawada *et al.* (1997) and Zawada (1996, 2000) correlated ORC slack water sediments with 13 palaeoflood events of a magnitude up to 14 660 m^3s^{-1} over the past 5 500 years. A number of these slack water deposits appear to have been laid down during flood events of the Orange River in bedrock-controlled reaches (Zawada 2000). The sedimentology of these slack water deposits has yielded information that Zawada *et al.* (1996) used to calculate discharge, velocity and frequency of palaeofloods of the Orange. The 13 flood events described are interpreted to have varied in discharge volume from 10 000 $m^3.s^{-1}$ to 15 000 $m^3.s^{-1}$, far exceeding the magnitude of the 1974 flood (8 330 $m^3.s^{-1}$) and the 1988 flood (7 700 $m^3.s^{-1}$).

The persistence of these palaeodeposits is heavily dependent on their position relative to post-flood fluvial erosion. As such, two of these Zawada sites analysed as part of this research project (Bloeddrift and Lower Xobies) are records of the fluctuations in maximum flood threshold in the Lower Orange River rather than being a comprehensive record of flood events. The sequence of 13 flood events has been sub-divided into 4 periods (Table 4.2) by Zawada (2000). According to Zawada (1996) and Zawada *et al.* (1996), the periods or subdivisions can be summarised as follows:

- Period 1: This period includes 5 flood events and spans approximately 3650 years from about 1 800 ± 360 years to 5 450 ± 1 090 years (Infrared Stimulated Luminescence or IRSL). The threshold flood discharge for this period was 12 800 $m^3.s^{-1}$. This period included three floods at Lower Xobies spanning a 580 year period between 4 700 ± 70 years BP and 4 120 ± 160 years BP. Any other floods occurring in period 1 between 5 450 ± 1 090 years BP and about 1 800 ± 360 years BP, would have been below the threshold 12 800 $m^3.s^{-1}$.

- Period 2: This period includes four flood events spanning 400 years from 1025 years BP to about 685 years BP. The threshold discharge for this period was about 14 700 $m^3.s^{-1}$.

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- Period 3: This period includes a catastrophic flood event, three times more powerful than any other recorded for the area, at Lower Xobies and Bloeddrift and dated as probably post- 535 years BP. The approximate threshold discharge reached was between 25 700 $m^3.s^{-1}$ and 27 900 $m^3.s^{-1}$.

- Period 4: This covers the period 200 years BP to the present, where floods did not exceed 9 500 $m^3.s^{-1}$. The three largest floods occurred in the Lower Orange with discharge volumes as follows: 7 200 $m^3.s^{-1}$ (1925); 8 330 $m^3.s^{-1}$ (1974) and 7 700 $m^3.s^{-1}$ (1988) (van Bladeren 1995, Zawada 2000).

4.4.5 Existing Bloeddrift chronology (Zawada 1996)

Bloeddrift is the second of the Zawada (1996) sites which have been used in this research for palaeoenvironmental analysis and are discussed in chapters 5 and 6. Samples for this study were not directly taken from the same outcrop Zawada (1996) analysed, so new dating analysis had to be carried out; Zawada (1996) had originally obtained ten samples from three cross-sections of the Bloeddrift deposit using a combination of radiocarbon and infrared stimulated luminescence (IRSL) dating techniques which yielded varied results.

Three IRSL ages obtained proved anomalously old at 1 910 ± 380 years, 1 100 ± 220 years and 1 800 ± 360 years respectively, since the maximum radiocarbon age for these samples was 710 ± 40 cal yr BP.

Other IRSL dates also proved anomalously older, probably due to issues of residual luminescence during deposition (Zawada *et al.* 1996). Three ages between 450 ± 20 years BP and a maximum age of 710 ± 40 years BP were similar to Unit O at Lower Xobies. Three ages obtained using radiocarbon dating all fell approximately within the same period which ranges from 450 ± 20 cal yr BP to a maximum age of 710 ± 40 cal yr BP. This included samples from unit D (Bloeddrift), Annis River and flood unit F6. These sites also yield similar dates to Unit O at Lower Xobies. Other slack water deposits (at lower elevations) were dated at around 210 ± 50 cal yr BP to 270 ± 50 cal yr BP.

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4.4.6 Existing chronology analysis of the Lower Xobies slack water deposit (Zawada and Zawada *et al.* 1996)

Zawada (1996) and Zawada *et al.* (1996) described the Lower Xobies slack water exposure and obtained bulk radiocarbon dating of 13 sediment samples which are included in Table 4.3. The exposure was dated as follows:

- Bed O was dated at less than 610 ± 50 cal yr BP (material dated was ostrich egg shell or OES), suggesting the flood unit F9 above it was deposited after this date, although the IRSL date gives an anomalous age of 110 ± 220 years (not surprising given the OES is older, similarly for JKB N age).

- A zebra lower jaw bone in Bed I was dated at 1 660 ± 80 cal yr BP. Thus the flood unit F6 is approximately 1 100 years old but IRSL dates in unit F6 also gave anomalously old dates: additive and regenerative IRSL methods gave 4 000 ± 800 years and 4 040 ± 800 years respectively.

- F7 and F8 were dated between 1 160 ± 80 years BP and 610 ± 50 cal yr BP using radiocarbon dating. Two anomalous IRSL dates of F8 were 2 410 ± 480 years and 4 020 ± 800 years, using additive and regenerative IRSL methods respectively.

- Beds C to C4 section 2 (charcoal rich units), correlating to unit H, were dated at between 4 120 ± 160 cal yr BP and 4 770 ± 70 cal yr BP. Additional analysis by Zawada indicated that this is indicative of the three largest floods of the Orange River having occurred in this period; discharge volume was around 12 740 m^3s^1.

- The IRSL date for F4 (additive method) yielded an age of 5 450 ± 1 090 years, but the base of Lower Xobies flood unit F1 was 3 660 ± 730 years which appears anomalously young. Zawada maintains that F3, F2, F1 are possibly older than 5 450 ± 1 090 years BP. IRSL dating was not entirely successful, with many samples yielding much older dates than radiocarbon ages indicate, probably for reasons of residual luminescence during deposition.

- F2A-F4A correlate with unit H so from 4 770 ± 70 cal yr BP to 1 160 ± 80 cal yr BP

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the largest flood had a discharge of between 12 740 $m^3.s^{-1}$ to 13 130 $m^3.s^{-1}$, but another interpretation may be that between the F4A deposit of 4 590 ± 60 cal yr BP (maximum age) and I (1 160 ± 80 years BP), there was a single flood event with a discharge of about 13 130 $m^3.s^{-1}$.

- A surface termite nest yielded recent results of AD 1956 with no evidence of subsequent flood scouring, thus the previous flooding level threshold had not yet been reached by this time (Zawada 1996). Organic leaf and sheep or goat dung, together with overlying slack water sediments upstream of Xobies, was dated and yielded a calibrated date of AD 1958.

4.5 Chronology results

Several chronolometric methods have been applied in this thesis with the intention of directly improving the understanding of mudbelt chronology and to verify published data with sites sampled in order to achieve the palaeoenvironmental goals of this research. The first part of this section deals with the results of the Richtersveld (Jakkalsberg and Bloeddrift) samples in order to reconcile the previously analysed samples at the site with layers with those exposed at the time of sampling. Other results include those central to direct ageing, the mudbelt, comparison with the results of Meadows *et al.* (1997), new calibrations of the existing radiocarbon dates, results of picking of the macrofossils, foraminifera for AMS radiocarbon dating and the analysis of ^{210}Pb and ^{137}Cs and related total organic carbon (TOC).

4.5.1 New Richtersveld radiocarbon ages

Jakkalsberg site JKB A required additional radiocarbon dating, as this site no longer resembled those analysed by Brink and Webley (1996). In addition, new dating was required at a site adjacent to the Zawada (1996) Bloeddrift (BLD 32) exposure and another new site at JKB O. The following sections include the results obtained during sampling. A separate sample, from neighbouring site JKB "N" was simultaneously retrieved for a concurrent archaeological initiative (Halkett 1999) and serves to illustrate the age of certain archaeological organic artifacts from the floodplain. The newly established ages are tabulated

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in Table 4.3.

JKB A CL (20 cm), a Jakkalsberg sample found at a depth of 20 cm, was retrieved from a hearth found beneath a silt deposit and represented by a small lens of charcoal-rich sediment (Figure 4.2). This lens appeared similar to lenses identified by Brink and Webley (1996) (Table 4.2), but it was not possible to verify this without radiocarbon dating and was therefore sampled. The radiocarbon age was given as 1 250 ± 50 cal yr BP (Pta 8494).

This is supportive of previously dated hearths obtained by Brink and Webley (1996) dated at 1 330 ± 60 cal yr BP and 1 300 ± 25 cal yr BP and indicates the same herder occupation period that occurred between floods during low flow discharge in the Orange River.

Ostrich egg shell (OES) from an open site JKB "N" picked from the floodplain surface (0 - 1cm) was submitted for radiocarbon dating by Tim Hart. The resulting radiocarbon age of 4 500 ± 50 cal yr BP (Pta 8496) is indicative of sediments much older than some of the surrounding silt deposits and unexpectedly old given that a number of ostrich egg shell beads were found at that site on the floodplain.

JKB O (Figure 4.3) was represented by a silt column with two layers of organic-rich animal dung (sheep/goat), (JKB O L2 and JKB O L4) sandwiched between various silt layers. Projecting into this is an ash layer of Late Stone Age (LSA) origin (Hart pers. comm.). The organic dung-rich layer known as JKB O Layer 2 (70 cm) was radiocarbon dated at 310 ± 15 cal yr BP (Pta 8492).

JKB O AL2 and JKB AL3 are both ash lenses which were interspersed with a silt layer and dated at 303 ± 50 cal yr BP (Pta 8493) and 1 340 ± 50 cal yr BP (Pta 8495) respectively.

JKB O Layer 4, the dung rich (organic) soil layer was dated at 720 ± 50 cal yr BP (Pta 8500). Three samples fall between 300 and 720 years BP and therefore more recent than the JKB A and B hearths dated at around 1 300 cal yr BP by Brink and Webley (1996) and thus refer to a more recent occupation and low-discharge (non-flood) period. However, one sample JKB O Lens 3 of 1 340 ± 50 cal yr BP corresponds well with the age of the hearths at JKB A and

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Analytical No. Pretoria (Pta)	Sample designation	Material	$\delta^{13}C$ (‰PDB)	Radiocarbon age (calibrated) in years BP	Calendar date (Bracketed date is the most probable)
8494	JKB A CL (20 cm)	charcoal	-23.5	1250 ± 50	AD 766 (793) 886
8496 *	JKB N (0-1 cm)	OES	-6.8	4500 ± 50	3331-3216; 3184-3153; 3127 (3099) 3025 BC
8492	JKB O L2 (70 cm)	Org/soil	-21.4	310 ± 15	AD 1641 (1646) 1651
8493	JKB O AL2	Org/soil (ash lens)	-21.4	303 ± 50	AD 1516-1590; 1622 (1640) 1655
8495	JKB O AL3	Org/soil (ash lens)	-25.5	1340 ± 50	AD 668 (691) 771
8500	JKB O L 4	Org/soil	-25.3	720 ± 50	AD 1280 (1293) 1308; 1367-1379
8497	BLD 32 CL1 (102 cm)	charcoal	-24.4	350 ± 30	AD 1516 (1540) 1590; 1622 (1634) 1643
8498	*BLD 32 CL (72 cm)*	*charcoal*	*-24.8*	*370 ± 35*	*AD 1492 (1521, 1576, 1627) 1638*

Table 4.3 Calibrated bulk organic radiocarbon analysis of Richtersveld sites: Jakkalsberg and Bloeddrift. * appears in Halkett (2001).

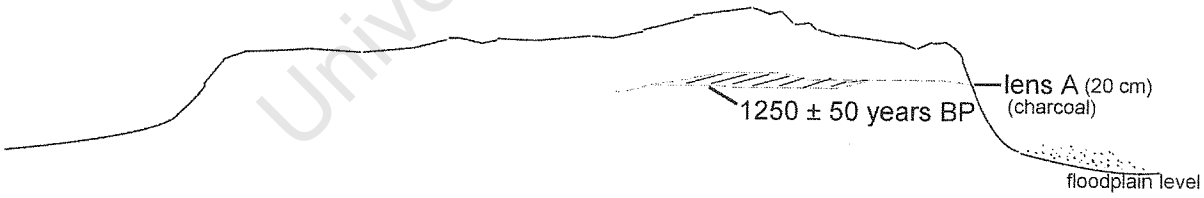

Figure 4.2 Jakkalsberg A (JKBA) cross-section during the year 1999, indicating calibrated bulk organic radiocarbon age of lens A.

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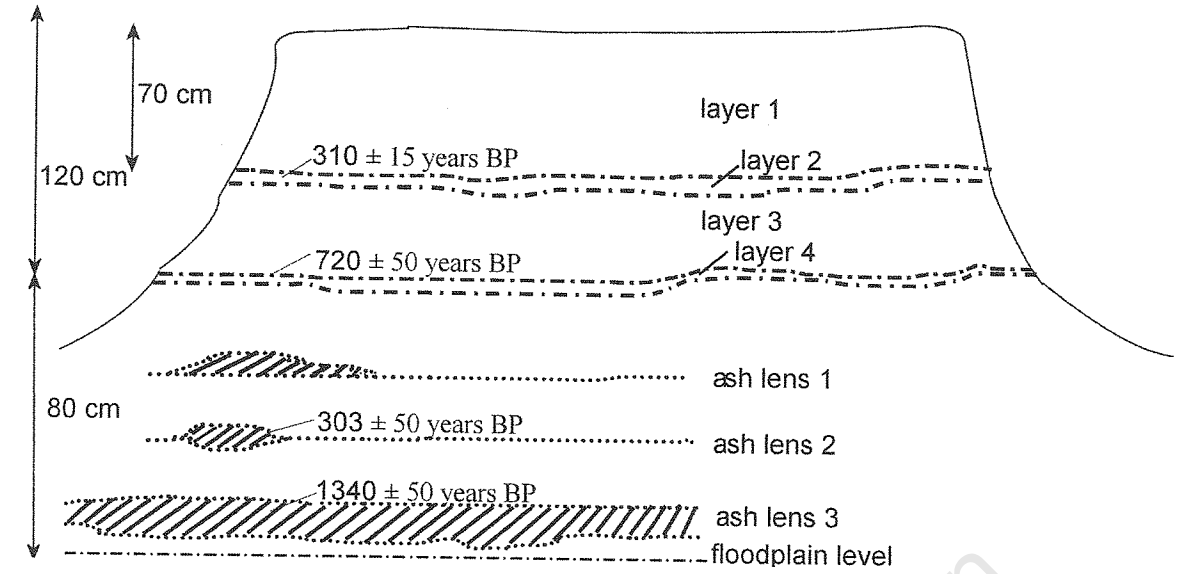

Figure 4.3. Jakkalsberg O (JKBO) in cross-section indicating calibrated bulk organic radiocarbon dates.

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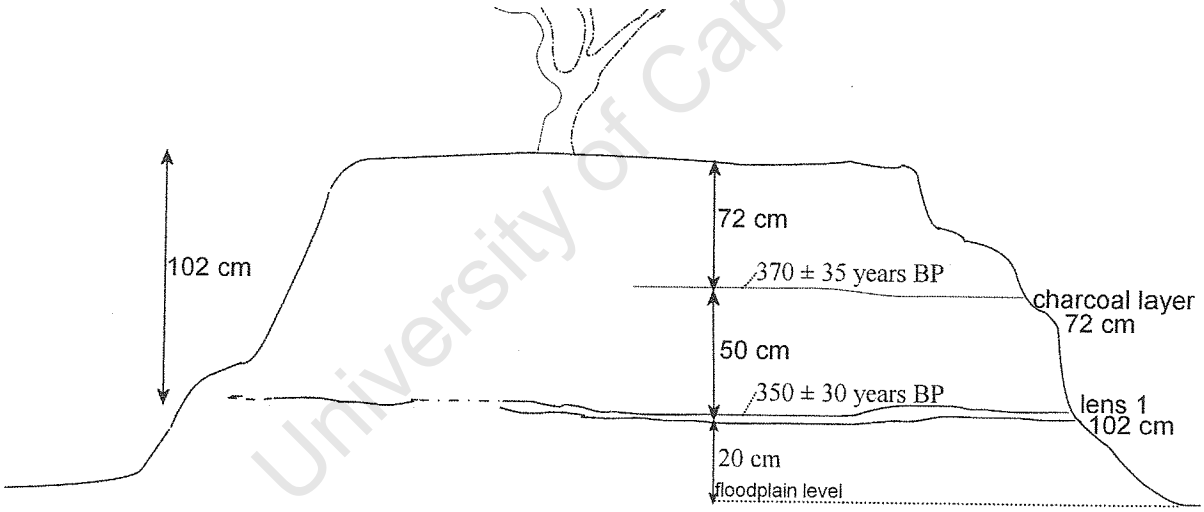

Figure 4.4 Bloeddrift 32 (BLD 32) in cross-section indicating calibrated bulk organic radiocarbon ages.

B (1 300 years BP). Radiocarbon results of two bulk samples from Bloeddrift 32 (BLD 32) (Figure 4.4) were as follows:

- BLD 32 CL 1 (102 cm): a charcoal-rich lens; dating yielded an age of 350 ± 30 cal yr

BP (Pta 8497).

- BLD 32 CL (72 cm): charcoal-rich organic soil dated at 370 ± 35 cal yr BP (Pta 8498).

These ages are slightly younger than the youngest age (450 ± 20 cal yr BP) from Zawada's Bloeddrift material and either relate to a younger deposit, or are younger than expected due to leaching and root penetration of the soil, as a small tree was located 3 m from the sample site. However, root contamination was not visibly evident in the sediment sampled.

4.5.2 Macrofossils

Few macrofossils were identified within the mudbelt sediments during any stage of the coring or analysis by Mabote (1997). Macrofossils were only identified when sediments were sieved and none were identified during sub-sampling and processing for ^{210}Pb and pollen for this research.

Initial interest in foraminifera in the mudbelt material was ignited during Mabote's research (1997) and Mabote *et al.* (1997). Mabote identified foraminiferal material in the HODSA core sediments and had managed to identify benthic species of foraminifera potentiall y suitable for AMS ^{14}C dating. Unfortunately these mixed species samples were contaminated due to improper laboratory preparation (Mabote pers. comm., Susan Handwork pers. comm.). Planktonic foraminifera species were known to occur in trace quantities within the cores (H1-H7), yet sufficient material for small samples appeared to be available for AMS radiocarbon dating in these cores according to Mabote's initial investigation reported in Mabote (1997). Benthic species were less common than planktonic and found in trace quantities in H2, not H7. However, on the basis of Mabote's observations, and with sufficient material being available, the possibility of using foraminifera remained a viable option to complement existing dating, ongoing pollen (Gray 1996), stable isotope work (Gray *et al.* 2000) and other research reported in this thesis.

4.5.2.1 Results of foraminiferal analysis

Unfortunately this method, although tremendously time consuming, involving many months

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of processing and picking, and which initially appeared viable (Mabote 1997), did not produce any results as the foraminifera were very poorly represented in the mud. The foraminifera were identified using a light microscope (UCT Archaeology Materials Lab) and a sorting tray. A dampened (distilled water) photographic retouching brush was used for picking the foraminifera. The foraminifera were separated according to species morphology and placed in separate vials for identification.

The total number of foraminifera picked of mixed species combined, including both benthic and planktonic species, fell well below the required weight of 5 mg to facilitate AMS radiocarbon dating (Handwork pers. comm.). The total quantity of foraminifera picked was far below the quantity of benthic or planktonic foraminifera in each sample planned for dating.[4] In addition, the quantity of mud required to produce sufficient foraminifera weight (the 5 mg minimum of foraminifera) would have exceeded an estimated 2 kg, based on the relative proportion of foraminifera found in the samples analysed. A total of 5 mg equals a minimum average of 350 foraminifera specimens, although more would be advantageous. None of the mudbelt samples analysed contained this number of specimens. Indeed, picked and cleaned foraminifera samples ranged between a total weight of 1.5 mg and 3.5 mg. A two kg sample is much larger than the combined material from both working and archive halves of the gravity cores for the depth required and also exceeds the total original mass of material that was retrieved from the mudbelt at that depth.

Discammina compressa, Globerigerina bulloides, Neogloboquadrina pachyderma and *Ammonia japonica* were the dominant species of foraminifera noted, but since further investigation was not the goal of this research, detailed identification of species was not pursued. These attempts at obtaining sufficient foraminifera for AMS dating is alluded to in Meadows *et al.* (2002).

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[4] Small sample AMS radiocarbon dating had been planned through the Groningen ^{14}C AMS facility in collaboration with the Quaternary Dating Research Unit (QUADRU, Pretoria, South Africa).

4.5.3 Scanning Electron Microscopy

The Scanning Electron Microscopic (SEM) analysis of untreated mudbelt samples run at the University of Cape Town SEM facility showed a thin silt layer blanketing most fragments in the sediment and very little was discernible. Thus, the nature and type of organic carbon in the mudbelt sediment remains unspecified. Results of SEM analysis were therefore inconclusive, yielding nothing new about the character of the organic fraction of the mudbelt sediment and did not throw light on any new information.

4.5.4 Results of total organic carbon (TOC)

Analysis of total organic carbon (TOC) of mudbelt sediment is useful in assisting in characterising the mudbelt, although it does not assist in resolving the chronology *per se*. However, it does shed light on the amount of organic carbon available in the mudbelt from which the bulk organic radiocarbon and stable carbon light isotopes may be analysed. The values for the results of total organic carbon or TOC (Walkley – Black) and total carbon (loss on ignition or LOI) are listed in Tables 4.4 and Table E1-E5 (of Appendix E) respectively. Both these methods yielded low values, but TOC values (Walkley-Black) were particularly low in the Richtersveld slack water sediment samples. Lower Xobies and Jakkalsberg samples yield a mean TOC percentage of 0.38% compared with the mean value in the mudbelt of 2.27% (varying between 0.91% and 4.45%). Total carbon (LOI) values, on the other hand, average 3.56% for Richtersveld samples (Orange River low flood discharge and Lower Xobies) compared with 13.88% for the mudbelt, with these values varying between

Sample	Sample ID	Lab No		% TOC (m/m)
JKBACi (C layer)	JKBA CL	3463	/01	0.55
JKBO layer 4	JKBO L4	3469	/01	0.24
JKBO layer 2	JKBO L2	3470	/01	0.57
SIXH/N4 (Ocm)	SIXH/N4 (0)	3466	/01	0.25
SIX/P3 (0-5)	SIX/P3 (0-5)	3473	/01	0.31
BLD32 CL	BLD32 CL	3472	/01	0.57
H2.7.4 (0-4.5)	H2 (0)	3479	/01	1.55
H2.7.2 (9-12.5)	H2 (10)	3489	/01	1.14
H2.7.2 (9- 12.5)	H2 (10)	3517	/01	1.56

Table 4.4 Total Organic Carbon for Mudbelt and Richtersveld sites (page 1/3).

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H2.6.11 (22.5-27)	H2 (25)	3502	/01	0.94
H2.6.10 (27-31.5)	H2 (30)	3529	/01	1.25
H2.6.9 (31.5-36)	H2 (35)	3490	/01	1.12
H2.6.8 (36-40.5)	H2 (40)	3533	/01	1.43
H2.6.6 (45-49.5)	H2 (45)	3492	/01	1.74
H2.6.7 (40.5-45)	H2 (45)	3495	/01	1.44
H2.6.5 (49.5-54)	H2 (50)	3531	/01	1.17
H2.6.4 (54-58.5)	H2 (55)	3488	/01	1.42
H2.6.3 (58.5-63)	H2 (60)	3535	/01	1.52
H2.6.2 (63-68.5)	H2 (65)	3486	/01	2.54
H2.5.19 (77-82)	H2 (80)	3532	/01	1.38
H2.5.17 (87-92)	H2 (90)	3544	/01	1.47
H2.5.15 (97-102)	H2 (100)	3541	/01	1.24
H2.2.5 (102-107)	H2 (105)	3501	/01	1.97
H2.5.11 (117-122)	H2 (120)	3551	/01	1.38
H2.5.7 (137-142)	H2 (140)	3483	/01	1.35
H2.5.3 (157-162)	H2 (160)	3545	/01	1.59
H2.4.19 (177-182)	H2 (180)	3550	/01	1.47
H2.4.15 (197-202)	H2 (200)	3543	/01	1.55
H2.4.11(217-222)	H2 (220)	3481	/01	1.99
H2.4.7 (237-242)	H2 (240)	3539	/01	1.31
H2.4.3 (257-262)	H2 (260)	3484	/01	1.56
H2.3.19 (277-282)	H2 (280)	3552	/01	1.56
H2.3.15 (297-302)	H2 (300)	3540	/01	1.24
H2.3.11 (317-322)	H2 (320)	3547	/01	1.29
H2.3.7 (337-342)	H2 (340)	3491	/01	1.40
H2.3.3 (357-362)	H2 (360)	3548	/01	1.70
H2.2.19 (377-382)	H2 (380)	3542	/01	1.40
H2.2.15 (397-402)	H2 (400)	3537	/01	1.12
H2 2.11 (417-422)	H2 (420)	3482	/01	1.17
H2.2.7 (437-442)	H2 (440)	3546	/01	1.22
H2.2.3 (457-462)	H2 (460)	3549	/01	0.91
H2.1.19 (477-482)	H2 (480)	3494	/01	1.04
H2.1.17 (487-492)	H2 (490)	3554	/01	1.44
H2.1.16 (492-497)	H2 (495)	3556	/01	1.42
H2.1.15 (497-502)	H2 (500)	3538e	/01	1.35
H2.1.11(517-522)	H2 (520)	3480	/01	2.22
H2.1.7 (537-542)	H2 (540)	3485	/01	2.42
H2.SP.1 (587-592)	H2 (590)	3487	/01	1.31
H2.CC2 (592-597)	H2 (597)	3478	/01	2.24
H5.3.6 (0-4.5)	H5 (0)	3503	/01	1.89
H7.6.20 (0-5)	H7 (0)	3510	/01	2.59
H7.6.18 (10-15)	H7 (10)	3512	/01	2.11
H7.6.16 (20-25)	H7 (20)	3499	/01	2.65
H7.6.14 (30-35)	H7 (30)	3513	/01	2.36
H7.6.12 (40-45)	H7 (40)	3509	/01	2.20

Table 4.4 Total Organic Carbon for Mudbelt and Richtersveld sites (page 2/3).

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H7.6.11 (45-51)	H7 (45)	3580	/01	2.93
H7.6.10 (50-55)	H7 (50)	3518	/01	2.61
H7.6.8 (60-65)	H7 (60)	3514	/01	3.08
H7.6.6 (70-75)	H7 (70)	3555	/01	3.74
H7.5.20 (100-105)	H7 (100)	3496	/01	3.86
H7.5.16 (120-125)	H7 (120)	3508	/01	3.24
H7.5.12 (140-145)	H7 (140)	3515	/01	3.43
H7.5.9 (155-160)	H7 (155)	3506	/01	3.35
H7.5.8 (160-165)	H7 (160)	3511	/01	3.74
H7.4.20 (200-205)	H7 (200)	3477	/01	2.50
H7.4.16 (220-225)	H7 (220)	3516	/01	4.17
H7.4.12 (240-245)	H7 (240)	3521	/01	3.24
H7.4.8 (260-265)	H7 (260)	3526	/01	3.32
H7.4.4 (280-285)	H7 (280)	3527	/01	3.82
H7.3.16 (320-325)	H7 (320)	3523	/01	3.43
H7.3.12 (340-345)	H7 (340)	3536	/01	3.39
H7.3.11 (345-350)	H7 (350)	3553	/01	3.90
H7.3.8 (360-365)	H7 (360)	3522	/01	4.29
H7.3.4 (380-385)	H7 (380)	3520	/01	1.79
H7.2.20B (400-402.5)	H7 (400)	3519	/01	3.04
H7.2.16 (420-425)	H (420)	3504	/01	3.47
H7.2.12 (440-445)	H7 (440)	3524	/01	4.45
H7.2.8 (460-465)	H7 (460)	3525	/01	3.63
H7.2.4 (480-485)	H7 (480)	3534	/01	3.08
H7.1.20B (500-502.5)	H7 (500)	3498	/01	3.39
H7.1.16 (520-525)	H7 (520)	3530	/01	2.85
H7.1.12 (540-545)	H7(540)	3497	/01	3.28
H7.1.8 (560-568)	H7 (560)	3528	/01	3.94
H7.1.4 (580-585)	H7 (580)	3505	/01	3.16
H7.1.1 (595-600)	H7 (600)	3493	/01	3.51
H7.CC2 (600-605)	H7 (600)	3500	/01	3.04

Table 4.4 Total Organic Carbon for selected Namaqualand Mudbelt and Richtersveld sites (% TOC by Walkley-Black procedure) (page 3/3).

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9.78% and 18.48%. The Mudbelt is considerably higher in TOC and contrasts with the arid Richtersveld, which exhibits poor productivity and similarly low TOC topsoil values but compares well with the Upper Orange, an area of relatively high productivity and high TOC values and a primary contributor to the sediment (Compton and Maake 2007).

4.5.5 Results of ^{210}Pb and ^{137}Cs analysis

Both ^{210}Pb and ^{137}Cs fallout have a strong affinity for clay minerals and organic material (Walling and He 1999) and because of this it was expected that significant levels of

excess ^{210}Pb would occur in recent mudbelt material. If excess ^{210}Pb was found to be significantly present, it was deemed possible that ^{137}Cs would also be detected.

In any modern mudbelt deposit, a detectable and exponential decrease in excess ^{210}Pb is observed with depth if no post-depositional reworking has occurred. This occurs as a direct result of continuous input of ^{210}Pb into runoff, at the water-atmosphere interface and through the water column. An important objective of this thesis, noted in chapter 1, was to test whether surficial mudbelt sediments are chronologically modern using the null hypothesis. It was expected that the presence of excess ^{210}Pb would be detected in the surface mudbelt sediment if indeed the sediment was modern.

Initial ^{210}Pb results showing excess ^{210}Pb activity, published in Gray *et al.* (2000), indicate the surface of both the box and gravity cores is indeed modern material. This indicates that the surfical mudbelt sediment was less than 150 years in age. This is in contrast to the much older bulk radiocarbon ages for the same sediment. These and subsequent ^{210}Pb results are listed below in Table 4.5 (combined results), Figures 4.6.1 to 4.6.4 and Table D1 (Appendix D) and confirm the surface is modern.

These results (Figure 4.5 and Figure 4.6) clearly indicate excess ^{210}Pb values for surface mudbelt material represented by the H2-, H5- & H7- equivalent box cores and gravity cores H2 and H7, showing a significant increase in excess ^{210}Pb value from a depth of at least 10 cm upwards. In H2, H5 and H7, some reversals in this trend are seen (especially at depths between 26 cm and 12 cm), although the general trend is one of increasing excess ^{210}Pb towards the surface. This proves unequivocally that the mudbelt surface deposit is modern.

The single sample of Orange River bedload sediment (Table 4.5) yielded reasonably high levels of excess ^{210}Pb, similar to the gravity cores, but these levels are lower when compared with the so-called Africana box cores. This suggests the marine environment is enriched with excess ^{210}Pb compared with the terrestrial fluvial situation. However, when comparing the excess ^{210}Pb values, the results also point to the surface of the box cores being deposited perhaps more recently than the gravity cores and thus suggesting that the gravity cores did

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Core	Depth (cm)	^{210}Pb (Bq/kg)	Precision
H2 (Afr)	0	106	14
H2 (Afr)	4	76	10
H2 (Afr)	7	95	8
H2 (Afr)	12	46	8
H2 (Afr)	16	43	9
H2 (Afr)	24	52	8
H2 (Afr)	26	32	9
H5 (Afr)	0	135	13
H5 (Afr)	4	96	12
H5 (Afr)	7	102	11
H5 (Afr)	12	22	10
H5 (Afr)	16	32	8
H5 (Afr)	20	16	7
H5 (Afr)	24	38	9
H5 (Afr)	26	31	10
H7 (Afr)	0	144	14
H7 (Afr)	4	69	10
H7 (Afr)	7	77	12
H7 (Afr)	12	26	14
H7 (Afr)	16	43	9
H7 (Afr)	20	26	10
H7 (Afr)	24	125	7
H7 (Afr)	24	21	9
H7 (Afr)	26	26	14
Orange River	-	66	10
H2 7.4 (GC)	0	80	11
H5 3.6 (GC)	4.5	88	11
H5 2.1 (GC)	122	38	10
H7 G2 (GC)	0	66	11
H7 6.2(GC)	85	64	11
H7 6.1(GC)	95	33	10

Table 4.5 Results of ^{210}Pb for box core (*Afr) and select gravity core (GC) samples of the Namaqualand Mudbelt. The ^{210}Pb units are measured in Bq/kg. (*Africana box cores).

not sample the actual topmost layers due to the nature of the gravity coring method. Instead, the more passive box-coring operation successfully retrieved more recent material and the procedure did not result in loss of a small amount of sediment on the core surface layer. Comparison of ^{210}Pb values in both box and gravity cores indicates that the surface of the

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gravity cores appears equivalent to a depth of 4 cm in the box cores. Upon inspection of Figure 4.6.4, the expected reduction in ^{210}Pb with depth in gravity cores does not mirror the box cores. Indeed, extrapolation of the values would suggest that levels of ^{210}Pb would never reach zero in gravity cores, but remain at levels of ±30 Bq/kg reached somewhere between 30 cm and 60 cm depth in the box cores. Although the box cores were only retrieved in the year following the retrieval of the HODSA cores, it is possible that, due to the nature of storage, the HODSA cores and samples became exposed to background levels of ^{210}Pb excess isotopes, whereas the box cores were not as they were preserved intact until being split just prior to ^{210}Pb isotope analysis. This is difficult to test without obtaining additional samples and/or obtaining further analyses. Therefore it is the box cores that are used to further interpret the overall chronology. Certainly the top 30 cm appears to represent modern sediment (i.e. less than 150 years).

Interestingly, H2 (Figure 4.6.1) when compared with H7 (Figure 4.6.3), shows a similar drop off in excess ^{210}Pb in near surface sediments and it is possible that similar and uniformly high rates of deposition (human induced erosion) are represented in these modern surface mudbelt sediments both near the mouth and distally. However, radiocarbon ages suggest that earlier depositional events were either deposited under low inland erosion (and/or low flood discharge) or during a period when post-depositional erosional forces were more dominant (the latter is less likely). A compilation of all ^{210}Pb excess values is included in Figure 4.6.4, which indicates that H2 box core values are slightly more recent and sampled slightly younger material than H7. This is understandable if H2 receives more sediment in greater volumes than H7, which receives sediment less frequently and in reduced volume due to distance from the Orange River Mouth. For future reference, it is of interest that various reports suggest that sustainable management of land lowers the concentration of ^{210}Pb in surface soil (Dörr and Münnich 1989, 1991), so appropriate farming may ultimately result in reduced values in surface sediment. Recent widespread management of the ORC arable land will possibly have had some influence on the ^{210}Pb signal and this should be considered in future analysis of surface sediments (Walling *et al.* 1993, 1995; He and Walling 1997, 1999; Walling *et al.* 1993, 1995 and Wallbrink and Murray 1996).

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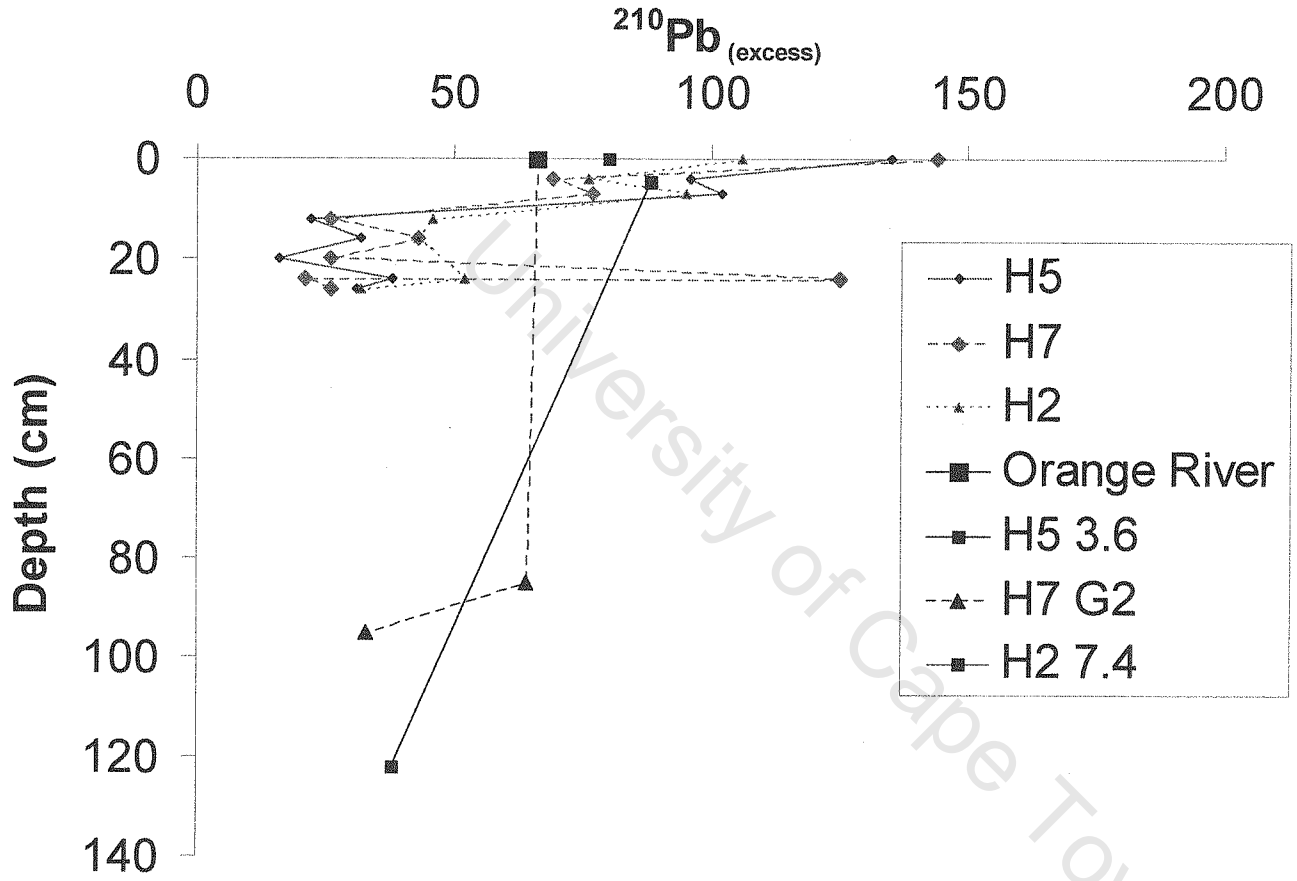

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Figure 4.5 Excess ^{210}Pb analysis of Namaqualand mudbelt box and gravity cores H2, H5 and H7. Note single Orange River sample. The ^{210}Pb units are Bq/kg.

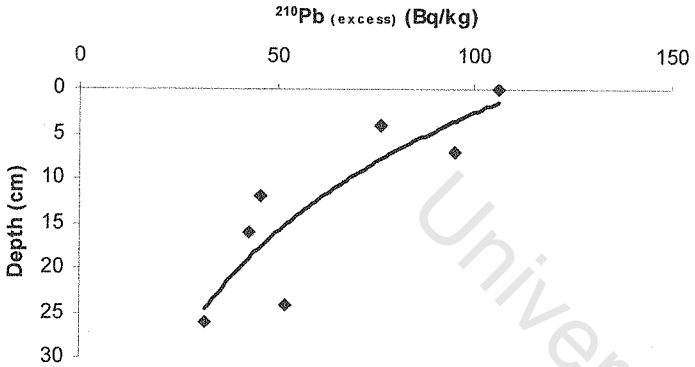

Fig 4.6.1 H2-equivalent Box core ^{210}Pb results

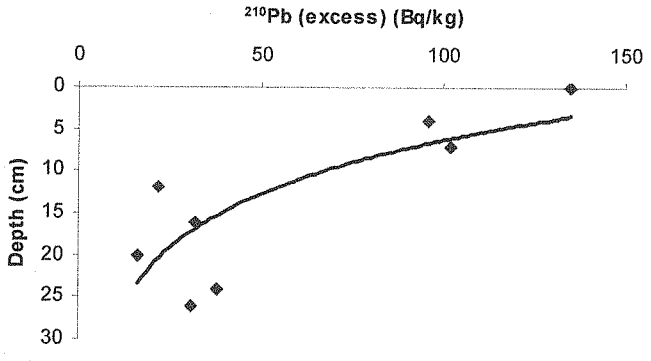

Fig 4.6.2 H5-equivalent Box core ^{210}Pb results

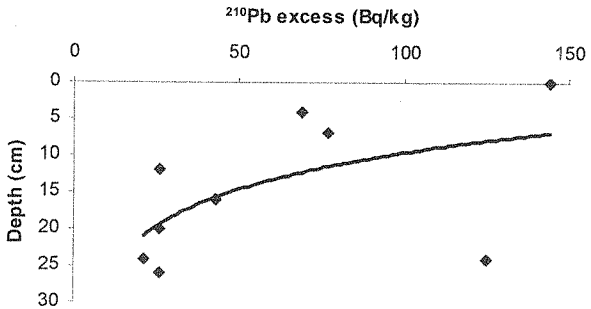

Figure 4.6.3 H7-equivalent Box core ^{210}Pb results

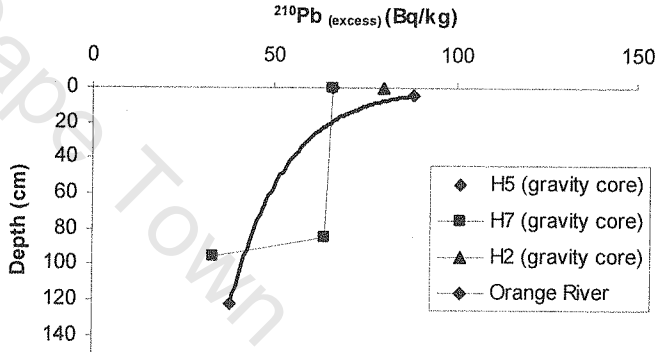

Figure 4.6.4 H2,H5 and H7 gravity core ^{210}Pb results

Figure 4.6 Excess ^{210}Pb for box cores H2, H5 and H7 and compilation of gravity core results. Note single Orange River sample.

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Preliminary unpublished analysis of a surface mudbelt sample for ^{137}Cs was carried out on core H2 prior to 1996 during which ^{137}Cs was not detected (Meadows pers. comm.). Nevertheless, ^{137}Cs was revisited in this work and analysis was conducted on the same samples, immediately following ^{210}Pb analysis (Table 4.5 and Figure 4.7). Most of the samples analysed show negligible (< 8 Bq/kg) to very weak ^{137}Cs activity with the single modern sample from the lower reaches of the Orange River showing no detectable ^{137}Cs.

Core Description	Depth (cm)	Cs (137) (Bq/kg)
H2 (Afr)	4	8.7
H2 (Afr)	12	7.2
H2 (Afr)	16	7.4
H2 (Afr)	26	0
H5 (Afr)	4	5.3
H5 (Afr)	12	4.9
H5 (Afr)	16	4.3
H5 (Afr)	20	0
H5 (Afr)	26	0
H7 (Afr)	4	10
H7 (Afr)	12	6.5
H7 (Afr)	16	0
H7 (Afr)	20	0
H7 (Afr)	24	5.1
H7 (Afr)	26	0
Orange River	0	0
H5 (gravity core)	122	0
H7 (gravity core)	95	0

Table 4.6 Results of ^{137}Cs analysis values of box cores and select gravity core samples of Namaqualand mudbelt. The ^{137}Cs isotope is measured in Bq/kg.

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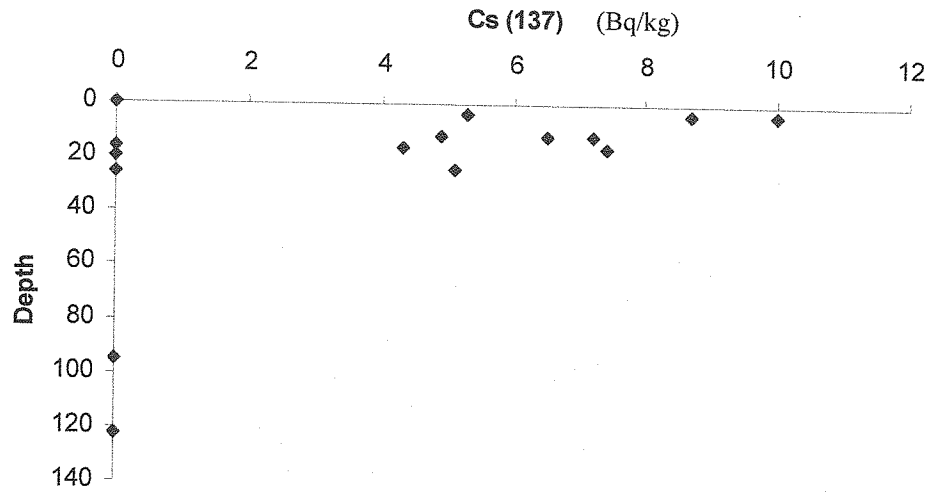

Figure 4.7 Results of ^{137}Cs analysis plotted against depth (Table 4.5). Note negligible amounts of ^{137}Cs. Units of ^{137}Cs measured in Bq/kg.

4.6 Discussion of chronology data in context of new chronology data

This section includes a discussion and synthesis of new mudbelt chronology data of this thesis with that of previously published chronology data. It is useful to synthesise the chronology first, before moving on to the stable isotopes and pollen chapters and the synthesis thereof in chapter 7.

All chronology–related objectives set out in chapter 1 are addressed and have improved the understanding of mudbelt chronology in as much as was possible using the HODSA cores. Reconciling the radiocarbon ages was of primary importance and this new analytical data has made significant inroads into examining the unexpected bulk organic radiocarbon ages important to properly characterising the mudbelt. Inland sites, which are relevant because of their situation within the ORC, were used to complement the mudbelt chronology and new ^{210}Pb analyses were conducted on the sediment. These analyses represent renewed initiatives in mudbelt characterisation (partially published in Gray *et al.* 2000) as part of the findings towards this thesis and have been successful and imperative to further understanding the context of the other palaeoenvironmental data (discussed in chapter 5 and 6) analysed for this research initiative.

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4.6.1 Mudbelt surface sediment

Although there was approximately a one year delay between the gravity and box core coring operations, this delay was not expected to have made a significant difference to the ^{210}Pb isotope analysis, given that the isotope half-life is 22.3 years. Similarly, the delay of a few years between the coring of 1994 and its final ^{210}Pb analysis during 2001 should also not have affected the results. However, given the dynamic environment of the region it cannot be ruled out that fresh sediment may have been deposited on the surface during the intervening time.

The presence of significant excess ^{210}Pb in the near surface sediments means that the surface of the mudbelt, certainly at the sites for H2, H5 and H7 is modern and therefore this represents two key objectives achieved in the chronology of the mudbelt. Firstly, this has implications for interpretation of the bulk organic radiocarbon ages and points to old reworked carbon from the catchment and the marine organic reservoir contributing towards older carbon in the modern sediment. Secondly, this means that the gravity cores did indeed retrieve modern sediment.

Notwithstanding this, excess ^{210}Pb measured at the surface of the box cores, when compared to the surface of the gravity cores, shows that the surface sediment of the box cores was slightly more enriched in ^{210}Pb than the gravity cores surface sediment. This observation is consistent across the three cores, H2, H5 and H7. Sediments sampled at or near the tops of gravity cores yield about 20% lower excess ^{210}Pb than for the box cores (Table 4.5) which appear to be consistently higher and above 100 Bq/kg. This is probably explained by the method of retrieval, with gravity cores perhaps sweeping a thin sediment layer off the top surface immediately prior to impact, whereas the method of box core retrieval is usually less clumsy and more of the surface is retained during sampling. Therefore the surface of the gravity cores is possibly not fully representative of the top most modern surface present at the time of sampling, although its surface may still be considered essentially 'modern within the error limits of most dating techniques. This lends support to the initial assertion that the gravity corer, while effective in retrieving modern sediment, was not as efficient in retrieving surface sediment as the box corer.

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A further perceived problem is that most surface samples from which bulk organic radiocarbon ages were obtained were not at the immediate surface, but instead at near surface 5 - 10 cm depth or greater (Table 4.1). However, significant quantities of excess ^{210}Pb values found at these depths confirm these are indeed modern deposits (i.e. comparable to surface).

4.6.2 Reworking old carbon

It is not surprising that results of ^{210}Pb analysis yield modern mudbelt surface sediment ages, indicating that the bulk organic radiocarbon determinations were not capturing the age of the depositional event *per se*, but rather the age of reworked and recirculated carbon (reservoir effect). The bulk organic ages of the mudbelt undoubtedly refer to the collective age of both the marine and terrestrial organic carbon represented in the sediment, but do not reliably represent the precise age of deposition.

Unfortunately, attempts at applying more detailed and, more importantly, more specific deposition age specific methods, such as AMS radiocarbon dating of foraminifera picked from the mudbelt cores, were unsuccessful. This exercise represented a re-attempt, as Mabote (1996) had initially pointed to the potential of approaching AMS dating of the foraminifera, as his previous attempt had been hampered by poor technique and bad preparation. Unfortunately, it was only during the preparation for this analysis in this thesis that it was concluded that there was insufficient material to obtain sufficient amounts of foraminifera let alone that of the correct type (benthic versus planktonic species). Thus, this finding represents a significant result having explored and firmly established the limitations of using this method in the Namaqualand mudbelt represented by these cores. If larger cores had been obtained, the resulting larger volume per core depth would probably have been sufficient for successful AMS radiocarbon analysis. The use of the existing mudbelt cores was a limiting factor within the constraints of this project as it was not possible to obtain new and larger volumes of material.

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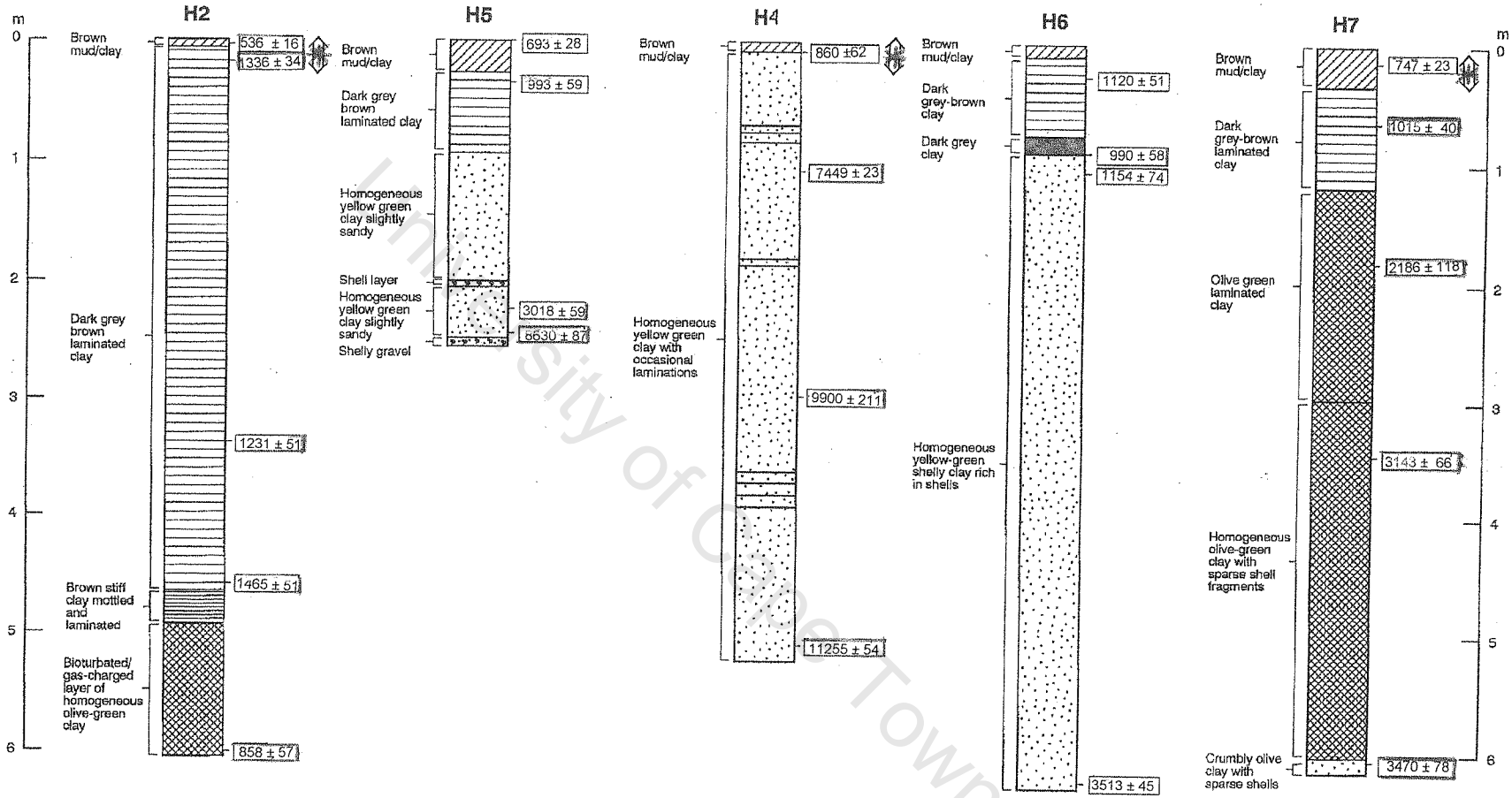

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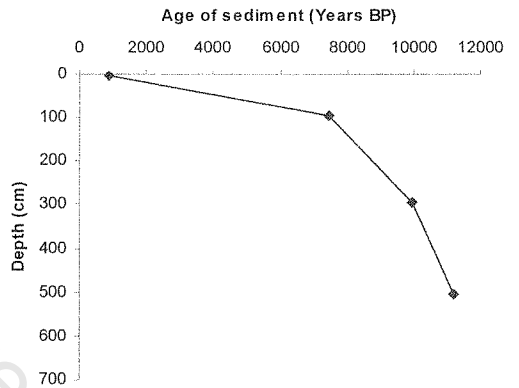
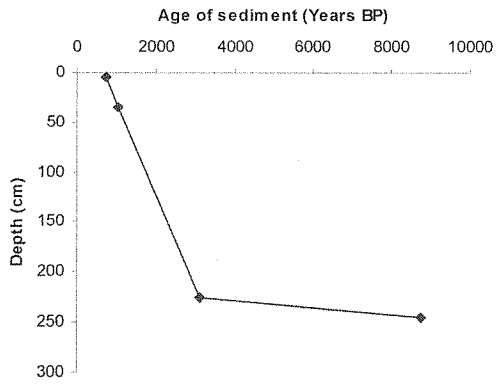
Figure 4.8 Stratigraphy of Namaqualand Mudbelt gravity cores showing calibrated bulk organic radiocarbon ages (after Meadows *et al.* 1997, 2002 and Mabote 1997). Excess ^{210}Pb illustrated by asterisks ⁑ indicates modern sediment.

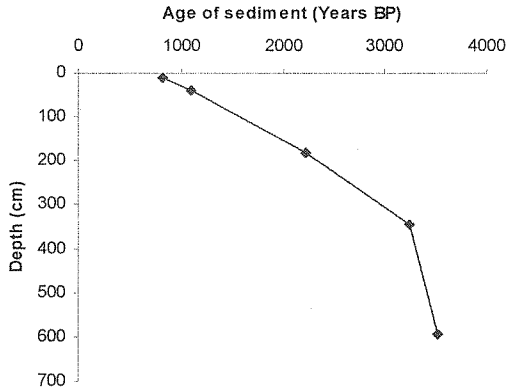
H2



H4

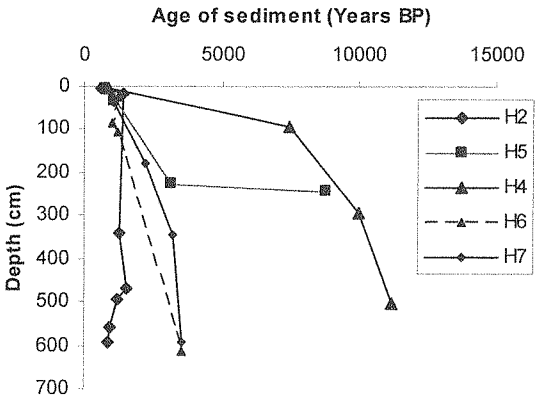


H5



H7 (placed below H2 for comparison)

H6



Combined graph (box & gravity cores). [Note variety of ranges used in x-axis]

Figure 4.9 Bulk organic calibrated radiocarbon age against depth for mudbelt H2, H4, H5, H6, H7 and comparative figure. (After Meadows *et al.* 1997).

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There is a relatively consistent trend of reduced values of detected excess ^{210}Pb with depth through all three box cores, but variation within this decrease gives evidence of some mixing occurring. This trend concurs with some of the bulk organic radiocarbon ages (Figure 4.9), which are similarly subject to the age of source sediment rather than the depositional event. These two sets of data are not directly comparable as the resolution is much higher and largely restricted to the top 26 cm for ^{210}Pb analysis as opposed to the low resolution bulk organic radiocarbon dating of the entire 6 m cores (of H2 and H7). These data suggest that some minimal reworking does occur, as the ^{210}Pb trend does not show much in the way of apparent age reversals and inconsistencies on the scale of the radiocarbon ages. Radiocarbon dating of the mudbelt illustrates that a mixing of organics of different ages are produced by a reworking within the river rather than *in situ* reworking. Mixing is to some degree an ever present process in the marine environment, affecting sediment deposition and altering the depositional characteristic of the mudbelt; given the more subtle ^{210}Pb trend, *in situ* reworking is not as significant as the reversal in radiocarbon age suggests. This is an important consideration when interpreting the overall palaeoenvironmental data from the core.

Limited interpretation of ^{137}Cs data may be made given the low resolution, mixing of sediment, few samples and the extremely low to negligible value of detectable ^{137}Cs. Many of the samples showed no ^{137}Cs presence, but some samples do display very weak ^{137}Cs activity. No ^{137}Cs was detected below 12 cm in H7 or below 16 cm in H2 and H5 box cores, but even these surface layer values may be considered so small as to be almost negligible, as they largely fall within the detection limit range between 5 and 7 Bq.kg^{-1} (Ritchie and McHenry 1990). In addition, measured ^{137}Cs values of less than 420 Bq.kg^{-1} are considered to be low in the southern hemisphere (He and Walling 1999). Either way, a drop to zero ^{137}Cs might indicate that the sediment is older than AD 1954 (at least) or 1963/1964 (Holmes *et al.* 2003), but this is largely conjecture, given the negligible values measured at this site. A number of studies have indicated this trend in the southern hemisphere (Walling and He 1999 after Hewitt 1996, Owens and Walling 1996, He and Walling 1997, 1999, Wallbrink 1997) suggesting that ^{137}Cs measurements are perhaps not as useful as in the northern hemisphere. These results show that ^{137}Cs analysis of the mudbelt is of little interpretive use for

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understanding the mudbelt chronology, however they do represent a successful revisit of the initial single sample analysis by Meadows where no ^{137}Cs was detected.

Despite the significant difference between the results of bulk organic radiocarbon dating and ^{210}Pb analysis in surface layers, the radiocarbon ages are still useful for determining age of OM in the sediment. The single OSL age determination (Meadows *et al.* 2002) close to the base of H7, which has been correlated with a nearby bulk organic radiocarbon date, appears to provide additional support for the validity of bulk organic radiocarbon ages in the distal parts of the mudbelt at least. However, this is not statistically robust, nor is the result in any way conclusive as the OSL method used at the time in this analysis has since been improved upon (Thomas pers. comm.). As limited or partial resetting of the luminescent signals (zeroing) of the grains during depositional events is possible (due to low light exposure), this method too is subject to possible inaccuracy, sometimes resulting in age over-estimates (Walling 2002), although in this instance the OSL dates are younger than the radiocarbon dates. In addition, the now calibrated ages suggest there is more of a difference in age between the radiocarbon and OSL dates than was originally argued. However, the issues of reworking old carbon and the global phenomenon of older carbon in deltas should be taken into consideration: Radiocarbon dating of deltaic sequences is typically problematic (Stanley and Hait 2000) and shelf deltaic environments, such as the Namaqualand mudbelt, should be interpreted with caution due to the effects of currents, storm, bioturbation, tides and other mechanisms of mixing. The mudbelt itself offers something of a conundrum with young deposits containing older remnants: older, less enriched radionuclides are found at the surface containing older carbon, whereas "younger" modern material is found at depth. However, results of ^{210}Pb and ^{137}Cs analysis of the mudbelt cores H2 and H7 appear to suggest the mudbelt follows a chronologically correct pattern to a greater extent (with some minor mixing demonstrated by ^{210}Pb results). This provides more support for a stable environment, where sediments

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Sample	Significant Flood events	Date and flood discharge volume	Spans age	Year AD	Published	Description	Mudbelt radiocarbon age (calibrated)	depth (cm)	Core
							11255 ± 54	505	H4
							9900 ± 211	295	H4
							8630 ± 87	245	H5
JKBN	floodplain	floodplain surface , dated to herder occupation	4500 ± 50	3099 BC	(unpublished -Hart and Halkett pers. Comm.)	OES	7449 ± 23	95	H4
LX F1-F3		F3, F2, F1 are possibly older than 5450 ± 1090 years BP.	5450 ± 1090 years BP (possibly older)		Zawada (1996), Zawada et al (1997)		3513 ± 45	615	H6
Period 1-4	4 high threshold flood periods	13 paleoflood of up to 14 660 m3s^{-1} (range:10 000 m3.s-1 and 15 000 m3.s-1)	the past 5500 years		Zawada (1996)		3470 ± 78	595	H7
Period 1	5 major flood events	floods at Lower Xobies (between 4700 ± 70 years BP and 4120 ± 160 years BP).	approx. 3650 years.1800 ± 360 years - 5450 ± 1090 years (IRSL).	Before AD 200	Zawada (1996)		3143 ± 66	345	H7
LX (F4A-I)	1 single event	single flood event with a discharge of about 13 130 m^3.s^{-1}	4770 ± 70 years BP (F4A) to 1160 ±80 years BP (I)		(Zawada et al. 1996).		3018 ± 59	225	H5
LX (C - C4; section2; H)	1 of three major events	discharge volume was around 12.740 m^{3}s^{-1}; representative of 3 major events of this Period	4120 ± 160 years BP to 4770 ± 70 years BP		(Zawada et al. 1996)	charcoal	2186 ± 118	180	H7
LX (I)	1 single event	zebra lower jaw bone in flood deposit	1660 ± 80 years BP	961 AD	(Zawada et al. 1996)	bone	1465 ± 51	470	H2
JKB 'O' Lens 3			1340 ± 50 years BP	691 AD	(uunpublished)	Org/soil	1336 ± 34*	15	H2
JKBA1; JKBA2; JKB B		JKBA1:1330 ± 60 years BP (Pta 5958) ; JKBA2: 1300 ± 25 years BP (Pta 6100) ; around 1300 years ago	±1300 years BP	AD 691; AD 762	(Brink and Webley 1996).	hearths	1231 ± 51	340	H2
JKB 'A' (20 cm)			1250 ± 50 years BP	793 AD	(unpublished)	charcoal	1164 ± 79	495	H2
LX (F6)			1100 years BP		(Zawada et al. 1996)		1154 ± 74	105	H6
LX	F7 and F8		1160 ± 80 years BP to 610 ± 50 years BP		(Zawada et al. 1996)		1120 ± 51	25	H6
Period 2	4 major floods	threshold discharge volume for this period was about 14 700 m^3.s^{-1}.	400 years. approx. 1100 years BP - 700 years BP (estimated from AD)	AD 961 - AD 1332	(Zawada et al. 1996)		1015 ± 40*	40	H7
JKB 'O' La 4			720 ± 50 years BP	1293 AD	(unpublished)	Org/soil	993 ± 59*	35	H5
BLD; LX (O)			Min.age: 710 ± 40 years BP (IRSL, RC).	AD 1785	(Zawada et al. 1996)		1990 ± 58	85	H6
Period 3	1 catastrophic event	includes a single catastrophic flood event (LX, BID). Approx. threshold discharge between 25 700 m^3.s^{-1} and 27 900 m^3.s^{-1}.	after 500 years BP (estimate)	probably after AD 1450	(Zawada et al. 1996)		873 ± 58	560	H2
LX (O, F9)		Bed O and above and including bed F9	<610 ± 50 years BP, thus F9 prob deposited after this		(Zawada et al. 1996)	OES	888 ± 57	595	H2
JKB 'O' La 2 70 cm; JKB 'O' Lens 2;			310 ± 15 years BP; 303 ± 50 years BP	1646 AD; 1640 AD	(unpublished)	Org/soil;	86 ± 62*	5	H4
column 1 102 cm; BLD 32 lens 1 72 cm			350 ± 30 years BP; 370 ± 35	1540 or 1634 AD; 1576 AD	(unpublished)	charcoal	747 ± 23*	10	H7
Period 4	4+ major floods	Between 1919 and 1992 the three largest floods occured in the Lower Orange. Discharge volumes did not exceed 9500 m 3.s^{-1}: 8330 m^3 .s (1974); 7700 m^3.s^{-1} (1988) and 7200 m^3.s^{-1} (1925).	after 200 years BP	AD 1785 to the present	(van Bladeren 1995, Zawada 1996, 2000)		693 ± 28*	5	H5
LX (surface)		termite nest, leaf and sheep or goat dung, together with overlying slack water sediments		AD 1956 -AD 1958	(Zawada et al. 1996)	Org/soil,	536 ± 16*	5	H2

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Table 4.7 Compilation of samples and sites described in this chapter. Ages include previously published and new calibrated results. Note *asterisks in right hand (shaded) column indicate modern samples as determined by ^{210}Pb (excess) analysis.

represent the order in which they were first deposited without dramatic episodes of reworking and mixing having occurred in the mudbelt. However, it should also be noted that the nature of the mudbelt is that of a terrestrial repository of sediment from a riparian source. Therefore it is reasonable to suggest that some reworking and flushing events will also occur in the river from time to time and this will contribute to an enhanced age of the Mudbelt sediment.

4.6.3 Lower Xobies, Jakkalsberg & Bloeddrift inland sites in context of depositional chronology

The Richtersveld sites (Jakkalsberg, Bloeddrift, Lower Xobies) have been useful not simply as palaeoenvironmental proxies, which are discussed in the following chapters but also in elucidating the chronology of the mudbelt.

Some of these inland sites relate to distinct flood events, especially Zawada's four high volume threshold flood periods, and have been previously dated, although additional dating was required in some cases due to absence of or discrepancy with published dates resulting from site deterioration (Zawada 1996). These results are included along with those of the mudbelt in Table 4.7, which is a chronological compilation of sediments using a variety of methods. Lower Xobies represents a high threshold flood deposit and therefore high discharge volume of sediment described by Zawada *et al.* (1996). Bloeddrift and Jakkalsberg, however, generally represent lower threshold flood events. These flood deposits represent sediment with a potential to be reworked and deposited in the mudbelt. Indeed, by way of illustration, the Richtersveld Jakkalsberg sites have been completely eroded in subsequent flooding and washout during the year following the sampling in 2000 (Tim Hart pers. comm.). This sediment of between 303 ± 50 cal yr BP and 1 340 ± 50 cal yr BP, pertaining to Zawada's Period 3 of high flood threshold (Zawada 1996), is therefore potential modern fluvial sediment load ultimately appearing in the contemporary surface mudbelt sediment during the year 2000.

Units from the Lower Xobies, Bloeddrift and select Jakkalsberg sites used in this research show some age correlation to varying degrees. The following examples from Dingle (1994), Zawada (1996), Meadows *et al.* (1997) and new analysis included in this project are the most

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notable:

- The strongest correlation is between Bloeddrift F6 (710 ± 40 cal yr BP, 450 ± 20 cal yr BP, 490 ± 40 cal yr BP) and Lower Xobies 610 ± 50 cal yr BP (Zawada *et al.* 1996) and with the Jakkalsberg site, JKB O layer 4, which has a single date at 720 ± 50 cal yr BP, corresponding to herder occupation that pre- and post- dates two significant flood events. Compared to dated mudbelt material, this is of similar age to the bulk organic radiocarbon ages of surface samples in H2, H4, H5 and H7. This falls within Zawada's 'Period 2' of high flood threshold.

- An IRSL date of 1 100 ± 220 years at Bloeddrift correlates with the unit F6 Lower Xobies radiocarbon date of 1 160 ± 80 cal yr BP (Zawada *et al.* 1996). This also correlates well with JKB A (20 cm) at 1 250 ± 50 cal yr BP and JKB O lens 3 with an age of 1 340 ± 50 years BP. This corresponds to mudbelt material radiocarbon calibrated ages at 1 015 ± 40 cal yr BP in H7 (at a depth of 40 - 45 cm;) and a number of samples between 13 cm and 497 cm in H2 (1 336 ± 34 cal yr BP, 1231 ± 51 cal yr BP, 1465 ± 81 cal yr BP, 1164 ± 79 cal yr BP respectively.) These dates fall within Zawada's 'Period 1' of high threshold flood.

- A palaeoflood unit underlying the Annis river, has an IRSL age of 4 360 ± 870 years suggesting the F1, 2 or 3 at Bloeddrift correlates with unit F5 of Lower Xobies (Zawada *et al.* 1996). This has some relevance to the age of the ostrich egg shell retrieved from surface floodplain sediments at JKB N, dated at 4 500 ± 50 cal yr BP, although for sociological reasons, these artefacts are easily older than the surface they are found on as herders are known to retain old artefacts.

- The bulk organic radiocarbon at the base of cores H4 and H5 predate the first high threshold flood event of the last 5 500 years, identified by Zawada (1996) as 'Period 1'.

4.6.4 TOC and other chronological characteristics of the mudbelt

The TOC analysis of mudbelt sediment was expected to yield low organic carbon values in

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the mudbelt (Rogers 1977a); moreover, it was expected that the few samples analysed by Mabote (1997) for LOI would be complemented using LOI and/or Walkley-Black. These results confirmed a low carbon proportion throughout both cores (H2 and H7), but organic carbon amounts to less than a third of the total carbon and averages less than 3% which is favourable for using TOC analysis. As Mabote had limited the number of samples analysed, comparison between the two datasets is restricted; however, despite the differences in statistical rigour, the LOI values and range were similar for both sample sets.

Results of ^{210}Pb and ^{137}Cs can be individually useful in terms of estimating sedimentation rate and age of modern sediment and are often analysed. There are insufficient ^{210}Pb–analysed samples of sufficiently high resolution with which to calculate sedimentation rates with confidence and a greater resolution is not possible within the constraints and limitations of this project.

Bulk sediment radiocarbon ages seem to indicate that laminated mudbelt material is younger than a bulk organic age of 2186 ± 118 cal yr BP (H7 180) (Figure 4.1). Mabote (1997) suggests this sediment represents steady deposition, which implies recent increased inland soil erosion at constant rate, probably through anthropogenic means and related to the open state of the ORM during the last 20 years. Although detailed geochemistry was not conducted in this study and the chronological results obtained are inconclusive in this regard, part of this question may be investigated by looking at ^{210}Pb graphs in this region and/ or in the palaeoenvironmental signal (this is also discussed in chapters 5 and 6). The excess ^{210}Pb is found only within laminated sediment, except in H5 (at a depth of 122 cm, where the sediment is distinctly homogeneous) and H7 (122 cm on the edge of the laminated sediment), but these values are low and appear to suggest background levels of contamination. So the implication is that modern sediment was deposited with minimal post-depositional erosion; ^{210}Pb values also suggest post-depositional reworking is less important than apparent radiocarbon age reversals might have originally implied.

A further question with regard to laminated sediment arises as to the source of reworking. While laminations would tend to suggest the absence of *in situ* reworking, it does not preclude reworking within the ORC prior to deposition, nor does it preclude inclusion of

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older marine carbon. Homogeneous sediment on the other hand, could have undergone *in situ* reworking in the mudbelt in addition to possible reworking within the ORC. However, bulk organic radiocarbon age reversals occur in both laminated and homogeneous sediment in the most affected core, H2 thus lending support to reworking being more a product of pre-depositional reworking and/or marine carbon influence rather than in situ reworking. Further, it is probable that a number of sediment hiatuses occur in the mudbelt and the rate of sedimentation is difficult to determine on the basis of the available ages and analyses.

Mabote suggested that further south, at sites H6 and H7, the appearance of grey laminations (not identified in H2 and H7) may have originated in ephemeral rivers of southern Namaqualand. Although it was not an objective to investigate this, it is worth considering in terms of palaeoenvironmental data. In the absence of more detailed lithology and ages, these sediments may warrant future research through new cores in this area. Further analysis reported in chapter 5 (isotopes) explores this further, but the available age chronology alone is not helpful in this regard.

4.6.5 Broader context of this chronological work

These mudbelt chronology findings have contributed to an improved understanding of the Namaqualand mudbelt characteristics and support the premise that the surface of the mudbelt is indeed modern and that the modern surface was sampled during coring operations. The "older" ages obtained through bulk organic dating (Gray 1996, Meadows *et al.* 1997) can be ascribed to the carbon reservoir, old marine carbon and/or reworking issues and when comparing cores it is imperative to compare them depth-wise and not simply age- wise; however, it is still a challenge to examine the precise proportion of each. These findings also suggest that although the mudbelt prodelta remains more complex with regard to chronology, it is probably less complex than the radiocarbon ages would suggest, given that the excess ^{210}Pb values display fewer apparent inconsistencies up-core compared to the bulk organic radiocarbon ages.

Figure 4.10 represents an attempt at comparing cores H2 (the prodeltaic) and H7 (the distal) on the basis of age and not depth and stratigraphy alone. Figure 4.10 is constructed to

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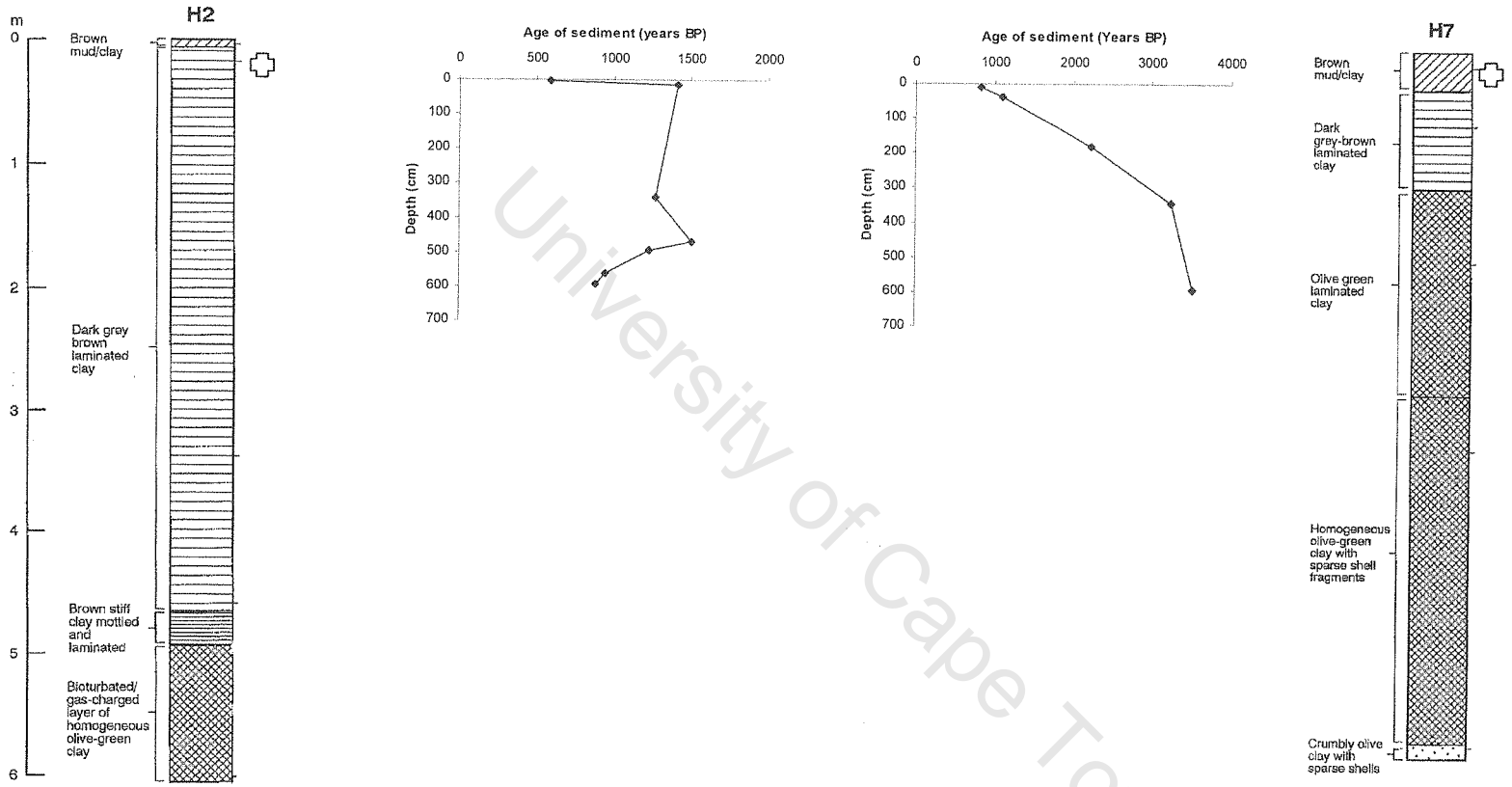

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Figure 4.10 Comparison of Namaqualand Mudbelt cores H2 and H7 indicating age comparison on the basis of calibrated bulk organic radiocarbon ages (graphs are included). H2 is estimated to be roughly equivalent in age to the top portion of core H7. Note asterisks denote modern surface sediment based on ^{210}Pb (excess).

illustrate the radiocarbon and ^{210}Pb age and relative age of H2 compared to H7. H2, with a maximum radiocarbon age of about 858 ± 57 cal yr BP, is represented as a crude proportion of H7 (with a maximum radiocarbon age of 3470 ± 78 cal yr BP), roughly corresponds to only the top section of H7. As age reversals and limitations include low and uneven resolution of mudbelt age, it is not possible to simply illustrate the cores on the basis of age without making assumptions. However, the surface bulk organic radiocarbon ages of H2 and H7 emphasise the difference in radiocarbon lag between the prodelta and distal areas of the mudbelt in that H2 had a 'lag' represented by its surface as at least 520 years and H7 as at least 750 years, thus highlighting the greater probable presence of older (marine) organics in distal sediment of the mudbelt compared to the prodelta. Further, the existence of older radiocarbon ages situated above younger ages, implies that older terrestrial sediment is found at intervals above younger marine sediment. Indeed, the surface ages coincide with high energy flooding events during and after Period 3 (Zawada *et al.* 1996) and the implications of these events would potentially have an impact on chronological history and palaeoenvironmental record of this sediment.

It is useful to revisit the reversals of age within the core, as illustrated by the age/depth graphs (Figure 4.10) for both cores. H2 clearly shows more reworking than H7, probably as a result of higher sedimentation in H2 and more opportunity for reworked sediment to have flooded the radiocarbon signature with reworking events during high flood discharge. The more distal H7 on the other hand is diluted and has a much reduced deposition of sediment from the mouth of the Orange and potentially deposited over a broader time period.

The ^{210}Pb results suggest that *in situ* reworking of organic material is not of primary importance in the mudbelt, whereas reworking is more important within the ORC during flood events. There is a trend of reduced values of detected excess ^{210}Pb with depth through all three box cores but variation within this decrease gives evidence of some mixing occurring. Mixing is to some degree an ever present process in the marine environment.

Thus, once sediment is deposited in the mudbelt, it is more likely to be undisturbed. This highlights the difference between the depositional event and the age of the bulk organics deposited during that event, which is illustrated by ^{210}Pb values in near surface sediments.

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However, it is not possible to fully explore this at depth, as there is no equivalent to ^{210}Pb for exploring older sediments. Issues of old carbon, therefore, are perhaps of more use in terms of investigating bank erosion and erosion during flooding and tend to mislead the age of deposition within the mudbelt.

This study of the HODSA mudbelt cores, although not as successful as hoped (given that insufficient foraminifera were available for AMS dating and development of a full chronology model for the mudbelt was therefore not possible) represents new and more detailed results in terms of literature for the mudbelt and improves the existing literature. However, it is not without problems in that the precise dating of hiatuses and increased levels of sedimentation are difficult to ascertain. Nonetheless, these efforts have produced useful results and enhance previously held understanding of chronology dynamics within the mudbelt. These and other aspects of chronology, including recent work by Herbert and Compton (2007) are synthesised and discussed in chapter 7 alongside additional aspects of this research.

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5 STABLE LIGHT ISOTOPE ANALYSIS OF THE SEDIMENTS OF THE NAMAQUALAND MUDBELT AND RELATED SITES

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5 Stable light isotope analysis of the sediments of the Namaqualand Mudbelt and related sites

This chapter deals with characterising the bulk organic matter of the Namaqualand mudbelt sediments using stable light isotopes of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$) based on the differences in isotopic composition between marine and terrigenous organic matter. For methodology, refer to chapter 3 and for further synthesis of the results, refer to chapter 7.

The focus of interest is the by-products of different types of photosynthesis represented in the bulk organic portion of the mudbelt sediment. Terrigenous organic material differs from marine organic matter: the terrigenous organic matter may reflect the C_3, C_4 or CAM photosynthetic pathways of the overlying vegetation, whereas the marine organic matter reflects the C_3 photosynthetic pathway of marine organic matter. Therefore sediment from both terrestrial and marine sources can overlap over this range of values, thus creating difficulty when interpreting isotope signatures in a mixed marine-terrestrial (C_3, C_4 and CAM environment). These by-products of photosynthesis are verifiable through isotopic analysis and may be produced in either the marine environment, terrestrial environment or an admixture of the two and overlap in an average range of between -26‰ and -28‰; the total organic carbon (TOC) component of the marine system may therefore be of mixed terrestrial and marine organic carbon origin. A combination of both nitrogen and carbon isotope analysis was therefore used to characterise the mudbelt and thereby yield some insight into the relative influence of various sources through changes in the proportions of terrigenous and marine carbon and, possibly, the dynamics of terrestrial vegetation in the contributing catchments. The terrestrial signal of palaeoproductivity is invaluable in the understanding of the mudbelt data and the stable isotope analysis compares and contrasts two cores, H2 and H7 to attempt to assess a measure of the relative influence of terrestrial and marine dynamics within the mudbelt. The Lower Xobies palaeoflood site (Zawada 1996, 1999 and Zawada *et al.* 1997), additional slack water deposits and contemporary sediment deposits (all from the Richtersveld) are used to provide inland data references. Evidence from the mudbelt for the source and volume of deposited sediment and insight into changes

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thereof has been primarily based on terrestrial materials such as pollen and sedimentological studies. Although these can offer more qualitative estimates of climate or environment change, stable isotope analysis provides a different perspective to characterising the mudbelt. These isotope analyses of terrestrial sediments in the marine environment are intended to complement the pollen analysis. Stable isotopes offer some advantage over other palaeoclimatic proxies, such as pollen (chapter 6) (Goodfriend 1999). For instance, the $\delta^{13}C$ can provide evidence for proportions of C_3 vs. C_4 plants although this is complicated by the intermediate signal for marine bulk organic matter. The $\delta^{15}N$ data can provide some indications about the relative amount of marine vs. terrestrial organic matter in the sediments. Together the isotopes, $\delta^{13}C$ and $\delta^{15}N$, show different trends and dynamics to that of pollen. However, all palaeoclimatic proxies are determined by more than a single factor and possess a certain amount of ambiguity. Stable isotopes are no exception, but they are useful palaeoenvironmental proxies nevertheless.

Although widely used elsewhere, there are a limited number of fluvio-marine isotopic studies at the terrestrial margin in the eastern Atlantic area that have been used as indicators of relative change in the associated vegetation regimes. Studies by Holtvoeth *et al.* (2001, 2005), Holmes *et al.* (1996, 1998) in the Angola basin and Twitchell *et al.* (2002) ODP1085 study on the continental shelf of the Cape Basin provide comparisons for the mudbelt are briefly compared in section 5.2.4.

Assuming that the isotopic character of the mudbelt is useful for palaeoenvironmental interpretation, this analysis investigates the potential fluctuation in terrestrial isotopic data in order to reconstruct valuable evidence of continental climatic change. Such an investigation must consider source sediment with the influence of the oceanic situation producing variations, and perturbations within both the marine and terrigenous systems together with the input from a variety of sources of either marine (C_3) or terrestrial (C_3 or C_4) organic matter and time scales, where values may overlap and composition may be affected by the carbon reservoir. Due to the close proximity of H2 to the source of terrestrial nutrients and suspended matter, and the distance of H7 from that source, it is expected that H2 has a stronger terrestrial influence and H7 a more marine influence. Variations within that data are expected to show terrestrial information pertaining to inland change picked up within the catchment due to a combination of dynamics in climate, fluvial and human influences. In addition,

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isotopic analysis of modern Lower Orange River samples taken in the Richtersveld and during low flow discharge was conducted so as to provide contemporary reference data to contrast with the mudbelt. Sediment at the Jakkalsberg and Lower Xobies sites was analysed to provide isotopic data with particular reference to terrestrial palaeoflood material. This inland isotopic data is intended to facilitate comparison of modern and past sediment isotopic values with the two sites in the mudbelt to achieve the above goals. Research by Compton and Maake (2007) offers some insight into the terrestrial isotopic signature of the source sediments; this points to the upper catchment where a large proportion of runoff occurs and is further discussed in section 5.2.2.

Analysis of organic carbon and $\delta^{13}C$ isotope in this type of region is a challenge due to the aforementioned mixed marine and terrestrial signal. It is typically assumed that a simple mixing equation using two "extreme values" or end members of approximately -20‰ for marine materials and -26‰ to -28‰ for terrestrial vegetation can be used but these are rough estimates only (Wefer *et al.* 1999 and Wagner and Dupont 1999, after Muller *et al.* 1983 and 1994, Fontugne and Duplessy 1986). These assumed terrestrial $\delta^{13}C$ values assume catchment terrestrial vegetation is dominantly C_3 and not C_4, as was considered to be the case for the ORC based on the dominant C_4-type vegetation in the upper catchment, where the majority of the fine mudbelt sediment is sourced (Compton and Maake 2007). Therefore, it can be predicted that the values should trend towards values which are more C_4-enriched (with a mean value of -13‰) for the ORC than previously thought. Indeed Compton and Maake (2007) show mean values of -19.3‰ in the Orange River (specifically the Free State and Aliwal North Rivers which represents the gateway of the Upper ORC) closer to mean $\delta^{13}C$ values of -19.7‰ in H7; this suggests an equal mix of C_3 and C_4 vegetation being delivered to this section of the ORC. Since the catchment sediment (sediment load) originates largely in the upper Orange; the lower reaches and CAM-rich area immediately adjoining the continental margin are limited in terms of runoff and airborne organics thereby limiting the input of Succulent Karoo organics and therefore CAM input. Compton and Maake (2007) also show that there is strong evidence for the soil runoff originating mainly in the valley fill areas of the high altitude and not the high altitude slopes, where the basaltic soils are thin and the underlying bedrock resistant to erosion.

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5.1 Results of stable isotope analysis

As the mudbelt organic content is low (Rogers 1977a, Mabote 1997, Meadows *et al.* 1997), this can pose problems for isotopic measurement. Some samples were not successfully analysed for both $\delta^{13}C$ and $\delta^{15}N$ due to the low carbon levels present and variable content. Although repeat sampling using larger quantities of sediment was carried out in order to obtain sufficient carbon (and thus carbon dioxide from combustion) for isotopic analyses, some gaps persist in the data. Once the samples were analysed, the carbon and nitrogen isotopic data were cor rected and plotted against depth for the various sites as shown in Table 5.1. This was done for the following sites: Lower Xobies (terrestrial) slack-water deposit cores and H2 and H7 from the mudbelt. Selected values from the Orange River ("WT", "R" and POT) and Jakkalsberg ("JKB") are included in Table 5.1 and Table 5.2 respectively. The results of each site are presented separately with the exception of a subsection dealing with TOC and C/N ratios.

5.1.1 Modern Orange River sediment

The carbon isotope values of selected terrestrial modern Orange River (WT) sediment samples, retrieved during a low flow discharge period in 1999, vary between -24.8‰ and -17.7‰ (mean of -21.5‰; Table 5.1). Given the extent of the catchment and retrieval of these samples in the lower reaches of the river, the values may indicate the average modern low discharge signal. The average $\delta^{13}C$ values for C_3 vegetation in the southern African region are - 27‰, whereas C_4 vegetation averages -13‰ (Codron *et al.* 2005a) and CAM vegetation may vary.

Nitrogen isotope values of the same WT samples are plotted together with the carbon isotope variations in Table 5.1. δ^{15} N (‰) values vary between zero and 9.2‰ (average 4.3‰) and are also representative of low-discharge suspended sediments.

5.1.2 Additional terrestrial sites: Jakkalsberg

The palaeoflood sites Jakkalsberg, JKB O and JKBA (detailed in chapter 2), yielded values at various non-contiguous depths and sediment layers. The $\delta^{13}C$ values average -21.9‰ and fall within a range of between -24.2‰ and -18.4‰ (Table 5.1).

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Nitrogen isotope values at sites JKB vary widely and range between 4.5‰ and 15.8‰ yielding a mean value of 10.6‰.

5.1.3 Lower Xobies palaeoflood site

Carbon isotope values at Lower Xobies range between -21.1‰ and -17.3‰ (mean value of -19.2‰; Table 5.2, Figure 5.1). From the base of the profile at 600 cm to a depth of 322 cm, the data generally lie within a narrow but steadily more positively shifting band of $\delta^{13}C$ values between -20.3‰ and -18.7‰ (with one exception at -21.1‰) and a mean value of ±-19.0‰. Between depths of about 322 cm and 146 cm, the values vary broadly, before narrowing in range to cluster around -19.3‰ for the top 130 cm of sediment.

Lower Xobies $\delta^{15}N$ values are illustrated in Figure 5.1 (Table 5.2). These values vary across a broad 10.6‰ range from -1.2‰ to 9.4‰ (mean value of 5.5‰). Three possible flood events represented as pulses of sediment, show some overlap (Zawada 1996). These fall within the following $\delta^{15}N$ ranges: 4‰ to 6‰ (50 cm -150 cm); 7‰ to10‰ (30 cm - 120 cm); 5‰ to 9‰ (300 cm - 560 cm) and 3‰ to 4‰ (50 cm - 600 cm) but $\delta^{15}N$ is hard to categorise and for these terrestrial sediments, the numbers are very broadly scattered. This is possibly an analytical problem, although the poor voltages measured during analysis were removed. Alternately, the numbers are real and represent highly variable conditions, such as found in flood and non-flood sediments or simply vegetation from different environments. Given the potential for this within the ORC, this variation is not surprising. However, the mean value for this data (5.5‰) accords well with expected values for the area published in Heaton (1997).

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5.1.4 Namaqualand mudbelt: core H2

Carbon isotope values in H2 (Figure 5.2, Table E5 in Appendix E) cluster around a mean of -17.4‰ but there are two distinctive isotopic trends within this. The values fall within a narrow range in the basal 100 cm with a mean of -19.0‰, showing a steady 2‰ to 3‰ negative shift in values between 600 cm and 500 cm. From a depth of 500 cm to the surface, the values vary more widely, but consistently covering a range between -20.4‰ and -13.8‰ (mean value of -17.1‰). Some notable outliers occur at depths 472 cm (14.5‰) and 63 cm (-20.4‰).

Three pulses of sediment origin are indicated by a wide range of values (from -14‰ to -20‰) interspersed by a narrower range. These can be found at depths of between 492 cm to 472 cm, 317 cm to 162 cm and 97 cm to 0 cm.

Sample	$\delta^{13}C$	$\delta^{15}N$ (‰)	%C	%N (‰)	1/N	C/N
R/C/99	-20.6281	9.196867	0.278481	0.052202	19.15638	5.33469
WT/1/#1	-18.7746	—	0.250227	—	—	—
WT/1/BPM	-21.2706	—	0.180735	—	—	—
WT/1/LNCH	-24.7714	-0.50316	0.204356	0.025126	39.79984	8.133318
WT/13/#3	-21.4455	—	0.131709	—	—	—
WT/13/#4	-23.0077	—	0.191843	—	—	—
WT/1/#2	-23.1195	—	0.500912	—	—	—
WT/2/SC	-20.9552	—	0.147711	—	—	—
WT/2POT	-21.3921	—	0.204418	—	—	—
WT/4/NO3	-23.4103	—	0.102363	—	—	—
WT/4/R2	-17.7193	—	0.244033	—	—	—
Std Deviation	2.051683	6.858954	0.106526	0.019146	14.59713	1.978929
Mean	-21.4995	4.346854	0.221526	0.038664	29.47811	6.734004
JKB A /AC	-24.0999	15.83802	0.228037	0.043834	22.81348	5.202317
JKB A /BC	-22.0508	13.68529	0.163444	0.029413	33.99813	5.556798
JKB A /CL	-22.8682	12.35869	0.425719	0.03277	30.51598	12.99124
JKB A /CL2	-23.4558	10.74962	0.495365	0.085316	11.72116	5.806254
JKB O /L1	-18.3963	11.09099	0.439206	0.094009	10.63731	4.671967
JKB O /L2	-20.6566	10.21397	0.469255	0.071426	14.00049	6.569803
JKB O /BL2	-22.7241	7.232056	0.178254	0.044862	22.29036	3.973348
JKB O /L3	-24.2035	12.64265	0.696125	0.052875	18.91268	13.1656
JKB O /L3	-21.3804	—	0.307347	—	—	—
JKB O /BL3(2)	-21.5522	—	0.113665	—	—	—
JKB O /BL3M	-21.0523	—	0.31354	—	—	—
JKB O /L4	-22.3978	6.277608	0.312103	0.026278	38.05424	11.87684
JKB O /AAL1	-21.2953	—	0.049824	—	—	—
JKB O /A1	-21.267	—	0.039937	—	—	—
JKB O /AAL2	-23.6874	—	0.301093	—	—	—
JKB O /BAL2	-20.8704	4.485682	0.069445	0.050249	19.90075	1.382009
JKB O /C2	-20.9201	—	0.3449	—	—	—
JKB O /AL2	—	7.984369	—	0.029837	33.51551	—
JKB O /CL3	—	11.12615	—	0.040766	24.5302	—
JKB O /CL3(2)	—	14.56299	—	0.062407	16.02372	—
Std Deviation	1.486336	3.352275	0.179702	0.02166	8.912629	7.420964
Mean	-21.934	10.63447	0.291015	0.05108	22.83954	7.119617

Table 5.1 Stable carbon and nitrogen isotope values, % carbon and % nitrogen (by weight), 1/N and C/N ratios (by weight) of modern Orange River sediments (WT) during a non-flood period of 1999 and from the Jakkalsberg (JKB) site. Note: C_3 plant values average range is between -26‰ and -28 ‰ and C_4 plant values average is between -12‰ and -14‰; soil $\delta^{13}C$ tends to be depleted by 1‰. C/N ratios between 7 and 9 indicate marine values, C/N ratios larger than 15 indicate terrestrial values.

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The $\delta^{15}N$ values of H2 sediments (, Table E5 in Appendix E) vary across a narrow 2‰ range (4.6‰ to 6.6‰) and have a mean cluster value of 5.8‰. Within this, the $\delta^{15}N$ value range broadens from a very narrow range at the base of the core, with a positive shift of about 2‰ to a depth of about 512 cm; the values range between 5.7‰ and 6.5‰ in this part of the core. This shift in $\delta^{15}N$ values is consistent with the positive shift in $\delta^{13}C$ values at the same depth (bottom 100 cm of the core). The mean value for depths 600 cm to 500 cm is 6.1‰. Above a depth of 500 cm and extending to the surface, the values vary broadly around a mean of 5.7‰.

5.1.5 Namaqualand mudbelt: core H7

Core H7 (Figure 5.3, Table E4 in Appendix E) $\delta^{13}C$ values cluster consistently around a mean of -19.7‰ (-16.8‰ and -23.5‰), which is well correlated with the standard marine value range of between -21‰ and -20‰. One notable outlier of -16.8‰ occurs at a depth of 355 cm. However, three sediment packets or pulses of varying $\delta^{13}C$ values occur at depths 560 cm to 505 cm, 285 cm to 150 cm and 75 cm to 20 cm where the values within these sediment packets vary within about 1‰.

In H7 (Figure 5.3, Table E4 in Appendix E), the majority of $\delta^{15}N$ values fall within a narrow 3.5‰ range between 5.4‰ and 8.9‰. From the base of the core at 600 cm to 300 cm, the values average 7‰, whereas between 300 cm and 200 cm, there is a steady negative 0.5‰ excursion from around 7‰ to about 6.5‰. The $\delta^{15}N$ values cluster consistently around 6.4‰ in the top 200 cm. Within this zone, smaller sediment packets are discerned exhibiting minor variations. Five samples cluster tightly around a depth of 200 cm, (between 215 cm and 190 cm) with a mean value of 6.7‰ (between 6.8‰ and 6.5‰). Box and Whisker plots (Figure 5.4) draw together isotope data from the OR (WT), Lower Xobies and the mudbelt cores. Box cores (Table 5.3) reveal less variation than do the gravity cores.

5.1.6 Total organic carbon (TOC), loss on ignition (LOI) and C/N ratios

In certain select mudbelt samples and a handful of inland samples (in Table 5.4), total organic carbon (TOC) values were derived from Walkley-Black titrations. This is an addition to the carbon percentile values obtained by using carbon mass spectrometer readings (LOI) and are not precise measurements of TOC. However, these can be used to give an indication of values derived from Walkley-Black titrations. For

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consistency, C/N values are calculated using mass spectrometer numbers (Table 5.1, Table 5.2, Table 5.3 and Table 5.4) and TOC (Appendix E).

The inland C/N ratio values at JKB, the modern Orange River bed load (WT) and Lower Xobies sites vary within a wide range of ratios between 1.4 and 22.8 and fall within terrigenous values. These C/N ratios may extend up to 200, but this is within the upper limit and not necessarily representative of the mean low flow discharge values of the lower reaches of the Orange River and a mean value below a C/N ratio of 20 is expected. However, given that these samples were retrieved during a low flow discharge period in arid conditions and with the input from bank vegetation along the Orange River, some alteration is possible.

JKB C/N values from JKB O CL, L3 and L4 prove reasonably high with ratios of 13, 13.2 and 11.9 respectively. However, some low C/N values included JKB O L1 (layer 1) (4.7), BL2 (4) and BAL2 (1.4) and others could be due to either the low organic carbon content of the sediment or to a significant proportion of the nitrogen being adsorbed by clay particles (Hu *et al.* 2006). In this instance, terrestrial values below 15 may be ascribed to an elevated organic matter content due to contamination from fires (charcoal) or due to a function of aridity. Samples analysed for percentage carbon derived from the mass spectrometer analysis, were also unexpectedly low, thus yielding 'marine' values with most C/N values in Jakkalsberg (JKB O) below 11 (with the exception of the above mentioned samples). More than a third of values at Lower Xobies were less than 11, with exceptions including SIX N3, N4 0, K, I and G2, where values of 12.6, 14.8, 12.6, 18.2 and 22.8 respectively were measured. Aridity, not charcoal, is the more important feature of Lower Xobies, as there is no sign of charcoal or other significant organic matter in the area; the low organic carbon content of the sediment ensures C/N values tending to be lower than expected. Both LOI and TOC C/N ratios show overlap between the terrestrial and marine samples, but the important result is that there is a tendency for higher carbon relative to nitrogen in terrestrial compared to marine values.

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Depth	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N
0	S1X/SURFACE	-19.0167	—	0.320565	—	—	—
40	S1X/P1	-19.1451	—	0.28492	—	—	—
50	S1X/P2 45 cm	-19.587	7.329209	0.504782	0.05449	18.35189	9.2637
55	S1X/P3	-19.2371	7.936593	0.271791	0.037987	26.32514	7.154932
32	S1X/P4	—	4.102426	—	0.027811	35.95762	—
70	S1X/P5 (30)	-19.677	8.763239	0.44742	0.115163	8.683307	3.885085
85	S1X/P5	-19.3793	5.458145	0.233757	0.049846	20.06179	4.68958
100	S1X/N1	-18.7699	—	0.301269	—	—	—
108	S1X/N2	-18.7921	9.397307	0.28074	0.098835	10.11792	2.840509
114	S1X/N3	-17.4213	5.927929	0.269906	0.021356	46.82586	12.63857
122	S1X/N4 O BASE	-18.0817	5.304945	0.430979	0.029195	34.25245	14.76207
140	S1X/L	-20.1157	—	0.251352	—	—	—
150	S1X/K	-20.7122	3.045796	0.210798	0.016689	59.92128	12.63128
170	S1X/J	-20.1795	—	0.426969	—	—	—
175	S1X/I	-17.3435	2.078036	0.486832	0.026743	37.39321	18.20421
175	S1X/I	-18.6803	—	0.303187	—	—	—
215	S1X/H TOP	-19.1115	—	0.226195	—	—	—
230	S1X/4 MID 5 cm	-19.5325	—	0.288842	—	—	—
235	S1X/H/0	-18.5724	—	0.175722	—	—	—
240	S1X/G1	-18.1143	—	0.290727	—	—	—
260	S1X/G2	-19.0783	3.824835	0.433762	0.01904	52.52007	22.7812
285	S1X/62V G3(V)	-18.5244	—	0.578137	—	—	—
336	S1X/63	—	-1.21239	—	0.016864	59.29696	—
304	S1X/B8 (45)	—	7.198313	—	0.045029	22.20805	—
310	S1X/1F	-18.2256	—	0.418444	—	—	—
320	S1X/E	-18.4487	—	0.072167	—	—	—
325	S1X/D	-19.4072	—	0.195027	—	—	—
400	S1X1/C1-15	-21.1196	3.191661	0.251553	0.032687	30.5932	7.695803
400	S1X/C1	-19.1547	—	0.109396	—	—	—
480	S1X/C3	-19.3974	5.582937	0.175457	0.043771	22.84644	4.008562
432	S1X/C4 (30)	-19.7322	5.883553	0.190803	0.050913	19.64121	3.747606
448	S1X/C5	-19.5059	7.365048	0.097779	0.053128	18.82235	1.84043
456	S1X/C6	-19.7272	—	0.068316	—	—	—
464	S1X/C7	-19.9859	5.351057	0.101777	0.045534	21.96177	2.235196
472	S1X/C8 (45)	-19.0558	—	0.089183	—	—	—
480	S1X/C9	-18.7938	6.44674	0.100347	0.044421	22.51209	2.259021
496	S1X/CO	—	7.660417	—	0.04793	20.86381	—
528	S1X/C10	-20.3141	6.958488	0.173142	0.048506	20.61622	3.56953
540	S1X/A1 60 cm	—	6.836289	—	0.046703	21.41187	—
595	S1X/5	—	2.782199	—	0.025888	38.62855	—
	Std Deviation	0.837324	2.445779	0.135389	0.023621	14.32881	6.254012
	Mean	-19.1747	5.53099	0.266531	0.043414	29.12231	7.894547

Table 5.2 Stable carbon and nitrogen isotope values, % carbon and % nitrogen (by weight), 1/N and C/N ratios (by weight) for the Lower Xobies (LX) site and C/N values for selected Orange River Catchment sites. C/N ratios between 7 and 9 indicate marine values, C3 plant values average range is between -26‰ and -28‰ and C4 plant values average is between -12‰ and -14‰; soil $\delta^{13}C$ tends to be depleted by 1‰ (C/N ratios larger than 15 indicate terrestrial values).

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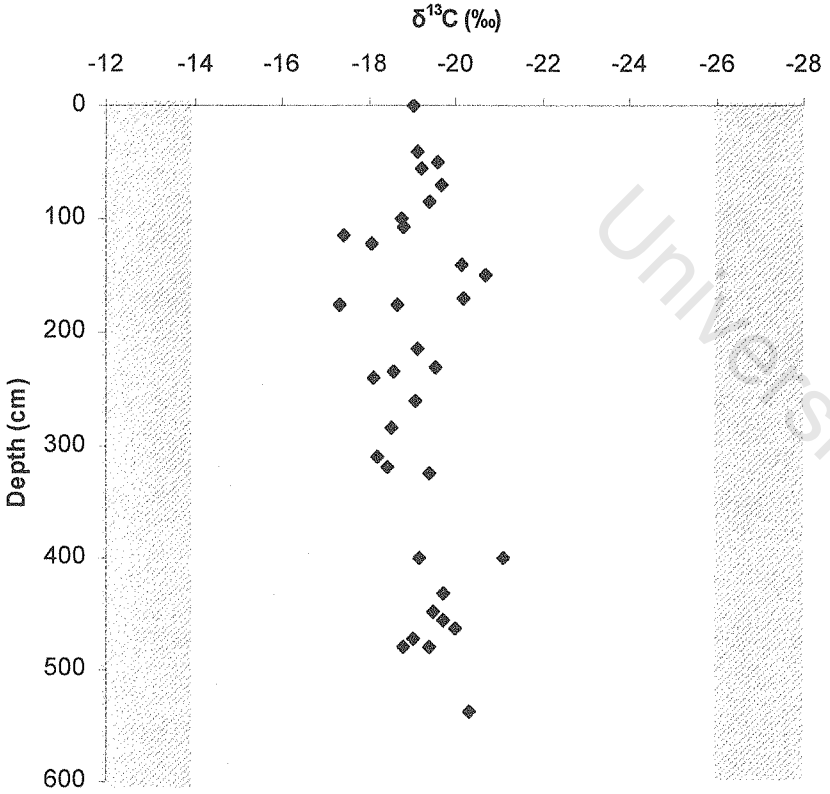
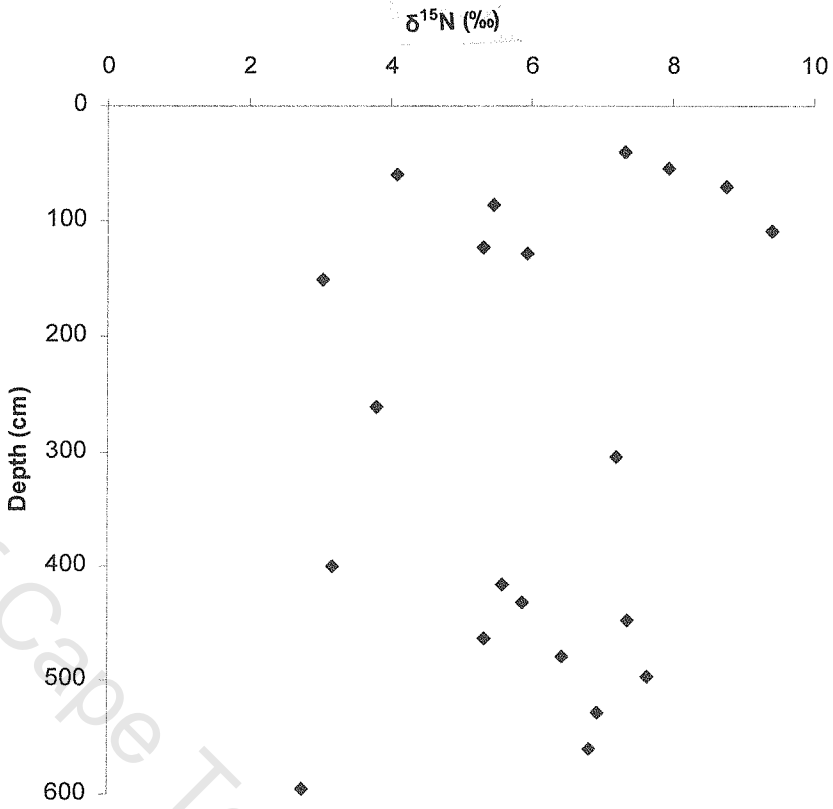


Figure 5.1 Lower Xobies $\delta^{13}C$ against depth. Note: average C4 (-12‰ to -14‰) and C_3 (-26‰ to -28‰) plant values shaded.



Lower Xobies $\delta^{15}N$ against depth.

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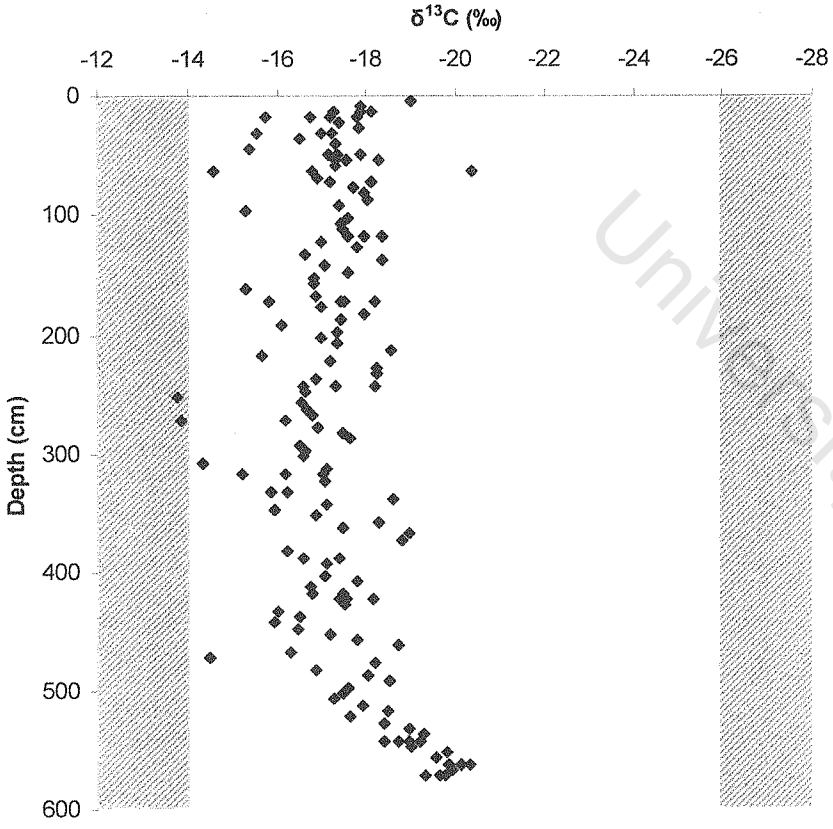
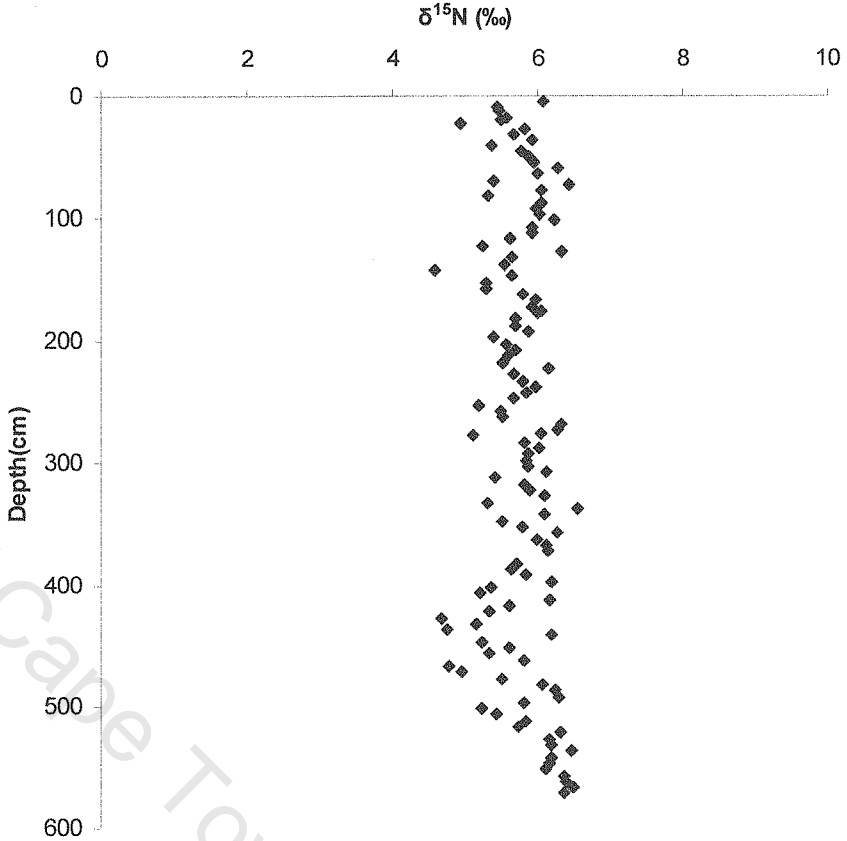


Figure 5.2 Core H2 (prodelta, off Orange River Mouth) $\delta^{13}C$ against depth. Note: C_4 (-12‰ to -14‰) and C_3 (-26‰ to -28‰) average plant values shaded. Standard marine value approximately -20‰.



Core H2 (prodelta, off Orange River Mouth) $\delta^{15}N$ against depth.

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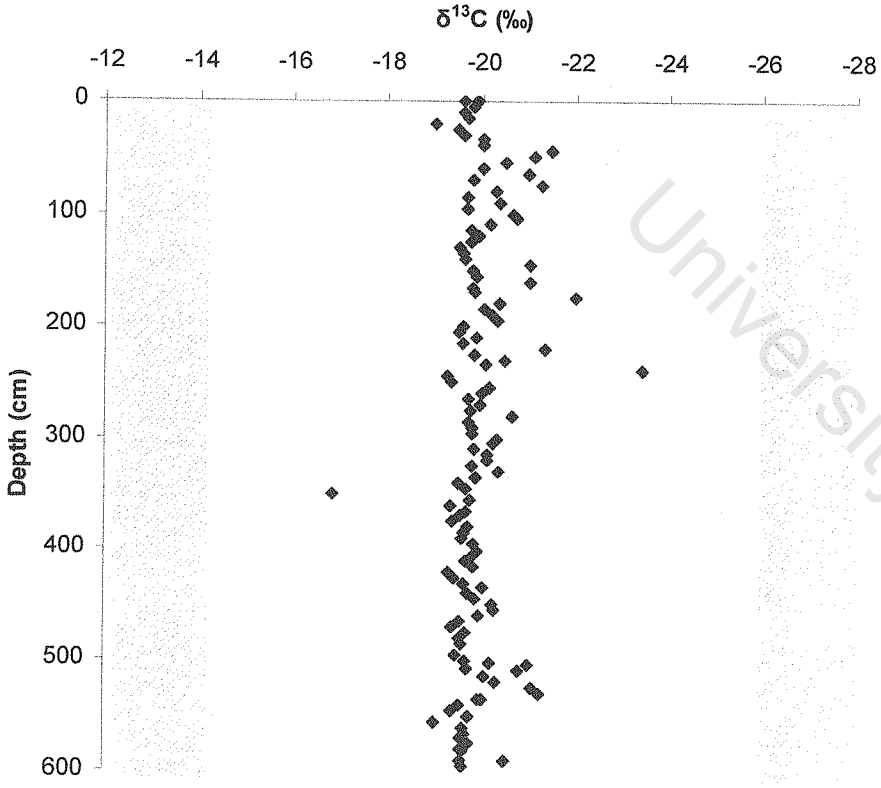
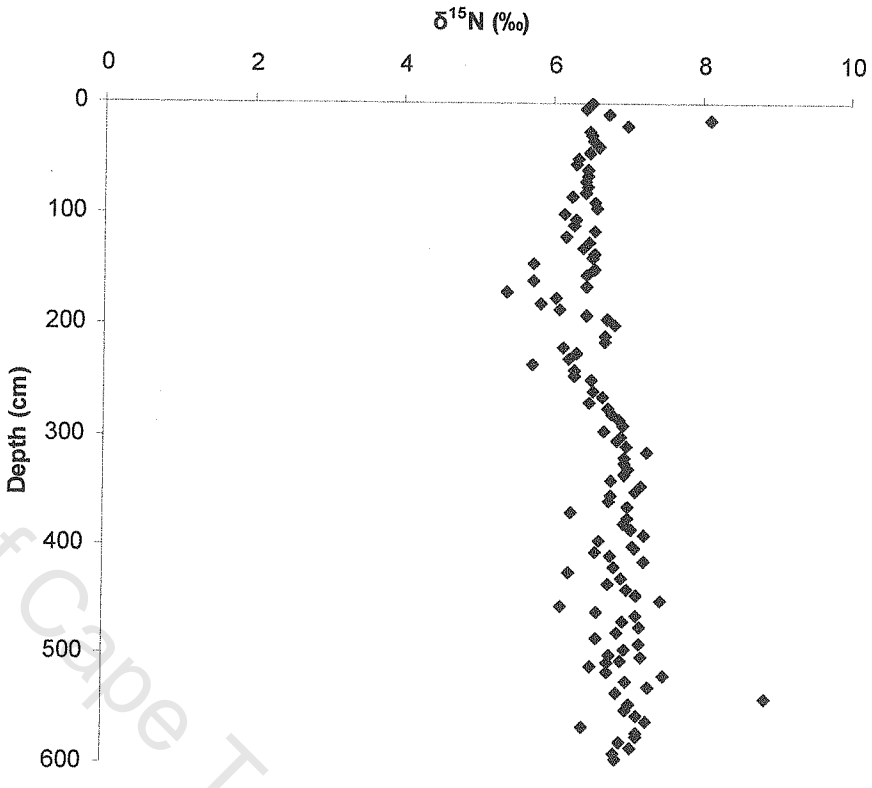


Figure 5.3 Core H7 (off Buffels River) $\delta^{13}C$ against depth. C_4 (-12‰ to -14‰) and C_3 (-26‰ to -28‰) average plant values are shaded. Standard marine value approximately -20‰.



Core H7 (off Buffels River) $\delta^{15}N$ against depth.

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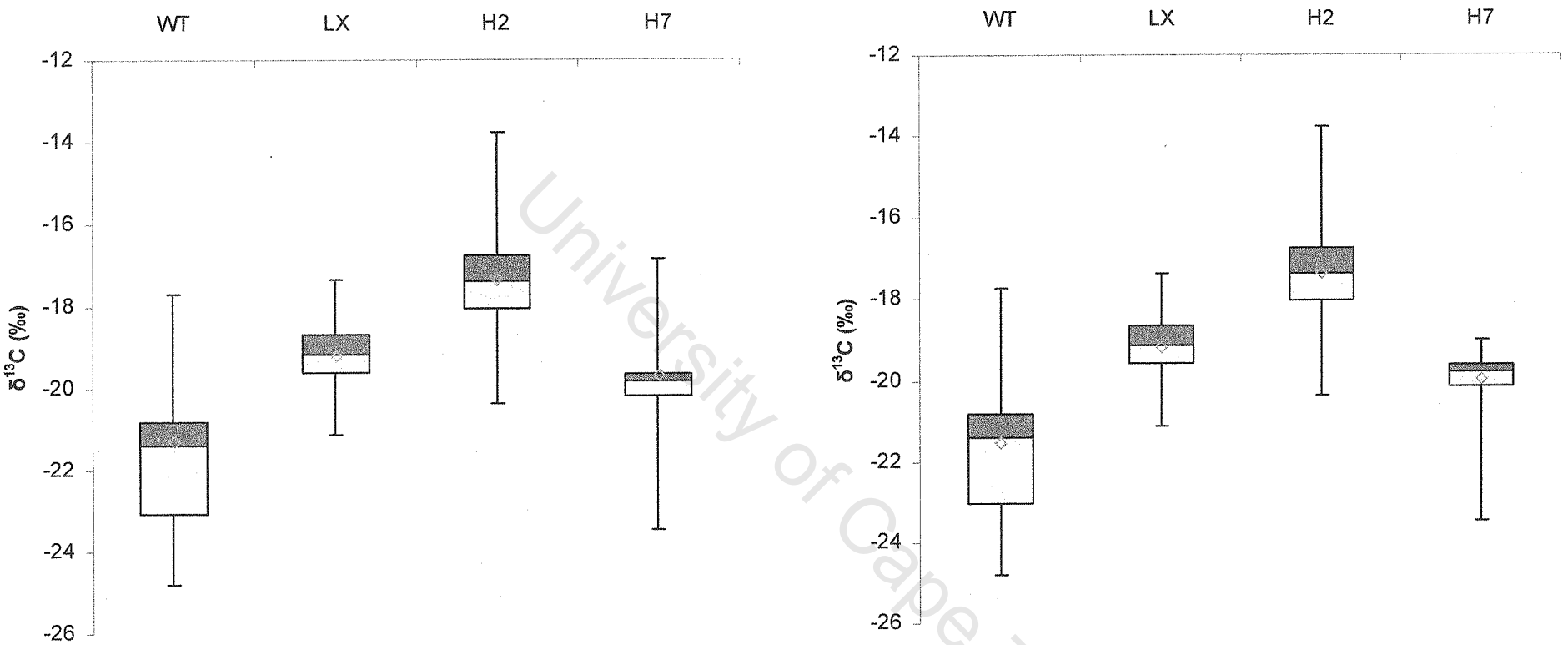

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Figure 5.4 Box and Whisker plots of 4 sites: Orange river-modern (WT), Lower Xobies, H2 and H7 (left). H7 adjusted by removing a single outlier of -16.8‰, to illustrate the significance of the remainder of the data (right).

Depth	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N
0	A30-0	-19.688	7.712493	1.05754	0.262229	3.813454	4.03288
2.5	A30-2.5	-19.5988	5.832623	1.032087	0.233947	4.27447	4.411624
5	A30-A5-N	—	7.261596	—	0.161134	6.206008	—
5	A30-5-N	—	6.540783	—	0.260664	3.83635	—
7.5	A30-7.5	-19.3949	10.62423	1.019303	0.238624	4.190696	4.271589
10	A30-10	-19.6642	6.505822	0.920499	0.207236	4.825423	4.441797
12.5	A30-12.5	-19.7928	—	0.777916	—	—	—
15	A30-15	-20.1607	5.328912	0.99973	0.236247	4.23285	4.231706
17.5	A30-17.5	-20.3826	—	2.067871	—	—	—
20	A30-20	-20.1855	—	1.036459	—	—	—
22.5	A30-22.5	-20.5779	7.036687	1.139984	0.152236	6.568749	7.488265
25	A30-25	-22.1352	10.0459	0.930796	0.152134	6.573169	6.118282
28	A30-28	-21.9068	7.982269	0.84508	0.165902	6.027647	5.093846
	Std Deviation	0.949133	1.705946	0.344703	0.04511	1.153669	1.204976
	Mean	-20.3695	7.487131	1.075206	0.207035	5.054881	5.011249
0	A37-0	-18.8468	5.155511	0.786348	0.199932	5.001703	3.933079
5	A37-5	-18.7925	-1.64524	0.683958	0.134822	7.417177	5.073039
10	A37-10	-18.6532	14.71814	0.650751	0.107269	9.322389	6.066557
15	A37-15	-18.9606	10.98039	1.404549	0.121506	8.230075	11.55955
20	A37-20	-17.3083	4.714191	0.676772	0.14363	6.962355	4.711924
21	A37-21-N	—	2.411212	—	0.167382	5.974358	—
25	A37-25	-17.5615	1.461189	0.714582	0.094658	10.5644	7.549128
27	A37-27	-18.2359	—	1.863308	—	—	—
	Std Deviation	0.661573	5.665411	0.475308	0.036135	1.913745	2.78238
	Mean	-18.337	5.399342	0.96861	0.138457	7.638922	6.482212
0	A49-0	-19.2541	4.778275	0.981217	0.218465	4.577395	4.491417
5	A49-5	-19.4533	10.13534	0.936897	0.191088	5.233182	4.902955
10	A49-10-N	—	2.565312	—	0.176041	5.680486	—
15	A49-15	-19.0839	-1.40018	0.748481	0.113388	8.819289	6.601075
20	A49-20	-17.2696	—	0.713817	—	—	—
25	A49-25	-17.2028	2.785967	0.656556	0.125712	7.954663	5.222684
27	A49-27	-18.5273	7.66523	0.913876	0.132529	7.545544	6.895693
	Std Deviation	1.000831	4.081897	0.135214	0.041818	1.700097	1.064844
	Mean	-18.4652	4.421659	0.825141	0.159537	6.635093	5.622765
Total	Std Deviation	1.286768	3.940517	0.353834	0.050408	1.871813	1.838287
Total	Mean	-19.2765	6.052029	0.981599	0.173773	6.253558	5.636689

Table 5.3 Box cores C/N values for the Namaqualand mudbelt box cores relating to H2, H5 and H7. (C/N ratios between 5 and 9 indicate marine values, C/N ratios larger than 15 indicate terrestrial values. Carbon percentage obtained by mass spectrometer readings not TOC methods).

5.2 Discussion of stable isotope analytical results

The stable isotope results are discussed under six sections; these include inland Richtersveld sites, total organic carbon analysis, the inland Richtersveld sites vs. the mudbelt prodelta, the prodelta vs. the more distal core and a comparison with isotope results radiocarbon age and also with other relevant published sites.

5.2.1 Stable isotope results of inland Richtersveld sites

The carbon isotope values of modern Orange River samples (prefixed by the letters WT) vary between -17.7‰- and 24.8‰. A coarse estimate of the proportion (as a percentage) of C_3 and C_4 vegetation may be determined by calculating the mean $\delta^{13}C$ value as a proportion of the range between mean photosynthetic pathways (taken as -27‰ and -13‰ respectively, referring to vegetation; although for simplicity, the vegetation to soil conversion of ± 1‰ is not used in this calculation). Using this calculation, the river bulk organic sample of $\delta^{13}C$ = -21.5‰ indicates ~60% C_3 and ~40% C_4 content. This is perhaps more depleted in ^{13}C than expected (certainly compared to the -19.3‰ of the Upper Catchment), given the dominance of C_4 grasslands in the ORC. These data point to a greater input from C_3 vegetation in the river material than expected and a wider reflection of the catchment in general. Alternatively, this may be input from C_3 river bank vegetation that is more significant during low river flow levels when C_4-rich upriver flood events are less significant. The impounding of the ORC over the last 40 years has restricted sediment circulation and this might moderate the C_3/ C_4 values. This is because the previously bimodal flood regime has given way to more moderate levels of sediment transport. It is therefore difficult to establish the historical low flood discharge situation using the current sediment circulation model. Although the results may have been moderated by low flow regime at the time, which in turn favours local vegetation, one way of testing this is to examine the values for flood events represented in the OR sites.

The mean $\delta^{13}C$ value of the Jakkalsberg site, JKB O is -22‰ (range -18.4‰ to -24.2‰). Again, these values indicate more C_3 vegetation than predicted (given the C_4 predominance in the catchment) and suggests significant input from localised sediment pulses of riverbank C_3 vegetation and soil rather than from grassland sediment further up in the catchment. The JKB O samples were probably influenced by charcoal derived from tree wood and therefore most likely to be C_3 vegetation. JKB O /L1 at -18.4‰ is the only more positive value.

WT samples have varied nitrogen isotope values, between 0.3‰ and 7.8‰. This spread of $\delta^{15}N$ values is consistent with the range of values published by Heaton (1986) for southern Africa in general, but with higher values appearing in arid and coastal areas. Variation within these $\delta^{15}N$ results suggests variable source materials and indicates a

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number of mechanisms of nitrogen mass balance on the OM. As is typical of arid or sodic environments (Shearer *et al.* 1978, Heaton *et al.* 1986, Sealy *et al.* 1987) it was expected that some $\delta^{15}N$ values would be relatively high and reflect a variety of mechanisms and processes throughout the catchment, although these values would tend to be lower than marine $\delta^{15}N$ values. The JKB samples show more variation between 0.6‰ and 15.8‰ -the upper values being much higher than the normal terrestrial values (Heaton *et al.* 1986). Effects of aridity in the Richtersveld area probably account for these upper values. In low rainfall areas such as the Richtersveld and arid areas, the system is open, has similar values to the Namib coast, which has a mean $\delta^{15}N$ value of 13.5‰.

5.2.2 Inland Richtersveld sites vs. mudbelt data of cores H2

At Lower Xobies, the mean value of carbon stable isotope data is -19.2‰ with values ranging between -17.3‰ and -21.1‰. An estimate of the average representative amount of C_3/C_4 vegetation using the average value of -19.2‰ for Lower Xobies is calculated as being 55% C_4 (45% C_3), which is very similar to the Upper Catchment, but perhaps more C_3 than expected. The majority of mudbelt sediment is predicted to originate from the upper to middle catchment area (Compton and Maake 2007, Mabote *et al* 1997, Rogers 1977a), where C_4 grassland dominates. From this, a mean value of C_4 plant values of around -13‰ can be assumed for this vegetation as C_4 grassland commonly ranges between -12‰ and -14‰ in southern Africa (Codron *et al.* 2005a). The $\delta^{13}C$ isotopic values at Lower Xobies, however are possibly more negative ("depleted" in ^{13}C) than expected. This may be indicative of an influx of predominantly C_3 sediment load (see below) or it may instead refer to the different type of material that is being laid down here in this dry environment (compared to that which is deposited in the mudbelt).

The inland region sampled (Richtersveld) is largely arid and it is important to be aware of what mechanisms, events and localities might be represented in the sediment deposited there. It was considered that the Lower Xobies stable carbon isotope values were representative of the estimate of how much C_4 is being contributed to the low flow discharge river sediment in that section of the Orange River and use these values to compare it with other sites of interest. Again, the relative proportion of C_3 or C_4 vegetation can be estimated for H2 and H7 respectively and although CAM input is considered limited, it would overlap with these contributions. The overall estimate for H2 is ~70% C_4 (~30% C_3) and shows a larger than expected input from the C_4–rich

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catchment while H7 is 52.1% C_4 (47.9% C_3), although this site is still more C_3-rich than H2. Lower Xobies and WT are surprisingly similar to H7 and are both C_3 -rich. Further, Lower Xobies is more variable than H7, which has a much narrower range within which values vary. However, the mean carbon isotopic values of these two sites differ; the mean value of H7 is -19.7‰ and -19.2‰ for Lower Xobies, with H7 being slightly more tightly correlated around the mean value, yet having a larger range between -23.5‰ and -14.1‰. This can be contrasted with the Lower Xobies range of -17.3‰ and -21.1‰. The estimated % C_3 and % C_4 based on mean $\delta^{13}C$ values (Table 5.4, Figures 5.1, 5.3 and Figure 5.5) show some indication of greater C_4 influence in H2 at the surface and at various depths within the core, and may suggest that flood events have been C_4-dominated at times, particularly in near-surface sediment. There is more C_4 content represented here in the prodelta (H2) than is evident in Lower Xobies and modern bedload proportions of WT (modern Orange River) values reflect a more C_3-rich source of vegetation than anticipated. H2, although composed of an admixture of terrestrial and marine organic carbon, is probably a more complete record of flood events compared with Lower Xobies; this is apparent in the age of the latter and the placing of the high flood threshold deposit in the floodplain. It would also be expected that the prodelta, H2, deposits would show a higher resolution record of Orange River sediment compared to the more distal deposit, H7. Lower Xobies may not be representative of the general flooding picture, but instead may be simply a snapshot in time (Zawada 1996) and be governed by additional factors such as (sediment) grain size vs. clay preservation and the environment. Unlike Lower Xobies, H2 is not representative of a threshold flood event and flood material is usually deposited in the mudbelt regardless of the severity of the flood event, whereas Lower Xobies floods would have to breach a particular level and exceed a threshold to be recorded in this area of the Richtersveld. It is possible that floods from higher up in the catchment, where C_4 vegetation is dominant, are represented in

	$\delta^{13}C$ (mean)	% C_3	% C_4
WT	-21.5	45	55
LX	-19.2	45	55
H2	-17.4	30	70

Table 5.4 Estimated %C_3 and C_4 in mean $\delta^{13}C$ values for WT, LX and H2 (rounded off to the nearest unit of 5).

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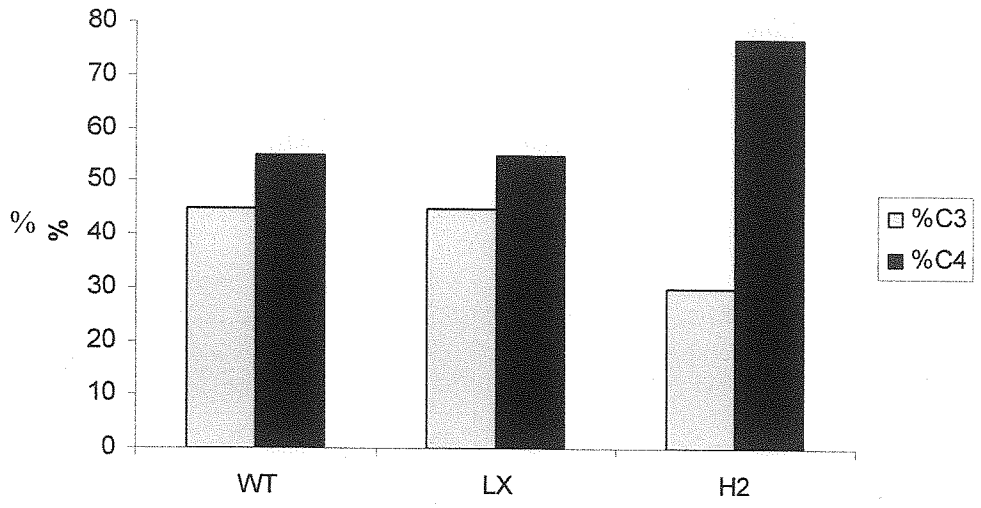

Figure 5.5 Estimated percentage C_3 and C_4 vegetation represented in mean values at three key sites: Orange River (WT), Lower Xobies (LX) and core H2 in the mudbelt prodelta. Note: marine organic matter component of bulk organic matter, which is predominantly C_3-rich, overlaps with terrestrial C_3 and it is for this reason that H7 is omitted.

Lower Xobies and, according to Zawada (1996), occurred in Period 1-4 (up to 5 500 years BP). This contrasts with the mean value of -19.2‰ with WT of -21.5‰ and JKB of -21.9‰ (both of the latter are more C_3-enriched). Another possible explanation for this unexpected data might be found in the type and volume of clay that is being deposited in either Lower Xobies or H2 sites. Further it is important to consider the marine-terrestrial admixture, which would be more marine with less terrestrial input (H7) or during periods of low terrestrial input.

One of the features of the HODSA cores is that the isotope values are more tightly clustered (more isotopically homeogeneous) than the inland flood deposits. When analysed separately from the Richtersveld material, the prodeltaic mudbelt sediment is consistent with strong C_4 influence. This accords with expectations that H2 would reflect more of the C_4-rich grassland interior in the ORC. However, when compared with the slack-water deposit of Lower Xobies and H7, the picture is not as clear as there is currently far more C_3 (or CAM input) at Lower Xobies than expected. At first this appears not to be as representative of the bigger picture as originally thought although the mean value is closely aligned with the average of -19.3‰. This is however confused by the JKB and WT values (which are more C_4 in character). It is surprising that H2 is more positive than the inland sites and this suggests a likely terrestrial input. So, where is the

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C_4 organic matter coming from? Clearly, more C_4-rich sediment is being deposited in the prodelta than has been deposited at the Richtersveld Lower Xobies site although it is not possible to fully resolve this question. This could be due to one or more of the following reasons:

- Localised influence: Perhaps the influence of the ORM estuarine salt marsh vegetation and algae which has become a less important contributor and has had a significant effect on bulk organic carbon in the mudbelt, due to its recently reduced size. The estuarine salt marsh at the ORM was extensive until recently, but has become severely degraded and reduced in size within the last two decades (Heath 2001, Anderson 2006). Although saltmarsh isotopic values vary widely, decomposition is rapid in bulk organic sediment and their contribution difficult to quantify due to overlap with other sources of organic carbon (Lamb *et al.* 2006) and the contribution of algae in salt marsh environments may potentially be affecting some pulses of sediment. Without additional localised research and a detailed palaeoenvironmental study of ORM history, it is impossible to determine the contribution and isotopic signature of the previous salt marsh vegetation. However, saline tolerant plants tend towards C_4 or CAM (Lamb *et al.* 2006). These isotope values would overlap with those inland values thereby defying attempts to identify them separately from others. Bulk marine algal $\delta^{13}C$ values tend to fall between -20‰ to -10‰ (Chikaraishi 2006 after Deines 1980).

- Different floods represent different sediments in the Richtersveld and on the basis of Orange River (WT) data and the JKB sites (which are more C_3 in character), do not all appear in the mudbelt.

- Preferential adsorption of $\delta^{13}C$ isotopes by the volume and type of clay in the deposit: Differing clay types are preserved at Lower Xobies (20% Plagioclase, 19% Smectite, 3% Illite) and in the mudbelt (H2: 24% Smectite, 33% Illite, 18% Vermiculite)(Appendix B, after Zawada 1996 and Mabote 1997); further, the finer grained mudbelt contains high levels of clay, whereas clay is under-represented in the coarse grained Lower Xobies. This difference in the type of clays being retained, might promote a difference in the adsorption potential of $\delta^{13}C$ isotopes by the volume and type of clay at the two sites. This may mean that comparison

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between the $\delta^{13}C$ isotopes at the mouth and that of the Lower Xobies site do not provide an accurate reflection.

The $\delta^{15}N$ isotopic values of the lower Xobies slack-water deposit and Orange River (WT) do not exhibit any particular trend and a wide range of values is evident. Lower Xobies values average 4.6‰ and vary broadly between 0.47‰ and 9.4‰. This covers the range of $\delta^{15}N$ values identified by Heaton (1987), of which the upper limit is probably related to the arid nature of the site. There is no direct $\delta^{15}N$ correlation of values between the mudbelt core samples and the Lower Xobies slack-water deposit, but the H7 samples in the mudbelt material include much of the upper limit of the values in Lower Xobies. H2 samples show this pattern to a lesser extent. This is consistent with H2 being more terrestrial in nature than H7. The slightly lower $\delta^{15}N$ values in H2 (compared to H7) are likely to be related to terrestrial sediment, but this is poorly understood and no $\delta^{15}N$ literature exists for local vegetation Succulent Karoo. Low values could also suggest intense upwelling, especially in the excursion at the base of H2. Both H2 and H7 isotopic data are markedly different from the Lower Xobies data in that the values are more tightly bounded.

5.2.3 Isotopic comparison of mudbelt prodelta (H2) and distal mudbelt H7

The Orange River is generally believed to be the primary source of mudbelt material. However, given the proximity of H2 to the ORM, compared with H7 further south where there is more marine influence, a different isotopic signature was anticipated for these two parts of the mudbelt (Mabote 1997, Rogers 1977a,b). Further, it is important to consider that the age of core H2 is equivalent to the age of the top portion of H7.

In H7, (Figure 5.3), the $\delta^{13}C$ values cluster around -19.7‰, which is near the standard marine signature (of between -20‰ and -21‰). A lthough their median value tends towards 20‰, these marine values vary extensively and there is opportunity for overlap from appropriate proportions of C_3 and C_4 (and CAM) of inland OM with the mean C_3-rich marine isotope values. It is more likely that the OM source is predominantly marine in H7, given that the values for the core in this distal part of the mudbelt are predominantly correlated within a narrow band of marine values. The $\delta^{13}C$ values in H2 average -17.4‰, covering a range between about -14.5‰ and -19‰, with some outliers at -14.5‰ and -20.4‰. The H2 core $\delta^{13}C$ values indicate a generally positive shift of +2‰ to +3‰ compared to the values in H7 (Figure 5.3). This shift is consistent with the

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$\delta^{13}C$ values of a core expected to be more representative of the Orange River drainage basin, dominated by C_4 enriched grassland (which usually average around -13‰) and indeed are very similar in value to the LX values, although the low discharge volume modern Orange River (WT) values and the JKB values, which are more C_3 in character. Unfortunately no values are available to compare with the Buffels River.

H2 was indeed expected to yield more positive stable carbon isotope values than the more marine site of H7 and the mean value of -17.4‰ determined for sediments of core H2, contrasted well within those of H7 which had appeared to be more $\delta^{13}C$ depleted at around -19.7‰, indicative of a strong marine signal (-20‰). These values are evidently more robust than the initial results published in Meadows *et al.* (1997). Figure 5.6, a composite graph of H2 and H7 $\delta^{13}C$ values, clearly demonstrates that H2 and H7 are isotopically distinct and lends support to the assertion that the OM of H2 is more terrestrial while that of H7 is more marine. However, this figure does not illustrate the significant age difference between H2 and H7 which should be considered. From the base of the core at 600 cm to a depth of 500 cm, there is a positive isotopic excursion where the mean value changes from about -20‰ at 600 cm depth to about -17.1‰ at depths of 500 cm to the surface. This excursion of 2.9‰ at the base of H2 appears to infer an increasingly C_4-enriched terrestrial nature between the base of the core, 600 cm and 500 cm, which suggests that the delta prograded at this level to where it is currently situated. This is in keeping with global sea level fluctuation and rise since the LGM.

The mean nitrogen isotope values in H2 (Figure 5.7), between the base of the core at a depth of about 600 cm and a depth of about 500 cm, decreases from a mean of 6.5‰ by 0.8‰ to around 5.7‰, where it remains the mean value for the sediment through to the core top. This excursion coincides with that of the carbon isotope signature in the same core and appears to indicate the same event (prograding delta mentioned above), although

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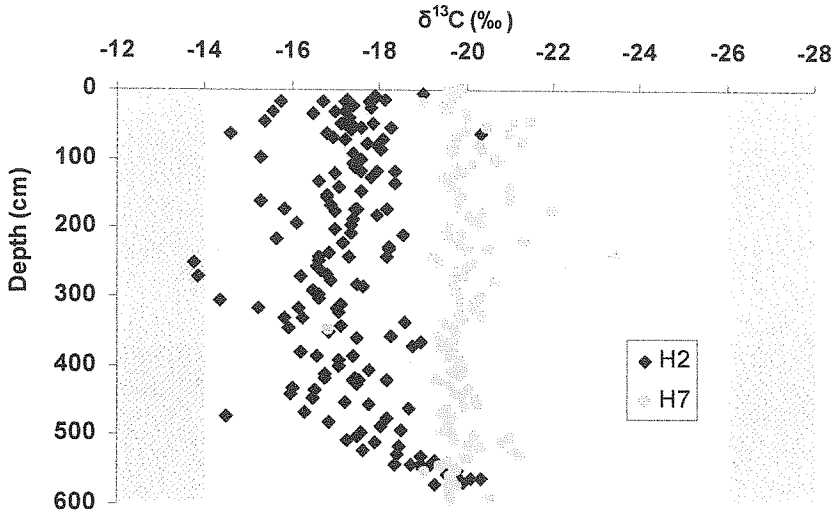

Figure 5.6 Core H2 comparison of prodelta (off Orange River Mouth) and the distal core H7 $\delta^{13}C$ against depth. [C_4 (-12‰ to -14‰) and C_3 (-26‰ to -28‰) average plant values shaded. Note: relative age of core H7 (older) compared with H2 (younger),].

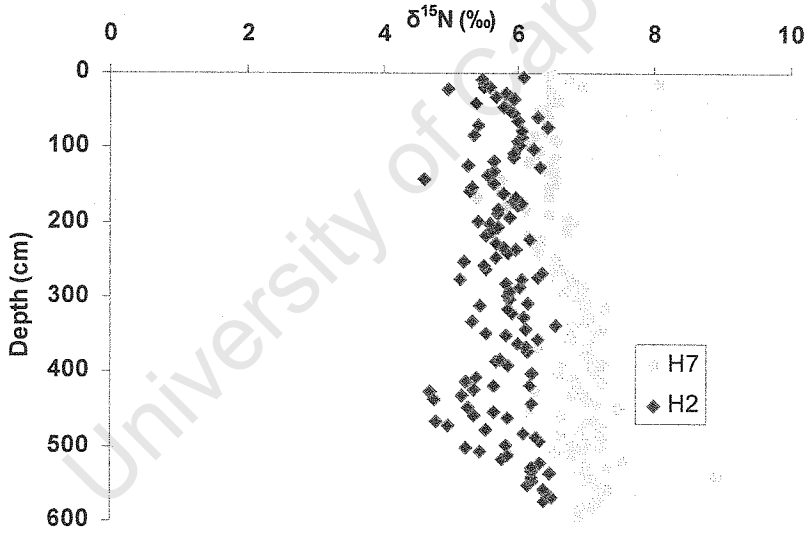

Figure 5.7 Core H2 comparison of prodelta (off Orange River Mouth) and the distal core H7 $\delta^{15}N$ against depth. [Note: H7 is older compared to H2].

using a different biotic marker. Two scenarios may explain the $\delta^{13}C$ excursion of values towards the base of H2: either a stronger marine signal is apparent (prograding delta, indicated by increased C_3 influence or sea level change) or this may suggest a more C_3-rich terrestrial influence. The more enriched $\delta^{15}N$ sediment on the other hand is not as clearly interpreted, but may suggest greater proportions of marine sediment input or evidence of greater productivity due to strong upwelling, although these values also

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include some terrestrial values, thus pointing to continued, less important inland contributions. In general, H2 is more terrestrial and both $\delta^{15}N$ and $\delta^{13}C$ lend support to this assertion. The $\delta^{15}N$ values vary more widely in core H2 than in core H7 but compared to H7, H2 is understandably lower in $\delta^{15}N$ values as it is situated close to the source of terrestrial organic matter at the ORM. In H7, the $\delta^{15}N$ isotopic signature indicates a marked change between 300 cm and 200 cm, where there is a steady excursion of values from 7‰ to 6.5‰, unlike in H2, where values are more consistent and tightly correlated, with a defined excursion of values. This marked $\delta^{15}N$ change in H7 does not coincide with a similar excursion in carbon isotopic values, but the values are more tightly constrained around the mean value 7.2‰ in a range between 5.2‰ and 7.5‰. Compared to H2, the $\delta^{13}C$ values of H7 show a more regional excursion at both the near surface and base of the core, suggesting increased strength of upwelling and/or increased fluvial input of OM. A change in nitrogen values appear to be offset from the near-surface excursion, but no change is evident at the base of the core; further interpretation is possibly using inverse nitrogen (as percentage, discussed later in this chapter).

The $\delta^{15}N$ of both H2 and H7 (Figure 5.7) are isotopically distinct and seem to indicate that different factors and mechanisms are involved at these two sites. Compared with H2, the slightly elevated $\delta^{15}N$ values in H7 are indeed consistent with a more marine influence in the distal mudbelt. Low value $\delta^{15}N$ sediment pulses in H7 occur at depths of 455 cm to 370 cm, 235 cm to 170 cm and 185 cm to 145 cm and could suggest a more terrestrial input of organic matter from the infrequently open Buffels River or stronger input from the Orange River (less likely).

TOC percentage carbon analysis was conducted on the samples from the gravity cores although only LOI values were available for the box core samples. The C/N values of box cores A49, A37 and A30, relating to cores H2, H5 and H7 respectively, are tabulated in Table 5.3 and also evident in the gravity cores (Figure 5.8; Table E4 and Table E5 of Appendix E). These C/N (weight-as-percentage) ratios of organic carbon (LOI) to total nitrogen values largely fall within the expected marine values of 5 and 9, with only a few exceptions extending to 11. The mean value of H2 (A49) is 8.0 and for H7 (A30) is 6.7. These C/N values are similar to those obtained from sediments in the inland sample sites in that they are within a variable range below 15 and the mudbelt sediment closer to the ORM tends towards terrestrial values, but is situated between those of the marine and terrestrial range, suggesting a mixed source of OM. The mean values do however also fall

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largely within the marine algal expected values of 5 and 9 and slightly increased values in the more distal mudbelt sediments, which would be expected in a more marine environment. This is contrasted with the box cores C/N ratios which average value of 5.6 and are on the lower end of the ratios in the gravity cores. However, there is one exception to this trend in the modern surface sample (A49-0, which relates to the surface of H2) that is strongly marine. This marine value is not unexpected, given the location of the mudbelt. The most southerly sites, H7 and A-37, contain predominantly marine to slightly 'sub'-marine (indicating some terrestrial input) C/N values. One sample in A-37 indicates values closer to the terrestrial range and this might suggest terrestrial input from the Buffels River which is consistent with C/N and inverse nitrogen values. A30, which relates to core H5, is situated further away from the mouth, yet still within the prodelta and has a predictably mixed signal of values tending towards terrestrial values with some marine values evident.

The similarity of C/N of sediments from the inland and parts of the mudbelt due to C_3 overlap, make it impossible to separate the marine and terrestrial signature on C/N ratios alone. A clearer indicator of the influence of terrestrial (versus marine) sediment input into the mudbelt, illustrated later in this chapter, may be obtained by plotting the inverse of the percentage nitrogen against the $\delta^{15}N$ value (Wefer *et al.* 2003).

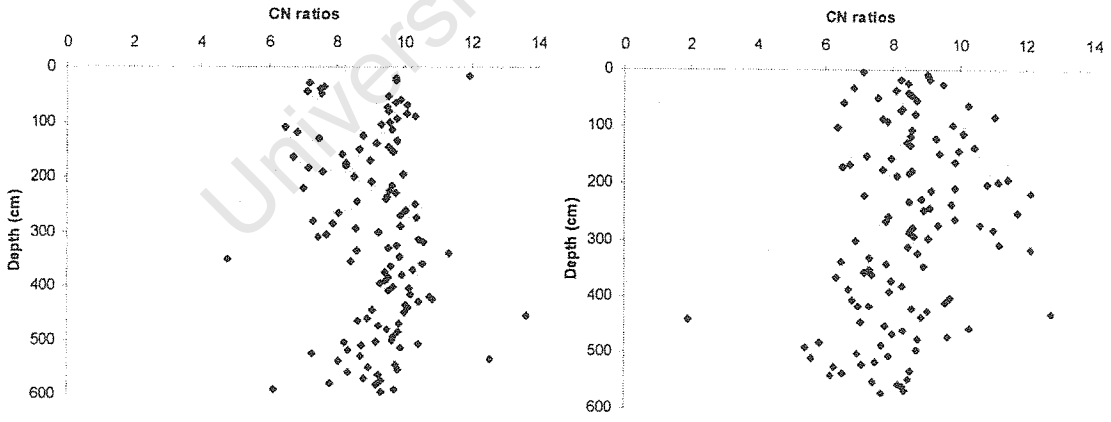

Figure 5.8 C/N ratios against depth in cores H2 (left) and H7 (right).

This data for H2 and H7 is plotted in Figure 5.9 and Figure 5.10 and the inverse of nitrogen is plotted against depth for the same cores in Figure 5.11 and Figure 5.12. In Figure 5.9, H2 is characterised by a moderately indirect relationship ($R^2 = 0.305$), showing a predominantly terrestrial influence, but a more marine influence is noticeable

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towards the core base, where the $\delta^{15}N$ values approximate 6‰ and inverse values of nitrogen approximate < 4 (Table E5). Despite the R^2 value being close to zero for the entire H7 dataset a direct relationship can be distinguished in a subset of the H7 data. This subset of data is characterised by higher 1/N values, which can be attributed to lower nitrogen content (compared to the remainder of the data set). These lower nitrogen values in the data subset tend towards terrestrial vegetation values, which point to a generally marine input in the distal core (H7) with a smaller contribution by terrestrial sources of organic matter (within the more dominating marine component) indicated by the subset mentioned. Taking this a step further, the values in this subset generally are 1/N values ≥ 2.5. From Figure 5.12, these particularly marine values are shown to occur at depths of 525 cm, 530 cm, 525 cm, 505 cm, 60 cm to 50 cm and 40 cm to 5 cm. The indirect relationship of values in H2 suggests a terrigenous function (except for the depth 600 cm to 525 cm where the sediment appears to indicate marine values in Figure 5.11), whereas the direct relationship in H7 indicates a generally marine signal with a minor secondary non-marine influence discerned in some of the data. This suggests the marine sediment is more significant in the distal mudbelt, but the data provides evidence of input from the Orange River or the more localised infrequently flowing Buffels River. This is further discussed in the synthesis chapter 6, in relation to other evidence.

Box and Whisker plots of $\delta^{13}C$ values for WT, Lower Xobies (LX), H2 and H7 are shown in Figure 5.4. These plots illustrate the spread of values of these sites and how they compare. The Orange River sediment (WT) is clearly shown to be more varied with a wider range of values than LX, which is expected given the high flood threshold required for the LX deposits and therefore, presumably a more restricted sediment source. WT sediments, estimated to be 40.7% C_4, have slightly more C_3-rich values compared to LX sediments, estimated to be 55.7% C_4. WT, LX and H7 are shown to have overlapping ranges, but clearly have different mean and median values. H2 is the most C_4-rich with an estimated 68.6% C_4, compared with H7, which is 52.1% C_4. Despite some variation in some $\delta^{13}C$ values in H7, a significant portion (50%) of the values are more closely clustered around a value of -20‰ than at the other sites; this is illustrated as a much narrower range compared to those of LX, H2 and WT, with WT being the largest and most weakly correlated. With the removal of a single outlier value of -16.8‰ in H7, it is possible to better illustrate the narrower range of the remainder of the H7 $\delta^{13}C$ dataset in Figure 5.2 and provides a more useful comparison. The standard deviation calculated for

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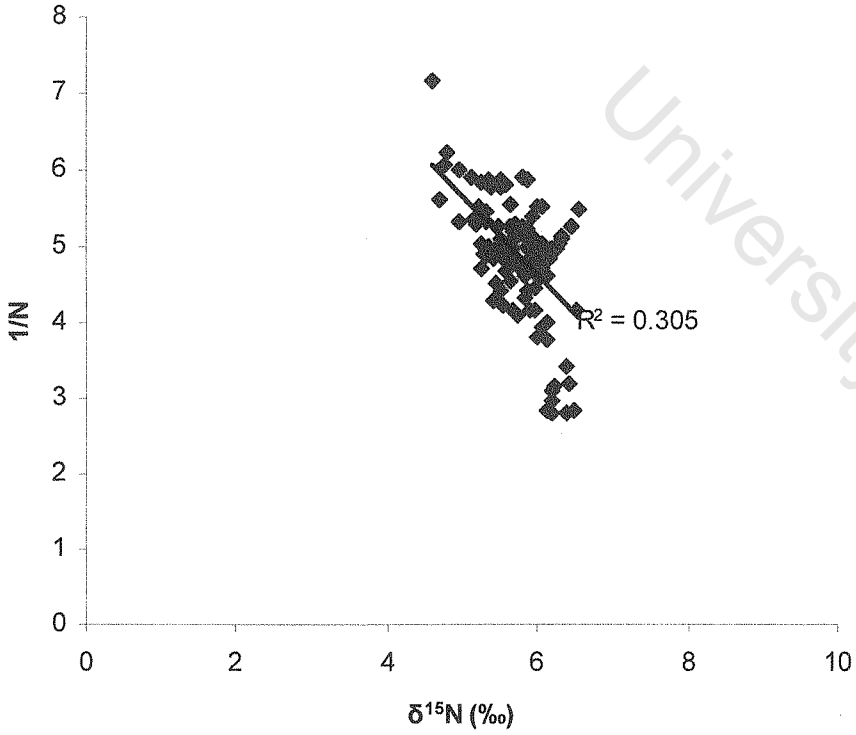

Figure 5.9 H2: 1/N vs. $\delta^{15}N$ ($R^2 = 0.305$).

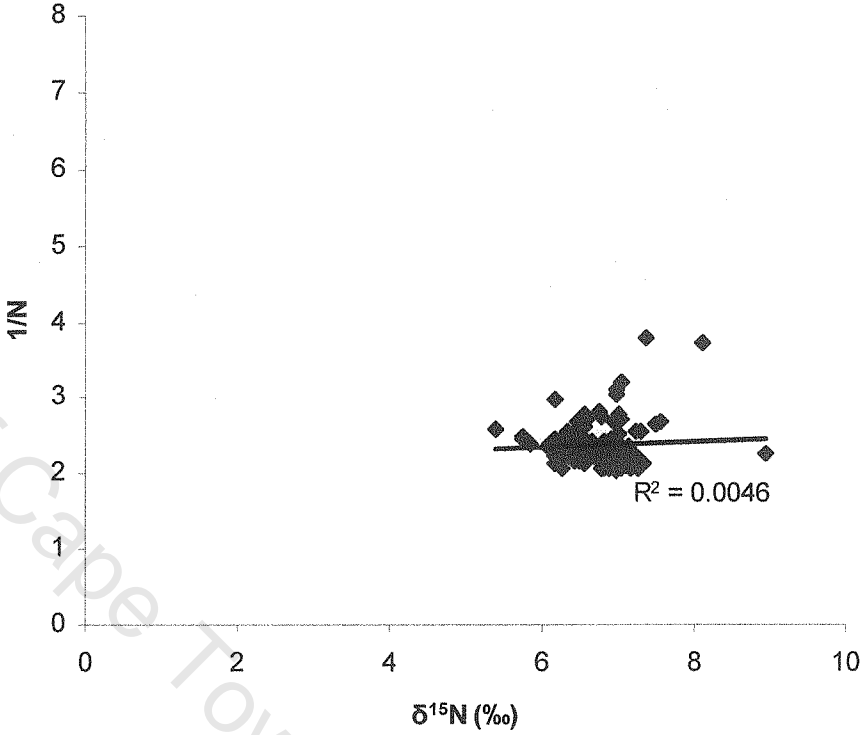

Figure 5.10 H7: 1/N vs. $\delta^{15}N$ ($R^2 = 0.0046$).

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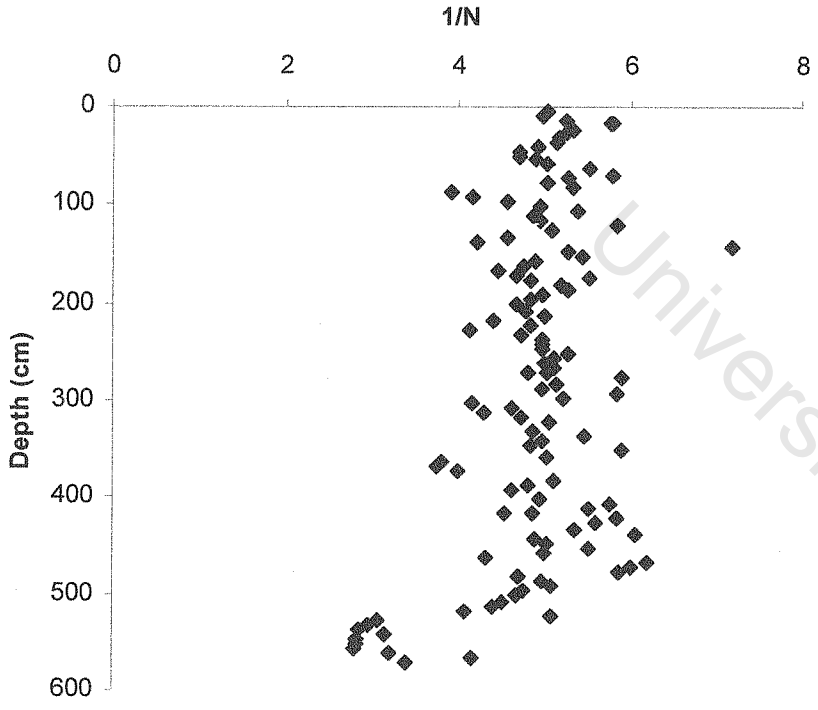

Figure 5.11 1/N against depth in core H2, showing the spread of values responsible for particularly marine and non-marine portions of sediment (noted in previous figure). This appears to suggest that non-marine values are found near the surface sediment (less than 100 cm and 600 cm to 400 cm).

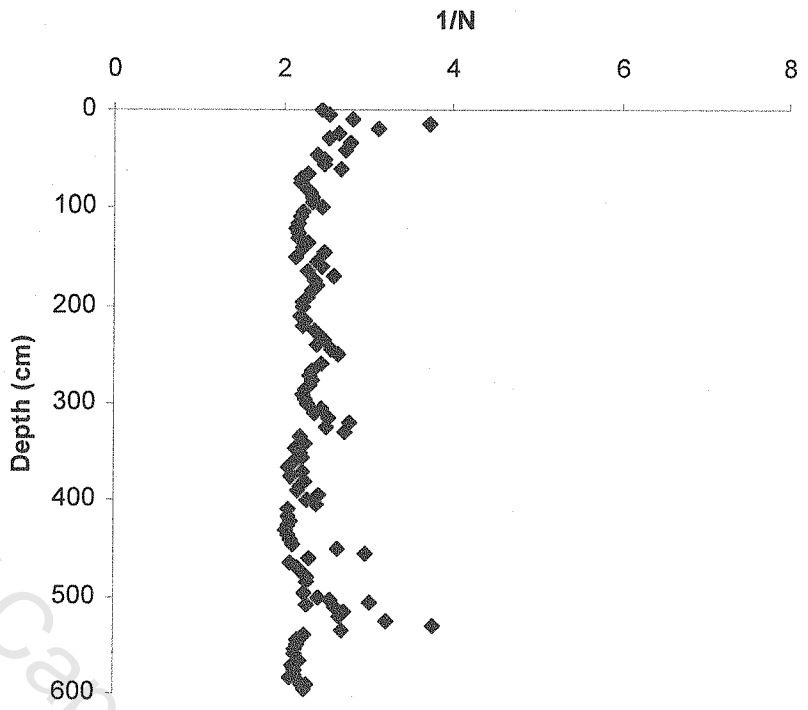

Figure 5.12 1/N against depth in core H7, showing some indication of the excursion at the base of the core from 600 cm to 500 cm.

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the $\delta^{13}C$ values at these four sites provides additional support to show how closely clustered the values are in H7 (with a standard deviation of 0.7) compared with the other sites LX (0.9), H2 (1.2) and WT (2.1).

Although the radiocarbon age is now better understood in terms of the true age of the organic fraction deposited (for instance the modern mudbelt surface has a bulk radiocarbon age of at least 520 years) and not necessarily the depositional event, it is unfortunately not possible to compare extrapolated dates with the isotopic values.

5.2.4 Comparison with additional relevant sites

The $\delta^{13}C$ values of the neighbouring ODP 1085 site (Twitchell *et al.* 2002) in the Cape Basin are slightly more depleted than in the mudbelt and range between -20‰ and -24‰ showing less terrestrial influence at this distance from the ORM. The mid-Miocene to mid-Pliocene core originates from directly within a zone of high productivity in the southern part of the Benguela upwelling, where the atomic C/N values are predictably higher (14 to 18) than in the younger sediments of the inner shelf, which is physically offset from the upwelling and has a stronger terrestrial fluvial influence. The Benguela upwelling is associated with high nutrient loadings (Shannon 1985). There are no $\delta^{15}N$ values in this ODP 1085 record, but some values are available in the Holmes *et al.* (1998) record and are useful for comparison with the Orange River Mudbelt.

The Holmes *et al.* (1998) study of a transect ("D") (Figure 5.13) off the Orange River is useful in terms of its $\delta^{15}N$ values but does not provide late Holocene terrestrial information from the Orange River, probably due to the distance from the ORM, with only two samples occurring on the outer continental shelf. This might be because the samples do not capture the depleted terrestrial values of the ORM that the H2 values do with a mean value of -17.4‰. Instead, the values of the "D" transect reflect something of the more marine H7 mudbelt $\delta^{13}C$ character (mean value -19.7‰, range: -16.8‰ and -21.5‰), with values for the transect ranging between -18.97‰ and -20.39‰ and mean of -19.6‰. Indeed, the authors assert that very little terrestrial material is being deposited in this area (Holmes *et al.* 1998, after Emery *et al.* 1973), although compared to the mudbelt and source sediment, this appears inaccurate. Transect D is situated in a line originating in the outer shelf within the upwelling zone, where it and the other study transects B-D to the north indicating some spatial variation. The $\delta^{15}N$ values tend to be depleted further away from the Orange River Mouth (from 5.9‰ to 11‰). The other

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transects display typically marine $\delta^{13}C$ values around -20‰ and therefore are more characteristic of H7 than of H2. [Transect A mean value is -19.7‰ (-19.21‰ to -20.16‰), B mean is -19.8‰ (-19.16‰ to -20.18‰), C mean is -19.6‰ (-18.97‰ to -20.19‰) and D mean is -19.6‰ (-18.97‰ to -20.39‰).

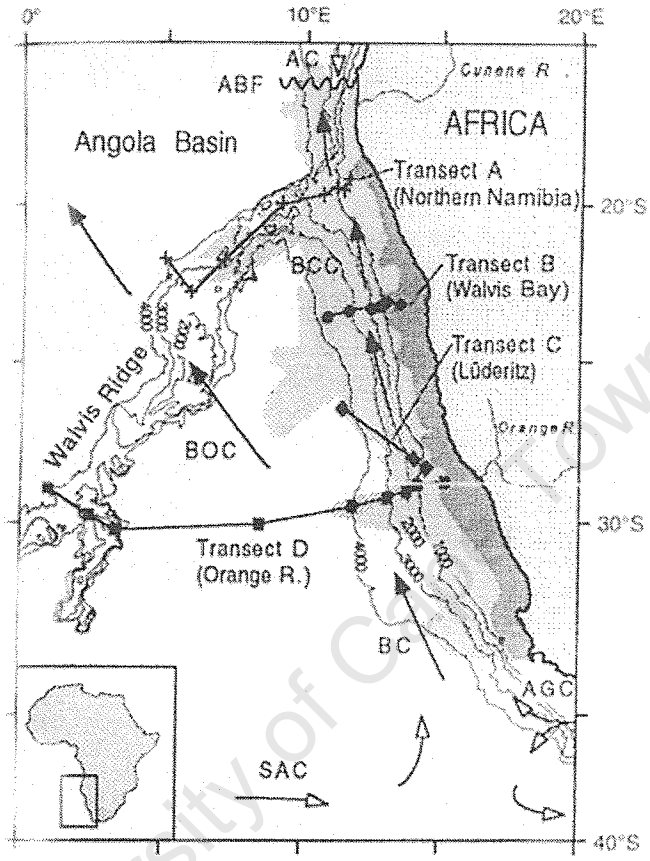

Figure 5.13 Map of study area off Northern Namibia (Transect A - crosses), Walvis Bay (Transect B - circles), Kyderutz (C- diamonds) and Orange River (D- squares) (from Holmes *et al.* 1998).

The Holmes *et al.* (1996) study of the Angola Basin included three transects: the Northern (Zaire fan), central and southern Angola Basin, along with two Zaire estuary samples. In the Zaire fan (to the north) and southern Angola, depleted $\delta^{15}N$ values were found near the coast and enriched $\delta^{15}N$ values are found with increased distance from the coast. Lower values (1‰ depleted) in the south and central sites are related to the effect of convergence of nutrient rich cold upwelling, warm equatorial waters and the strong Namibian upwelling zone. C/N values are highest close to the coast (12.5) and depleted in deep nitrogen-rich water (6.4) as would be expected in terrestrial surveys. The $\delta^{15}N$ values of the Angola basin are similar to the deep sea marine OM for oxygenated water which is between 5.0‰ and 6.0‰ (Holmes *et al.* 1996, after Wada *et al.* 1975). The

higher $\delta^{15}N$ values of the mid (central) Angola Basin (offset from direct terrestrial input) and the Zaire estuary are strongly contrasted with the tendency for the near–shore to be depleted in $\delta^{15}N$ and to be more enriched further away from the coast (Wada *et al.* 1987). This can be explained by diagenetic effects and depleted $\delta^{15}N$ terrestrial values. Recent work by Holmes *et al.* (2003) shows that $\delta^{15}N$ values in the South Atlantic are related to the organic carbon content of the sediment and upwelling, which supports the more simplistic view in this research of not taking surface water nitrate concentration into account (Wefer *et al.* 2003). Values on the Zaire fan closest to the shore are similar to values in H2 (average 5.8‰), whereas values further along the transect are similar to H7 (average 6.7‰), which parallels the terrestrial OM prodelta and more distal parts within the Orange River Mudbelt. The $\delta^{13}C$ values off the Zaire estuary are reflective of the C_3 inland vegetation, although C_3-rich values of middle and south Angola show more marine values, not necessarily inland terrestrial values, and thus are more depleted than H7 values. For further detail in this regard refer Holmes *et al.* (1996) and Holmes *et al.* (2003).

The Holmes *et al.* (1996) Angola basin study shows that C/N values are higher near shore, due to higher terrestrial input and this is also true within the ORM and is detected in the reduction in values further away from the Orange River mouth (Figure 5.8). This trend of graduated $\delta^{13}C$ and C/N values with distance between fluvial to marine sediment is widely applicable (Lamb *et al.* 2006).

The Congo deep sea fan (GeoB 1008) was investigated by Schneider *et al.* (1994, 1997) in a study of its terrigenous OM situated North of the Orange River in the equatorial eastern Atlantic some 50 km off the Congo River and just off a very narrow continental shelf and canyon. The region is more humid than the lower reaches of the Orange River and, being tropical rainforest and monsoon dominated, the catchment vegetation is C_3-rich and the terrigenous organic signal is correlated with climate (precessional insolation changes) and river fluctuations (Schneider *et al.* 1994, 1997); this correlation was also confirmed ODP site 1075 in the Congo deep sea fan by Holtvoeth (2001) with a positive correlation between lignin-derived phenols and bulk organic $\delta^{13}C$ of the fan sediment, where terrigenous OM is dominant.

The Holtvoeth *et al.* (2005) study of the Congo and Niger fans shows C/N ratios and $\delta^{13}C$ sediment values are well correlated with soil OM from their respective rivers. Compared

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to the Congo fan, the Niger fan has lower quantities of organic carbon, higher and more wide ranging C/N values and $\delta^{13}C$ values of up to -17‰. These values are related to nitrogen poor and ^{13}C enriched plants (significant contribution from C_3 vegetation) in the Niger Catchment. This is ascribed to less humification, less mature soils occurring in the catchment or more soil organic matter (SOM) present here than in the Congo. The Congo deep sea fan studied by Holtvoeth *et al.* (2003 and 2005) and others, however at first appears similar in character to H7 in that it is low in organic carbon, is dominated by C_3 plants (tropical rainforest) and has similar $\delta^{13}C$ and C/N values and is by virtue of its geographical proximity, of some interest for contrasting with the mudbelt data. The major differences of the inland vegetation of the Congo and the Orange River Catchments mean that direct comparison is not useful. However, it is of interest that the Congo River mean $\delta^{13}C$ values -20.8‰ (-22.3‰ to -19.9‰ range) are very similar compared with H7, which has a mean value of -19.7‰ (-16.8‰ to -23.5‰ range).

Understanding past changes in the $\delta^{13}C$ and $\delta^{15}N$ values of the mudbelt and the Orange River may assist in understanding major anthropogenic changes associated with nutrients in that they have tremendous potential for altering the OM within marine deposits (Hu *et al.* 2006, after Owen and Lee 2004). Given the above, any terrestrial palaeoenvironmental changes should potentially be represented more clearly by sediments from core H2 in the mudbelt prodelta. This appears to be a more informative record of the ORC than any other previously investigated inland palaeoenvironmental proxies for the period represented (up to 900 years BP at the earliest radiocarbon age) by H2 in the prodelta and more distally, by H7 with a minimum radiocarbon age of 3900 years BP. H2 is comprised of much younger material than H7 and is roughly equivalent in age to only the top third of H7, if we are to accept the ages (chapter 4). Therefore the data set of H2 can be effectively compared with only the top third of the mudbelt represented by H7 in terms of bulk organic radiocarbon age.

Given the mixed dynamics and pulses of sediment sourced from various parts of the catchment, it is difficult to interpret the data using the isotope values alone but, despite these limitations, some correlation and significance can be drawn from this comparison and instead these should be interpreted in tandem with other proxy data, such as the improved chronology (ch4) and pollen spectra (ch6).

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5.3 Summary

The aim of using stable carbon isotope analysis of the mudbelt material was to establish whether the two cores, H2 and H7 reflect the predominant C_3/C_4 plant signature from the terrestrial environment and, if possible, distinguish this fluvial signature from the standard marine values of -20‰. The cores H2 and H7 were confirmed as reflecting some variations in isotopic values, indicating that the OM is derived from both terrestrial and marine sources. It proves too problematic to attempt to separate the fluvial from the marine signature given the overlap of terrestrial and marine values in this region, but some observations are possible, particularly using a combination of $\delta^{15}N$ and $\delta^{13}C$ values, C/N ratios and graphs of the inverse percentage nitrogen against $\delta^{15}N$ or depth interpretation. As mentioned in the introduction chapter, the vegetation of the catchment is varied and encompasses Grassland, Savanna, Nama- and Succulent Karoo and Forest (Afromontane) Biomes. The Savanna and Grassland biomes dominate the interior and the catchment of the Orange River, with C_4 grasses dominating the upper catchment, although the sediment from this region is reflective of the mix of C_3 and C_4 vegetation of the upper catchment which varies widely (Compton and Maake 2007). Only the highest altitude grasslands (above 2950m on the warm slopes and 2750m on the cool south-facing slopes according to Morris *et al.* 1993) of the Lesotho Highlands are characterised by C_3 photosynthetic pathways and tend to be found on the thin soils overlying resistant basalt bedrock and therefore presumably are thinly eroded and contribute a less significant proportion of C_4 OM compared to the more easily eroded Karoo sedimentary rock (Compton and Maake 2007). Although the photosynthetic pathway of the catchment vegetation is largely C_4 in extent, the C_3-type grass dominance is present in some areas of Savanna (which exhibits a mainly summer rainfall component) with a significant component of winter rainfall (Rutherford and Westfall, 1986 and Low and Rebelo 1998). Most commercial farming in the summer rainfall part of the catchment has expanded dramatically over the last 100 years, and is characterised by crops such as maize and sorghum, which are C_4 crops, the predominant crop photosynthetic pathway. However, the recent increase in commercial and subsistence usage of C_3 crops such as wheat, soy and sunflower in the ORC may be responsible for very recent changes in the general photosynthetic vegetation 'imprint' in the modern surface sediment of the mudbelt prodelta area as represented by H2. At first this could be considered to be marine

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influence, although the C/N ratios in Figure 5.8 and the inverse of percentage nitrogen against depth in Figure 5.11 disagree. This signal is transferred further away from the ORM in the distal part of the mudbelt, represented by core H7, but further diluted by more marine influence. Although the modern Orange River (WT), the Jakkalsberg site (JKB) and near-surface mudbelt samples have a tendency towards C_3 values (note: the surface sample is C_3-rich) (Table 5.4), this is not consistent with the other inland Richtersveld sites of LX analysed as these have a tendency towards C_4 values. It is entirely possible that the low flow discharge represented in the modern Orange River (WT) samples may be carrying with it an isotopic signature representative of a mix of limited flow from the Upper Catchment (where C_4 vegetation is dominant), incorporating the Lesotho Highland headwaters and a more significant contribution from the lower reaches of the river heavily infused with the C_3-dominated riverbank vegetation. Further the C_3- rich values of the mudbelt surface, Richtersveld samples from WT and JKB are very similar to the values obtained at the 'gateway' to the Upper ORC. It is possible that the type of sediment being laid down during flooding at Lower Xobies for example, differs considerably from that laid down in the mudbelt due to differences in potential clay adsorption. This scenario would conceivably change from time to time and be diluted by large volumes of sediment load sourced from either C_4 or C_3-rich flood areas.

The terrestrial system presents the Orange River with tremendous potential for variability within both $\delta^{13}C$ and $\delta^{15}N$ values, which could be represented by different flood events for different sediment sources and different climatic mechanisms of climate change. Moreover, thick high threshold volume flood events tend to be preserved along with more recent events on the flood plain, thus preserving single events, rather than the mean signal over time. The question then arises - does the mudbelt tend to preserve sediment from these high threshold flood events or, rather the mean representation of sediment? Perhaps the answer can be found in part, by looking at the consistency of the chronology, isotope and pollen record, and by comparing isotope records between mudbelt and inland sites. If smooth records are found, this would more likely suggest the record is continuous (as previously thought), but if sudden changes in the palaeoenvironmental proxies occur (e.g. isotopes, pollen, dates), then it is more likely that the record is sporadic and deposited as a result of more extreme events. It appears impossible to answer this question fully but some evidence such as is found in the presence of laminations in mudbelt sediment, suggest the picture is one of more moderate continuous to semi-continuous deposition,

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rather than only recording high threshold events. By way of contrast, the inland sites such as Lower Xobies, may be seen as a whole, as representative of extreme events deposited over the short term, or at least the sediment layers are a series of high magnitude flood events. The mudbelt will contain within in it reworked high threshold deposits during intense flooding, this implies the mudbelt may explain a number of age reversals. Further, cessation in deposition may have occurred and these hiatuses might also be represented in the mudbelt.

On a localised level, the $\delta^{13}C$ isotopic signature of the prodelta (H2) appears to be explained by the dominating influence of the C_4 vegetation inland, with a smaller influence from marine sources. The marine influence is more significant in the distal sections of the mudbelt, which is represented in H7 by more consistent marine values, although the values indicate some terrestrial pulses within the predominantly marine sediment. The modern Orange River sediment (WT samples) retrieved from the lower reaches of the Orange River appear dominated by C_3. The original hypothesis that the river was contributing a dominantly C_4 carbon isotopic signal, with the marine signal making a more negative input, now appears to be somewhat in question, as these inland values are more indicative of a greater C_3 content in the C_3-C_4 mix than expected. However, this may be explained by lower than expected levels of C_4 sediment originating from the Lesotho Highlands or the type of adsorbed OM being deposited.

Generally, this input of C_3-rich plant OM, was far greater than initially expected. There is significant runoff through grassland areas, which are predominantly C_4 and this is under-represented in some of the modern river data, where values vary between -21‰ and -24‰. Due to the overlap in carbon values between typically marine signals of ±-20‰ and a C_3/ C_4 mix (as in the case in the Lower Xobies site) of -19.2‰, it is difficult to separate the influence of various mechanisms and the above results appear more qualitative rather than quantitative. H2 compared to H7 is more C_4 in character, with more positive $\delta^{13}C$ values than H7. As H7 is situated off the Buffels River, which experiences few recently recorded incidences of significant runoff, we can infer from the more depleted $\delta^{13}C$ (more C_3-rich) values that this is possibly a more marine signature, however, some sediment pulses of wider varying $\delta^{15}N$ values suggest input from either the Buffels or Orange Rivers, which implies that some of the C_3 signature is terrestrial in origin. The inverse of nitrogen (%) against depth suggest that this is more terrestrial input via the Buffels River and/or a change in upwelling regime. An influx of fluvial sediment

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is most plausible, especially when compared with the H2 data and the localised influence of CAM vegetation, characterised by an isotopic signature more difficult to discern, might also influence the influx at times with a CAM vegetation admixture.

Both carbon and nitrogen isotope values may indicate the progradational aspect of the deltaic mudbelt with C_3-rich values (upwelling or changes in sea level could also be contributing factors), at the base of H2, suggesting a more marine input at the base. This marine input decreases steadily between 600 and 500 cm depth. In addition, it appears that sediment pulses from various parts of the catchment contribute differing isotopic signals, i.e. the $\delta^{13}C$ values of source sediment from localised areas of the C_4-rich Orange Free State Grassland and Upper Catchment and other localised flood pulses feed into the river where they can be moderated by mixing with other sediment sources; fluctuations are evident within the mudbelt isotopic values, which point to either a change in the original source or change in regime.

The $\delta^{13}C$ excursion at 500 cm depth in the prodelta (H2)indicates a C_3-rich influx and implies a larger either marine (C_3) or C_3 terrestrial input, whereas the higher $\delta^{15}N$ values here suggests a more prominent marine input and this assertion is supported by C/N and the inverse of nitrogen (%) values. These nitrogen isotope values of the sediment around 6‰ and 7‰ could be related to nutrient input from the nearby zone of upwelling. The $\delta^{15}N$ values are more depleted closer to the ORM than further away to the south at H7 and in some samples in the modern Orange River sediment, although the ORC is characterised by a wide variation of $\delta^{15}N$ values during low flow discharge.

These results confirm that H2(the prodelta) is generally more terrestrial in nature and H7 more marine, although providing evidence for the occasional terrestrial input from the Buffels River in the more distal parts of the mudbelt. Core A30 (close to H5), situated between the two samples and providing a small data set gives some indication of the terrestrial-marine transition between these two sites on the mudbelt. The inverse of nitrogen (% weight) values plotted against $\delta^{15}N$ confirms the above and also suggests that the predominantly marine core, H7, has a smaller but noticeable component of terrestrial influence.

It is important to acknowledge the time period represented by the sites and mudbelt cores (discussed in previous chapters) in order to interpret the isotopic signature of H2 and H7,

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to determine whether it is representative of a recent changed event or whether sediment regimes have subsequently changed. The prodelta represents only the top portion of the more distal sediment deposit in age. Therefore, when considering Lower Xobies, it is important to note that the low discharge volume hiatuses at the Lower Xobies slack-water deposit site suggest that this exposure is not a product of a single event, but a number of events represented by a series of sediment pulses dating back to at least 4 500 years BP (Zawada *et al.* 1996) and therefore this sediment predates the mudbelt cores. The relevance of the isotopes lies more in the depth-relevant variations than the age-relevant variations. Further, it is difficult to use this data in isolation for palaeoclimatic reconstruction as issues of sediment and OM source appear to complicate the usefulness of this data. Other proxies should be used together with this in order to understand the dynamics in the palaeoenvironment represented by this material. This is further developed in chapter 7.

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6 PALYNOLOGY OF THE NAMAQUALAND MUDBELT

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6 PALYNOLOGY OF THE NAMAQUALAND MUDBELT

Findings of the Namaqualand mudbelt palynological data from the mudbelt cores (H2 and H7), selected inland sites and modern material relevant to the ORC are illustrated and discussed in this chapter. The methodology and principles have been dealt with in chapter 3 and a synthesis of the pollen data, along with chronology and stable isotope findings of chapters 4 and 5, is presented in chapter 7.

6.1 Introduction

Palynology is the dominant analytical tool used in this study and is heavily reliant on a synthesis of pollen data from both the mudbelt and inland Orange River sediment sites in order to improve understanding of the mudbelt pollen. Thus, the mudbelt data are discussed and interpreted using supporting inland ORC data which incorporate samples from both modern and older sites. The pollen data results are presented with additional statistical analysis. The remainder of this chapter discusses catchment vegetation, preservation dynamics and aspects of pollen diagram interpretation. This is followed by a detailed description of the H2 and H7 pollen diagrams. Raw pollen counts are included in Appendix F.

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6.2 Aspects of pollen data presentation

The fossil pollen data are represented as unmanipulated relative counts in appendix F and are displayed as percentages, selectively in a number of ways, according to specific criteria and data features discussed in the remainder of this chapter. These features are chosen for the purposes of this project, but they may be adjusted and expanded at a later date if future research may add to and highlight additional manipulation of the data. Therefore, the full data set is listed in the appendix for this purpose. The pollen data are presented against depth (cm) and not easily represented according to radiocarbon age, given the problems encountered in radiocarbon dating the mudbelt sediments. It is the depositional event, rather than the mean radiocarbon age of the sediment, that would appear to be particularly useful for the purposes of environmental construction in this palynological project, although this could suggest incorporation of older pollen in the sediment record and reworking must be

considered. However a portion of the pollen data, along with other isotope and chronology data are illustrated for completeness in chapter 7. Pollen samples do not necessarily correspond to specific dated radiocarbon age and stable isotopes, as different components may originate from different sources due to reworking. Pollen counts are generally presented against depth (cm) of sample and radiocarbon ages where appropriate. The percentage representation of each of the categories was calculated using the raw count for the purposes of graph construction and statistical analysis. Standardised biomes, described in texts of Low and Rebelo (1998) and Rutherford and Westfall (1986) were useful in assisting with these categories. Principal component analysis (PCA), detrended correspondence analysis (DCA) and cluster analysis of the samples is based on re-scaled percentages of relevant data. This is discussed in section 6.5.

6.2.1 Categorising pollen in the Mudbelt pollen diagrams

Categorising families into useful indicators of spatial and temporal extent is hindered by the cosmopolitan nature of many of the families identified. As there is some overlap of plant families between biomes, their interpretation may therefore be non-intuitive and categorising the families unavoidably leads to divisions that could be considered arbitrary. Nevertheless some simplification is necessary to aid interpretation. Some examples of spatially overlapping taxa include the Poaceae family, members of which are abundant in both Grassland and Savanna biomes and cannot be limited to a single biome. The Riparian category is also difficult as it is effectively azonal and represents vegetation found in all possible biomes. Some level of compromise has to be made in order to categorise this pollen data set in a useful way and in this case, the dominance of a taxon in a particular biome was used as a determining factor. It is therefore important to use these categories with a disclaimer and explain that certain taxa are represented in biome-type categories, but may not be limited to that biome. This categorisation serves a useful purpose in obtaining some indicators or trends in the stratigraphy and therefore in the palaeovegetation record. A number of analytical illustrations and manipulations are used later in this chapter, in order to overcome limitations made by this and other methods.

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The categories into which pollen families have been grouped are listed below. This is followed by Table 6.1, which lists the various families by category. Another table (Appendix B, Table B2) describes the main flowering taxa represented in the biomes and is available for comparison. The original pollen groupings used in Gray (1996) and Gray *et al.* (2000) are retained according to five categories, namely Riparian, Grassland, Nama Karoo, Succulent Karoo and Cosmopolitan. These broadly resemble the associated biomes but with necessary differences due to reasons outlined above:

Riparian

This category covers a broad range of riverine vegetation occurring along the Orange River. Note this is overlaps with families represented in the Buffels River.

Grassland

Grassland category covers a general vegetation type with few trees, dominated by grasses and broadly refers to the Grassland biome.

Nama Karoo

The category refers to the scrub-type vegetation, typical of parts of the South African Karoo geographical region. The Orange River Catchment includes the following vegetation types within the Nama Karoo Biome: Bushmanland, Upper Nama Karoo, Orange River Nama Karoo and Eastern Mixed Nama Karoo.

Succulent Karoo

Succulent Karoo includes succulent-type vegetation of the South African west Coast.

Cosmopolitan

This category includes all species not specifically associated with a particular biome or category mentioned above or their widespread nature is not considered characteristic to warrant retention within a specific category. Orange River Mouth salt marsh taxa such as *Sarcocornia* spp. (Chenopodiaceae) and *Phragmites* (Poaceae) have been omitted from this grouping as they are preferentially represented in other

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biomes, although this grouping is loosely defined and simplistic at best. Restionaceae are included as they represent the Cape Fynbos biome, a biome otherwise poorly represented in the mudbelt, with the exception of Ericaceae.

Riparian	Grassland	Nama Karoo	Succulent Karoo	Cosmopolitan
Chenopodiaceae	Poaceae	Aster-1 –(Tubuliflorae) Prev. incl. all Asteraceae types	Aizoaceae (Mesembryanthemaceae) But also found in Nama Karoo	Oleaceae
Caryophyllaceae	Rutaceae	Fabaceae	Euphorbiaceae	Bignoniaceae
Cyperaceae	Malvaceae	Thymeleaceae	Crassulaceae	Aster – 2 (*Artemisia*)
Juncaceae	Rhamnaceae	Prev *Acacia,* now incl. in Fabaceae	Campanulaceae	Rubiaceae
Iridaceae	Prev. Pinaceae, Unbelliferaceae		Liliaceae (prev as Riparian)	Convolvulaceae
Potamageton/ Aponogeton			Prev Zygophyllaceae, Amaryllidaceae	Aceraceae
(previously incl.Liliaceae)			Aster-4 (Stoebe-Elytropappus)	Acanthaceae
			Fabaceae (*Acacia*)	
				Anacardiaceae
				Apiaceae
				Celastraceae
				Ebenaceae
				Ericaceae (Fynbos)
				Geraniaceae
				Orchiaceae
				Plumbaginaceae
				Polyonaceae
				Restionaceae (Fynbos)
				Rosaceae
				Solanaceae Prev. Boraginaceae, Cucurbitaceae, Cruciferaceae*

Table 6.1 Orange River Catchment Pollen Taxa (families) according to loosely defined categories.
***Also prev: Cruciferaceae, Scrophulariaceae, Verbenaceae, Asteraceae-2 (*Artemisia*), Oliniaceae. Note Aster-1 (and 2 & 4) are also described as Asteraceae-1 or Asteraceae-Type1.**

6.3 Results and discussion of pollen data

6.3.1 Pollen identification and limitations of identification

Given the degradation of many of the grains and the use of a light (optical) microscope for identification, classification and identification of grains was limited to family level, though in certain cases further identification down to genus or species level was possible. The biomes found in the Orange River and Buffels River

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Catchment are described in chapter 2 and these plant species and their associated families are detailed in Appendix F. Aeolian transport is another important source of pollen entering the mudbelt (especially notable in this regard is Restionaceae from the Fynbos biome and Podocarpaceae (*Podocarpus*) from river banks near the ORM, although Lesotho Highlands regions would be more prolific, there is minimal chance of preservation over this distance), but this is difficult to fully evaluate as a certain amount of overlap between non-aeolian and aeolian sources of pollen is possible.

An important factor associated with effective aeolian transport is the prevailing wind in relation to the flowering season. Aeolian input from the interior into the mudbelt sites, situated between 25 and 33° S, is low. Dupont and Wyputta (2003) have determined aeolian pollen pathway trajectories in the south-eastern Atlantic. Wind transport from low-tropospheric trajectories runs parallel to the coast in summer and perpendicular in autumn and winter when the Nama and Succulent Karoo are favoured. Flowering season for the 'grassy scrub-land' Nama Karoo occurs after the unreliable summer rainfall (Dupont & Wyputta 2003). The Succulent Karoo and Fynbos exhibits spring flowering (after winter rainfall) and dispersal of elements of Succulent Karoo (especially Asteraceae-1) and Restionaceae (wind pollinated Fynbos pollen) is encouraged by the coast- parallel wind trajectories (Dupont and Wyputta 2003). Grassland elements may also be carried some distance via aeolian transport. The wind trajectory that runs from the Acacia Savanna perpendicular to the coast is just to the north of the mudbelt sites. South of 25°S, aeolian terrigenous input is low, as winter mid-tropospheric (wet) westerlies dominate and therefore discourage long distance transport of pollen and dust. Berg Winds, active only a few weeks a year and predominantly during the winter season may contribute Succulent Karoo pollen (in addition to the established input of sand grains) from the semi-arid Namaqualand interior depending on the timing of the spring flowering season and the Berg winds (which can occur during the later winter or spring months). Dupont and Wyputta ascertain that present-day ocean current dispersal of pollen is limited due to the relatively high sinking velocity of pollen in water (Dupont and Wyputta 2003 after Fischer and Wefer 1996). South of 25°S, aeolian transport is low.

A small number of pollen grains were difficult to identify and were classified as 'unknown'. These were not known to the author and were either absent from any

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available reference set or were too crumpled or deteriorated to be identified. They may have had some characteristic identifying feature removed by attrition or detritus obscuring the view, despite attempts to dislodge the latter and were included within this classification. Evidence of broken pollen suggests reworking and/or exposure to aridity in the lower reaches of the Orange River. There is undoubtedly a mix of sediments (and therefore pollen) represented in any given sample, although flood events may dominate a particular deposition event with a particular homogeneous pulse of sediment. These pulses of sediment-laden water rework and potentially deposit sediment further down the river, before they enter the prodelta and are distributed in the mudbelt or elsewhere on the continental shelf and ocean.

Certain pollen grain fragments, such as those of Asteraceae remain easily identified due to their characteristic exine sculpturing. Possible bias in favour of these taxa was averted by uniformly classifying such otherwise identifiable fragments as 'unidentifiable'. Thus, only whole grains were identified in this regard. However, bias caused by resilience of sturdy grains is unavoidable.

Some factors that have affected the interpretation of the sediments for paleopalynology include reworking of the material (along the river course or *in situ*), post-depositional alteration of palynomorphs in arid environments, breaking and alteration through attrition and post-depositional oxidation within the mudbelt. Hopkins and McCarthy (2002) have tested the post-depositional role of oxidation on Quaternary pollen in a marine environment and have detected a significant susceptibility to oxidation in this environment, resulting in the selective destruction of so called "susceptible taxa" and a "taphonomic skewing" in potentially useful palynological records.

Several pollen diagrams have been compiled to aid interpretation of the data. The comprehensive pollen diagram (Figure 6.3) illustrates all pollen taxa represented in cores H2 and H7 of the mudbelt, with a presence of 2% (by count) or above. Trace taxa are indicated where relevant. Relative counts were made and these data are used

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in all pollen spectra and figures. Samples analysed from the lower reaches of the Orange River are illustrated using pie charts of percentage pollen frequencies.

6.3.2 Modern pollen of the Orange River

The raw counts of the three modern Orange River samples of the lower reaches of the river are listed in Appendix F. The small modern Orange River pollen sample along with the grab sampling method of the river sampling exercise created an immediate problem with graphical illustration as it was not possible to use a conventional pollen diagram. Instead, a series of pie charts proved most useful and can be quickly visually interpreted. The pie charts for three samples of the Orange River namely, WTPT, WT13#4 and WT13#5 are presented in Figure 6.1. All three pie charts show a significant proportion of Poaceae (between 30% and 50%), and Asteraceae-1 (between 30% and 42%) with very similar Restionaceae (between 9% and 11%), Euphorbiaceae (between 2% and 9%) and Caryophyllaceae (between 7% and 9%) values. Very low quantities of Asteraceae-2 (*Artemisia*) pollen are represented. Samples in Jakkalsberg, Lower Xobies and Bloeddrift sites revealed some pollen, but most are regarded as palynologically poor and inert as the palynological material was either too degraded or broken to be identified. Raw counts are also made available in Appendix F. It is important to note that pollen samples deposited for any length of time in arid conditions are generally not well preserved (Moore *et al.* 1991). These areas of the mudbelt occur in the lower reaches of the Orange River, where the palaeoflood deposits (studied in this research) are located, where high temperature and low humidity conditions severely hamper pollen preservation and severely degrade grains. This is confirmed by analysis of floodplain sediment samples analysed in the area.

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6.3.3 Pollen zones and palaeoenvironmental interpretation of Namaqualand Mudbelt core samples

It is useful to categorise specific levels of a pollen diagram into pollen zones based on their pollen content. This is expedient for interpretation by visually displaying the important taxa elements. A number of pollen zones have been identified on the basis of certain interesting trends and associated trends in the taxa.

The H2 pollen assemblage in Figure 6.3 may be sub-divided into 4 identifiable zones, H2-A, H2-B, H2-C and H2-D, some of which contain inert sediment. Inert sediment is found in H2 at the following depths: 595 cm– 570 cm, 525 cm- 465 cm, 460 cm – 420 cm, 365 cm – 300 cm, 305 cm – 215 cm, 215 cm – 190 cm, 85 cm – 40 cm.

Three zones, H7-A, H7-B, H7-C, can be discerned in the pollen assemblage in H7 (Figure 6.3), but samples processed from the following depths were inert: 585 cm – 540 cm, 545 cm – 500 cm, 505 cm - 460 cm, 325 cm – 280 cm, 245 cm – 210 cm, 185 cm -100 cm, 75 cm - 40 cm, 45 cm -10 cm.

6.3.3.1 Proximal Mudbelt core H2

Zone H2-A. (602 cm – 570 cm depth).

The pollen zone is inert between depths of 595 cm and below 570 cm.

Pollen found at the base of this zone is characterised by reasonably high levels of Restionaceae, which suggests that wind transport from this area was prominent or that winter rainfall conditions in the Fynbos were favourable to proliferation of Restionaceae. This stands in contrast to some of the other pollen spectra: Asteraceae are moderately well represented pointing to a source in the seasonally arid conditions in the Succulent Karoo, which is accompanied by low levels of Cyperaceae, a wetland taxa. Moderate levels of Chenopodiaceae-Amaranthaceae are consistent with moderately arid inland conditions and the ORM saltmarsh, which was reasonably well developed certainly up until very recently and is consistent with historical evidence of increased aridity at the mouth of the Orange River. There is an absence of Asteraceae-2. As suggested by Baxter (1996) and others, the climate change indicators evident in

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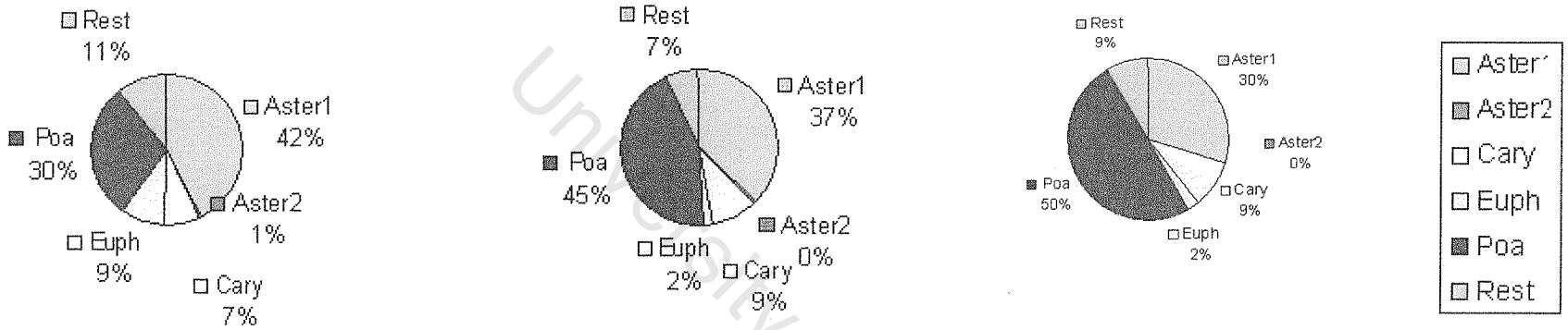

Figure 6.1 Pie Chart of modern Orange River pollen, Lower reaches of the Orange River (WTPOT, WT13#4,WT13#5).

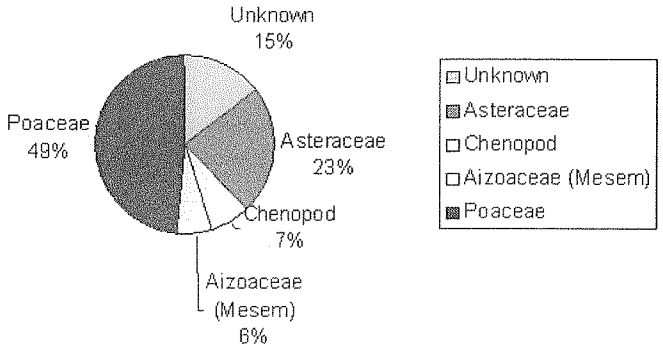

Figure 6.2 Pie Chart of Coetzee's Orange River Mouth pollen (Coetzee and Rogers 1976).

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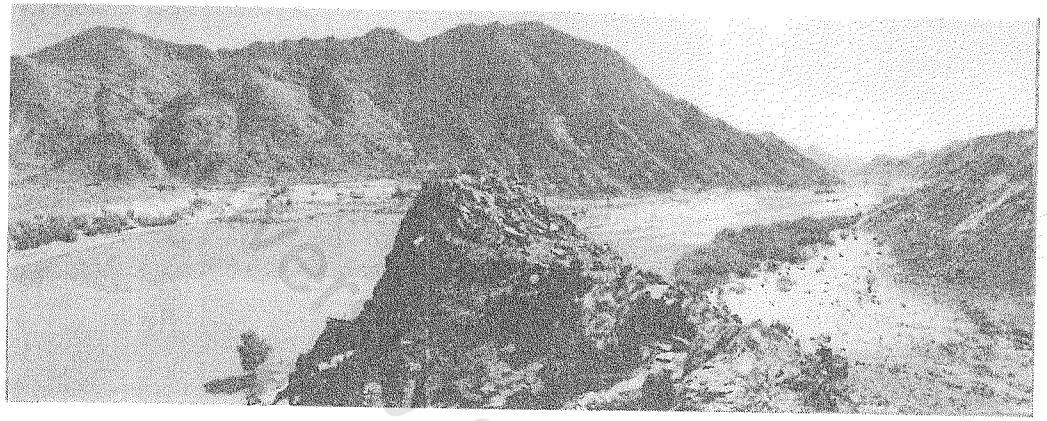

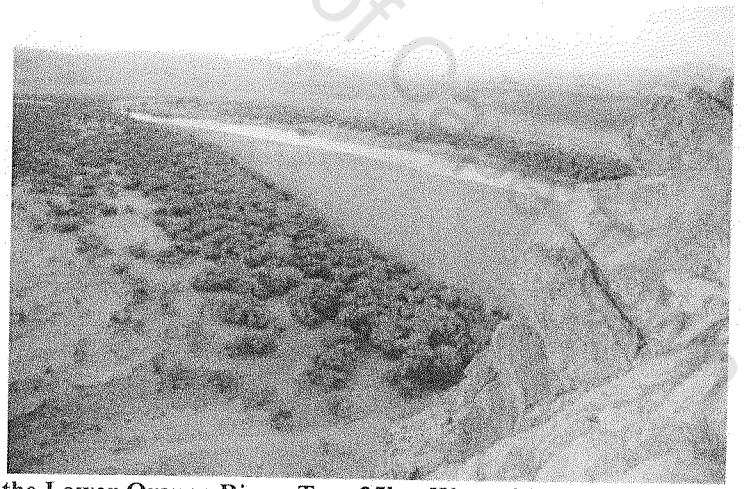

Plate 6.1 Photographs of the arid Richtersveld in the Lower Orange River. Top: 25km West of Vioolsdrif borderpost; Bottom: view of the Orange River west from Jakkalsberg (photos: Catherine Gray).

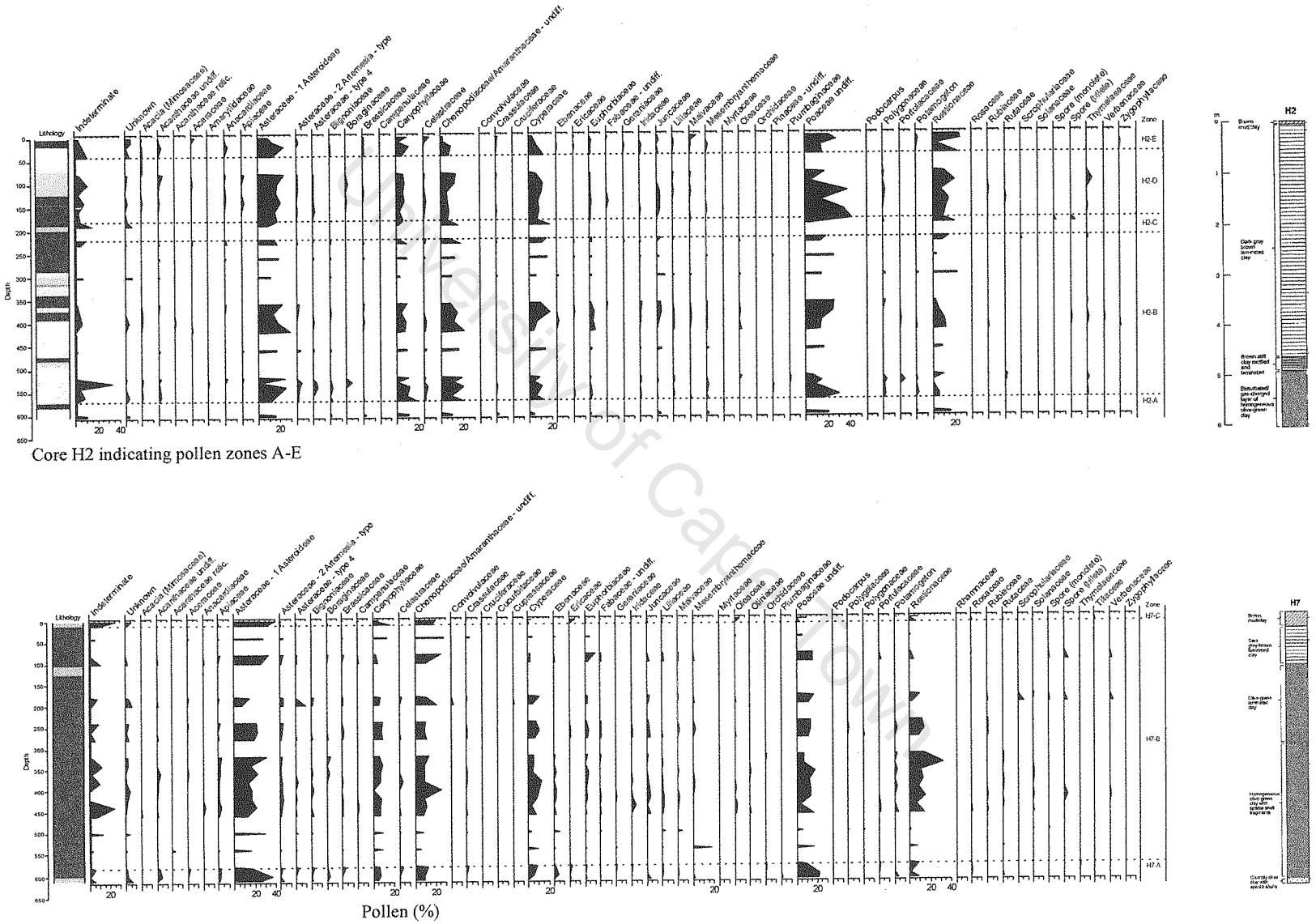

Figure 6.3 Pollen diagram of the Namaqualand Mudbelt off Orange River (H2, top) and Buffels River (H7, below). Stratigraphic zones, to the left (detailed) refer to Dingle (1994) and are described in Appendix B. Simplified stratigraphy is described on the right (after Meadows *et al.* 1997 and 2002).

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the Fynbos may be separate and appear unrelated to the climate change occurring in the interior, where part of the pollen spectra is sourced. Therefore it is not unexpected that pollen spectra could suggest distinctive climatic conditions based on (Cape) Fynbos and other biomes within the same zone such as is suggested above.

Zone H2-B. (570 cm - 220 cm depth).

The pollen zone is inert between depths of 525 cm- 465 cm, 460 cm – 420 cm, 365 cm – 300 cm, 305 cm – 215 cm.

The base of the zone to about 540 cm depth is marked by dynamic environmental conditions. Levels of Restionaceae are low at the base of this zone, but decrease and become conspicuously absent closer to 540 cm depth (which suggests possible reduction in wind transport from the Fynbos region or lower winter rainfall conditions in the Fynbos biome). Levels of Asteraceae-1 are high at the top of this level, but reduce to the background moderate levels of zone H2-A at the base. The level is dominated by increased levels of Caryophyllaceae, an indicator of aridity at the base of the zone and high values of Chenopodiaceae-Amaranthaceae (fluctuating noticably at a depth of between 450 cm and the base of the zone, but dramatically reduced towards the base at 560 cm depth). This reduction in Chenopodiaceae-Amaranthaceae coincides with the decrease in Caryophyllaceae and Cyperaceae (Riparian), decreases in Aizoaceae (Mesembryanthemaceae) and increases in Fabaceae (*Acacia*), Acanthaceae, Ericaceae, Euphorbiaceae, Poaceae, Polygonaceae, Potamogetonaceae and Restionaceae (although this continues towards the base of the core). All of the above, with the exception of Restionaceae, exhibit a dramatic about-turn above and below this depth. These changes suggest a substantial increase in indicators of aridity (lower rainfall) within the Nama Karoo and general OR Catchment at this level.

At a depth of between 540 and 530 cm depth, the assemblage is characterised by low Restionaceae and Poaceae levels, conditions which suggest either poor wind conditions (contributing to low levels of Restionaceae) or alternately poor winter rainfall. Low grassland levels (Poaceae and Malvaceae) may be associated with increased aridity (Chenopodiaceae/Amaranthaceae) and reduced Riparian elements (Potamogetonaceae, Caryophyllaceae and Juncaceae) all of which suggest lower

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fluvial input and possibly increased aridity around this time. Cyperaceae achieve intermediate levels, higher than the slightly lower levels exhibited at both above and below this level at depths of 560 cm and 520 cm, respectively. This is associated with an increase in certain Succulent Karoo (winter rainfall) elements such as Mesembryanthemaceae (also represented in Nama Karoo), but a decrease in others (Asteraceae-2, Iridaceae, Lilliaceae) and in certain Nama Karoo elements (Thymeleaceae). Myrtaceae has its highest levels reached at this level. This increase in indicators of aridity and winter rainfall may suggest an increase in seasonality.

Between depths of 520 cm and 460 cm, low levels of the Fynbos pollen element Restionaceae, which tends to be azonal, suggest prevailing wind direction was favourable from the Fynbos region, particularly between depths of 540 to 530 cm, but towards the top of 530 cm, levels have increased, although remaining moderate. Low riverine water levels in the Orange River are suggested by low Potamogetonaceae and Cyperaceae, Caryophyllaceae, along with poor representation of Grassland elements (Poaceae, Malvaceae) with the exception of the xerophytic Rutaceae, which shows a dramatic increase, suggesting that rainfall was possibly reduced in the Grassland biome (ORC). Indicators of aridity and disturbance are low (Chenopodiaceae and Asteraceae) and certain Nama Karoo elements flourish (Thymeleaceae, and Succulent Karoo elements). Amaryllidaceae pollen remains at a low level throughout the core, although this taxa reaches a maximum at this level. The boundary between these zones is characterised by the highest levels within the core of Asteraceae-2, Boraginaceae, Plumbaginaceae, Polygonaceae, Portulaceae, and lowest levels of Asteraceae-1 (and all other Aster types) pollen , which suggests that rainfall levels were probably favourable in the Succulent Karoo at this level.

At depths of between 520 cm and 460 cm, this boundary level is dominated by elements of aridity indicators (Chenopodiaceae-Amarantheaceae and Rutaceae, which tends to be a xerophyte) and disturbance (Asteraceae-1) in the Nama and Succulent Karoo and accompanied by low levels of Euphorbiaceae, significant representation of Caryophyllaceae and flourishing levels of Restionaceae, which suggest favourable wind direction from the Fynbos region. Grassland (Poaceae, Thymeleaceae) is poorly represented but Oleaceae and Fabaceae (*Acacia*) are significant. Cyperaceae, Potamagetonaceae, Mesembyanthemaceae/Aizoaceae, Crassulaceae, Asteraceae-2 &

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4 are not well represented also suggesting that conditions in Riparian and Succulent and Nama Karoo may have indicated low rainfall.

At a depth of around 460 cm, the pollen assemblage is characterised by an increased representation of Riparian elements (Cyperaceae and Juncaceae), an increase in Succulent and Nama Karoo elements (Mesembryanthemaceae and Asteraceae-2) and a moderate decrease in other Nama Karoo/Succulent Karoo elements (Asteraceae-1). This and the absence of Crassulaceae at this level suggest a possible decrease in aridity.

Between 420 cm and 360 cm depth, the assemblage is characterised by an increase in grassland elements towards 360 cm (Poaceae, Malvaceae) coinciding with an increase in Asteraceae-2 and Asteraceae-1 and a decrease upcore in Riparian components (Iridaceae and Juncaceae, with a moderate decrease in Caryophyllaceae), Chenopodiaceae-Amaranthaceae Oleaceae and Euphorbiaceae and a decrease of Restionaceae (this suggests a possible decrease of wind transport from the Fynbos or winter rainfall in the Fynbos). A significant representation of Verbenaceae occurs at a depth of around 390 cm, where it reaches a maximum. This coincides with increases in the Nama Karoo element, Thymeleaceae, but a decrease in Asteraceae-1 (particularly marked around 390 cm), compared to higher Asteraceae-1 values at depths of 420 cm and 360 cm, suggesting there is a possible mid-zone decrease in aridity. This decrease is supported by a strong decrease in Asteraceae-1 and Cyperaceae and a temporary increase in Chenopodiaceae-Amaranthaceae (although this decreases upwards). At depths of between 360 cm and 300 cm depth, an increase in Restionaceae levels appears to suggest an increase in prevailing wind from the Fynbos region or favourable winter rainfall in this region.

Between 260 cm and 230 cm depth, an increase in Restionaceae in the assemblage suggests favourable wind direction from the Fynbos biome, whereas Asteraceae-1 Poaceae, Cyperaceae and Caryophyllaceae show higher levels than samples found above and below this level and suggest water levels are improved. Succulent Karoo elements are well represented.

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At depths of between 230 cm and 220 cm, there is a distinctive presence of Nama Karoo (Thymeleaceae), disturbance vegetation (Scrophulariaceae), Succulent Karoo (Euphorbiaceae) and riverine trees (Oleaceae) in the pollen assemblage. Chenopodiaceae-Amaranthaceae decrease upcore at this level, which coincides with an up-core increase in Restionaceae (Fynbos), Poaceae, Juncaceae, Cyperaceae, Celestraceae, and slight decrease in Succulent Karoo elements (Liliaceae), although Poaceae levels are low and Asteraceae levels are moderate but slightly decreasing upcore. This level seems to imply a subtle increase in Grassland conditions and rainfall levels, as indicated by an increase in Riparian elements.

Zone H2-C. (220 cm – 40 cm depth)

The pollen zone is inert between depths of 215 cm and 190 cm and from 85 cm to 40 cm.

The pollen assemblage found at depths between 220 cm and 180 cm is characterised by a dramatic upcore increase in Grassland (Poaceae) elements compared to zone H2-B below, which then decrease slightly and simultaneously with Asteraceae-1 and Caryophyllaceae and directly opposite to the changes in Fynbos (Restionaceae), coinciding with a moderate increase in Succulent Karoo (Aizoaceae/Mesembryanthemaceae and Asteraceae-4). At 160 cm depth, Riparian levels (Cyperaceae) are high, but these reduce dramatically upcore in synch with Chenopodiaceae-Amaranthaceae and Restionaceae and a small decrease in Caryophyllaceae and Asteraceae-1. The general trend is difficult to distinguish as there are a number of complex dynamics characterising this level. There is a marked upper to mid-core increase in spores (both monolete and trilete) at this level.

Between 160 cm and 140 cm depth, Fynbos (Restionaceae) is found to decrease markedly towards the top of this level. This coincides with a slight upcore increase in Nama Karoo (Asteraceae-1) along with an upcore decrease in Grassland (Poaceae) and Riparian (Cyperaceae) elements. Between 140 cm and 120 cm depth there is an upcore increase in Grassland and Riparian elements (Poaceae, Cyperaceae) and an upcore decrease in Fynbos (Restionaceae), Xerophytic Riparian (Chenopodiaceae)

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and Nama Karoo (Asteraceae-1) characterise this level which may indicate drier conditions.

Midway between depths of 120 cm and 80 cm, the pollen assemblage is characterised by a maximum in the Nama Karoo element, Thymeleaceae. This occurs simultaneously with an increase in Fynbos (Restionaceae), indicating a possible increase in wind from this region before decreasing in the level above). This is also accompanied with an increase in Riparian elements (Cyperaceae) and a dramatic decrease in Grassland (Poaceae and Malvaceae) and Succulent Karoo (Liliaceae) elements. Chenopodiaceae-Amaranthaceae increases to one of its highest levels here, too and these levels are sustained towards a depth of 80 cm. Towards 120 cm, there is a decrease in the Nama Karoo element (Thymeleaceae), Fynbos element (Restionaceae) and Riparian elements (Chenopodiaceae-Amaranthaceae and Juncaceae) and a dramatic increase in the Grassland element Poaceae.

Zone H2-D. (40 cm – 0 cm depth).

There is a high level of Restionaceae at the base and surface of this zone, but a marked mid-zone decrease upcore. At the base of this zone, Poaceae show a decrease from the levels reached in the top 20 cm and indeed the levels achieved in H2-B above. Riparian elements (Potamogetonaceae, Iridaceae) increase at a depth of 20 cm and this continues towards the surface of the core. Myrtaceae shows an increase at a depth of 20 cm, from an earlier decrease at the base of the core. Similar trends are evident in Succulent Karoo (Liliaceae and Geraniaceae). There is a rapid decrease in Riparian elements (Cyperaceae and Caryophyllaceae) upcore between 40 and 20 cm and significant levels of xerophytic Chenopodiaceae-Amaranthaceae throughout.

Although the radiocarbon age would suggest otherwise, this sediment at the surface of both H2 and H7 is recently deposited (within the last 150 years) according to data presented in chapter 4. Thus the entire surface to at least 30 cm and arguably up to and beyond 80 cm was deposited within the last 150 years and therefore represents the vegetation of this time period. This surface sample is consistent with the recent decrease in the saltmarsh sediment found in the historical record and which is also implied by a sharp reduction in Chenopodiaceae pollen compared to the rest of the

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core. However this is also accompanied by a similarly sharp reduction in Asteraceae-1, which is unexpected given the general trend in Asteraceae (increase due to disturbance) over the last 200 years on the Cape West coast (Baxter 1996, Meadows and Baxter 1994, 1999). Poaceae, Malvaceae and Restionaceae levels are high, suggesting Grassland and Fynbos elements are favoured, perhaps due to increased or sufficient rainfall and wind transport from the Fynbos region to the south. Some Succulent Karoo elements increase (Crassulaceae, Euphorbiaceae) and certain Riparian elements (Potamogetonaceae and Juncaceae) are well represented although Potamogetonaceae increases midzone, but is reduced to background levels towards the top and base of this zone. Caryophllaceae, also a Riparian element, shows a more recent increase in representation, after an equally rapid mid-zone decrease. There is a mid-zonal increase in Asteraceae-2, consistent with a decrease in Caryophyllaceae and xerophytic Chenopodiaceae-Amaranthaceae and low levels of Asteraceae-1.

6.3.3.2 Distal Mudbelt core H7

Zone H7-A (610 cm - 580 cm depth).

Asteraceae-1 along with Acanthaceae (undifferentiated) shows a mid-zone increase, decreasing again towards the top of the zone. This mid-zone decrease coincides with a mid-zone increase in Caryophyllaceae (moderate), Ebenaceae and Poaceae, Ebenaceae Malvaceae and a mid-zone decrease in Restionaceae (marked decrease), Ericaceae, Euphorbiaceae, Boraginaceae, Chenopodiacae, and Asteraceae-2 (*Artemisia*). Poacaeae indicates a decrease from the highest levels found in this pollen assemblage of the lower section of this zone to midozone at this level. There is an upcore increase in Thymeleaceae, Bignoniaceae, Juncaceae, Potamogetonaceae from the mid-zone and an increase in Cyperaceae from the middle of this zone.

This is the basal zone of core H7 and it is characterised by an upcore increase to the highest levels of Asteraceae-1 in the core, which suggests disturbance in the Nama Karoo; a decrease in other Nama Karoo elements such as Thymeleaceae and Succulent Karoo elements (Myrtaceae, Euphorbiaceae, Ericaceae, Crassulaceae, Asteraceae-Types). This increase occurs simultaneously with Grassland elements (Poaceae, Malvaceae) where Poaceae also reaches the highest levels in the core. Restionaceae, however decreases markedly, pointing to potentially less than

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favourable conditions for wind transport or winter rainfall in the Fynbos region to the South. Riparian elements such as Cyperaceae and Iridaceae also decrease at this point, but Caryophyllaceae remains at a moderate level. This level of the zone may be interpreted as representing marked changes from that represented above it between 600 cm and 580 cm. At this level, the most noticeable change in this zone is the abrupt upcore decrease in Grassland taxa (Poaceae), increase in certain of the Riparian element (Cyperaceae) and decrease in others (Juncaceae, Potamogetonaceae), and a decrease in Nama Karoo (Asteraceae–1). Asteraceae-2 levels increase upcore. The Fynbos (Restionaceae) element levels increase markedly after the dramatic mid-zone reduction probably due to absence of suitable wind transport from the region.

Zone H7-B. (580 cm – 10 cm depth).

The pollen assemblage in this zone is inert between depths of 585 cm – 540 cm, 545 cm – 500 cm, 505 cm - 460 cm, 325 cm – 280 cm, 245 cm – 210 cm, 185 cm -100 cm, 75 cm - 40 cm, 45 cm -10 cm.

The base level of this zone between 580 and 540 cm is particularly unique in that it has the highest levels of Succulent Karoo (Aizoaceae/Mesembryanthemaceae) indicators in the core and among the lowest Nama Karoo levels (Asteraceae-1), but low values of Asteraceae-2, Crassulaceae, Ebenaceae, Riparian elements (Iridaceae, Juncaceae) and Oleaceae. This suggests that favourable rainfall occurred in the Succulent Karoo but perhaps this did not translate into similar conditions in the interior. The pollen assemblage found between 500 and 460 cm depth is characterised by remarkably low levels of Fynbos (Restionaceae), Grassland (Poaceae), Riparian (Cyperaceae Juncaceae) and Succulent Karoo (Iridaceae Euphorbiaceae and Asteraceae-2) but significant increases in (Grassland) Malvaceae and Succulent Karoo (Liliaceae). Aridity indicators (Chenopodiaceae-Amaranthaceae) are particularly low, while Caryophyllaceae and Asteraceae-1 values remain steady between the pollen bearing zones above and below.

The pollen assemblage found between depths of 440 cm and 340 cm is marked by fluctuations. Fynbos taxa, Restionaceae fluctuate but increase upcore, eventually peaking at 340 cm, where Grassland, Succulent Karoo and Riparian taxa are found to

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be greatly reduced. Restionaceae decrease markedly at a depth of 320 cm, perhaps indicative of reduced wind transport from the Fynbos region, while arid taxa (Chenopodiaceae-Amaranthaceae) spike at a depth of 410 cm. Cyperaceae increases upcore at a depth of 380 cm. The pollen assemblage between 260 and 240 cm is characterised by high levels of Fynbos (Restionaceae), Nama Karoo (Asteraceae-1), Succulent Karoo (Aizoaceae or Mesembryanthemaceae) and Grassland elements (Poaceae, Malvaceae), perhaps indicating strong wind movement from the south. This is accompanied by high levels of Riparian elements (Caryophyllaceae and Cyperaceae).

Arid taxa decrease upcore between depths of 180 cm and 100 cm (Chenopodiaceae-Amaranthaceae) and Asteraceae–1 increases (although this is poorly represented). This is accompanied by a decrease in Succulent Karoo (Asteraceae- 4) and increase in Solanaceae (the highest levels in this core). There is a simultaneous increase in Riparian taxa (Cyperaceae), Grassland (Poaceae) and Fynbos (Restionaceae). This suggests that conditions favoured Grassland, wind conditions were favourable from the south and rainfall levels may have increased in the Succulent Karoo.

Between depths of 100 cm and 80 cm, the pollen assemblage is characterised by high levels of Asteraceae-1 and moderate levels of Chenopodiaceae-Amaranthaceae and Euphorbiaceae, declining towards a lower part of this level. This is accompanied by high levels of Poaceae compared to sediment above and at the surface. However, these show a decline in the lower part of this section. Asteraceae-2 is reasonably high, but decreases towards the base of the zone. This decrease is accompanied by a small increase in Riparian, Succulent Karoo and Fynbos vegetation (Verbenaceae, Trilete Spores, Restionaceae, Portulaceae, Malvaceae, Liliaceae, Juncaceae and Cyperaceae). This suggests moderately arid conditions accompanied by higher levels of disturbance vegetation (increase in Asteraceae-1) but a small increase in indicators of increased moisture towards the base of the zone.

The pollen assemblage between 80 cm and 40 cm is marked by the absence of Restionaceae from the Fynbos and therefore probably associated with poor wind transport or low winter rainfall. The pollen assemblage at a depth of 40 cm suggests that aridity levels are significant (possibly low winter rainfall in the Nama Karoo) and

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these and other perhaps human induced conditions are unfavourable to saltmarsh elements. The strong representation of Caryophyllaceae suggests moderate Riparian conditions which strongly favour this taxon (this may be either high or low water levels), whereas moderately significant levels of Cyperaceae would suggest that levels were conducive to development of this Riparian taxa. Some Succulent Karoo indicators are strong (Asteraceae-2, Crassulaceae) within the core, whereas others show moderately significant status (Euphorbiaceae).

Zone H7-C. (10 cm - 0 cm depth).

This zone incorporates the surface of H7 and is characterised by particularly high levels of Asteraceae-1, showing a small decrease near the base of the zone which appears to be premature given that the sediment is deemed modern (chapter 4) and Asteraceae have proliferated for the past ± 250 years. Restionaceae and Ericaceae (which is strongly represented at the surface) decrease towards the base of this zone indicating that wind transport was probably recent or perhaps favoured good winter rainfall. However, an increase of Caryophyllaceae, Juncaceae and Riparian taxa near the base of this zone may suggest an increased or decreased fluvial input that would be conducive to higher pollen representation. Poaceae and Oleaceae are poorly represented towards the base, but not at the mudbelt surface, however the relation to the above is unclear. Nama Karoo (Thymeleaceae), Grassland (Rutaceae) and Succulent Karoo (Euphorbiaceae) are poorly represented and show an upcore decrease. Chenopodiaceae-Amaranthaceae, a salt marsh and Riparian taxa show similar increasing trends near the surface (although it is lower than the depths in the zone below); this suggests a tendency towards more salt tolerant arid conditions of either lower or more infrequent water conditions. This, too is consistent with the increased impoundment of Orange River water, but also may suggest that the more infrequently flowing Buffels River experiences drier conditions (and is contributing to the increase in Chenopodiaceae-Amaranthaceae). Potamogetonaceae presence near the surface, could imply some flow within the Buffels River, but not significantly so, although this is perhaps more likely to be coming from the Orange River. Fynbos taxa, Restionaceae and Ericaceae both have significant levels at the surface. The surface of H7 is characterised with particularly high levels of Asteraceae-1, often

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flourishing during aridification and as a result of disturbance; this is consistent with the published recent (last 250 years) increase of Asteraceae.

6.3.4 Discussion of Mudbelt pollen sequences

Over 49 pollen types are identified in the mudbelt sediment. This exceeds the 39 pollen types identified during the pilot study (Gray 1996), four families identified in Coetzee and Rogers' (1976) study and a total of 13 in a separate study by Coetzee (1976). Some of the families identified require further explanation as they are classed according to either controversial or somewhat unconventional groupings and nomenclature for the purposes of this study.

Many samples contained poorly preserved pollen. This is perhaps reflective of the distance from sediment source to mudbelt, attrition during flood events and effects of aridity during reworking in the lower reaches of the Orange River, an area which is extremely arid and not conducive to pollen preservation. In addition, oxidation and resulting degradation of pollen within the mudbelt cannot be ruled out. The pollen quality of samples was fair to poor within the mudbelt material. Although pollen concentration was particularly low (Figure 6.4), some variation occurred throughout the core and certain samples were palynologically inert. From Figure 6.4, it is interesting to note that pollen concentration within the Orange River during low flow discharge has similar concentrations to the upper twenty five percentile limit of many of the mudbelt samples and concentrations vary between zero (inert) to just less than 1200 pollen grains per gram wet weight ($P_{conc}.g^{-1}$). Inert samples are listed in Table F7 (Appendix F). Some samples proved impossible to process cleanly and as a result, identification was hampered. Modern Orange River samples yielded samples of similar quality to those found in the mudbelt, but samples from the Richtersveld sites, Lower Xobies, Bloeddrift and Jakkalsberg, with the exception of a surface Lower Xobies sample, proved to have low to negligible levels of pollen. Pollen found in these sites, proved to be either broken or degraded, presumably by the dry conditions. Asteraceae is subdivided into four categories, three of which are relevant to this study, namely: Asteraceae-1: Asteroideae- or Tubuliflorae-type; Asteraceae-2: *Artemisia*-type; Asteraceae-3: Fenustrate-type (these were not identified in this study and are not indigenous to southern Africa); Asteraceae-4: *Stoebe-Elytropappus*-type.

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Mesembryanthemaceae are included within the Aizoaceae (Mesembryanthemaceae) family, as the Missouri Botanical Garden and other systematics classification authorities favour the inclusion of Mesembryanthemaceae into the Aizoaceae (Mesembryanthemaceae) taxon (Angiosperm Phylogeny Group 1998) but both names are used interchangeably in this thesis as they are both well established.

Initial results in the pilot study (Gray 1996) indicated that the samples were spore-rich and a ratio of about 1:20 (pollen : spores) was observed.

Oleaceae, a poorly represented family, is represented below 2% in H2 and was therefore omitted from the pollen diagram. Oleaceae is represented in quantities higher than this in the vegetation, so the pollen is therefore under-represented. Only three indigenous Oleaceae species are represented in this cosmopolitan family. It is possible that Oleaceae represented in this pollen record is exotic, although this is not clear, as indigenous and exotic grains are not easily distinguished at this level of identification. In addition, Oleaceae appears to be poorly preserved for some reason. Gymnosperms, such as species of Podocarpaceae (*Podocarpus*) and *Pinus* produce more abundant pollen generally as they are wind-pollinated. Podocarpaceae (*Podocarpus*) has a relatively fragile bisaccate grain, so is less likely to be successfully carried fluvially from the Lesotho Highlands to the mudbelt (it is unlikely, given the wind pattern noted in chapter 2 that these would be carried directly westwards from the highlands, but it may possibly have been carried from localised pockets in the Buffels River or Lower Orange River). *Podocarpus* (Podocarpaceae) species are found in the Lesotho highlands, but also found further south, where its northerly-most extent is Vanrynsdorp or as a few specimens are known along the Orange River and Buffels Rivers. It is difficult to say where these are originating as it is possible that localised aeolian coastal sources (Buffels or lower Orange River) or even laboratory contamination may be the source of the few Podocarpaceae (podocarpus) grains represented. Since Podocarpaceae (*Podocarpus*) are prolific producers of pollen and readily wind-pollinated, this may be derived from a number of sources.

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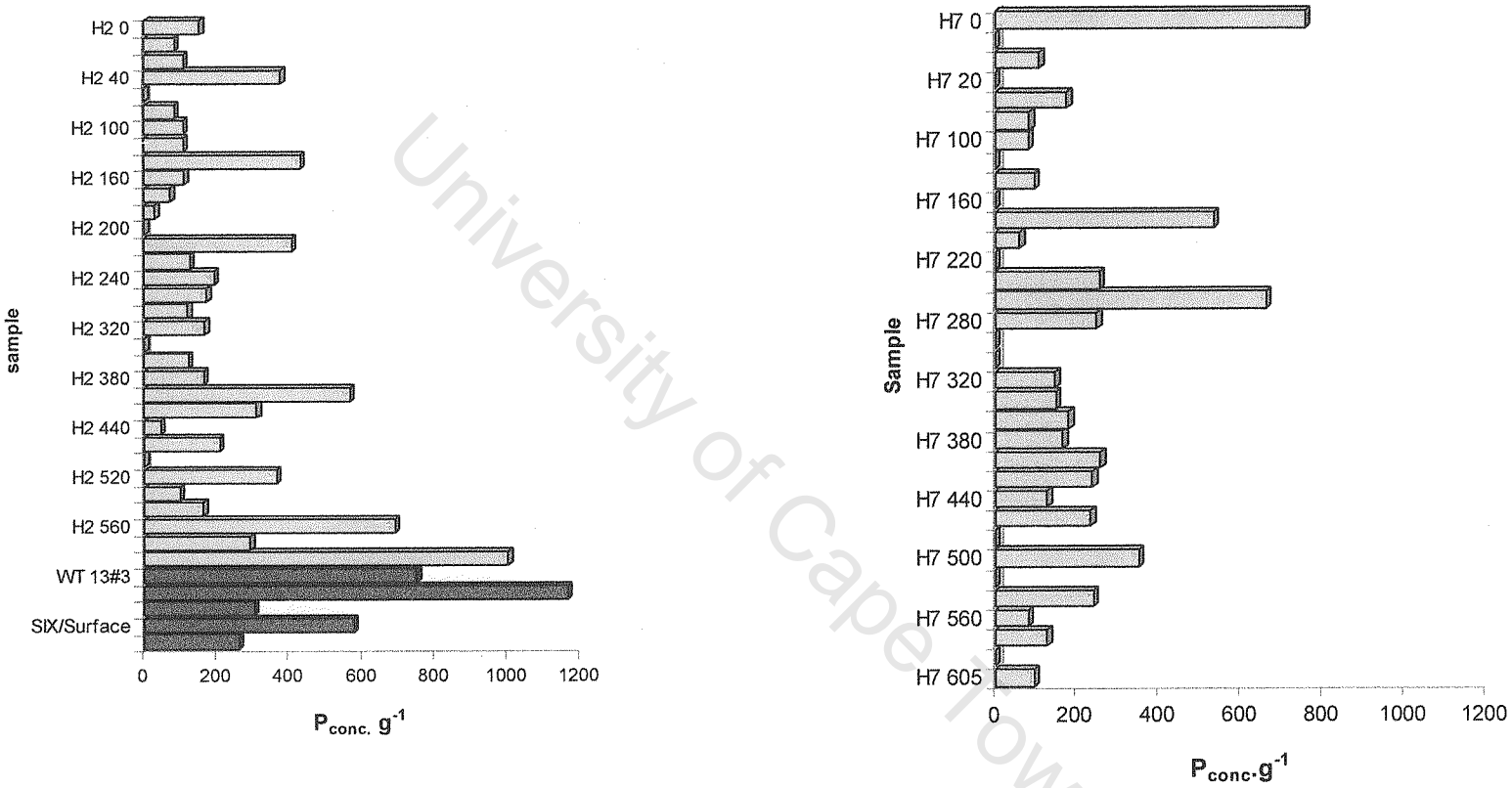

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Figure 6.4 Pollen concentration for core H2, individual Orange River (Richtersveld) samples (identified by solid black bars) and core H7. Measured in pollen concentration per wet weight, measured in grams ($P_{conc}.g^{-1}$).

Surprisingly few exotic species of pollen were positively identified in the mudbelt and Orange River material. Exotic species, such as pine and certain Fabaceae species were absent or poorly represented in the mudbelt pollen. Although initial indications suggested otherwise (Gray 1996), exotic species were not positively identified in surface sediments and no such trend was noted in this detailed study. However, increased levels of species of non-polyad Fabaceae represented towards the top of the H2 core may suggest increased levels of exotics of this family, but this is unclear. The Fabaceae family includes species that are both indigenous and exotic and are not easily distinguished from each other using light microscope methods. *Acacia*, also a member of the Fabaceae family, were present in small quantities despite pollen being produced in large quantity as polyads, they were not limited to the surface samples. Since this family is not entirely exotic, this argument could not be used, as hoped, to illustrate influx of exotic species and therefore identify dateable horizons. According to Wells (1986), after Wells *et al.* (1983), 50% of introduced exotic species of southern Africa fall under the Poaceae, Fabaceae, Asteraceae, Solanaceae and Brassicaceae families, thus posing an identification problem with light (optical) microscope work and providing inconclusive evidence of the arrival of exotics, largely due to the morphological overlap of indigenous and exotic pollen within the same families. Pine falls under less than 2% representation in the few samples in which it is found, so it does not appear in the pollen spectra except at a trace level. Myrtaceae are represented by indigenous species such as *Eugenia capensis* (a coastal dune shrub) and *Augustifolia metrosieros*, found in streams and on river banks. Exotic species, such as *Eucalyptus* species (originating in Australia) are also included within this family. *Prosopis* (Mesquite), another exotic may be included within the Fabaceae family, as similarity to other grains combined with grain degradation complicated definitive identification causing potential identification overlap.

6.3.5 Discussion of the Orange River and Mudbelt pollen data

The three Orange River samples (illustrated in Figure 6.1) are comparable and pollen spectra are broadly consistent with local Succulent Karoo vegetation. All have very

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similar counts with respect to Caryophyllaceae, Restionaceae, Asteraceae-1 and Euphorbiaceae. The three pie charts indicate significant portions of Poaceae and Asteraceae-1 and very similar representation of Restionaceae, Euphorbiaceae and Caryophyllaceae values, with very low Asteraceae-2 counts. Indeed these are very similar to the count made at the ORM by Coetzee and Rogers (1976) illustrated as a pie chart in Figure 6.2 although Asteraceae were then undifferentiated and "unknown" pollen types were high at 15%. A significant difference between the modern Richtersveld pollen and that of the Coetzee and Rogers' sample is the 6% Mesembryanthemaceae and 7% Chenopodiaceae representation, compared to a lower representation of less than 0.5% in the Richtersveld pollen. This may be attributed to direct local input from the lowland Succulent Karoo into the river, where it may have a direct influence on pollen represented during low flow discharge or 'flooding' of localised pollen due to seasonal changes, and the saltmarsh pollen of the ORM estuary, being usually diluted in the mudbelt pollen record. It is significant that there are a high number of "unknown" pollen types in the Coetzee study; this possibly accounts for some discrepancy between the data sets.

Much of the Richtersveld Orange River pollen spectrum is very similar to pollen of the H7 core off the Buffels River, particularly the (modern) surface sediment. Differences however, are found in levels of Poaceae between the Richtersveld OR and H7 core, where H7 levels are much lower and the levels are instead very similar to the H2 levels, as would be expected in a grassland dominated catchment (and given the proximity of core H2 to the OR catchment). This begs the question as to why there is a correlation between core H7 and the OR Richtersveld pollen (during low flow discharge). Is the background fluvial 'signature' perhaps limited to local input into the river during low flow discharge (and to what extent does this contribute to the mudbelt) or are aeolian sources responsible for the remainder? Perhaps the best explanation is found in establishing that geochemical evidence ($\delta^{13}C$) indicates that floods from various areas of the upper catchment at various times (Zawada 1996) may be assumed to contribute to the majority of sediment, with low flow discharge

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sediment creating the background pollen picture and being responsible for a much smaller portion of mudbelt compared to flood events. Aeolian mechanisms are possible means of pollen and sediment transport in a reasonably narrow coastal band which incorporates certain Succulent Karoo elements, allowing for an overlap with fluvially transported pollen e.g. Poaceae. In addition, aspects such as oxidation, source of flood sediment within the expansive catchment, seasonality of transport mechanisms, reworking, attrition and seasonality of flowering all contribute towards the mudbelt pollen contribution. Further, the pollen composition of the mudbelt is determined not just from the Orange River input, but by the proximity of portions thereof to additional sources of pollen, for example the Buffels River, the seasonal wind that blows Succulent Karoo pollen offshore, the wind that blows Restionaceae north of its contemporary source in the Fynbos, resulting in certain parts of the mudbelt being enriched in for example, Restionaceae. Given the prevailing wind and based on work by Dupont and Wyputta, it is determined that the Restionaceae are carried northwards to below 25°S, the pollen concentration is found to peak, particularly north of the research area off the Namib coast at GeoB1203-5 (Dupont and Wyputta 2003).

H2 and H7 have distinctly different palynological characteristics (Figure 6.3, Figure 6.5), yet both are characterised by significant levels of Poaceae and Asteraceae. H2 is dominated by Grassland elements such as Poaceae, to a greater degree than is H7, although significant levels are found in both cores. Nama Karoo (Asteraceae) and Succulent Karoo elements are less dominant in H2. This is expected given the extensive drainage area of Grassland in the Orange River Catchment. Fabaceae (*Acacia*) and Riparian elements such as Cyperaceae dominate H2 and are better represented than in H7. Cyperaceae and other Riparian elements are expected to be significantly represented in the Orange River due to the perennial nature and extensive area of the Orange River Catchment, compared with the episodic and much smaller Buffels River. However, this picture is inconsistent, as Riparian elements are also well represented in H7. The Orange River may be perennial, but the combination effect of Orange River sediment and erratic ephemeral Buffels River pollen provides for a boost in representation of Riparian elements here too. This is highlighted by a common situation when analysing Riparian pollen elements, which is the detection of

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these elements in the pollen record at either high water levels or particularly low water levels (Scott 1999).

Core H7, located near the Buffels River and close to the Strandveld and Succulent Karoo vegetation to the south of the prodelta, is significantly different from core H2, but pollen frequencies do not fluctuate as dramatically. Asteraceae pollen (all types) display a recent increase in the top 100 cm, determined to be largely recent, which is consistent with disturbance patterns in the *Sandveld* area over the past 200 years (Baxter 1996) and these data indicate a coincidence with increased Caryophyllaceae. This increase starts near a depth of 100 cm in Zone H7-B, but is particularly marked upcore. This trend is not confined to the period from 200 years BP to the present, but the effect on pollen spectra is marked here and strongly suggests a causative factor. Scrophulariaceae is often taken as another indicator of disturbance (Baxter 1996) but is not well represented in either core H2 or H7. However, a Scrophulariaceae spike is detected at a depth of 200 cm (in Zone H7-B), a depth at which a number of significant changes occur in concert within the pollen record. This spike coincides with a reduction in Grassland biome elements such as Poaceae and Malvaceae and an increase in Chenopodiaceae-Amaranthaceae. Cyperaceae (a Riparian element) shows a decrease at this level. Perhaps, this spike relates to a flood event originating in the Buffels River or adjustment to environmental change as elements of Nama Karoo e.g. Mesembryanthemaceae and Euphorbiaceae show slight increase at a radiocarbon age of 2186 ± 118 cal yr BP and not necessarily aeolian as both Restionaceae and Poaceae decrease. In contrast, Chenopodiaceae and other Riparian elements exhibit a gentle increase towards the top of the cores.

Other significant trends at this level include an increase in spores, Verbenaceae and cosmopolitan elements. Here a decrease in Asteraceae-1, but an increase in Type-2 and a significant increase in Asteraceae-4 are noted. Most marked is the decrease in Restionaceae. Chenopodiaceae generally increases upward from this depth of 200 cm, despite an initial reduction.

Asteraceae-2 and Euphorbiaceae became more dominant above 100 cm depth and are dated as recent (in the area around a depth of 100 cm in Zone H7-B). Restionaceae, however, indicate a different trend in that they remain relatively poorly represented in

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the top 100 cm of the core compared to the levels below (with the exception of the sediment found at the depth of 325 cm, which is less than 3143 ± 66 cal yr BP in age where the taxa peak midcore). This peak is possibly an artefact of the low count in this sample. It may also be related to significant vegetation changes (low Restionaceae levels occur at depths above and below this mid-core level) as fewer grains were preserved but may also be driven by increased southerly wind combined with possible increase in pollen production of Restioanaceae. After this apparent peak, Restionaceae then declines gently, whereas Poaceae shows a slight recent decrease, and also a mid-core peak which again may be an artefact related to a low count (degraded grains and reworked pollen bearing sediment), but may also imply increased Poaceae due to increased moisture (rainfall).

The depths of 500 cm (H7-B), 40 cm (base of H7-C) are characterised by the absence of Restionaceae pollen, coinciding with low Poaceae, low Asteraceae-1 counts, low levels of Juncaceae and low levels of Potamogetonaceae, Celestraceae, Aizoaceae (Mesembryanthemaceae), Asteraceae-2 and Asteraceae-4. This reduction in Poaceae and Restionaceae, elements of the Grassland and Fynbos biomes respectively, may be explained by factors such as decreased summer rainfall or perhaps Grassland and Savanna burning by Khoi farmers. Fire-induced Grassland reduction (this is termed disturbance, which also refers to grazing and agriculture) was introduced by Khoi herders and was known to have occurred at about 2 000 years BP (Maggs and Whitelaw 1991) and may correspond with the radiocarbon age of 2186 ± 118 cal yr BP (of bulk OM at 180 cm in H7) at a depth of around 200 cm, supports this possible explanation. However, this assertion is somewhat controversial as researchers generally believe that the intensity of this burning was not great enough to significantly influence the landscape. The question of the intensity and influence which the disturbance had on the landscape is discussed in further detail in the synthesis and discussion chapter 7. Chenopodiaceae-Amaranthaceae, usually interpreted as indicative of arid conditions, dominate the top 100 cm of H7 to a greater degree than in older sediment below this level or indeed throughout H2. This might suggest arid conditions in the Succulent Karoo including parts of the Buffels River Catchment for this time period and this is consistent with other studies of the area discussed below.

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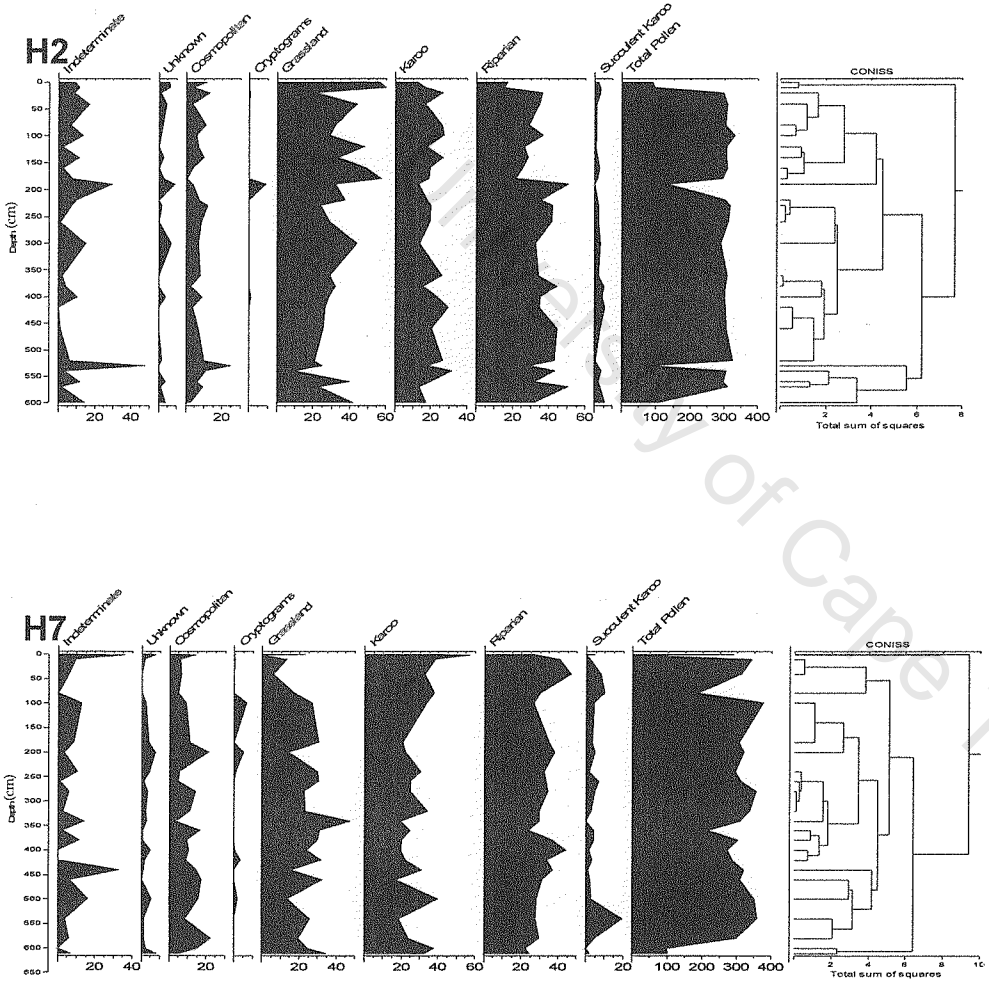

Figure 6.5 Pollen diagram grouping of H2 and H7 of the Namaqualand Mudbelt according to vegetation category.

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More Succulent Karoo elements are represented in the surface sediments of H7 than those represented in H2. This is expected due to the close proximity of the Succulent Karoo Biome. These Succulent Karoo elements include Euphorbiaceae, Crassulaceae, Campanulaceae and Aizoaceae (Mesembryanthemaceae). Another example of this biome is the Ericaceae family (primarily of the Fynbos biome), which is poorly represented in H2 (less than 2%). A Succulent Karoo Biome spike occurs at a depth of 550 cm, containing particularly Mesembryanthemaceae (Aizoaceae), a delicate pollen type which is often poorly preserved. This spike perhaps relates to a pulse of sediment from the Buffels River or aeolian transport of local vegetation. The spike is also associated with an increase in reticulated Acanthaceae, Cyperaceae, Aizoaceae and Poaceae. According to the grouping of categories at this level, there is a decrease in cosmopolitan species, which is associated with a decrease in Grassland, a relative decrease in the Karoo Biome, and a relative drop in Chenopodiaceae-Amaranthaceae and Celestraceae.

Asteraceae pollen is well represented in H7 and specifically so in recent times; it displays an apparent inverse relationship with Succulent Karoo elements near the surface in recent sediment of H7, although this is not discerned in H2. This relationship in H7 is possibly due to the small catchment in the Buffels River. H2 does not have a similar relationship and Succulent Karoo elements are even more poorly represented here than in H7. The richer representation of Succulent Karoo in H7 may be explained by the proximity of the Succulent Karoo and the coastal aeolian influence and/or the ephemeral Buffels River, compared with the perennial Orange River.

Anacardiaceae, (a family that incorporates the tree genus, *Rhus*), increases in association with increases in Asteraceae and simultaneous decrease in Poaceae in both cores, but H7 in particular, This genus occurs along the Orange River in the form of *Rhus viminalis*, although a proliferation of other species of this genus could also account for these changes (refer Table 6.1 for ecological niche of taxa and Appendix F).

Both H2 and H7 are well represented by Karoo elements, with H7 slightly more so, increasing in (recent) surface sediment. By contrast, Succulent Karoo is relatively

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poorly represented compared with Nama Karoo, Grassland or Riparian elements, and is slightly better represented in H7 than H2. This is expected from the proximity to a smaller catchment area localised in the neighbouring Succulent Karoo Biome. A dramatic increase occurs as Succulent Karoo spikes at a depth of 550 cm in H7 and could be indicative of a major flood event in the Buffels River Catchment and/or dramatic change to the environment to encourage a proliferation of Succulent Karoo elements.

Asteraceae-2 pollen is better represented in H7, than H2 which may be explained by the increasingly arid climate northwards along the west coast. Juncaceae is slightly more significant in H2. Apart from a spike at a depth of 25 cm, Aizoaceae (Mesembryanthemaceae) appears to have been more significant in H7 from the base of the core to a depth of 175 cm. Recently, Caryophyllaceae has become more significant in core H7 local input (which probably implies an increase in that vegetation), and also very recently Chenopodiaceae-Amaranthaceae increased in the core from a depth of 178 cm to the modern mudbelt surface. Euphorbiaceae is more significant in the H7 local input. Restionaceae is less significant in recent times in H7 compared with H2. This trend suggests reduced aeolian input from the Cape Fynbos and/or a reduction in Restionaceae productivity in combination with a possible significant increase in disturbance and arid vegetation, suggesting recent aridification. Given the ^{210}Pb isotope determined age of the top 80-100 cm which implies the sediment is younger than 150 years, these aridification indicators are consistent with the recent increase in aridification and disturbance (Asteraceae) features identified at Verlorenvlei by Baxter (1996) and Meadows and Baxter *et al.* (1999).

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6.3.5.1 Pollen spectra changes over depth at mudbelt sites

Zones H2-C is marked by fluctuating Poaceae which also reaches a maximum here. At the base of this zone, the assemblage displays a dramatic drop in Poaceae, which coincides with an increase in Restionaceae, Cyperaceae, Chenopodiaceae-Amaranthaceae and an absence of Asteraceae-2. Poaceae and other Grassland elements fluctuate throughout the core but show a recent increase (as indicated in the base of zone H2-D), indicating a strong signal from the Grassland Biome, which points to conditions or factors conducive to pollen supply from this biome. The reduction in Euphorbiaceae indicates a reduction in arid succulent plants into the

catchment while the lower count of Cyperaceae and Chenopodiaceae indicates the reduction in contribution from freshwater and saline water bodies respectively. The surface of the core in Zone H2-D, is characterised by a decrease of Asteraceae, Cyperaceae, Euphorbiaceae and Chenopodiaceae/ Amaranathaceae and a noticeable maximum in Malvaceae compared to the rest of the pollen record. This differs markedly from the base of the zone at a depth of 40 cm.

Fabaceae (*Acacia*) (polyad-type) pollen is poorly represented in the cores, although the family occurs widely in southern Africa and is not uncommon in the Orange River Catchment (the possible reasons for this have been discussed previously). The pollen diagrams include only pollen represented by 2% or more. Fabaceae (*Acacia*) pollen is present in H7 but it is below this 2% margin (See Appendix F). Fabaceae also include some exotic (alien) species and displays a marked increase towards the surface of cores H2 and H7, consistent with the recent increase in exotic Fabaceae species. Asteraceae pollen has also fluctuated throughout the core but there have been significant amounts in the near-surface sediment of H7 in particular (this near-surface increase in the mudbelt pollen was projected in Gray 1996). Further, the surface sediments are proven to be modern (chapter 4) and the trend is supported by the findings at Verlorenvlei (Baxter 1996, Meadows and Baxter 1999) further south on the South African West Coast. Restionaceae fluctuates dramatically in H2 particularly (two spikes at 300 cm and 190 cm depth) but shows a gentle increase upcore pointing to a recent increase, which in turn points to an increase in prevailing wind from the south (Figure 6.5). Very low counts of Restionaceae were present at a depth of 230 cm and 360 cm. Cyperaceae (a riparian element) shows a more recent decrease (180 cm and 300 cm), although it has fluctuated throughout the core, greatly depleted in the surface sediment of core H2 and slightly increased in the surface sediment of H7, although not significantly so. This is difficult to interpret, but could be related to the increased water impoundment on the Orange River and reduction in river volume.

Near-surface samples between the surface and about 25 cm depth, now proved to be younger than 100 years in age (chapter 4), show an increase in Nama Karoo elements, with a significant decrease in Grassland elements, such as Poaceae and Caryophyllaceae (Riparian). Although this decrease is not confined to the last 250 years, it is marked at this point. This is contrasted with a noticeable increase in the

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Fynbos taxon, Restionaceae, significant increase in Asteraceae–1 and Chenopodiaceae-Amaranthaceae, which in turn is associated with an increase in the top quarter of the core and a near surface decrease in Riparian elements. Potamogetonaceae (*Potamogeton*), an obligate aquatic disappears at the surface of the core, suggesting an effect of aridification. There is an inverse relationship between Asteraceae and Poaceae found only in the surface sediments of H7 which may imply a stronger influence of inland Grassland biome over Succulent Karoo (although some grasses are present here, too). A notable increase in Euphorbiaceae occurred at a depth of 80 cm which then decreased steadily upcore until recent times. To some extent, this change in certain arid species may imply drier taxa are favoured which might suggest an upcore aridification.

There is a tendency towards larger size Poaceae pollen grains in the surface sediment; although this was not quantified, this was observed in the top surface sediments in particular, consistent with a proliferation of cereals in the Orange River Catchment.

6.3.5.2 Catchment vegetation and aspects of pollen preservation

Interpretation of any pollen results would be incomplete without mention of the potential for evidence conspicuously absent from the pollen record and the reasons behind such phenomena. Reasons for this are not limited to purely climatic or human disturbance factors and may include limitations of methodology, in identification, pollen type (light vs. heavier pollen grains), aerodynamics of pollen grain, mode of transport, production volume of pollen, unidentified pollen, artefacts of the pollen diagram and methodology, destruction of delicate pollen or preservation of identifying features of more robust grains and temporary preservation in arid environment. Indeed, the mudbelt stratigraphy does not appear to show any correlation with the pollen assemblage i.e. the source of sediment in the catchment does not correlate with the development of the pollen assemblage. Further, the assemblage and the (limited) radiocarbon age of the sediment suggest that sedimentation hiatuses occurred; there are depths at which pollen are non-existent and these and the aforementioned hiatuses result in gaps in the record.

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6.4 Further analysis and comparison

6.4.1 Statistical interpretation of pollen data

In order to conduct the statistical analysis, Riparian pollen elements and pollen taxa with less than 5% representation were removed from the data set, leaving six key taxa common to both cores H2 and H7 (Figure 6.6). Raw values of these taxa were re-scaled as a percentage of the new (subset) total (Appendix F) and used to run the results of DCA (detrended correspondence analysis), PCA (principal component analysis) and cluster analysis. Although these statistical methods are proven and established, the analytical results should be treated with caution given that they are drawn from a reduced dataset, based on only 6 key taxa.

Results of the DCA are found in Figure 6.7 and Figure 6.8 (Table F9, Appendix F), where three important components were identified. Here, Axis 1 is plotted against axis 2, and axis 2 is plotted against axis 3. For completeness, the correspondence analysis is included, without detrending, for comparison (Figures F4 and F5, Appendix F), although interpretation is not affected. DCA, as with PCA, both illustrate analysed data using up to four axes which explain the majority of changes within the data. In this case, the DCA results indicated that PCA would potentially be very useful and thus DCA data is of limited use compared to PCA and will be discussed briefly. The plot of ordination axis 1 against axis 2 (Figure 6.7) shows that the taxa are generally well separated and show some dissimilarity, but there are some instances of close correspondence of taxa within the data. In Axis 1, the axis shows that Caryophyllaceae and Asteraceae-2 corresponded well, but from close inspection of this axis, this may be suggesting a factor relating to dry environment or a proliferation of Succulent Karoo. There is strong dissimilarity between Asteraceae-1 and Restionaceae in particular and this may be explained in one of the principal components. Axis 2 shows a correspondence between Asteraceae-1 and Caryophyllaceae, which may point to a disturbance factor. Asteraceae-1 and Euphorbiaceae are also correlated, but not as closely. There is low similarity between Caryophyllaceae and Asteraceae-2; this dissimilarity should be explained by one of the principal components. The third axis indicates a correspondence between Asteraceae-1 and Poaceae, which appears to suggest a Grassland-based explanation for the underlying factor or axis, but there is also a correspondence between

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Restionaceae and both Asteraceae-1 and -2, which appears to explain a presence or lack of more localised aeolian elements. This information suggests the usefulness of pursuing PCA in order to investigate the underlying components. As is apparent from the DCA results, many of the above mentioned correspondence in taxa are further developed in the PCA results.

The significant number of principal components for PCA were established using both the Jolliffe cut-off value, (a value of 0.69085) and the 'scree plot' (Table F11, Appendix F). This established the presence of four significant principal components. The first component with an eigenvalue of 36.55 explains 69.9% of the variance, whereas the second component with an eigenvalue of 7.69 explains 14.7%, the third with an eigenvalue of 6.4 explains 12.2% and the fourth component with an eigenvalue of 1.4 explains 2.8% (Table F11). The PCA loadings may be viewed for each principal component in Figure 6.9 to Figure 6.12.

The first component (Figure 6.9) explains the core and modern river samples very well. This probably explains the background signal (common to all the samples) and includes part of the Succulent Karoo contribution into the lower reaches of the Orange River. This refers to aeolian sources of Succulent Karoo and among other taxa, may explain the presence of Poaceae. Close inspection of the small number of samples least strongly correlated with this first component shows that they tend to have low to moderate Asteraceae-1 and Euphorbiaceae (Succulent Karoo) percentages, which would suggest this component explains elements of the aeolian source of the Succulent Karoo. Although these samples alone do not provide sufficient evidence for explaining this component, they appear to support the following observation: The majority of samples are dominated by this factor, which might easily be considered as either fluvial or aeolian transport or a combination of both (supported by high Asteraceae-1 values which are slightly more significant in H7 than H2), as the samples that most closely are explained by this component, H2 80 and H7 360, are strongly represented by high Asteraceae-1 levels and relatively moderate Poaceae levels. A sample that does not show this as strongly is H2 530, which is the least affected by the first factor, although still governed by it (in terms of Asteraceae-1 presence). This sample is particularly high in Asteraceae-2 and Poaceae, but Asteraceae-1 is relatively poorly represented. Thus, the best explanation is possibly a

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mixed signal from the Grassland, Succulent Karoo and Nama Karoo, through which the Orange River runs and the river, as the primary transport mechanism, is implied within this factor. However, it is also possible that much of this factor may be attributed to aeolian transport. This is supported by the scatter diagram in Figure 6.13 and Figure 6.14.

The second factor (Figure 6.10), explaining 14.7% of the variation is most strongly represented by three neighbouring H7 samples, namely H7 1, H7 10 and H7 40. These samples are found in pollen zones H7-C and the top section of H7-B. The common factor that appears to explain these samples is the high values of Asteraceae-1, relatively high values of Caryophyllaceae and relatively low Poaceae values. Figure 6.13 indicates Euphorbiaceae, Caryophyllaceae and Asteraceae-2 are well correlated in explaining this. From the PCA loadings (Figure 6.10), it is evident that this factor is more effective at explaining core H7 and its surface than core H2, thus the factor might be more useful for explaining the influence of pollen in the Buffels River or local aeolian influence than the Orange River. Since Euphorbiaceae is a fragile grain, it is most likely that this component is primarily explained by aeolian transport.

The third factor (Figure 6.11) explains 12.2% of the variance and is more significant at the base and surface of H7; this component is not significant in explaining the mudbelt pollen found at depths between H7 500 and H7 280 i.e. between 3 470 ± 78 cal yr BP and 747 ± 23 cal yr BP (deposited within the last 150 years). It is evident from the PCA loadings graph that this component explains the surface and base of H7 and the modern pollen samples. This component appears to influence H2 in a fluctuating manner, but significantly less so in H7. Samples which are well explained by this component all represent low values of Restionaceae (with moderate representation of Euphorbiaceae and Poaceae). This suggests a factor of climate that might discourage Restionaceae and therefore could suggest an aridification component.

The fourth factor (Figure 6.12) explains 2.8% of the variance and is therefore not as important as the other factors (and indeed even the third factor should be treated with caution). However, the fourth factor strongly explains sample H2 570 in particular (with an age of approximately 873 ± 58 cal yr BP) and is responsible for a subtle

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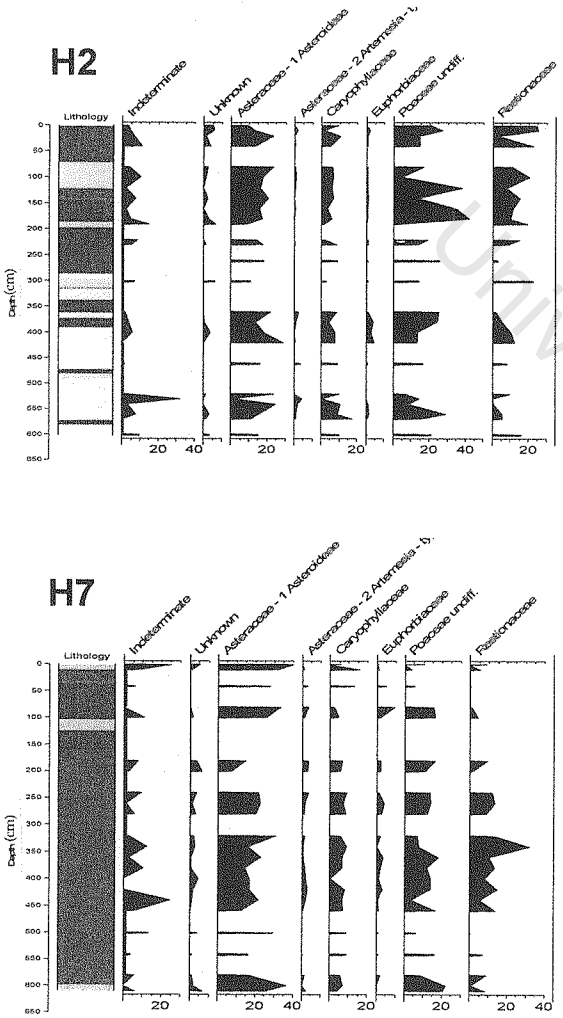

Figure 6.6 Pollen diagram of Namaqualand Mudbelt off Orange River (H2) and Buffels River (H7): reduced dataset for ordination analysis.

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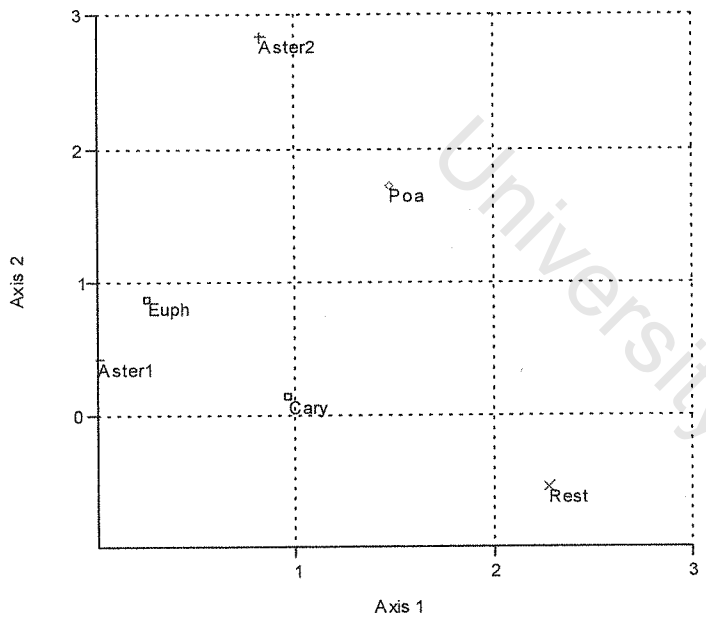

Figure 6.7 Detrended correspondence analysis results: axis 1 vs 2.

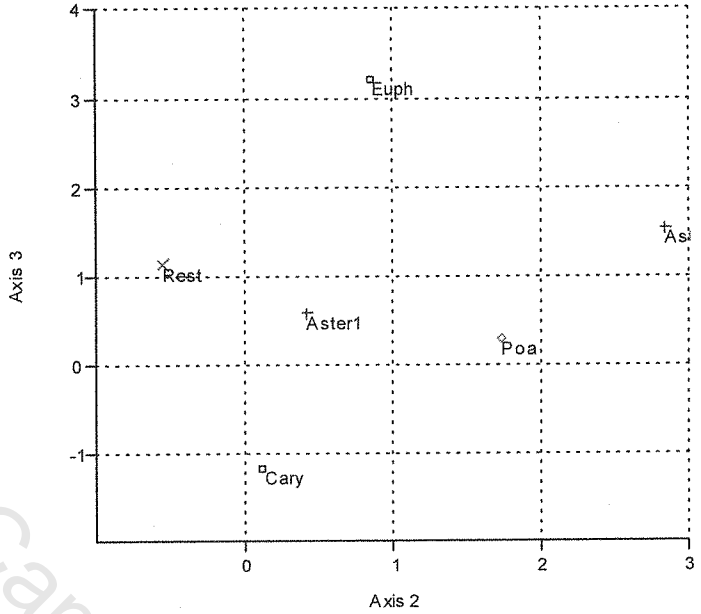

Figure 6.8 Detrended correspondence analysis results: axis 2 vs 3.

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influence, either positively or negatively, on the remaining samples. It is negatively correlated with all the modern Richtersveld samples and those at the base of H7. This factor may be explained by the presence of Caryophyllaceae in the pollen record. The underlying presence of this taxa might also suggest aridity, as there is some overlap with factor 3.

The scatter diagrams, Figure 6.13 and Figure 6.14, show most points are well separated in the first three components, thus indicating that statistical analysis of this data is useful and the scatter diagrams (plots) confirm the interpretation of the above data. However, Euphorbiaceae and Asteraceae-2 pollen are strongly correlated with respect to factors 1, 2 and 3, in the PC1 vs. PC2 plot (Figure 6.13), PC1 vs. PC3 plot (Figure 6.14) and Asteraceae-2, Euphorbiaceae and Caryophyllaceae are clustered in the PC2 vs. PC3 plot (Figure 6.15), although Asteraceae-2 does not indicate this contributes significantly to any of the first four components. This suggests these points are strongly correlated. There is however, a significant influence of Poaceae on the components, but the absence of this may be explained by the removal of the mean value during PCA, as Poaceae is a common representative of most samples.

Cluster analysis of the data was conducted on the same set of data (relative percentage values) used for DCA and PCA, in order to establish subsets of samples based on their similarity. Although it was possible to conduct this on the existing pollen diagrams, it was statistically more appropriate to allow for shuffling of dataset samples according to similarity, than observing similarities between neighbouring samples (Grimm 1987). The cluster analysis was calculated on the basis of Euclidean distance of paired groups (calculated by the square of the distance between the variables, summing the square and obtaining the square root of the sum). The results illustrated in Figure 6.16 show that, although the clusters are not well separated or resolved, there is some similarity and interpretive value within the individual cores and close correlation between Asteraceae-2 and Euphorbiaceae, indicated by a cluster diagram of the 6 taxa (Figure 6.17). However, there is also some similarity between select samples in cores H2 and H7, with a strong correspondence between samples

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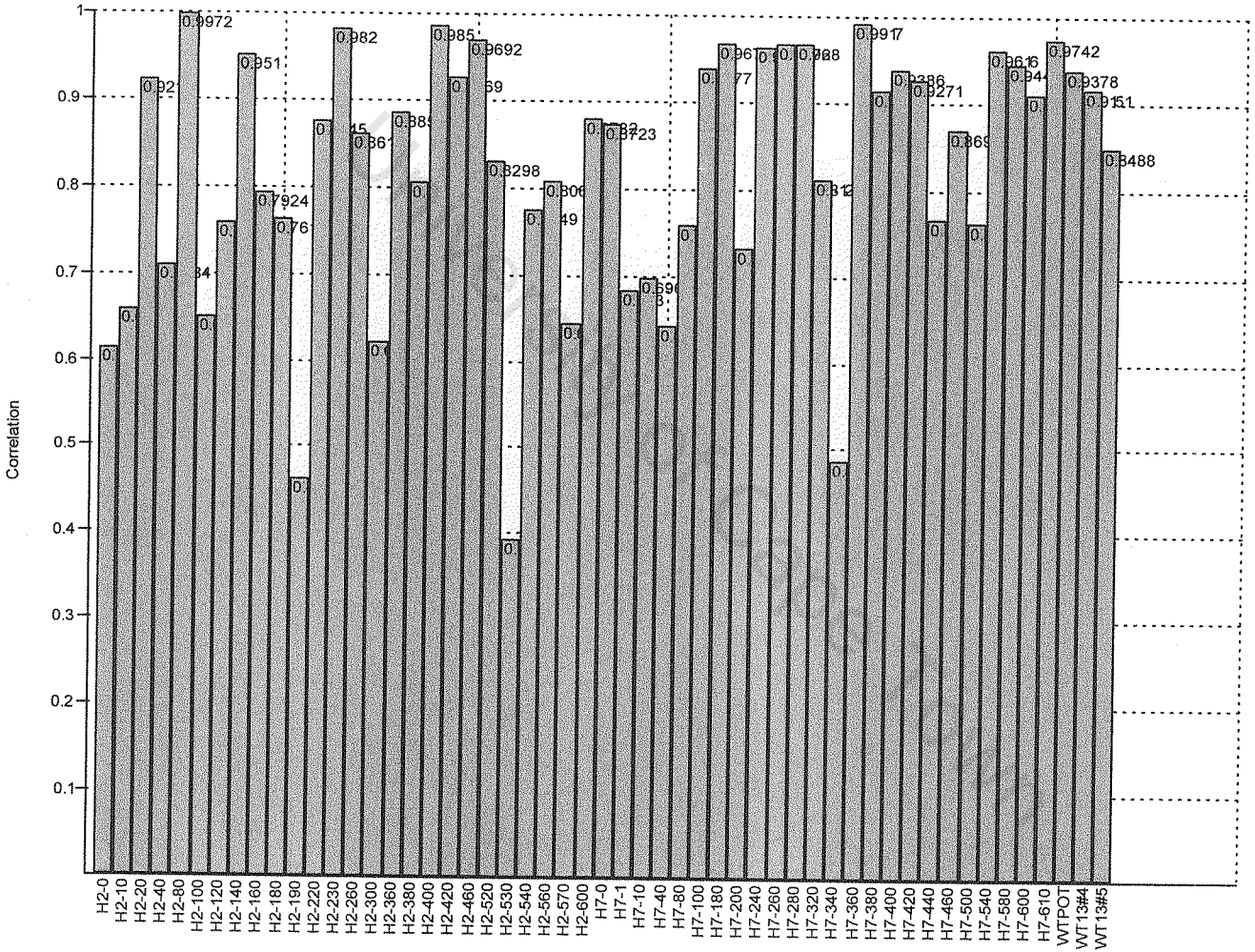

Figure 6.9 PCA loadings - component 1.

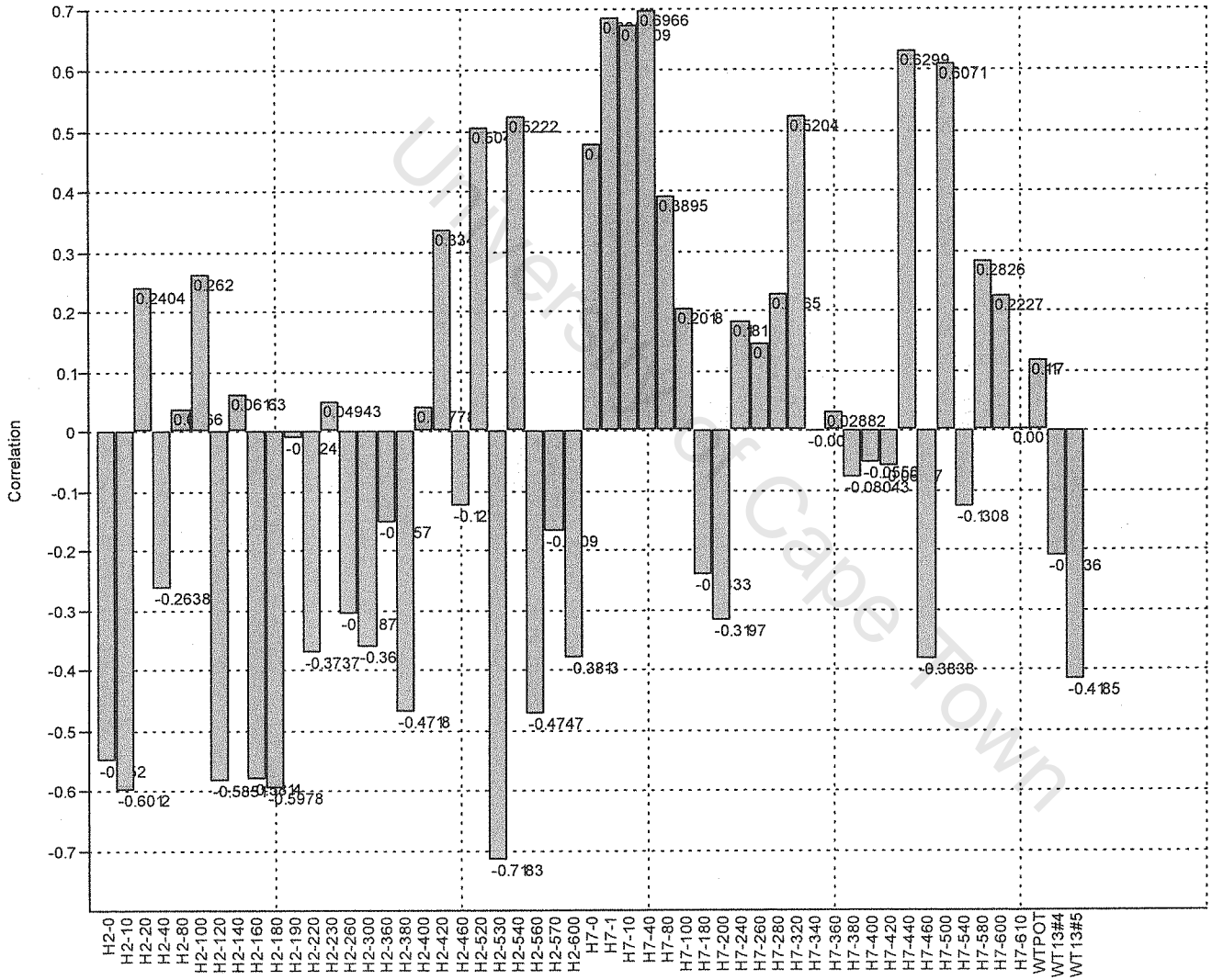

Figure 6.10 PCA loadings - component 2.

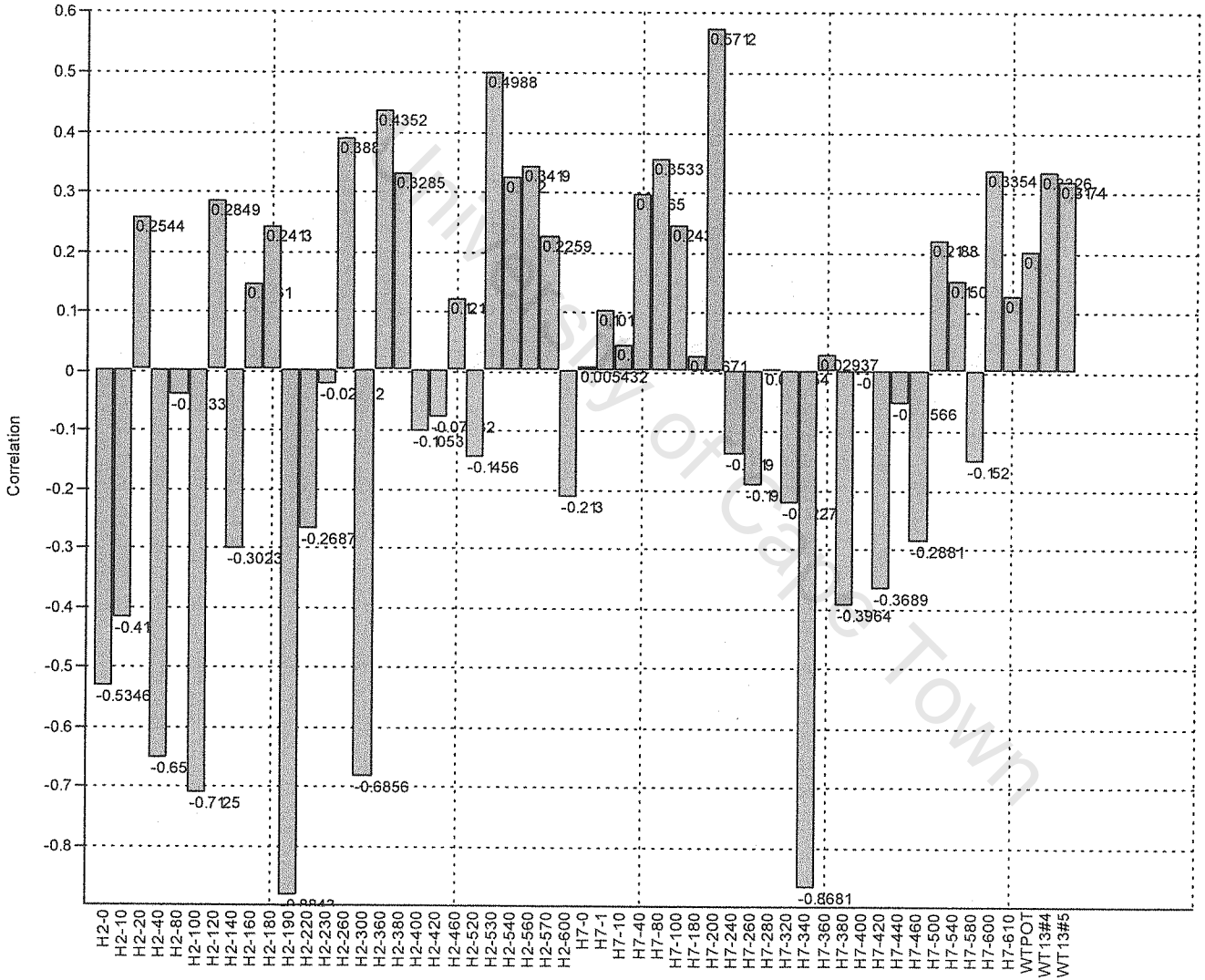

Figure 6.11 PCA loadings - component 3.

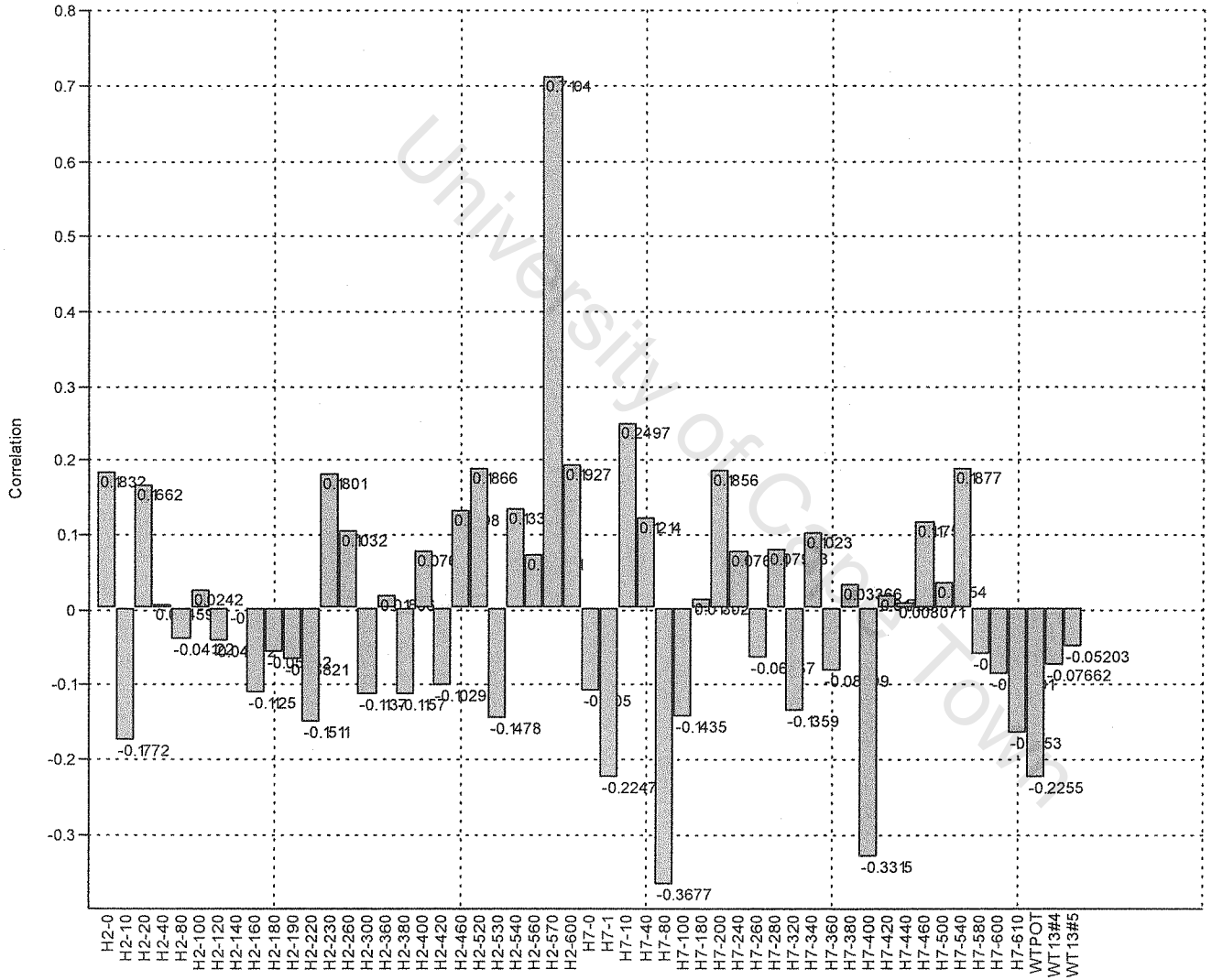

Figure 6.12 PCA loadings - component 4.

H2 460 and H7 180. Indeed, closer inspection of these values reveals a very close fit between the two samples.

Both samples occur reasonably close to radiocarbon dated bulk organic material. H2 460, which is found 12 cm above the radiocarbon age is 1 465 ± 51 years cal yr BP and H7 180 coincides with an age of 2 186 ± 118 years cal yr BP (at 180-185 cm). This amounts to roughly 700 radiocarbon years difference between these two closely correlated samples. It is therefore possible that these samples were deposited during the same event and that this provides evidence for a direct effect of the Orange River on the more southerly core with more marine OM of older age incorporated into the more southerly deposit; there is potential for wide variation within a given sample as it is comprised of sediment of various ages and source. This single sample may be accounted for by a lack of flooding in the Buffels River and influence of airborne materials. Although the samples are not strongly indicative of Grassland origin, they do not exclude the influence of this biome on the pollen.

Another significant similarity indicated by cluster analysis, is the strong correlation between two modern pollen samples from the Richtersveld, namely WT 13#5 and WT 13#4, with those of the mudbelt H2 380 and H2 360 respectively. Moreover, both Richtersveld samples are very similar to each other, as noted from Figure 6.1. Both H2 samples have distinct lithological differences but are characterised by pollen from the Richtersveld region; however, this lends more support to using this pollen data to inform and reconstruct past palaeoenvironmental changes from these samples, as the source sediment and lithology does not necessarily reflect the pollen assemblage. Therefore, from these samples at the depths and ages indicated, it may be suggested that conditions were sufficiently arid, to encourage proliferation of Nama Karoo and/ or Succulent Karoo vegetation during the mudbelt deposition and thereby produce similar pollen presence at different time periods spatially within the core and from different flood soil origins.

H7 100 is found to be similar to the OR pothole sediment (WT POT), which is not unexpected, given the similarity in some components of vegetation in the Richtersveld, the Succulent Karoo and Nama Karoo. Another interesting detail observed from the cluster analysis is that H7 1, the surface sample of H7, is very

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different from the other samples, but this is due to Asteraceae-1 being the only taxa represented (as 100%) as other pollen grains are not well preserved. Perhaps this points to the unique situation that is occurring in the vegetation of the Succulent Karoo of the west coast, where unprecedented change is occurring, rendering the landscape and vegetation entirely different from the late Holocene record. Further, this is supported by the increase in Succulent Karoo, Nama Karoo elements and reduction in Poaceae elements towards the surface in H7. This surface pollen sample indicates much higher levels of Asteraceae-1 (an indicator of disturbance) in recent times and indeed the core in general, although this taxon has also exhibited much fluctuation with some higher levels near the base of the core in zone H7-A. The increase in Asteraceae-1 is associated with a decrease of Asteraceae-2 and Restionaceae. An increase in Poaceae and Boraginaceae could also be due to a significant event in the Buffels River Catchment, as there appears to be a poor contribution of aeolian pollen from the South (Restionaceae) and a proliferation of local pollen taxa.

From the PCA analysis in particular, it appears that the mudbelt pollen is indeed influenced by more than one factor, but that the primary factor, the Orange River (probably combined with aeolian elements) is still the underlying dominant driver. Therefore it lends more support to interpreting data on the basis of changing vegetation, rather than changing source. However, there are exceptions to this rule (as in the above mentioned case), and it is important to evaluate this carefully on a sample by sample basis.

It is clear that depositional age and sediment age, despite the paucity of data, differ dramatically in the mudbelt cores (chapter 4). The major conclusion from chapter 4 is that the radiocarbon dates do not provide a reliable age of deposition. Therefore, recent deposits of pollen may easily become trapped within older aeolian, fluvial (or marine) reworked or recirculated sediment. Core H2 possesses a number of age reversals with depth and it was initially hoped that a similar treatment of the pollen data against radiocarbon age would investigate any relationship not obvious in the simple pollen vs. depth figure discussed earlier in this chapter. Unfortunately there is insufficient reliable radiocarbon data available in order to extrapolate the radiocarbon age of the sediment to this end. Instead, the available radiocarbon dates

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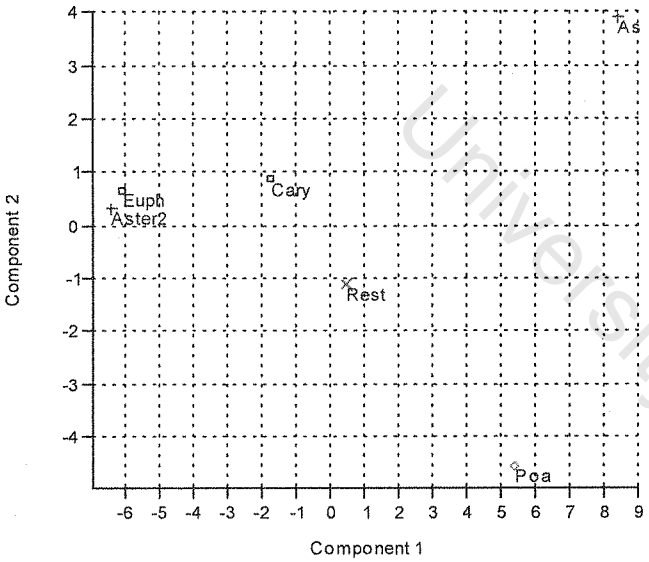

Figure 6.13 PC1 vs PC2 scatter diagram.

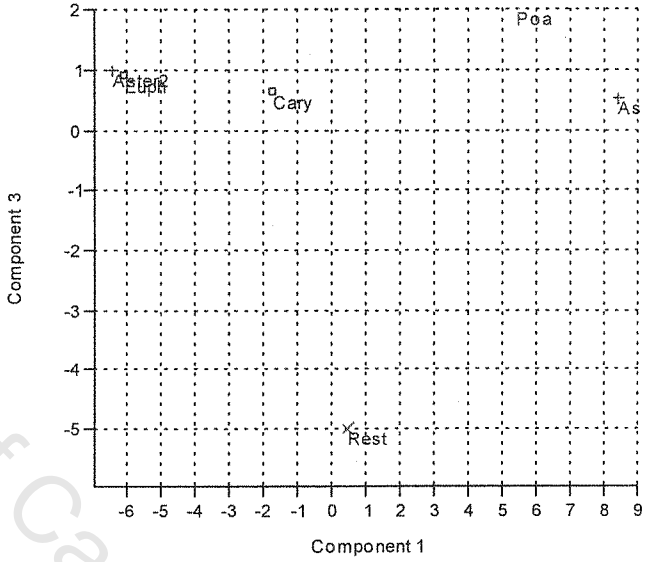

Figure 6.14 PC1 vs PC3 scatter diagram.

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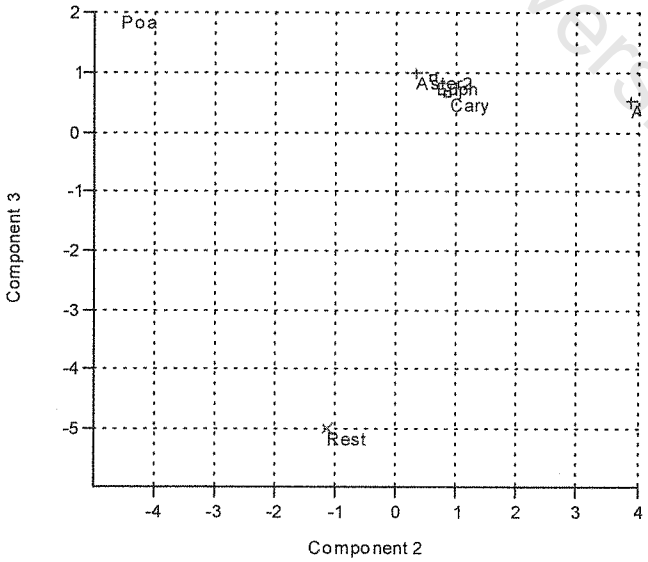

Figure 6.15 PC2 vs PC3 scatter diagram.

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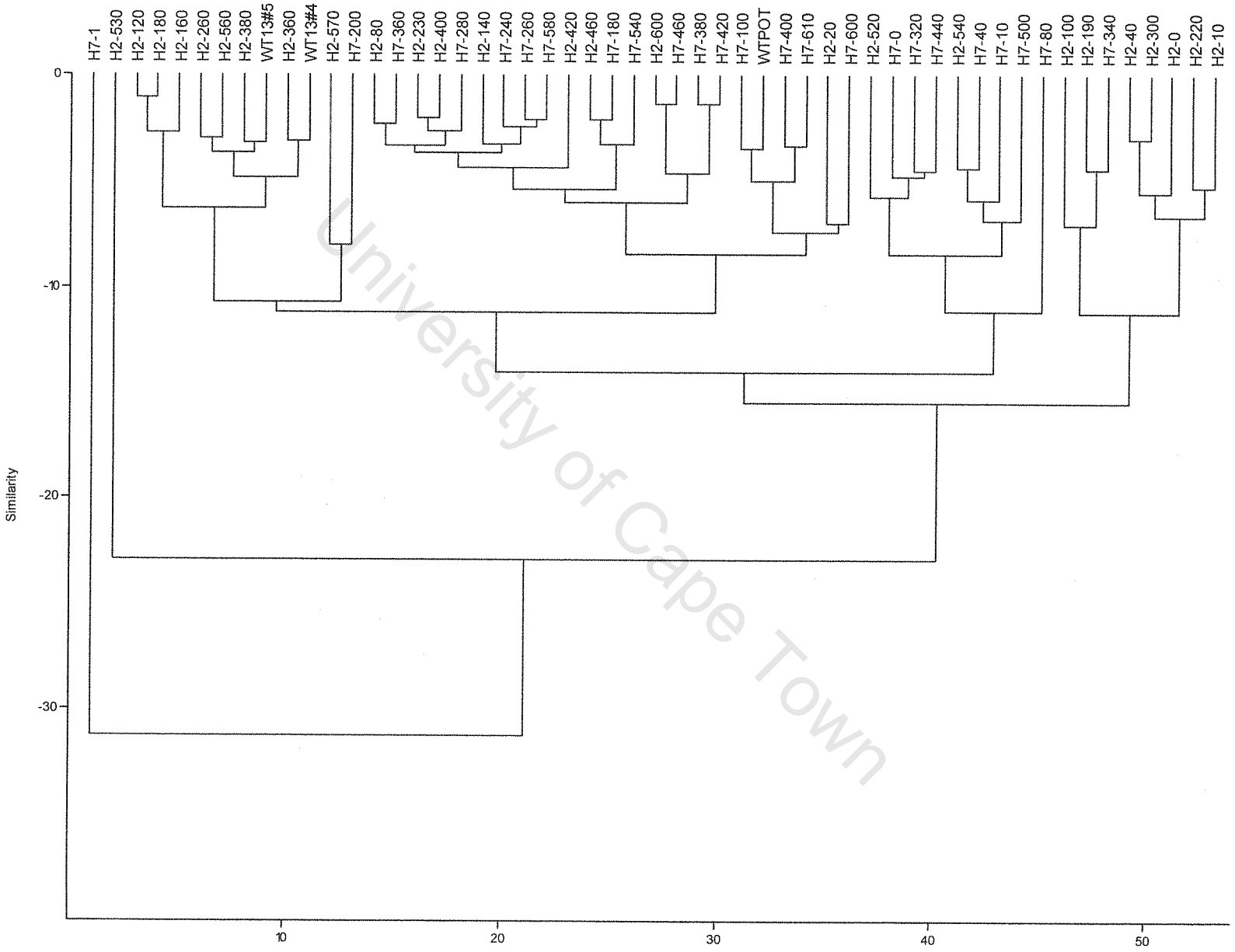

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Figure 6.16 Cluster diagram of samples, showing correspondence between individual samples.

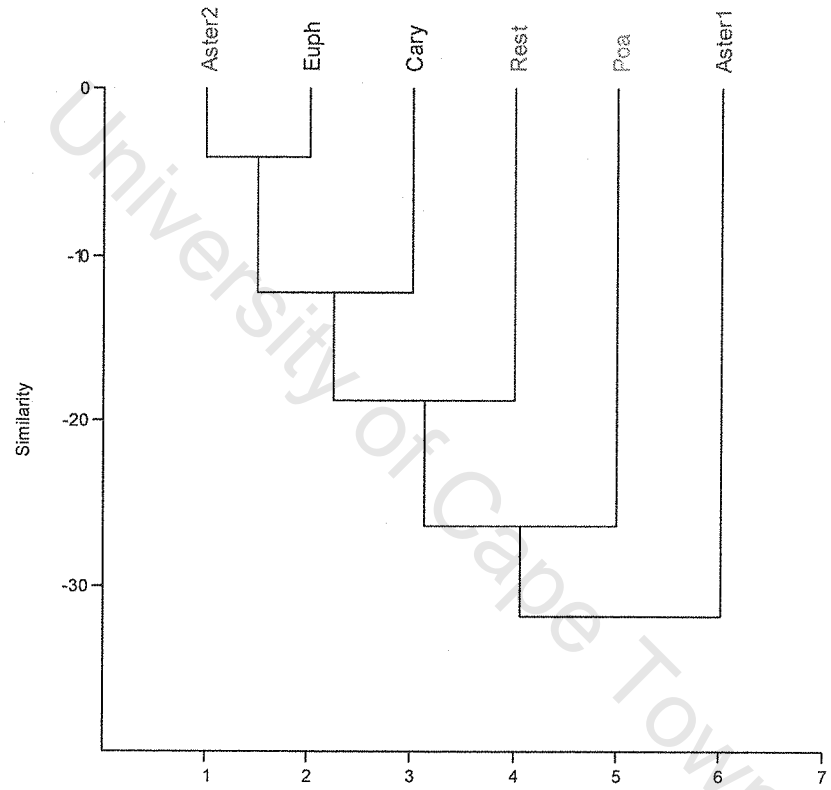

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Figure 6.17 Cluster diagram of 6 taxa indicating correlation between taxa.

suggest that core H2 (the younger core) should be compared with only the top third of H7 (Figure F3, Appendix F).

6.4.2 The fluvial (Buffels and the Orange Rivers) and the aeolian pollen components

Windblown or aeolian pollen is difficult to differentiate from fluvial and other derived sources of pollen and this problem has frequently faced palynologists working with offshore sediments. The solution in quantifying the relative contribution of pollen from fluvial, aeolian and other sources does not lie in simple pollen morphology and is particularly difficult given the catchment size of the area represented. In this instance, the term "catchment" includes not only the catchments of the Orange River and the Buffels River, but the areas represented by the windblown pollen destined for the mudbelt. Pollen 'rain' is primarily produced by anemophilous plants (Faegri *et al.* 1989) and it is these pollen grains which prove most useful in pollen catchment studies by virtue of the quantity produced with potential to be preserved in the sediment (Faegri *et al.* 1989). Quantification of fluvial and aeolian pollen is beyond the scope of this study, although some comments may be made regarding these components.

The question arises as to whether the pollen signal off the Orange River (H2) and Buffels River (H7) is significantly derived from windblown (anemophilous) pollen or from additional sources not represented by the Orange River input in addition to that sourced from runoff. A simple visual comparison between the general pollen assemblage of cores H2 and H7 indicates the component represented in H7 that is not present in H2. This may be the component of the Buffels River which remains when removing the Orange River (fluvially-derived pollen) component that is present in the fine clastic sediment of both core H2 and H7. Using this visual ('eyeballing' or interpretation) comparison of the pollen assemblage as a whole, the following components remain: Asteraceae-1, Caryophyllaceae and Chenopodiaceae/ Amaranthaceae estimated between 30% and 40% and Asteraceae-2&4, Boraginaceae, Euphorbiaceae, Iridaceae, Poaceae and Rutaceae all have been 3% and 5% which provides a strong indication of Succulent Karoo elements. By contrast, Restionaceae (probably windblown as it is primarily sourced in the Fynbos) values are higher by

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about 15% in H2. However, due to complex factors affecting the individual samples, mean pollen content across a sediment unit rather than individual samples is useful for interpretation is useful for this purpose. This simplification is, by definition, generalised but perhaps more effective in examining any general influence or difference in pollen produced by differing sediment sources. Although the Buffels River is an episodic river and little is known of its history, there is however, strong evidence pointing to H2 being more 'terrestrial' than H7 from previous chapter 5 and convincing evidence for H7 receiving more aeolian pollen from the Succulent Karoo. When comparing H2 and H7 only the top 80 - 100 cm of H7 is significant, where the sediment radiocarbon age and ^{210}Pb analysis compares favourably. The Buffels River and its catchment fall under the Nama Karoo Biome, which alters to Succulent Karoo in the lower reaches. This means that the modern signal would be expected to include families from both of these biomes. Species of particular importance would include: Mesembryanthemaceae (Aizoaceae), Euphorbiaceae, Crassulaceae and Asteraceae-4 (*Stoebe*-type). Problems exist as to establishing the long term records of pollen within the river catchment. Not only is the Buffels River region arid and therefore not conducive to pollen preservation, but access is limited due to the presence of high security requirements for this diamond mining area thereby restricting the establishment of long-term pollen records for the area. Setting up such a study was beyond the logistical scope of this research. While the modern pollen signal off the Buffels River mouth could clearly best be established through study of the actual modern pollen in the vicinity, it was necessary to explore this only through consideration of the contemporary vegetation of the region.

An important aspect of interpretation of the mudbelt involves the analysis of sediment type, with the prominence of fine sediment fraction to the south of the ORM and much of the coarser sediment further to the north. It is significant that heavier grains, such as Fabaceae (*Acacia*) polyad-type pollen, which may fragment during flood conditions, are not represented in the pollen signature of the fine grained clastic marine deposit mudbelt. A number of sources cite the aerodynamic limitations of certain *Acacia* species in the southern Sahara and elsewhere as reason for paucity of such pollen in the record (Dupont and Agwu 1991, after Lezine 1987 and Cour and Duzer 1976).

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A question which begs investigation relates to frequency and volume of sediment supply into the mudbelt emanating from the Buffels River itself. The question as to how often and what magnitude of flood and indeed general runoff is represented are not easily answered as yet, given the paucity of research in this area. The Buffels River is episodic (Mabote 1997) and by definition does not flow as regularly as the Orange River. Assuming the Orange is a more important source of fluvial sediment to the mudbelt in general (compared to aeolian and other fluvial sources) and that dust (including aerosols such as pollen) is usually deposited during only a few weeks each year and in low quantities compared to other sites, the aeolian contribution would surely be a less important contributor of pollen compared to the Orange River itself. Certainly, work by Dupont and Wyputta (2003), Rogers (1977a,b), Mabote (1997) and others would suggest this.

6.4.3 Comparison with previous Namaqualand Mudbelt - related studies

The initial pilot study of the cores H2 and H7 during 1996, confirmed the existence of pollen in the cores. This research was disclosed in 1996, in an unpublished Honours thesis (Gray 1996) and also in a paper by Gray *et al.* (2000). It was on the basis of this research that a more detailed pollen study of the cores was formed. The presence of pollen in all six samples initially studied, suggested that there would be sufficient pollen of reasonable quality adequate for identification in the remainder of the cores and this has been fulfilled. Indeed, this research has greatly expanded the 1996 dataset. Some of the postulations, which have now been expanded upon, were made on the basis of these six samples from H2 and H7 with grab, top and base of each core are as follows:

1. The problem of exotic marker species arose in the original project. Tentative interpretation of an increase in some families known to include both exotic and indigenous and of some exotic species (specifically Fabaceae) in surface sediments, suggested that surface sediments were indeed modern. Unfortunately little more information in this regard was obtained due to the broad overlap of species morphologies and exotic mix of species within indigenous families, although increased resolution of samples lends support

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for the initial suggestion that elevated levels point to increased presence of exotic species.

2. Fabaceae (*Acacia*) pollen found only in the grab and top core surface samples of both H2 and H7 were possibly alien or exotic pollen grains and therefore considered to represent recent material, as none was found in the sediments lower down the cores (Gray 1996). However, more detailed pollen analysis in this study does not accord with the original observations, as results at higher resolution indeed reveal Fabaceae (*Acacia*) pollen grains to be found elsewhere in the cores. As this grouping includes both indigenous and non-indigenous species, the previous postulation is disproved. The Fabaceae (*Acacia*) pollen however, was poorly represented throughout the cores and as mentioned in section 6.4.3.1, this is probably due to the Fabaceae (*Acacia*) pollen grains being relatively heavy and aerodynamically unsuitable for effective fluvial transport to the mudbelt.

3. The modern age of surface samples was implied by the relatively high representation of Asteraceae in the surface sample in H7, compared with the base sample (Gray 1996). This has been confirmed for recent sediments in H7 and is supported by new chronology results (chapter 4). However, this trend does not apply to H2.

4. An inverse relationship between Poaceae and Restionaceae was noted in the samples (Gray 1996). Subsequent analysis indicates that this is only true of the surface 40 cm in H7 and to a lesser degree in H2.

5. A comparison between the Coetzee (1976) study and this research confirms that few pollen taxa were identified in both the Orange River and the Buffels River Mouth sediments. The reason for this might be found in the following:

- Limited numbers of pollen taxa may be found at river mouths during low flow discharge.

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- It is possible that surrounding river mouth vegetation flooded the sediment signal during a non-flood period, resulting in over-representation of the pollen signal represented in the mudbelt.
- Windblown pollen might well have more of an influence offshore than within the river at times.
- Coetzee oversimplified counts of the pollen taxa.
- The sediment related to a single flood event (no mention is made of the time of year or conditions of sampling).

Unfortunately it is not possible to verify the Coetzee (1976) and Coetzee and Rogers (1976) information as the samples no longer exist, but it does point to the need for additional sampling off the Orange and Buffels River Mouths for future study. Some noticeable differences between Coetzee's (1976) analysis and work presented here include the absence of *Tamarix* from the mudbelt cores, as these are present in low quantities in Coetzee's Buffels and Orange River mouth counts. It is possible that these pollen grains do not survive in the mudbelt due to oxidation, or that they were misidentified. However, other taxa found are common to those counted at other sites in the study, though they are represented in different proportions. Another reason for the reduced number of taxa identified by Coetzee, might be related to the nature of the mouth at the time of sampling. In the recent past and indeed, particularly since construction of dams on the river and massive water extraction by industry and agriculture, water outflow has been severely reduced. This has resulted in significant reduction in the wetland vegetation at the Orange River mouth and led to siltation and regular closure of the Orange River mouth to the sea. It is possible that sampling corresponded to a non-flood period when the influence of the wetland vegetation was still a significant feature, although starting to decline. Therefore, the local river mouth sediment signal might be over-represented by local pollen, surrounding and associated with the wetland and samples taken further off in the mudbelt may be diluted showing greater diversity of taxa. However, wetland taxa do not appear to have a dominating effect on the surface of the pollen diagram, although some elements such as Chenopodiaceae-Amaranthaceae are prominent.

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In this project research and, indeed, in the pilot study, many more pollen families were identified than published in Coetzee's work. As a result it was possible to utilise more nuances of the vegetation change to aid interpretation.

Some samples exhibited very low pollen counts. Indeed certain samples indicated such low pollen counts as to be negligible or inert. This could be attributed to factors such as high energy reworking, high energy flooding and flooding from an arid environment (lower reaches of the Orange River) diluting the more pollen bearing sediment. Others, namely H2 190 and H2 530 were low and the counts were limited to a total of 100; these are associated with high proportions of indeterminate pollen grains, indicating that pollen quality was poor and some statistical inaccuracy was introduced. The low counts in these two samples, (H2 190 and H2 530) were perhaps caused by some degradation of the sediment as pollen in these sediments tend to be eroded and poorly preserved. It is interesting, however that the H2 190 drop in representation of Asteraceae-1 is associated with an increase in Asteraceae-2 and -4. However, it is possible this is simply an artefact of the low count. The relation between isotopes, age and pollen is detailed in chapter 7; however, some observations can be made on the basis of age of sediment and lithology type and these are presented where relevant.

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7 DISCUSSION AND SYNTHESIS

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This chapter draws together the results of the palaeoenvironmental records of the Orange River mudbelt and related sites using the three main methodologies, namely chronology, stable isotopes of carbon and nitrogen and palynology. These findings have already been discussed individually in chapters 4, 5 and 6, but here an attempt is made to explore the implications of this offshore terrestrial record in the broader southern African context.

7.1 Towards a synthesis of proxy data

The geographical extent, the climatic, environmental and the biological diversity of the Orange River Catchment pose challenges to palaeoenvironmental interpretation. Sediment deposition in the mudbelt is controlled by a number of mechanisms that include, *inter alia*, climate and sediment supply, rainfall in the Orange River Catchment, floods, upwelling, sea level rise and bioturbation. In recent years, impoundment, abstraction of groundwater and surface water, together with other agricultural practices have impacted vegetation cover and erosion, superimposing their influence on the natural changes in palaeoenvironments as expressed in the various parts of the mudbelt. Each of the proxy tools used in this research has both benefits and drawbacks. The three main methodologies of this thesis contribute to an improved understanding of the palaeoenvironmental record of the Orange River Mudbelt. However, problems of taxonomic resolution affect interpretation of fossil pollen, while overlap in the geographical distribution of plants of different photosynthetic pathways in the different biomes and environments (C_3-rich marine and C_3-rich terrestrial vegetation) affects interpretation of the isotope record. This has been further compounded by problems of establishing a reliable chronology.

Although the pollen, chronology and stable isotope proxy records of the mudbelt are integral to the synthesis of the whole, developing an understanding of its chronology is essential to the resolution of palaeoenvironments. Indeed, it is challenging to interpret climatological information from the pollen and only tentative observations may be made that allude to wind direction, some aspects of moisture/aridity and also

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disturbance.

7.2 Synthesis of chronology data: ^{210}Pb and additional radiocarbon analysis

A number of attempts have been made to resolve the age of the mudbelt using the two cores H2 and H7, and related box and gravity cores. The depositional age of the mudbelt surface has now been firmly established as being recently deposited ('modern' - within the last 150 years) by means of ^{210}Pb analysis employed here. This was conducted in combination with the pre-existing bulk organic radiocarbon ages and the true age of the organics, compared to their depositional age has been illustrated. The radiocarbon ages are based on bulk OM and these revealed age discrepancies; older than expected ages were recorded at the surface of the sediments (Meadows *et al.* 1997). Therefore modern sediment was indeed sampled during core retrieval. This is an important conclusion in relation to the proximal mudbelt surface, where uncalibrated bulk organic radiocarbon ages yielded an age of 570 ± 35 years BP[1] (Meadows *et al.* 1997, 2002 and Gray 1996, Gray *et al.* 2000). These older ages were initially ascribed to the removal of modern surface sediment due to the coarse grab-sampling technique or disturbance by the wake of large floating vessels in the vicinity. Although other mudbelts and offshore deposits had been widely reported as representing reworked OM (Mayer 1994), this had never been fully articulated within the mudbelt data and as such represented a unique opportunity for resolution. Given the pilot pollen investigation of the mudbelt reported in Gray (1996) and Gray *et al.* (2000), resolution of the mudbelt chronology was a priority and framework upon which investigating any additional proxy palaeoenvironmental data rests.

It is difficult to determine the precise depth at which the excess ^{210}Pb levels off completely. By extrapolating the ^{210}Pb curve, this occurs somewhere between 30 cm and 80 cm depth, but comparison with pollen spectra suggests this is closer to 30 cm.

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[1] Equivalent to 536 ± 16 cal yr BP

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The bulk organic radiocarbon ages previously published in uncalibrated form appear for the first time as calibrated dates in this thesis. Results of ^{210}Pb analysis suggest that bulk organics within the mudbelt prodelta are at least 590 ± 41 years (or 536 ± 16 cal yr) older (Gray 1996, Meadows *et al.* 1997) than the depositional event they represent. Therefore, the proximal mudbelt sediment surface has a radiocarbon age of at least 520 years. The bulk organics refer to the mean residence time and age of organic material from both terrestrial and marine sources deposited in the mudbelt rather than the age of deposition *per se*. This may be explained by reworking, incorporation of old marine carbon and issues of cycling within the carbon reservoir. Sources cite the average radiocarbon age of North Atlantic surface waters and other parts of the Atlantic Ocean as being ±400 to ±800 years old (Bard *et al.* 1987b, 1991, Stanley and Hait 2000) with similar values for the south Atlantic (Vogel pers. comm.), where upwelling zones have a standard age lag of 400 years or older, which may vary from place to place. This recent surface layer extends to a depth of at least 30 cm in both the prodeltaic core H2 and the more distal core H7 of the mudbelt. The ^{210}Pb results are not of sufficiently high resolution to calculate sedimentation rates with any degree of precision. Further, mudbelt sedimentation hiatuses could well be a feature of the deposits, not least of all due to closure of the ORM from time to time but this could only be confirmed with the use of detailed dating of the sediment as other methods do not provide conclusive evidence. The lithology of the mudbelt however, shows distinctive yet subtle variations in the mudbelt which could be indicative of hiatuses; pollen spectra indicate some hiatuses in pollen data (some depths are devoid of pollen) but these have nothing to do with possible interruptions (hiatuses) in sedimentation; stable isotope curves do however show smooth variations more suggestive of continuous deposition. Fine age resolution of the mudbelt deposit at depth, although attempted in this study, was not possible using foraminifera, as these were poorly represented in the mudbelt sediment, thereby preventing a more accurate form of examining the mudbelt chronology. Should this initiative have been successful, the small sample AMS radiocarbon ages may have yielded specific ages of deposition at exact depths in the mudbelt, rather than the existing bulk organic radiocarbon ages representative of an average of potentially reworked and 'old' terrestrial and marine carbon. New work by Herbert and Compton (2007) has established radiocarbon ages of parts of the mudbelt using mollusc shells and

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foraminifera from a set of cores obtained which were more fossiliferous than the original HODSA cores reported on here. Results also show calibrated bulk organic radiocarbon ages in H4 and H7 using the Southern Calibration curve dataset, SHCAL04.14c (McCormac *et al.* 2004) and the International dataset, INTCAL04.14c (Reimer *et al.* 2004) and CalPal, where available, are comparable to those using the ages obtained by Herbert and Compton (2007), thus adding support to the validity of ages obtained using this method. Analysis for ^{137}Cs revealed negligible to near negligible levels of the radioisotope, which was to be expected, as ^{137}Cs levels are considerably lower in the southern hemisphere.

The successful retrieval of the surface layers was established through ^{210}Pb analysis, where the surface of the box cores yielded slightly more excess lead than in the grab samples. It is probable that this is a result of one or more of the following factors:

- The time lag between box and gravity core sampling may have resulted in changes to the mudbelt surface between these two core retrieval exercises, as all three box cores were slightly more enriched in excess lead than their grab (gravity core) sample counterparts. This is more likely as box cores have a greater chance of sampling more cleanly than a gravity corer in tandem with a grab sampler.

- A second possibility, although less likely, is that because the box cores were retrieved a few months after the retrieval of the gravity core and grab samples, the samples contained more recently deposited sediment that had accumulated on the mudbelt surface.

- A further possibility involves *in situ* human disturbance: Although the sediment from both the box cores and grab samples are found to be modern, the box core material represents slightly more recently deposited sediment than the surface (grab samples) of the gravity cores. This minor difference is unlikely to be due to the time lag of a few months between the two sampling exercises. Although the mudbelt is considered to be undisturbed during diamond operations, diamondiferous sediment is further off the shelf, it should not be completely discounted that offshore work might disturb material and

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possibly account for a slight discrepancy in surficial layers.

There is evidence of some mixing occurring within the sediment column of the mudbelt; however, there is a general incremental trend in reduced excess ^{210}Pb with depth in the three box cores, thus pointing to an upcore 'younging' of the sediment. The ^{210}Pb analysis of the mudbelt cores H2 and H7 follow a largely chronologically logical pattern with minimal mixing, which is possibly due to the effects of currents, storms, bioturbation, tides and other mechanisms of mixing. This lends support to the usefulness of the other palaeoenvironmental proxies and provides evidence for less *in situ* mixing than bulk organic radiocarbon ages suggest. The occurrence of even relatively minor mixing is noted as a caution to the interpretation of the other evidence presented here. However, evidence from stable isotope data indicates a smooth data excursion suggestive of a minimal mixing effect. Further, the radiocarbon ages and ^{210}Pb analysis suggest that reworking within the river and the reservoir effect (on both land and ocean) contribute to the age reversals more than *in situ* reworking within the mudbelt. This explains why even laminated sediment in core H2 indicates some age reversals despite an absence of post-depositional reworking. Indeed, subsequent to sampling at Jakkalsberg, these sites have been eroded, thus illustrating the erosion of older sediments and their potential re-deposition in the mudbelt. This provides support for the palaeoenvironmental proxies that tend to relate more to depositional age than reworking, as this sediment can be interpreted to be chronologically correct.

The single sample OSL analysis reported by Meadows *et al.* (2002) corresponds and lends support to the bulk organic radiocarbon age at the base of H7. However, given the well publicised deltaic situation regarding recent sediment containing older relict organics and the validity of this argument is put into question, it is surprising that the bulk organic date at the base of core H7 represents an accurate age of deposition. Although the sampling was done according to standard procedures and overseen by Mabote and the author, the single OSL date was obtained using older, less accurate analytical techniques than currently used (Dave Thomas pers. comm.).

The overall interpretation of the mudbelt chronology is still problematic, but notable improvements have been made to the previous findings of Meadows *et al.* 1997, 2002

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and Mabote 1997 and all logistically and financially possible avenues for further examination of the HODSA cores of the mudbelt have been explored. This revised chronology is crucial for the interpretation of pollen and stable isotope analysis results in the HODSA mudbelt cores and contributes to a growing body of work on the Namaqualand mudbelt and the inner continental shelf.

Now that an improved understanding of the mudbelt chronology has been established (in as much as the surface sediments have been established as recent and old carbon is present in the sediment, pre-dating age of deposition), what then are the implications for the comparison between H2 and H7? This question has significant implications for understanding the age of proximal sediments off the Orange River compared to other similar sites which are only occasionally open to the sea and how this affects the age of the surface layers of the mudbelt. This thesis does not cover this question in spatial detail beyond that which may be deduced from the simple comparative study between proximal and distal mudbelt cores, H2 and H7[2]. However, this does raise some interesting questions as to how to go about a future study and what can be interpreted from the results presented here. The surface sediment of both cores H2 and H7 exhibit very similar excess lead values and are both modern (less than 150 years in age). Mudbelt sediment from the base of H2 (597 cm) has a radiocarbon age of 858 ± 57 cal yr BP. The basal age of H2 is roughly equivalent to sediment found at a depth of 175 cm in H7, as core H7 has a maximum radiocarbon age of 3470 ± 78 cal yr BP. H2 has a younger record of sediment which begs the question as to where the older sediment went and how this was effected? Perhaps this was eroded during high flood conditions or during significant sea level change which facilitated erosion of sediment in the prodelta more than in the distal portion of the mudbelt. Herbert and Compton (2007) confirm that older sediment of up to a mean value of 12 769 cal yr BP is indeed found in the southern sections of the mudbelt; older ages tend to be found at depths below the maximum 600 cm sampling possible with the gravity corer used in this study. The fact that H2 has a higher sedimentation rate compared with H7 is

[2] Herbert and Compton (2007) have established a southward younging of the mudbelt and an increased rate of deposition in the mudbelt south of the area investigated in this thesis.

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understandable given that the Orange River is a significant source of sediment to the mudbelt and is located in the immediate area of the prodelta. This is particularly true in H2, which is of more interpretive value than radiocarbon age. Depth is therefore retained as the basis on which the palaeoenvironmental indicators are determined, given problems of poor radiocarbon age resolution. Pollen and other palaeoenvironmental data (e.g. stable isotopes) should perhaps be interpreted by depth and, in some cases, on a sample by sample basis with radiocarbon age serving only as a guideline as to the bulk radiocarbon age of the sediment.

7.3 Interpretation and synthesis of chronology, stable (carbon and nitrogen) isotope and pollen data

The data obtained from three different analytical directions used in this thesis demonstrate an improved understanding of the mudbelt sediment and provide palaeoenvironmental evidence for the Orange River Catchment, a significant expanse of southern Africa, surrounding adjacent biomes and incorporating the Buffels River Catchment. There is however the challenge posed in separating the regional and local indicators with the result that interpretation is limited. At some depths, changes in one proxy are found to be consistent with changes in other data sets at other depths, the data are complicated and interpretation hampered by inconclusive proxy evidence; this may be a function of the large catchment source area, which could become clearer on the basis of future work.

Conclusive evidence of the presence of modern sediment at the mudbelt surface has established the relevance of the record in comparing the palaeoenvironmental data against historical and current vegetation patterns. Indeed, the cores were found to include the mudbelt surface and thus have provided a modern proxy against which to compare the palaeoenvironmental data from the mudbelt. Further, this research establishes that the Namaqualand mudbelt radiocarbon sediment age differs dramatically from the age of deposition. The discrepancy between depositional age and sediment radiocarbon age, combined with differences in age of proxy evidence, poses a challenge to isolating specific ages of palaeoenvironmental indicators. Although deltaic mudbelts are established as useful for

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palaeoenvironmental interpretation, the challenge has consistently been one of overcoming problems associated with organic carbon recirculation. This study highlights the significance of the Namaqualand mudbelt as unique records of inland vegetation change for the subcontinent.

It was possible to display only a portion of the pollen, palaeoenvironmental and chronology results for cores H2 and H7 and these are represented in Figure 7.1. This figure incorporates the bulk organic radiocarbon age (where available), the ^{210}Pb data showing an overlap of modern sediment to a depth of at least 30 cm, a truncated pollen diagram (based on significant taxa used for the statistical data, this excludes the Riparian elements), stable carbon and nitrogen isotope data in addition to the inverse percent nitrogen (as weight) against depth data. The figure also includes the detailed lithology obtained from the original core log, although surprisingly neither this nor the simplistic lithology corresponds well with significant palaeoenvironmental changes. Indeed some of the laminated sediment found in H2 indicate significant age reversal, suggesting that although reworking along with input from the marine carbon reservoir could well occur prior to deposition, *in situ* reworking is not of primary importance in the mudbelt. H2 is more affected by bulk organic radiocarbon age-reversals than the more distal core H7, which is further from the ORC source (where sedimentation rate and volume is therefore higher). This would explained H7 receives more diluted input from the Orange River at a lower sedimentation rate prone to spurious bulk organic ages. Mudbelt research of the cores in question has previously relied on the simplistic lithology interpretation supplied by Dingle (1994). Closer inspection of the original ship's log revealed subtle changes in the lithology as illustrated in the synthesis figure (Figure 7.1). However, both the more detailed lithology and the simple model (discussed in chapter 2) do not correspond with any fluctuations in pollen and isotope data and it is again apparent that depth rather than lithology or radiocarbon age is more useful to aid in the interpretation of palaeoenvironmental data in this study; further mineralogical investigation is required to examine a more likely connection with sediment source.

An attempt is made at distilling this information into interpretive tables (Table 7.1 and 7.2) which include some of the pertinent palaeoenvironmental information for the

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proximal (Table 7.1) and distal mudbelt (Table 7.2). Here, pollen data are described and listed in order from surface to base of the cores (this differs from the manner in which the pollen is described) to provide a more visually correct (rather than chronologically correct) table. The pollen data are complex and it is not possible to interpret all palaeoenvironmental implications adequately by way of a synthesis.

Although pollen and stable isotope methods represent different proxies of the vegetation represented in the ORC, their data present varied perspective and insights. For example, although the essentially CAM vegetation of the Succulent Karoo are considered to have a minimal influence on the organic composition of the Orange River Mudbelt (as discussed in chapter two), the pollen obtained from the same vegetation of the Succulent Karoo certainly makes a contribution to the pollen spectra of the mudbelt. The pollen are easily incorporated into the mudbelt from the Succulent Karoo (wind transport) but this contribution is limited and the majority of pollen is carried fluvially from inland, and isotopes are considered to have a minimal input from this area as aeolian and fluvial sourcing of isotopes is considered negligible from this sub-region.

The $\delta^{13}C$ isotopes are derived from the organic fraction of the sediment. Both $\delta^{15}N$ and $\delta^{13}C$ are sourced in the ORC from fluvial and marine sources; aeolian input is minimal. This contrasts with the significant but unquantifiable portion of pollen transported into the mudbelt this way. It is assumed the pollen tends to be deposition-specific with a small portion restored from older sediment. Pollen tends to be corroded in highly arid conditions, and post-depositional reworking is minimal.

A valid question regarding the pollen data is to what extent do shifts in the pollen spectra indicate one or more of the following: local climate or vegetation change, a shift in catchment sediments or a reworking of old sediments as is demonstrated by the age of the organic fraction. These spectral variations cannot be exclusively determined by either climate or vegetation change alone and would surely indicate a combination of both. A number of periods of aridity are indicated by the mudbelt pollen, although it is difficult to identify the precise time at which these are occurring.

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It is also difficult to ascertain to what extent this is perhaps a feature of the sediment source rather than a product of real environmental change and indeed of large scale palaeoenvironmental significance.

Although pollen is found in relatively low concentration in the mudbelt, considerably more pollen taxa were identified in this study compared to other studies in the vicinity, such as Coetzee and Rogers (1976) and Coetzee 1976. Certainly more taxa were identified since the pilot pollen study (Gray 1996 and Gray *et al.* 2000), although the sample results which were re-counted for this study are comparable to the earlier 1996 analyses. In addition, resolution of sampling and analysis was much increased from the pilot study, where only three samples from each core were analysed. Pollen analysis conducted on a small number of WT samples representing OR low flow discharge sediment correspond well with the pollen assemblage of the H2 surface samples. This is contrasted with the negligible levels of pollen found in the Richtersveld slack water deposits that are affected by oxidation, due to arid conditions. Stable isotope analysis, on the other hand, was more easily and rapidly established compared to pollen analysis due to the relatively significant proportion of organic and nitrogenous compounds in the sediment.

The Orange River pollen samples (WT), retrieved during low flow sampling, proved comparable to both the local Succulent Karoo vegetation and the Coetzee and Rogers (1976) ORM study in many respects, although the latter provided more simplistic results than obtained in this study. In addition, this pollen analysis presents new research for the growing record of offshore pollen studies in the South Atlantic including Dupont *et al.* (2007), Rommerskirchen *et al.* (2006), Dupont and Wyputta (2003), Shi *et al.* (1998, 2001) and specifically OR studies such as Coetzee (1967) and Coetzee and Rogers (1976) which point to a strong correspondence between the marine pollen profile and latitudinal distribution of inland vegetation (Dupont *et al.* 2007). These studies tend to fall north of the ORM and therefore are useful to vegetation largely part of the adjoining vegetation of this research area, with the exception of windblown elements to the south (Restionaceae, Asteraceae) which are found at study sites associated with the Walvis Ridge (Dupont *et al.* 2007).

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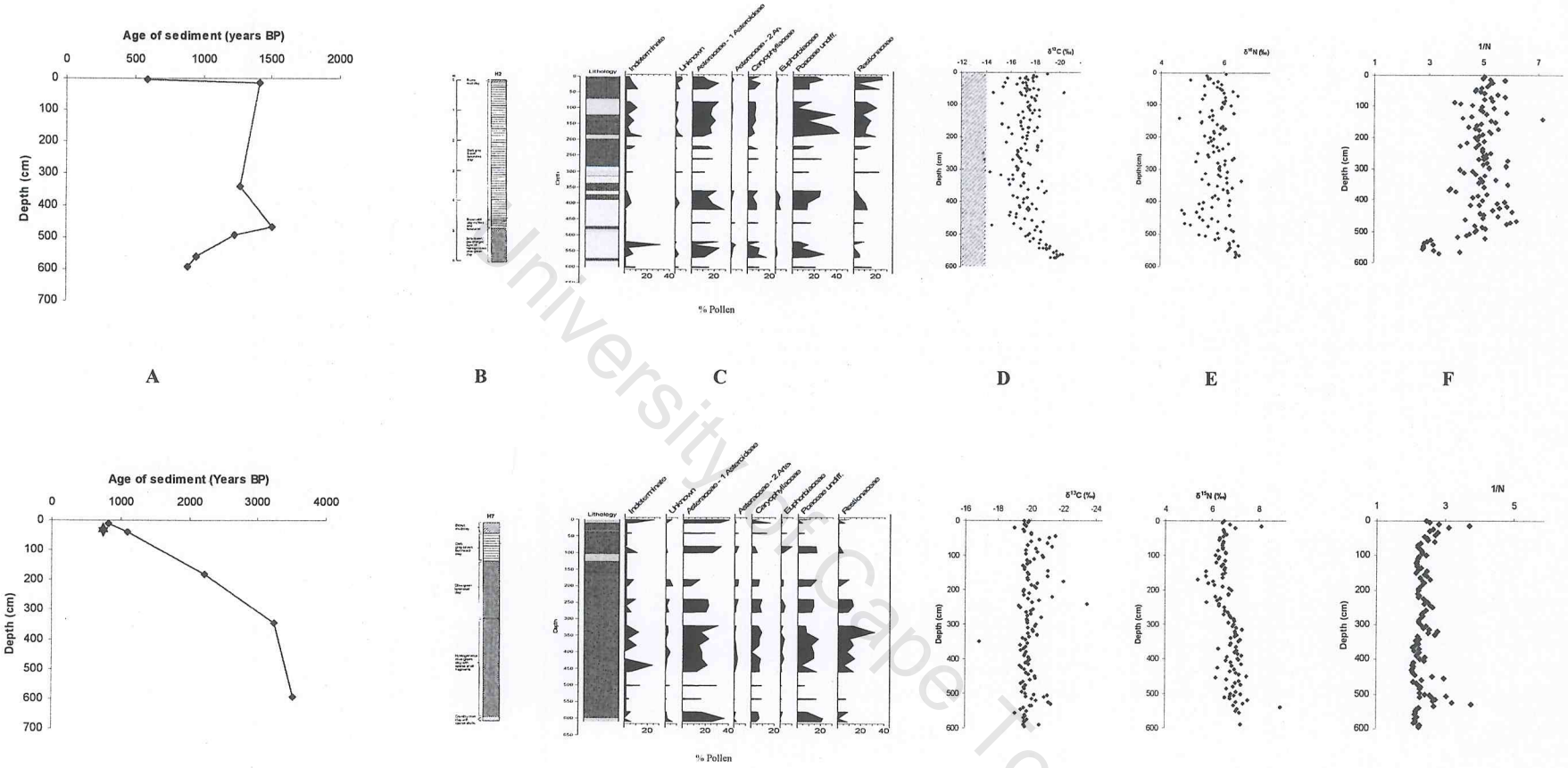

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Figure 7.1 Synthesis of chronology (A), pollen (C), carbon (D) and nitrogen (E) stable isotope and inverse nitrogen (F) data for cores H2 and H7. Note * denotes modern age of surface (0-30 cm) sediments ($^{210}Pb_{excess}$) in A, along with calibrated radiocarbon dates (cal yr BP). Simplified lithology (after Meadows *et al.* 1997 and 2007) is found in B. Detailed changes in lithology (Appendix E) are included with the pollen diagram for reference (after Dingle 1994).

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There are a number of biomes represented by pollen and wind pollinated taxa in the mudbelt but not all are useful to understanding the catchment area. Indeed, it is difficult to differentiate fluvial from aeolian pollen. The Fynbos biome which routinely includes Restionaceae as a common element of the vegetation is sourced in a winter rainfall biome; the biome is currently located further to the south of most of the catchment areas, providing evidence of influence of southerly wind direction and is spatially separate from the majority of pollen taxa represented in the Orange and Buffels River Catchments. Few exotic taxa were positively identified in the mudbelt, mainly due to overlap of pollen morphology. In addition, indigenous taxa such as *Acacia* (polyad-type Fabaceae) are poorly represented in the fine sediment of the mudbelt, probably due to these and other relatively heavy pollen being carried as coarse grain materials to the north of the mudbelt by longshore drift. Further, there is some overlap between indigenous and Australian morphologic types, although this does not present a problem in this study given the limited representation of this pollen type.

It is clear that the proximal and distal areas of the mudbelt are characterized by isotopically distinct palaeoenvironmental proxy data. The distinctiveness of the two cores is illustrated by the palaeonenvironmental data of the proximal H2 core and its age equivalent 175 cm depth of the distal H7 core, which are not well correlated. The distal mudbelt, represented by core H7, is characterized by more depleted $\delta^{13}C$ (C_3 enriched) sediment than the proximal core H2; H2 tends towards terrestrial stable isotope values, whereas the distal mudbelt (H7) tends towards marine values (although H7 contains some significant components of terrestrial influence). In addition, the mudbelt cores are more isotopically homogeneous than the inland sites. More depleted $\delta^{15}N$ values in H7, suggests a more marine environment with less influence of terrestrial organic carbon in this section of the mudbelt, due to less direct influence by the Orange River and the ephemeral Buffels River. The surface of the distal mudbelt (H7) is characterized by lower nitrogen (higher values of inverse nitrogen) and stronger terrestrial values than sediment below the surface, although this core is more marine in general. This suggests that the modern surface sediment received an increased fluvial (flood) input from the Buffels River (which is more likely due to its close proximity) or a larger and recent input from the Orange River. The distal mudbelt (H7) appears to indicate two main periods of terrestrial input (high inverse nitrogen values); the injection of terrestrial

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sediment in both modern deposit (top 30 cm) and near the base of the core (at a depth of about 550 cm) suggests a strong influence from the Succulent Karoo via the Buffels River. Although it is not clear where the pollen is originating, the Buffels River is a reasonable assumption given that the pollen represented at these depths is characterized by negligible amount of Restionaceae. This suggests that the wind blown pollen has been diluted by a strong local fluvial influx. Further, the levels of Poaceae are also at their lowest level in the core at these depths, providing additional support. In addition, core H7 appears to be dominated by C_3-rich OM potentially from the Buffels River rather than from marine sources at this depth.

Regarding carbon and nitrogen stable isotopes, it is a challenge to separate the regional terrestrial (C_3/C_4 mixed vegetation) data from the marine (C_3-rich) signature in the stable carbon isotope data given the overlap in values. In addition, there is great potential for a wide range of values from the $\delta^{13}C$ and $\delta^{15}N$ results within the terrestrial vegetation and the mudbelt cores, H2 and H7 differ in bulk organic age. Additional interpretive tools such as inverse nitrogen and C/N values have been useful to further aid interpretive terrestrial vs. marine indicators. LX, JKB and modern OR bed load vary widely (1.4 to 22.8), with more than a third of JKB values below 11 and therefore within marine values. Indeed C/N values are lower and closer to marine values than expected and parts of the mudbelt show overlap with some inland sites; H2 values range between 4.0 and 7.5 and H7 values range between 4.5 and 6.9. However, inverse nitrogen has proved consistently more useful than C/N value.

Both the inland modern and the distal mudbelt surface isotopic values tend towards C_3 values, which stand in contrast to the Lower ORC (Richtersveld) palaeoenvironmental sites, where values tend toward C_4 values. H2 indicates a greater influence of C_4 rich sediment at times with $^1/_N$ values indicating the surface of H2 has lower marine input for the surface sediment. This possibly suggests C_4 rich flooding events or input from algal deposits in the salt marsh at the ORM but the marine – terrestrial admixture varies from time to time depending on terrestrial input from the ORC. Given the average values for:

- the prodelta, H2 (-17.4‰, which adjusts to -17.1‰ for the top 500 cm of the core

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from -19.0‰ for the depths 600 cm to 500 cm),

- the distal mudbelt, H7 (-19.7‰),
- Jakkalsberg site (-21.9‰),
- Lower Xobies, the high threshold flood deposit site (-19.2‰) which has larger grain size and differs with the mudbelt regarding clay type and is more C_3 in character than expected,
- the Richtersveld Orange River (WT) bed load (-21.5‰),
- the Upper Catchment (-19.3‰) after Maake and Compton (2007),

The above values probably explain an equal combination of the mixed marine and terrestrial signal in the mudbelt based on the modern terrestrial low flow bed load (-21.5‰) and the isotopic signature dominated by C_3 vegetation from the Lesotho Highlands (highest rainfall region) in the Upper Catchment, which may from time to time be diluted with large flood packages of sediment from C_4-rich regions. The modern Orange River (bedload) is more depleted in ^{13}C than expected given the -19.3‰ of the Upper Catchment but may indicate a significant input from the C_3- rich river bank vegetation. The prodelta is strongly dominated by C_4 vegetation but inland values are more representative of the C_3 contribution to the C_3/C_4 mix than previously examined. Further, significant portions of sediment in the ORC is sourced in the Upper Catchment according to stable isotope work (Compton and Maake 2007). The relatively high TOC values found in the mudbelt compare well with those values of high productivity, the Upper Orange published in Compton and Maake (2007). The modern sediment may also be affected by the increasing impoundment in the ORC and moderation of the previous bimodal flood regime. The surface isotopes indicate an increase in C_3 rich sediment, which could be related to increased relative input from C_3 rich river bank vegetation as opposed to large C_4 rich sediment load flood events from the Upper Catchment and C_4 enriched grassland. Further study of current flood events at the Orange River mouth

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and other ORC sites would be useful in confirming this.

H7 and LX display similar $\delta^{13}C$ values although it may be that LX is not an accurate record of inland high threshold deposits as the type and quantity of clay deposit differs between LX and the mudbelt and this may translate to the adsorptive abilities at the sites (regarding stable isotope adhesion). Indeed there is great variation within the stable isotope values within the ORC and Orange River itself depending on the source of flood events and associated climatic influence, however, the presence of a largely smooth isotope record hints at the mudbelt being a repository of semi-continuous to continuous sediment deposit and not just during high threshold events. The pollen spectra is not smooth but does, despite the presence of some inert depths and sudden changes in the spectrum, does indicate some continuity within the sediment deposit. Indeed some of these changes would be related to reworking of sediment within the ORC

Nitrogen isotope values indicate the Orange River low flow bed load average is 4.3‰ in the Orange River (bed load), 10.6‰ at the JKB Richtersveld site, 5.5‰ for Lower Xobies, 5.8‰ for the prodelta (H2) and about 6.8‰ (varying between 5.4‰ and 8.9‰ at H7); these values are consistent with Heaton's (1996) for southern Africa and higher values account for arid (JKB samples exhibit these higher values) and coastal regions. The variation within these values is consistent with the varying nitrogen mechanisms within the OM.

Bulk organic age reversals are, as stated above, most concentrated in the proximal mudbelt (H2) and indeed show significant variation within a small difference in depth; some of this may indicate hiatuses in sedimentation but this is not conclusive and the accompanying stable isotope data tends to indicate smooth trends. The bulk radiocarbon age is undoubtedly a product of carbon reworking and the reservoir effect; a flushing event post-dating sampling of the JKB sites resulted in these sites being eroded and carried into the Orange River, with the result that the fine fraction potentially contributes towards the modern mudbelt deposit. The significant age reversal from the base of core H2 at 597 cm to a depth of 477 cm coincides with a significant positive excursion in $\delta^{13}C$ (more C_4 rich) and $\delta^{15}N$ values along with a change in lithology, although this age-lithology appears to be coincidental. This

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positive excursion could signify sea level change and upwelling. The marked excursion at the base of H2 refers to decreasing marine input upcore. Above ±477 cm, the core is characterized by a generally more C_4-rich terrestrial input. Between 597 cm and 477 cm the mudbelt represents a steady increase in terrestrial signal, possibly resulting from reduced upwelling or sea level changes. Here, the pollen is marked by the low Restionaceae representation, pointing to low levels of SE wind (carrying pollen from the Fynbos biome).

The pollen from the proximal mudbelt (H2) is particularly rich in terrestrial material and the modern sediment found from a depth of 30 cm to the surface of the mudbelt illustrates that the Grassland pollen elements, which exhibited a decrease around 150 years ago or shortly thereafter, has also experienced a recent increase in the ORC. However, Chenopodiaceae pollen, indicative of arid and evaporative conditions, exhibits a significant decrease in the last 150 years. This is consistent with siltation of the ORM and subsequent degradation of the saltmarsh vegetation, of which Chenopodiaceae-Amaranthaceae pollen is a dominant taxon; this taxon may also be a useful indicator of arid conditions. As this ORM closure is particularly relevant to the last 15 years, perhaps this data suggests a predominance of very recent sediment in the surface to 30 cm of the proximal mudbelt. Other elements of taxa affected by abstraction of the water due to 20th century river impoundment include low levels of Potamogetonaceae (*Potamogeton*), reduced Cyperaceae and Juncaceae pollen; however, Riparian pollen elements are not limited to the ORC and are also present in the Buffels River Catchment. Reduced levels of Asteraceae point to a reduction in moisture levels in the ORC; these are unexpectedly low given their increase within the last 200 years due to increased levels of disturbance and/or aridity (Baxter 1996, Meadows and Baxter 1999). This puzzling decrease may be a function of dilution of the local Asteraceae-1 by significant flood input, as Caryophyllaceae pollen are well represented at this depth and the accompanied influx of pollen from the Fynbos. Restionaceae pollen are well represented, suggesting a strong contribution from wind transport (South East winds), which plays a major role in transporting Restionaceae (Fynbos biome) elements from this biome into the mudbelt. The surface material should potentially reflect something of the impact from commercial farming in stable carbon isotope analysis; however, this is not clear from the stable isotope data, as although C_4 (maize and sorghum) are known to have increased in the last 100 years, there has

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also been a recent upsurge in commercial C_3 agriculture (wheat, soy, sunflower etc.), which may be the dynamic responsible for the inconclusive changes of isotope data in the modern mudbelt surface sediment. The pollen assemblage, on the other hand, shows a much higher presence of Poaceae in the proximal mudbelt (H2) compared with the distal sediments (H7) and a strong increase in cereals (large grained Poaceae) is observed in the ORC towards the mudbelt surface. There is a decline in grass elements in the last 100 years to the north of the study area in the Ncamasere (Nash *et al.* 2006); perhaps this is related to the recent (modern) drop in Poaceae noted in the proximal part of the mudbelt and might be similarly ascribed to an increase in disturbance.

The distal mudbelt surface is dominated by high levels of Asteraceae-1 pollen, which points directly to the human disturbance, documented to have increased in this taxa within the last 200 years (Baxter 1996, Meadows and Baxter 1999). This is accompanied by an increase in Nama Karoo elements and Chenopodiaceae-Amaranthaceae, a significant decrease in Grassland elements and a decrease in Riparian elements - particularly Potamogetonaceae, which disappears at the surface. Indicators of poor wind transport from the south (Restionaceae) are also found in the surface sediment deposited below. The levels of Nama Karoo and Succulent Karoo are higher in the distal mudbelt than the proximal mudbelt, given the proximity of this part of the mudbelt to the relevant biomes and the increase in Nama Karoo levels at 100 cm depth and above, is possibly linked to the expansion of Karroid shrub in the last 300 years (Scott and Vogel 2000, after Scott and Bousman 1999, Bousman and Scott 1994 and Scott and Vogel, after Bond *et al.* 1993). Euphorbiaceae, along with Asteraceae-2 pollen (which includes *Artemisia*) are statistically significant in explaining the pollen data. Euphorbiaceae pollen is found to decrease from a maximum at 80 cm in the distal mudbelt (H7) towards the surface. These taxa, together with arid taxa (and a reduction in Riparian taxa), are favoured near the surface and this is suggestive of upcore aridification. *Artemisia* pollen, which is more prominent in the distal mudbelt (H7), may indicate arid conditions, although it does incorporate an exception in the form of *Artemisia afra,* a taxa which is found at higher elevations under more humid conditions. Therefore, it is difficult to establish what palaeoenvironmental indicator the Asteraceae-2 generally represents.

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H2 and H7 are both characterised by Poaceae and Asteraceae, but are generally palynologically distinct: H2 is dominated by grassland more than H7 and is generally less dominated by Nama and Succulent Karoo elements and more Cyperaceae elements; however Riparian elements are also well represented in both cores although this could be the case in the Buffels River due to either particularly high or low water levels (Scott 1999). Restionacaeae is less important in modern surface sediment in H7 compared to H2 and the concurrent increase in Asteraceae (aridification and/or disturbance indicators) suggests an increase in aridity as identified at Verlorenvlei (Baxter 1996 and Meadows and Baxter 1999). A comparison between the Orange River bedload (WT) pollen and the mudbelt pollen yields a similarity between H7 and the WT site, with the exception of differing Poaceae levels (H7 has lower values comparable to H2), which is this indicative of the low flow discharge situation.

Statistical treatment of six key taxa in the pollen data yields some insight into the driving forces behind the pollen record. DCA (direct correspondence analysis) analysis highlights the usefulness of PCA (principal component analysis) analysis and points to several statistically corresponding pollen taxa identified in the mudbelt:

High Asteraceae-1 and moderate Poaceae pollen levels are found throughout most of the pollen spectra and these pollen types therefore appear to explain variation in the pollen spectra of most of the mudbelt and river samples very well and are tied in with the **first component (PC1)**; this component includes the Succulent Karoo contribution, which feeds into the Lower OR and mudbelt and is probably explained by a mixed signal from the Grassland, Succulent and Nama Karoo with aeolian sources of this biome combined with a fluvial factor, (which may also explain the presence of Poaceae). This component is least strongly correlated with low to moderate Asteraceae-1 and Euphorbiaceae of the Nama and Succulent Karoo and most strongly correlated with high Asteraceae-1 and moderate Poaceae levels.

Caryophyllaceae and Asteraceae-2 (*Artemisia*) have a close correspondence possibly relating to drier environments or a proliferation of elements of Succulent Karoo and these are

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important in defining the second component (PC2). The **second component (PC2)** is best explained by the local Nama and Succulent Karoo aeolian influence. Although the Buffels River may contribute, the factor is not well correlated with stable isotope data that suggests flooding from the Buffels River. There is also a correspondence between Caryophyllaceae and Asteraceae-1 pollen, which may have a similar significance and a strong dissimilarity between Asteraceae-1 and Restionaceae pollen. This points to the differing sources of pollen (Nama Karoo aridity and disturbance versus wind transported Fynbos taxa) and therefore different factors driving their deposition in the mudbelt. The first three principal components (PCA) are strongly correlated with Euphorbiaceae and Asteraceae-2 (*Artemisia)* pollen. However, the second, third and fourth components are not as statistically significant and should be used with caution. The **third component (PC3)** is best explained by prominent factors at play in the surface and base of the distal mudbelt (H7). These depths are correlated with the C_4-enriched terrestrial influx from the Buffels River, an observation further supported by low values of Restionaceae pollen. The **fourth component** (PC4) appears to be explained by the presence of Caryophyllaceae and therefore aridity, as there is overlap with PC3.

Although there is some overlap in factors, PCA analysis has demonstrated clearly that there is more than one factor driving the pollen characteristics of the mudbelt. This also establishes that the Orange River or fluvial factor combined with aeolian factors, is the dominant underlying mechanism driving the pollen assemblage. This adds support for using the data for vegetation interpretation over changing source of that vegetation, although exceptions to this generality occur. Stable isotope, inverse nitrogen values and pollen data suggest that the proximal mudbelt (H2) is more directly affected by the Orange River than the distal mudbelt (H7).

Pollen appears to be representative of the depositional age and not necessarily reworked sediment, particularly in the more arid biomes. It is probably more useful to compare the general pollen trend within the modern surface age, which corresponds roughly to the equivalent age at the top fifth of core H7. Core H2 appears to indicate a fluctuating Grassland

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Pollen Zone	Depth (cm)	Age or ^{210}Pb estimated time lag / depositional age & RC age (CalPal calibrated)	Riparian elements	Grassland	Nama/ Succulent Karoo	$\delta^{13}C$, 1/N, PCA	Fynbos (wind transport: Restio)	Palaeoenvironmental interpretation
Surface	0	Modern; 536 ± 16 cal yr BP (5 cm - 10 cm)	Low	Crop cereals = commercial farming; decreased Poaceae	Low Asteraceae-1			Aridity, disturbance on the West Coast; increase in Restionaceae, reduced Chenopodiaceae, Cyperaceae = ↓water (impoundment). Unexpectedly low surface Asteraceae-1
H2-D	0-30	Modern; 1336 ± 34 cal yr BP (13 cm - 15 cm)	Low	Poaceae moderate	Asteraceae-1: high values near 30 cm depth;	Terrestrial values dominant (more C_4 rich than the distal H7)	High (strong SE trade winds)	Chenopodiaceae decrease = siltation of ORM; impoundments; High Asteraceae-1 high at 30 cm depth, = increased disturbance, aridity on West Coast
H2-C	160-190			Marked upcore increase	Decreased Asteraceae-1, Caryophyllaceae			Disturbance in Grassland & Succulent Karoo (mid-core increase)
H2-B	300-360	1231 ± 51 cal yr BP (337 cm - 342 cm)	Increase		Disturbance increase		Poor	Arid West Coast, Nama and Succulent Karoo – Asteraceae-1; poor Restionaceae
(H2-B)	360-420		Decrease upcore	Increase	Increase Asteraceae-1&2		Decrease Restionaceae	Arid towards top and base of zone with respect to Riparian and Asteraceae-1 increases (disturbance); mid-zone increase in moisture
(H2-B)	420-460		Higher		Increase in elements, decrease Asteraceae-1			Increase in moisture, increase in Riparian elements; fewer disturbance indicators on the West Coast.

Table 7.1 Significant elements in the proximal Namaqualand pollen profile (page 1/2).

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Pollen Zone	Depth (cm)	Age or ^{210}Pb estimated time lag / depositional age & RC age (CalPal calibrated)	Riparian elements	Grassland	Nama/ Succulent Karoo	δ^{13}C, 1/N, PCA	Fynbos (wind transport: Restio)	Palaeoenvironmental interpretation
(H2-B)	460-520	1465 ± 51 cal yr BP (472 cm - 477 cm); 1164 ± 79 cal yr BP (492 cm - 497cm)	Lower	Proliferation of Rutaceae	Increase in some elements			Lower (summer) rainfall in Grassland/ arid. Aridity increase in Grassland & interior; more moist coast
(H2-B)	540-530							Low winter rain (arid); disturbance in Nama Succulent
(H2-B)	540-570	873 ± 58 cal yr BP (557 cm - 562 cm)	Poor	Poor	Low Asteraceae	Terrestrial values dominant	Poor	Low water levels in Rivers; indicators, contrast with sediment above & below. Very low Riparian and Restionaceae representation (different from assemblage above and below)
H2-B: 570 cm – 220 cm; H2-A: 570 cm – 220 cm	470 - 602	Major age reversal in RC ages below this level; 858 ± 57 cal yr BP (592 cm - 597 cm)	Decrease in Cyperaceae and Potamogeton aceae (*Potamogeton)*	Low levels; small Poaceae spike: 575 cm depth	Increase in some elements (Asteraceae-1, Euphorbiaceae)	Excursion: < marine to > terrestrial upcore (upwelling, sea level) change); PC4 aridity correlation at 570 cm	Significant Restionaceae (SE trade winds)	Increased aridity in Grassland; increase in Chenopodiaceae; Grassland influx linked to strong marine isotope signal (less influence from fluvial), aeolian pollen important. Excursion from more marine to more terrestrial environment upcore (upwelling/ sea level/less fluvial input) ; equivalent in radiocarbon age to a depth of ± 175 cm in core H7

Table 7.1 Significant elements in the proximal Namaqualand pollen profile (based on pollen from core H2), showing depth (cm), estimated depositional age, Riparian, Grassland, disturbance, Nama & Succulent Karoo, relevant δ^{13}C, 1/N and PCA information, Fynbos elements and palaeoenvironmental interpretation. Radiocarbon ages are indicated (page 2/2).

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Pollen Zone	Depth (cm)	Age or ^{210}Pb and estimated time lag/depositional age & RC age (CalPal calibrated)	Riparian elements	Grassland	Nama/ Succulent Karoo	Extra on $\delta^{13}C$, 1/N, PCA	Fynbos (wind transport)	Palaeoenvironmental interpretation
H7-surface	0	Modern; 747 ± 23 cal yr BP (10 cm - 15 cm)	Low	Near surface presence of crop cereals = commercial farming; Poaceae increase				↑ Poaceae, cereals; low Riparian; Low Poaceae (Grassland), < Succulent Karoo, > Nama Karoo; > reworked carbon than H2; significant terrestrial Buffels River input
H7-C (0 cm – 10 cm); H7-B (580 cm – 10 cm)	0-30	Modern (the last 150 years); (819 ± 61 yr BP); lag is at least 758 yr = greater than the more terrestrial proximal delta	Low near surface	Poaceae lower	Succulent. Karoo decrease upcore; Restionaceae increase Nama Karoo	> RC age lag than H2 (> re-circulated marine carbon); terrestrial input from the Buffels River (> C_3 - rich, PC3)	High SE trade winds, [increasing from base]	Low moisture, impoundments
(H7-B)	0-50	1015 ± 40 cal yr BP (40 cm - 45 cm)	Increase to maximum upcore					↑ upcore Riparian
(H7-B)	0- 80				Euphorbiaceae decreases upcore (with Asteraceae-2) from maximum reached at 80 cm			> rainfall (warming upcore);
(H7-B)	100			Moderate to low Poaceae	Very high Asteraceae and high Succulent Karoo levels, Nama Karoo levels increase markedly			High aridity and/or disturbance; increased Nama Karoo level =linked to possible expansion of Karroid Shrub in the last 300 years.

Table 7.2 Significant elements in the distal Namaqualand pollen profile (page 1/2).

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Pollen Zone	Depth (cm)	Age or ^{210}Pb and estimated time lag/depositional age & RC age (CalPal calibrated)	Riparian elements	Grassland	Nama/ Succulent Karoo	Extra on δ^{13}C, 1/N, PCA	Fynbos (wind transport)	Palaeoenvironmental interpretation
(H7-B)	180	2186 ± 118 cal yr BP (180 cm - 185 cm)			Karoo elements Increase from 180 cm			Spike in Scrophulariaceae at 180 cm associated with lower Asteraceae-1, Aster-4 and Cyperaceae and increased Chenopodiaceae suggest disturbance and increased aridity at this level; Equivalent in radiocarbon age to a depth of ± 600 cm in core H2
(H7-B)	345	3143 ± 66 cal yr BP (345 cm - 350 cm)						Higher sedimentation rate below this level
H7-B (580 cm – 10 cm); H7-A (610 cm – 580 cm)	500–600	3470 ± 78 cal yr BP (595 cm - 600 cm)	Gentle increase, except 575 cm and 600 cm	Highest Poaceae levels at base but decrease upcore, Rutaceae increase dramatically at 525 cm before decreasing coincides with marked drop in Asteraceae-1, Caryophyllaceae, Cyperaceae	Spike in Nama Karoo at a depth of 500 cm (but decreases upcore) and Succulent Karoo at 550 cm increases upcore	Terrestrial input from the Buffels River (more C_3 rich, PC3)	Lowest	Aridity increases upzone (Grassland, Nama Karoo); highest Poaceae; Rutaceae spike at top of zone; > Succulent Karoo. Significant terrestrial Buffels River input

Table 7.2 Significant elements in the distal Namaqualand pollen profile (based on pollen from core H7), showing depth (cm), estimated depositional age, Riparian, Grassland, disturbance, Nama & Succulent Karoo, relevant δ^{13}C, 1/N and PCA information, Fynbos elements and palaeoenvironmental interpretation. Radiocarbon ages are indicated (page 2/2).

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(Poaceae and Malvaceae) contribution. Indeed, it is possible that this portion of the pollen record relates to the bulk radiocarbon age and does not postdate the age of the bulk source sediment, as the Grassland does not provide quite as much opportunity for degeneration of pollen as in the case of the arid Nama Karoo and Succulent Karoo.

South of 25° S, aeolian terrigenous input is low and sediment transport into the mudbelt area occurs due to Berg winds only a few weeks each year; stable isotope input via aeolian transport is considered negligible but is important with regard to pollen input into the ORC depending on the timing of Berg winds with the spring flowering season. However, although fluvial contribution of pollen is considered more important than the aeolian contribution, quantification of the relative proportion of these pollen sources is not dealt with in this thesis. Low or inert counts of pollen in the sediment may be a result of arid or high energy sediment input.

However, the distal mudbelt is at times almost exclusively affected by the Orange River compared to pollen from aeolian and/or the Buffels River. Further analysis of closely correlated samples reveals samples with similar pollen assemblage but different lithologies, further supporting the observation that lithology type is not a helpful tool in palaeoenvironmental analysis of the mudbelt.

7.4 Palaeoclimatic inferences in the context of southern Africa and comparison with other records

There is a tendency towards arid climate in the palaeoclimate data at various time intervals represented in cores H2 and H7 (Table 7.1 and Table 7.2) and a number of fluctuations are indicated along with limited periods of increase in moisture. These hint at the climatic fluxes affecting inland vegetation of the biomes over the last 3 500 (radiocarbon) years BP. How then does the above accord with and add to the existing southern African record of change? The data appears to be in general agreement with the literature which points to an inland trend fluctuating between moist to dry conditions for the Late Holocene as observed at the Makapansgat study in particular (Holmgren *et al.* 2003), but also supported by other studies

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such as Scott and Vogel (2000) and Scott *et al.* (2005). The Holmgren *et al.* study points to a period of cooling between 6 000 and 2 500 years BP (Neoglacial period) followed by warming from 2 500 to 1 500 years BP (Medieval Warm Epoch) and at the maximum Holocene, cooling around 750 yr BP (around AD 1 200 during the Little Ice Age), however, the maximum cooling does not feature prominently in the data which is characterised with a number of fluctuations.

Scott and Vogel (2000) suggest that between 1200 and 420 years ago, an increase in C_4 vegetation may be related to an increase in summer rainfall. This in turn would have increased sweeter grasses (over unpalatable sour grasses which tend to be C_3). This is indicated in evidence from hyrax middens, where hyrax which usually favour C_3 and CAM vegetation over C_4 vegetation, exhibited a tendency towards favouring C_3 and CAM vegetation. However, this trend may not be the case in the wider region of southern Africa, therefore similarities between the Scott and Vogel (2000) study and this study are tentative. Comparison with the mudbelt data regarding the above is inconclusive given the discrepancy between depositional and bulk organic radiocarbon age of the sediment. Further, the prodelta although found within the above time frame, indicates a more C_4-rich nature (demonstrated by the excursion upcore between 600 cm and 500 cm), this does not show any sign in reduction at around 450 years and indeed only indicates a more C_3 input in the modern surface sediment.

Increased levels of Ericaceae pollen from 4000 to 2000 yr BP were identified at Blydefontein in the eastern Karoo (Scott *et al.* 2005) and from 3590 yr BP in the southern Karoo (Meadows and Sugden 1988 and after Scott *et al.* 2005). Pollen data from the distal mudbelt (H7) indicate a presence of Ericaceae at 375 cm, compared with a negligible presence elsewhere in the core (with the exception of the modern sediment surface), with a dramatic increase in Restionaceae at a depth of 350 cm, which has a bulk radiocarbon age of 3143 ± 66 cal yr BP; this is consistent with the above trend found in the literature. Speleothem records indicate this greater representation of Fynbos may be due to cooler climatic conditions at this time (especially 3000 yr BP), although increase in Ericaceae pollen appear to predate this (Scott *et al.* 2005, after Talma and Vogel 1992). Prior to this, between 11850

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and 5400 years BP, increased Asteraceae pollen indicated conditions were drier with much lower rainfall (Scott *et al.* 2005) although other studies indicate considerable climatic variation at this time (Scott *et al.* 2005, after Smith *et al.* 2002 and Holmgren *et al.* 2203); variation is probable, however this increase in Asteraceae may suggest a decrease in summer rains (Scott *et al.* 2005) and not necessarily a simultaneous decrease in winter rains for this period. From 5370 cal years BP, Scott *et al.* 2005 point to climate in the Karoo being more humid as indicated by an increase in grass (summer rain) and Chenopodiaceae/Amaranthaceae (evaporation components increasing), although this trend is indicated much earlier in studies to the north of this region (Scott *et al.* 2005, after Scott and Nyakale 2002, Scott and Lee Thorp 2004). The distal mudbelt (H7) pollen data indicate an increase in Poaceae pollen at the base of the cores, which relate to a bulk organic age of 3470 ± 78 cal yr BP; this is again consistent with the above trends, although a decrease instead of an increase in Asteraceae types is discerned in the distal mudbelt pollen spectra. From 5000 years BP, the climate is indicated to be dry and perhaps cooler with reduced evaporation (lower Chenopodiaceae/Amaranthaceae) (Scott *et al.* 2005). Then, from 4600 years BP onwards, Scott *et al.* 2005 note that conditions were more moist, becoming drier (increased Asteraceae) after 4000 years BP whereafter the pollen record is relatively poor until 2000 years BP and robust fern spores are selectively preserved possibly due to prevailing arid conditions. Scott and Bousman 1990, after Bousman 1988 and Scott *et al.* 2005, after Bousman 1991, indicating a short arid period at around 2000 years BP (Asteraceae increased); this is consistent with the pollen trend in the distal mudbelt (H7) where an increase in Asteraceae-1 occurs in the sediment above 180 cm (corresponding to a bulk organic age of less than 2186 ± 118 cal yr BP). Combined with evidence from Talma and Vogel (1992), the C_4 rich grass at the Cango Caves suggests a lack of winter rain with prevailing summer rainfall. Low winter rainfall and predominantly summer rainfall are indicated to have occurred just before and after 2000 years BP (Scott *et al.* 2005 and Scott and Vogel 2000) and also around 420 years BP (Scott *et al.* 2005), however this may not necessarily apply to the entire ORC. A cooler or more moist environment may have prevailed in the Cape (south of the ORC) and therefore possibly in the ORC, according to Scott and Vogel (2000). Karoo shrubs are indicated to have expanded since 300 years BP, consistent with isotopic data and a recent decrease in Grass in the Karoo (Scott *et al.* 2005, Bond

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et al. 1993). Indeed, the isotopic data from the mudbelt for these depths is inconclusive regarding these above mentioned environmental changes; the pollen data in the distal mudbelt indicates a decrease in Poaceae pollen around the Restionaceae maximum (at a depth of 180 cm (corresponding to a bulk organic age of less than 2186 ± 118 cal yr BP). Below 185 cm, the bulk radiocarbon age corresponds to older sediment and the base of the core corresponds with a bulk organic age of 3470 ± 78 cal yr BP. This age period is referred to in the literature as being poorly represented in the pollen record due to possible increased aridity and it is of interest that the sediment at these levels represents consistent levels of pollen compared to the (younger) sediment above. Indeed the sediment here indicates increased Cyperaceae and Potamogetonaceae levels (riparian elements).

Although it is difficult to pinpoint specific depositional ages to the sediment, this problem of lack of absolute dates harks back to the work by van Zinderen Bakker and Coetzee (1988) who pointed to the paucity of palynological ages and consequent lack of clarity in the palaeoclimatic interpretations. The general scarcity of palaeoclimatic data in many parts of southern Africa and limited nature of long-term broad ranging sites is reason enough to be cautious of over-interpretation of data sets that are often chronologically poorly resolved and represent only a limited geographical area. Conversely, this study site is very large scale and is governed by numerous dynamics which are easily generalised at the risk of losing clarity of local change to a 'conflation' of climate and sub-region idiosyncrasies (Chase 2006). In such instances replication of similar results is useful in providing support and substance to the palaeoenvironmental picture that is beginning to develop in southern Africa and the palaeoenvironmental interpretation of this data provides such an opportunity.

There are numerous fluctuations apparent in the proxy data and it poses a challenge to pick out additional palaeoenvironmental indicators. However, the most prominent indications are summarised as follows (described from the base up):

In general, the proximal mudbelt, represented by 602 cm long H2 which corresponds with a bulk organic age of 858 ± 57 cal yr BP, is dominated by age reversals and has the following

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trends:

- At a depth of between 610 cm and 500 cm, there was an upcore excursion towards less marine OM in the mudbelt prodelta related to either upwelling or stabilizing sea level change (upwelling is present but not well developed in this region, as it is some distance from upwelling cells according to Shannon and Nelson 1996). This is associated with an increasingly arid Grassland environment which is supported by the fourth principal component which has high scores in this interval. At a depth of about 570 cm – 540 cm, the pollen data indicates a very different environment from that both above and below it, indicating conditions were briefly not well suited to Riparian vegetation (low rainfall and lower water levels) and Restionaceae are poorly represented pointing to weakly developed SE winds.

- The sediment level at about 540 cm to 530 cm suggests that the precipitation levels of the inland winter rainfall region (Grassland and parts of the Nama Karoo) are low and conditions xeric. Disturbance is indicated for the Nama and Succulent Karoo biomes.

- Increased aridity is indicated again for the sediment above this at 520 cm - 460 cm for the Grassland Biome (Rutaceae proliferate) and interior, but a more moist coastal region (Strandveld/Succulent Karoo) is also indicated. Above this at a depth of 460 cm to 420 cm, the sediment appears to be more moist with increased rainfall and improved Riparian vegetation.

- Arid environments are indicated for both the top and base of 420 cm to 360 cm, but mid-zone shows a sudden increase in moisture levels in the Riparian vegetation. An increase in Asteraceae-1 points to an increase in disturbance on the West Coast, but also could be originating deeper inland, as an interior (eastern Karoo) increase in Asteraceae in the last 300 years is indicated by Scott *et al.* (2005).

- Above this level, the aridity trend continues with the sediment at a depth of between 360 and 300 cm being characterised by arid indicators from the Succulent and Nama Karoo. Restionaceae pollen from the Fynbos biome are poorly represented,

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suggesting poorly developed SE winds. Above this level between 190 cm and 160 cm, the sediment is characterised by disturbance indicators in the Grassland and Succulent Karoo (mid-zone there is a significant increase in Grassland, disturbance and Restionaceae).

- The increase in Nama Karoo elements and decrease in Grassland from a depth of 30 cm and the near- surface accords well with this trend found at Deelpan by Scott (1988) and Scott and Brink (1992) for the period 820 BP onward.

- The palaeoenvironmental indicators in the surface sediment (modern day to ±150 years) shows aridity and/or disturbance on the West Coast along with increased Restionaceae levels and increased C_3 input. There is also significant evidence of lower water levels in Riparian vegetation (decreased Cyperaceae and Chenopodiaceae pollen) due to recent impoundment of the Orange River.

The distal mudbelt (H7) with a bulk organic radiocarbon age of 3 470 ± 78 cal yr BP illustrates the following trends:

- A Poaceae pollen increase at the base of H7 which is consistent with the cool and grassy conditions indicated at Makapansgat; this occurs near the beginning of the onset of cooling. Stable isotope and inverse nitrogen data indicate there is a strong inflow of terrestrial carbon from the Buffels River at the base of the zone. This is possibly a manifestation of the cool conditions indicated by the literature (Holmgren *et al.* 2003). In addition, the increased sedimentation rate at this level supports higher rainfall and sediment volume (Buffels and Orange Rivers), although the relative contributions of these two rivers is hard to quantify.

- Comparison between the base of H7 with the rest of the core shows that there appears to be an increasingly arid trend above this layer. Again this is consistent with the findings at Makapansgat. The study by Beaumont *et al.* (1984) and Scott *et al.* (2005) covering the period 7 400 to 4 500 BP, just outside the basal limit of the distal core, is also consistent with the findings at the base of H7 - locally wet grassland (sub-

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humid).

- Although the Poaceae pollen reveal their highest levels in this core and a spike of Rutaceae at a depth of 180 cm indicates a trend towards aridification towards the top of this zone; this is supported by an increase in general aridity indicators in the Grassland and Nama Karoo, but Succulent Karoo pollen indicators increase with Scrophulariaceae which is consistent with disturbance poorly represented in the mudbelt spikes at 200cm.

- Above this level at about 100 cm, there is a noticeable increase in Nama Karoo elements which may be ascribed to the documented expansion of the Karoo about 300 years ago. In the basal layers of this sediment, there is an increase in Asteraceae, Scrophulariaceae and Chenopodiaceae pollen, indicators of disturbance and aridity respectively. In the upper layers of this section, there is a particularly low Grassland pollen element accompanied by indicators of high aridity and/or disturbance.

- Sediment above this level at about 80 cm indicates increased rainfall and perhaps increased warming. Scott's (1988) study at Deelpan, maintains that by 820 BP and certainly onward, warmer conditions with poor ground coverage were prevalent at least in parts of the Free State grassland; this is consistent with the mudbelt data in H7 from sediment.

- The sediment above this level between about 80 cm and the surface shows an increase upcore in Riparian elements which decreases very recently in the surface sediment, where Potamogetonaceae disappears, possibly indicative of aridification. Cereals (commercial Poaceae crops) represented by a recent increase in Poaceae, are present (probably ascribed to increased impoundments, disturbance and noticeable input of terrestrial OM from the Buffels River), although levels of the Poaceae pollen are generally low just below the surface layers. At the surface there is an unexpected decrease in Succulent Karoo, pollen elements together with an increase in Nama Karoo and Restionaceae pollen, although the reason for this is not clear.

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- A recent decrease in Poaceae has already been indicated by Bond *et al.* 1993 (Scott and Vogel 2000, after Bond 1993) for a large section of the Karoo region; this decrease has occurred due to increasingly arid conditions, which have been exacerbated by overgrazing by stock farming. Scott *et al.* (2005) and Scott and Bousman (1990) indicate a particularly moist and grassy condition in the Karoo (Blydefontein) between 1 200 BP and 300 BP, with a more shrubby karroid vegetation predominating around 100 BP and this is consistent with the mudbelt near surface sediment where Nama Karoo elements increase along with a reduction in Poaceae and Caryophyllaceae (Riparian) pollen elements

With regard to sea level change, the basal age of the distal core, H7, should coincide with a 2 m (increased) sea level change indicated at Verlorenvlei (Baxter and Meadows 1999) and is consistent with work done by Jerardino (1993) and Illenberger and Verhagen (1990) and the subsequent regression to present day levels. However, this is not evident in H7 and possibly did not have as pronounced an effect on the mudbelt record, although the sea level rise may have been less than as indicated by Meadows and Baxter (1999) and others. Although the sea level fluctuated over the period indicated for the mudbelt, the only indicators of this event possibly occur as an isotopic excursion towards the base of proximal core H2, which is dated at 858 ± 57 cal yr BP (which is consistent/appears too late). This is consistent with a stabilising trend towards today's sea levels, although upwelling near the base and decrease in primary productivity are indicated. Aridity would have increased with strengthening of upwelling associated with higher sea levels. This is partly confirmed by the pollen spectra, as indicators of coastal aridity present as an increase of Asteraceae-1 and Chenopodiaceae and a decrease in Cyperaceae pollen as the sea level dropped. Reworking and age reversals in the sediment due to sea level change, although possible, are less likely given the presence of age reversals in laminated sediments in this core.

Perhaps the more important discoveries made in this thesis are not so much associated with the identification of palaeoenvironmental indicators of vegetation change (other than that which can be verified by existing literature and inconclusive fluctuations), but the elucidation of the dynamics which created the mudbelt: fluvial input from the Buffels River has been

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significant at both the surface and base of the distal core H7; the base of the proximal mudbelt, H2, appears to indicate an upcore excursion towards more terrestrial values than are represented at the base of the core. Indeed the chronology of the mudbelt has improved significantly and the surface is confirmed to be modern.

Considering the observations discussed here and the logistical and sampling limitations, the mudbelt cores analysed in this study have, as far as possible, been fully explored in the task of characterising the mudbelt itself. In addition, this study represents an attempt to synthesise the data obtained from the mudbelt into a meaningful record with which to compare and contrast inland southern African palaeoenvironmental implications. Results appear to correlate well with existing literature. The mudbelt represents a significant expanse of geographical extent; this repository represents not only summer and winter rainfall zones and variations in some areas but is subject to reworking complexities thus hampering more precise palaeoenvironmental interpretation.

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8 CONCLUSIONS

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This chapter presents a summary of the key results and findings of this thesis pertaining to the character of the Namaqualand mudbelt. It incorporates analysis from three main methodologies, namely chronology, stable carbon and nitrogen isotopes and palynology together with the implications of these findings, which are discussed within a broader palaeoenvironmental context. The strengths and limitations of this thesis are outlined along with proposed future directions of research.

8.1 Key findings of this study

The primary aim of this study was to characterize the Namaqualand mudbelt by way of proxy data in the so-called HODSA mudbelt cores. The overall intention was to extract information about the environments of the southern African interior against a backdrop of large, high threshold flood events and inland palaeoflood deposits (identified by Zawada 1996). However, establishing a reliable chronology posed a significant impediment to this aim. Prior to this study, there were some clues to the true ages of the mudbelt sediments, but there were significant problems within the bulk organic radiocarbon ages. These analyses yielded older-than-expected surface ages for the mudbelt and also age reversals in the most proximal of the cores. Further, potential palaeoenvironmental information had not been explored and the complicated chronology therefore needed to be re-addressed in order to provide a suitable framework against which to interpret the palaeoenvironmental data. This study has made a significant contribution to improving on the earlier understanding regarding the character and palaeoenvironmental interpretation of the mudbelt and it has helped to resolve some of the chronological problems; noticeable improvements have been made in understanding the complexities of the mudbelt chronology compared to what was known before (Dingle 1994, Gray 1996, Gray *et al.* 2000, Meadows *et al.* 1997, 2002 and Mabote *et al.* 1997).

The physiographical expanse, climatic, environmental and phytogeographical complexity of the catchment and numerous other marine and terrestrial controls on the mudbelt deposition mean that the indicators and components from this complex mixture are not easily separated. This poses significant challenges to

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palaeoenvironmental interpretation. Further complications arise at the level at which pollen may be taxonomically interpreted and also with the overlap of taxa and photosynthetic pathways from the biomes and environments represented in the mudbelt. There is inevitably some overlap resulting in somewhat indistinct palaeoenvironmental interpretations of the mudbelt data and subtleties such as seasonality are not easily identified. Seasonality is an important aspect which could not be adequately dealt with in this thesis (for example seasonality vs. aridity, wind direction and disturbance). Where possible, this has been addressed (Berg Winds and the presence of Restionaceae pollen in the pollen spectra and summer rainfall regarding C_4 and C_3 sweet and sour grasses respectively) but any interpretation is tentative, given the expanse of catchment and variable source within the catchment based on a range of factors. The treatment of data is necessarily simplistic as a result.

The following aims and objectives were realized; these are listed using the same numbering system of the aims and objectives laid out in chapter 1:

Chronology

1. The application of ^{210}Pb analysis was successfully applied to the mudbelt and several Orange River sediment samples, thus resolving the age of the mudbelt surface and establishing it as essentially modern (less than 150 years). This confirms the fact that modern sediment *is* being deposited in the mudbelt in spite of "old" radiocarbon ages obtained for the surface sediments. It also confirms that modern sediment was indeed sampled during the coring exercise, therefore providing a modern reference for palaeoenvironmental data. It further serves to resolve the discrepancy in bulk organic radiocarbon ages against the actual depositional chronology of the mudbelt, which is a product of reworking and reservoir effect and marine OM in the mudbelt. Previously uncalibrated bulk organic radiocarbon ages are now presented in calibrated form according to the international standard: adjusted Southern hemisphere calibration curve CALIB according to the age of the mudbelt surface (according to ^{210}Pb analysis).

    - The surface samples bulk organic material contain organic sediment aged at least 520 years older (in H2), and at most 750 years older (in H7) than the date of deposition consistent with other estimates for the age lag in

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south Atlantic waters. This lag is due to reworking within the ORC and recirculation of oceanic carbon (reservoir effect) and the disparity points to differences in parts of the mudbelt with the younger proximal sediment of the prodelta and older distal sediment. Based on estimated age, the base of H2 (a 6m core) is roughly equivalent to only the top portion of H7. Assuming this lag is consistent throughout the core, the basal core age can be adjusted according to the surface radiocarbon age as being approximately at least 330 years BP for H2 and 2 650 years BP for H7. Thus, interpretation based on the age of the mudbelt is limited to the extent to which the depositional age may be projected on the basis of the lag between bulk organic radiocarbon date and ^{210}Pb analysis in the surface sediment. Because it is not possible to produce extrapolated radiocarbon age based on this small sample of dates alone, it is of greater interpretive value to use depth rather than bulk organic radiocarbon age with which to illustrate and interpret palaeoecological data and instead radiocarbon age (or presence of excess ^{210}Pb) should inform the interpretation. Similarly lithology is of little interpretive use regarding paaeoenvironmental changes and again depth is the most useful basis on which to present this data.

- Box cores reveal the surface to be 20% more enriched with excess lead than the gravity cores, suggesting the age of the surface of box cores is marginally more recent than gravity cores obtained through grab sampling (though both are effectively modern). [Evidently the original grab sampling exercise of the HODSA cores did not retrieve the top-most sediments that the box cores sampled. However, this discrepancy is unlikely to be due to the time lag between grab sampling and box coring operation].

- A limited degree of mixing occurs within the sediment column of the mudbelt, and ^{210}Pb analysis reveals less *in situ* mixing than the bulk organic radiocarbon ages suggest by their age reversal (particularly in H2). This lends more support to the palaeoenvironmental interpretation of the sediment data and suggests that older carbon originates from a combination of the re-circulated oceanic carbon (reservoir effect) and

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reworking in the ORC. Further, this explains why age reversals are present in some laminated sediments in core H2 despite an absence of post-depositional *in situ* reworking. Stable isotopes data provide a relatively smooth excursion of data suggesting minimal mixing, thus adding support to that suggested by the radiocarbon and ^{210}Pb analysis. However, even this minor mixing should be noted as a caution; the region is highly dynamic and tides, currents, storms, major flood events and bioturbation can provide a potential mechanism for mixing *in situ*, albeit severely limited. Indeed, the phenomenon of reworked OM is common in mudbelts and deltaic environments.

- The ^{210}Pb analysis revealed that the top 30 cm depth of the mudbelt is modern as ^{210}Pb (excess) rapidly decreases beyond this point, thus indicating a high sedimentation rate which may be a product of recent human intervention.

- Based on these radiocarbon ages, it is evident that H2 exhibits a higher sedimentation rate in the prodelta than further from the ORM in H7. This disparity in sedimentation rate is most probably because of the proximity to the Orange River as the primary sediment source.

- The results of ^{137}Cs analysis show near negligible levels.

- The prodelta mudbelt sediment (H2) postdates the third ORC flooding period of AD 1450 (or 535 years BP) identified by Zawada (1996); this is consistent with the bulk organic age of modern prodelta deposit surface of 536 ± 16 cal yr BP. The fourth flooding event occurring after 200 BP (Zawada 1996) is coeval with part of the modern mudbelt deposit and coincides with the bulk organic age of AD 1785 to present.

2. Unfortunately ^{210}Pb analysis was not of a sufficiently high resolution to calculate actual sedimentation rates. However, the upper 30 cm of sediment of both distal and proximal cores is modern in age and therefore sedimentation rates appear to have been higher for this most recent period. The age model curve shows rapid

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sedimentation at the surface being comparable to the deposition of sediment represented between 500 and 600 cm in core H2.

3. AMS radiocarbon analysis of foraminifera, which would have provided a direct perspective on age of at least some of the bulk organic content proved non-viable because of low foraminiferal concentration in the mudbelt HODSA cores, therefore this objective was not met. However, Herbert and Compton (2007) have successfully addressed this problem elsewhere in the mudbelt, thus pointing to the variability of deposits within the mudbelt.

4. In order to compare the chronology of the various deposits discussed in this study (mudbelt and inland palaeoflood sites), a table (Table 4.7, page 141) was constructed collating the relevant study sites indicating time of deposition. Although this is useful for illustrative purposes, it serves mainly to indicate the lack of continuity represented by the various sites (apart from the Jakkalsberg sites which overlap with the mudbelt cores and were subsequently eroded) i.e. palaeoflood deposits are by definition high threshold events and not semi-continuous sedimentary records.

Lower Xobies and Jakkalsberg (Richtersveld) in context of the mudbelt

5. Inland ORC sites successfully helped contrast palaeoenvironmental information, particularly the stable carbon and nitrogen isotope values with those of the mudbelt as described above. The rationale for using this site was to examine the isotopic composition of Orange River sediment that was not in any way mixed with the marine component thereby presenting the data with a purely terrestrial signal.

    - Carbon isotope values are more depleted in ^{13}C than expected at Lower Xobies. Some of the differences in stable isotope values between the prodelta and Lower Xobies may be due to the differing size fraction and clay type of the two sites, as this affects the type of adsorbed organics. Lower Xobies has a coarser sediment fraction than the clay-rich mudbelt and differs in type and quantity of clays deposited at Lower Xobies. This

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may account for the different sediment sources deposited at these two sites. Another reason for this may be that heavier sediments are deposited first within the river and more of the lighter clay-rich deposits get deposited in the Orange River Mudbelt (although sediment is separated at the mouth with larger size fraction travelling north and the finer fraction to the south to be deposited in the mudbelt). A further possibility lies in the source of sediment; which might be particularly C_3-rich compared to the more general ORC record represented in the mudbelt.

- Inland palaeoflood sites in the lower Orange River were processed for pollen analysis, but these samples did not yield anything more than negligible pollen. Only pollen extracted from the river samples was useful for comparison with the pollen of the mudbelt.

Vegetation input (pollen)

6. High resolution pollen analysis of the mudbelt samples and a few selected inland riverine samples in the Lower Orange River show the following:

    - Over 80 taxa were identified in the mudbelt, many more than Coetzee and Rogers (1976) identified at the ORM and more than were identified in the pilot study (Gray 1996 and Gray *et al.* 2000).

    - In some respects the palynology analysis of this research project was made simpler by having conducted an earlier pilot pollen study (Gray 1996 and Gray *et al.* 2000) which established its viability. Adjustments to the pollen processing methodology were still required to improve on the earlier successes. A cleaner sample along with a shortened processing time was achieved for each sample, even though this process still remained time consuming due to the large number of samples processed.

    - Although the ^{210}Pb data suggest the box cores represent slightly more recent sediment than the gravity cores, the surface pollen assemblage of both these cores is comparable.

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- Exotic pollen are not easily identified in the mudbelt due to the overlapping of taxa morphologies and limitations in identification capabilities; therefore it was not possible to secure depositional age on the basis of exotic presence in the pollen assemblage.

- A number of key trends were found in the pollen data: the recent disturbance on the West Coast (Baxter 1996, Meadows & Baxter 1999) is indicated by a significant increase in Asteraceae-1; Poaceae are well represented in the proximal mudbelt but decline very recently; cereals (indicated by large Poaceae grains) are present in modern sediment; other trends are well correlated with stable isotopes and are discussed separately.

- Evidence of the expansion of Karroid shrubland of about 300 BP is detected in the mudbelt pollen by the increase in Nama Karoo pollen levels and a decrease in Poaceae. Evidence of upcore aridification is found in the decrease of Euphorbiaceae towards the surface of the distal mudbelt.

- Pollen was heavily oxidized in the arid conditions of the Richtersveld interior yielding negligible counts in the palaeoflood deposits. The objective to compare inland palaeoflood deposits of pollen with that of the mudbelt could not be met.

7. Some trends in windborne vs. riverborne pollen can be determined from the pollen abundances and although fluvial input is considered to be the dominant contributor of pollen, quantification is not possible. For instance, Restionaceae enter the mudbelt primarily through SE winds. Poaceae pollen may be associated with both fluvial and airborne transport.

8. Exotic biostratigraphic markers were not easily identified given overlap with other taxa and thus limit identification. However, the presence of larger size Poaceae in the modern surface layers was noted; these larger grains are best ascribed to domesticated (exotic) cereals resulting from recent commercial farming.

Information derived from stable isotopes

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9. Stable carbon and nitrogen isotope analysis of the mudbelt cores show that the proximal (H2) and distal mudbelt (H7) are isotopically distinct. The strong similarity between Lower Xobies and H7 is surprising.

   - H2 and H7 differ in both the absolute $\delta^{13}C$ values and the trends. H2 is more enriched in ^{13}C suggesting a more C_4-rich terrestrial component while H7 has lower $\delta^{13}C$ values indicating a predominantly marine component. Since $\delta^{13}C$ values of average marine organic material fall between the average bulk organic values for C_4 and C_3 terrestrial vegetation, it is not possible to disentangle the C_3, C_4, marine signals completely. Nitrogen isotope values are less informative but complement the $\delta^{13}C$ data and are consistent with Heaton's 1996 southern African terrestrial values and higher values indicating arid and coastal areas. Inverse nitrogen and C/N ratios (although there is some overlap in C/N ratio values between mudbelt and inland sites) confirm that H2 is predominantly terrigenous and H7 is predominantly marine in nature. However, pollen analysis does indicate that the distal mudbelt is at times affected only by pollen from the ORC. Isotopes are considered to be incorporated into the mudbelt via fluvial transport with a negligible amount being sourced via aeolian transport.

   - The OM in H2 is generally more C_4-rich, suggesting a steady input for a significant period of time, although this is not as it was first thought to be (this is a mixture of both C_3 and C_4-rich OM). However, these changes occur towards the base of the core, where a greater C_3 input is reflected, which, based on these values alone, could be either from terrestrial or marine C_3-rich values. The nitrogen isotopes indicate that the base is more marine, becoming less so towards the surface.

   - This excursion at the base of the proximal core H2 shows a trend from more marine (C_3-rich) at the base to more terrestrial values within about 100 cm. This is associated with an upcore increase in arid Grassland and a general increase in aridity indicators (a principal component mainly associated with aridity is strongly correlated at this depth). In addition, this

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is associated with significant age reversals in the bulk organic radiocarbon ages (between depths of 597 cm and 477 cm). This excursion may be consistent with stabilizing sea level changes, upwelling dynamics and/or reduction in flooding. The surface sediment in H2 shows a slight C_3 enrichment, possibly due to a C_3 rich flooding event significant bank erosion, the recent increase in commercial C_3 agriculture or increase in algal OM from the ORM salt marsh. Other than the evidence regarding the above isotope excursion, there is no evidence of sea level change in the mudbelt. The excursion at the base of H2 is too late to coincide with the major changes suggested in the literature, although it is consistent with the stabilizing trend; the significant 2 m increase in sea level identified at Verlorenvlei by Baxter and Meadows (1999) and others would have coincided with the basal age of the distal core H7.

- Two excursions from marine to more terrestrial values are found in H7. These occur at the base and near the surface of the cores; the most plausible explanation is that these may be associated with the influx of terrestrial organic material from the Succulent Karoo during flooding in the Buffels River Catchment as nitrogen isotope values are lower. However, the near-surface excursion is accompanied with a positive increase in nitrogen isotopes and may also be due to stronger upwelling.

- The results from Lower Xobies proved useful for illustrating some of the inland dynamics in terms of wide variation in nitrogen isotopes rather than providing "typical" localised inland bulk organic $\delta^{13}C$ reflecting C_3/C_4 variation. The $\delta^{13}C$ data showed less C_4 input than expected and yielded surprisingly similar values to the distal mudbelt sediment; this is possibly due to differing types and quantities of clay being deposited, with accompanying differing portion of adsorptive ability. The mudbelt cores proved to be more isotopically homogeneous compared with Lower Xobies sediment.

- The relatively smooth isotope record suggests that the mudbelt sediment is deposited semi-continuously and not simply during high threshold flood

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events suggesting hiatuses were not significant. Pollen spectra do not exhibit a smooth continuous arrangement, although expected in the pollen assemblage, there is evidence to suggest potential hiatuses in sedimentation. The rapid change and reversal of bulk radiocarbon ages may also point to the presence of sediment hiatuses in the mudbelt sediment. Bulk radiocarbon ages provide further proof that hiatuses in sedimentation are a possibility and caution should be exercised when interpreting the data as a limited amount of *in situ* reworking is possible.

Combined Proxy Data

11. The mudbelt proxy data were successfully interpreted and synthesised. The key findings of this data lies in the following interpretation:

    - The surface of the mudbelt represents a significant increase in disturbance indicators (Asteraceae-1), increased Restionaceae pollen levels and increased C_3 input at the prodelta surfaces but there is also some indication at a depth of 180 cm (H7) where the bulk organic age of the sediment is 2186 ± 118 cal yr BP. In addition, there is an indication of Karoo expansion associated with an increase of aridity and/or disturbance in this biome that is consistent with that noted by Scott and Bousman (1990) and Scott *et al.* (2005). An increase in Chenopodiaceae in modern sediment is consistent with impoundment of the Orange River and associated siltation and degradation of the ORM saltmarsh. In the distal mudbelt, a decrease in Poaceae is correlated well with the recorded decrease in Poaceae due to aridity and stock farming (Scott and Vogel 2000, after Bond *et al.* 1993) but the surface sediment shows a recent decrease, which is consistent with disturbance noted in the Ncamasere (Nash *et al.* 1996). A reduction in Cyperaceae and Juncaceae pollen are probably also related to the increasing impoundment of the ORC.

    - There is general agreement between the mudbelt pollen data and the literature despite the problems with mudbelt chronology; this data points to fluctuating moist and dry periods for the Late Holocene. The prodelta, H2

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tends to C_4-rich, compared with the distal H7 and this is consistent with the increase in C_4 vegetation suggested by Scott and Vogel (2000) for 1200 to 420 BP, although surface sediment has a distinctive increase in C_3 OM. There are some indications of an increase in Fynbos components, consistent with a cooler climate between 4000 BP and 2000 BP.

- From the base (depositional age) of the proximal core H2 to a depth of about 500 cm (±1 049 BP) is characterized by an excursion from strongly marine to more terrestrial stable isotope values (supported by inverse nitrogen and C/N ratios). This period is strongly associated with an increase in aridity indicators particularly in the Grassland biome and the fourth principal component (PC1), which is well correlated at this level. Indeed the prodelta appears to be dominated by grassland pollen more than H7, which tends to be dominated by Nama and Succulent Karoo pollen elements. The distal mudbelt pollen compares well with the low flow discharge Orange River bedload, with the exception of differing Poaceae pollen levels, which are higher in the ORC.

- Principal component analysis has yielded some useful analysis of the mudbelt pollen data: Most of the mudbelt pollen variation is explained by high levels of Asteraceae-1 and moderate Poaceae levels in the first principal component (PC1) and probably a combination of aeolian and fluvial factors within the ORC, lending support to the use of pollen spectra for interpretation of vegetation change within the ORC. The second component (PC2) appears to be governed by aeolian and aridity levels and is explained by a close correspondence between Caryophyllaceae and Asteraceae-2. The less significant components, PC3 (explaining the surface and base of the distal mudbelt and possibly related to the influx of terrestrial OM at these levels) and PC4 (with PC3 with indicators of aridity) overlap.

- There is a strong correlation with the timing of grassier conditions noted in the Makapansgat speleothems (Holmgren *et al.* 2003) and a cooling event at the base of the core (H2) dominated by grassland; aridity indicators

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increase upcore as this tails off and a moist event occurs in sediment at a depth of ±570 cm, which is slightly younger than the bulk organic age of 1465 ± 51 cal yr BP suggests (520 cm – 460 cm), after which the aridification trend resumes (with a brief moist spike at a depth of about 400 cm. An increase in Poaceae at the base of the distal mudbelt, H7 is consistent with other indicators suggesting an increase in summer rain (Grassland), along with increased humidity (Scott *et al.* 2005). A Short arid period occurring around 2000 yr BP appears to be recorded in H7, where an increase in Asteraceae-1 is found at a depth of 180 cm and is consistent with a few C_4- rich samples suggesting the presence of sweet grasses and a possible increase in summer rainfall.

- A terrigenous influx, possibly from the Buffels River or upwelling into the predominantly marine dominated mudbelt at the base and surface of the distal core possibly occurs twice. The pollen assemblage does not add to this interpretation as it is very different at these two depths, but the near-surface sediment pollen assemblage coincides with recent Buffels River assemblage. The reduced Asteraceae-1 levels and low Poaceae levels are in keeping with the recent trend of reduced Poaceae due to stock farming and other commercial endeavours together with increased levels of disturbance in both Grassland and Nama Karoo. This can be contrasted with the lower depth, where Asteraceae levels were high (but lower compared with recent levels) and Poaceae levels that are greater than at the surface. The basal excursion may possibly be directly attributed to a flooding event during the documented cool and less arid conditions relevant to that time period. Increased sedimentation rate is noted at this depth and suggests increased rainfall and fluvial deposit.

- The reversals in bulk organic radiocarbon ages of H2 suggest marked changes in sedimentation rate and periods of major flooding accompanied by sporadic influx of sediment into the mudbelt. Nevertheless, the various proxy data presented contrast strongly with these ages and indeed indicate a relatively incremental accumulation within the sediments. This suggests that the record is relatively smooth. Also, depths where age reversals are

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particularly marked appear to have a relatively constant stable isotope signature. Indeed, additional chronology data discussed above promote the mudbelt as a semi-continuous deposit.

- In the prodelta sediment deposited after the excursion at a depth of 500 cm shows considerable fluctuation between moist and arid conditions for the ORC:

  There is evidence from the isotopes and pollen to indicate a succession of xeric and disturbance conditions in the Grassland, Nama and Succulent Karoo (540 cm – 530 cm). This period is followed (520 cm - 460 cm) by another period of increased aridity in the Grassland but this time associated with increased moisture in the coastal region (Succulent Karoo), which is then followed at 420 cm – 360 cm by an increase in moisture associated with increase in disturbance on the West Coast. This period is then followed with indications of arid conditions in the Succulent and Nama Karoo and continued disturbance but incorporated into the Grassland. In the surface sediment of both core H2 and H7, a decrease in Grassland and increase in Nama Karoo is consistent with work at Deelpan by Scott (1988) and Scott and Brink (1992), which identified increased rainfall and warmer conditions.

- Considerable variation within the distal core, H7 is evident, too: Above the cool and locally wet grassy base of H7, there is an increase in arid indicators and disturbance in the Grassland and Nama Karoo. Above this, there is evidence of the Karoo expansion of 300 BP in the Nama Karoo elements. Above this and consistent with information in the prodelta, there is evidence of the increased rainfall identified at Deelpan for the period 820 BP onwards. Between 80 cm and the surface there is evidence of an increase in Riparian and Grassland elements, which decrease at the surface, pointing to the recently increased aridity, impoundments and disturbance.

- Stable isotopes, inverse nitrogen and pollen data all confirm that the prodelta, H2 is more strongly influenced by influx from the ORC than the

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distal mudbelt, H7. A further consideration is that the pollen data is probably most closely associated with the depositional age, although it is possible that some well preserved pollen grains may be reworked, this depends on the climatic conditions surrounding the initial deposition. Isotopes on the other hand are associated with the bulk OM and therefore may well predate the pollen data in the same sample depth.

A number of attempts were made to resolve the chronology, palynological and palaeoenvironmental potential of the Namaqualand mudbelt HODSA cores within the logistical and financial limitations. This has been achieved specifically through the use of two cores, H2 and H7 and related box and gravity cores. The palaeoenvironmental interpretation of the pollen assemblage (cores H2 and H7) has corresponded well with some established inland findings of environmental change in the last ±3 500 years. This revised understanding of the mudbelt chronology is crucial for the interpretation of pollen and stable isotope results of analysis and contributes to a growing body of work on the Namaqualand mudbelt and the inner continental shelf.

8.2 Strengths and limitations, contributions and implications

The strengths of this research rest on the identification of proxy data retrieved from the Namaqualand mudbelt. This mudbelt sediment relates directly to inland changes over a wide area of the subcontinent (ORC) during the last ±3 500 years (older sediment was not retrieved from the mudbelt). This is especially useful given the rarity of such a scale of record in the subcontinent, where only a few sites, such as the Makapansgat speleothems (Holmgren *et al.* 2003) and the Wonderkrater pollen record (Scott *et al.* 2003) are comparable. However, the strengths of this mudbelt study also represent its limitations due to the broadness of its scale. The mudbelt is by its very nature a product of a large catchment covering numerous biomes, climate and altitudes, and therefore multiple factors influence the record. Any interpretation of this broad scale environmental change is challenging regarding the extent to which it can be interpreted and clarity achieved.

Unfortunately aeolian terrigenous input is low south of 25°S and limited amount of Berg winds carry sediment for just a few weeks each year.

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The major constraints in this thesis lie in the scope of the analytical work on the mudbelt which was limited to the existing HODSA material and associated box cores; no additional coring operations in the area were possible. Further constraints involved the limited nature and amount of additional radiocarbon dating and OSL dates; although additional radiocarbon ages were available, this was restricted to Richtersveld sites (as funding was limited to this area in the Richtersveld). As far as possible, existing viable sites and associated supporting literature were utilised due to:

a) valuable information being partially available

b) time and scope of project constraints and limits of this thesis and

c) some previous dating analysis having yielded useful results.

The three main methodologies were separated by data sets into data categories as a means of managing the large amount of data, namely dating results - chronology (chapter 4), stable isotopes (chapter 5) and palynology (chapter 6). Thus, apart from the chronology chapter, immediate synthesis of the data was retarded and a certain amount of discontinuity introduced. An attempt to remedy this was made in a single chapter synthesis of the data sets in chapter 7, but it remains a limitation of the research.

Due to logistical and financial reasons, it was not possible to retain the same resolution of sampling for all analyses. A moderately coarse sampling resolution was required for pollen analysis (given the length of time required for processing) and financial limitations prevented additional bulk organic radiocarbon dating analyses. It was possible for the stable isotope analysis to be sampled at a much finer resolution as these were relatively quick and inexpensive to process. Results of chronology analyses also had to be reconciled at a much coarser resolution than that of the vegetation proxies (stable isotopes and pollen). A finer sampling resolution for ^{210}Pb was not possible given that the archive half of the core required to be sub-sampled. This had unfortunately suffered shrinkage during the extended period between retrieval and sub-sampling. Ideally, the sampling for analysis should have occurred immediately after retrieval. This does not present much of a problem, but should be considered when interpreting the data and obtaining a cohesive understanding of what the resolution of these data imply. However, ^{210}Pb results are not of sufficiently high

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resolution to calculate sedimentation rates. Further, because of the delay between sampling and analysis and resulting archive strategies, the research was limited as certain analyses were not done during coring (e.g. magnetic susceptibility and other fresh sampling and analytical methods). A further constraint lies in the radiocarbon ages which refer to sediment age and NOT the age of the mudbelt deposition of that layer. Therefore the bulk organic radiocarbon age of a specific sample does not necessarily correspond to the correct proxy data of the same sample. However, notable improvements have been made to the previous findings of mudbelt chronology. New research by Herbert and Compton (2007) complements this research in successful radiocarbon dating of foraminifera and mollusc radiocarbon and in obtaining older sediment below 6 m, the depth represented by HODSA cores. Although it would have been preferable to have successfully obtained the precise age of foraminifera in the HODSA cores, it does provide complementary chronology content to results obtained in this thesis.

Interpretation of pollen analysis is hampered to some extent by overlapping taxa, the extent of pollen research in the Buffels River and also in terms of flood analysis. Furthermore, this study is limited to a simplified distal vs. proximal study. Stable isotope analysis is also limited by the dearth of inland bulk organic soil studies; certainly the Nama Karoo and Succulent Karoo are poorly understood with respect to general stable nitrogen and carbon isotopic values. In addition, the lack of stable carbon and nitrogen isotope data from flood analysis studies in the ORC and Buffels River Catchment is a limiting factor.

Notwithstanding these limitations and problems, the data represented in the mudbelt is invaluable in elucidating the character of the mudbelt and the timing and record of palaeoenvironmental change over a large area of southern Africa. This study contributes to the improved understanding of the character of the Namaqualand mudbelt and represents a fundamental step forward in closing the gap in the record. Indeed a number of papers (Meadows *et al.* 1997, 2002, Gray *et al.* 2000, Mabote *et al.* 1997) pointed to the need for further investigation of the cores in question and this research presents answers to many of the questions posed. The growing list of terrestrial margin literature (largely further to the north of the ORM) is testimony to the dearth in the literature and research in the south. This study presents a

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multidisciplinary approach to investigating inland change represented in the mudbelt that has not previously been attempted, referring to a broad area and drawing on the palaeo record. Findings for the period represented by the mudbelt cores correlate well with those of the last ±3 500 years BP at Makapansgat.

8.3 Directions for future research

Limitations serve to define the scope of research and in so doing invariably omit aspects of worthy analysis. There are a number of directions that are recommended in any future follow-up to this study.

A more detailed spatial analysis of the mudbelt for pollen analysis and stable isotope analysis would provide a more complete interpretation as to the spatial extent of the distinct character of the distal and proximal part of the mudbelt. (This thesis does not cover this question in spatial detail beyond that which may be deduced from the simple comparative study between proximal and distal mudbelt cores, H2 and H7). Further to this, a more detailed inland study of the pollen and the stable isotope analysis of flood events, along with sedimentological and geochemical analysis in both the Orange and the even lesser known Buffels Rivers would assist in further interpretation of some of the nuances of the mudbelt data. This should include detailed long term pollen aerobiology studies on the West Coast and various geologically- and biome-specific points on the rivers; pollen, stable isotope and sedimentological monitoring of flood events combined with careful mapping of sediment (flood) source in the catchment (all of which necessitate long term monitoring and equipment requirements).

This research makes an important contribution towards palaeoenvironmental characteristics of the mudbelt studies in the area and is expected to complement future and upcoming research in the sub-region. Studies of particular interest in this regard include a palaeoflood investigation of the Buffels River Catchment by Hoffmann (current status: early stages of investigation) and sedimentological and geochemical studies pertaining to the mudbelt which are nearing completion: suspended load mineralogical analysis of the Upper Orange River (Maake *et al.* 2006); clay mineralogy, trace element and isotopic (Strontium and Neodymium) studies of the

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mudbelt sediment highlighting issues of source and transport mechanisms (Herbert pers. comm.) and a study involving relict deposits on the continental slope and off-shelf transport (Wiltshire pers. comm.) are currently being carried out.

This study represents a focused attempt at extracting high resolution dating (fairly high compared to studies of the Amazon which are resolved at 1000 years) and the implication of this in a global context may be that perhaps a higher resolution does not mean greater detail of the mudbelt sediments. It is apparent that the variable dynamics of the OR combined with the highly variable climate, make the scale of this study overambitious and we should perhaps rethink what we can justifiably do in arid landscapes subject to infrequent and catastrophic flooding events. The amount of information that can be extracted for study of arid landscapes is limited as this is largely determined by scale and amount of preserved proxy data and presents a larger set of problems than when examining other sites such as the Congo or Amazon fan. In this study, there are vastly different rates of influx of sediment and proxies are not always complementary as they reflect such disparate processes. This questions the extent to which high resolution dating (restricted by the cores used) and other palaeoenvironmental information may be derived from a dry-land arid landscape and can be useful as a cautionary lesson in studying offshore sediment from a large (or major) river in an arid landscape.

These initiatives focus on issues of sedimentology and geochemistry and are expected to complement this study and together contribute further to an improved understanding of the geochemical and sediment flux record of the mudbelt. Ongoing research by Compton involving a simple mass balance investigation of fine Orange River sediment has, to date, highlighted a discrepancy in the fate of fine sediment; much of the fine fraction does not reach the mudbelt and appears destined for other areas of the ocean (Compton pers. comm.). Other workers have assumed that the majority of the fine fraction is deposited in the mudbelt. Additional sites of palaeoecological and sedimentological interest are present in the ORC and the geochemical and palaeoenvironmental study of such sites should help to inform us of the bigger picture. Further radiocarbon and OSL analysis may assist in such a venture.

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The application of the palaeoenvironmental research presented in this thesis to future research output by Herbert, Compton and others is expected to further contribute to broadening understanding of this complex and fascinating depository.

The HODSA program sought to examine the erosion of the landscape and use river/mudbelt deposits to investigate this. In as much as can be examined in the HODSA cores taken from the mudbelt, this and more has been achieved (such as pollen identification and isotope analysis), than what was initially intended under the HODSA banner.

8.4 Summary of findings

This research set out to show something of the past inland environment from offshore marine accumulations. Some of the intentions modelled on the Amazon and Congo River fans were overambitious as it was quickly evident that the proxies were vastly different from each other and it was not always possible to distill what was occurring due to differing scales, sources of sediment and organic fraction (both terrestrial and marine). The isotope and pollen data appear to be the most useful, although it also was not entirely clear (i.e. shifts in Poaceae pollen concentration do not coincide with obvious shifts in isotope patterns) as these proxies do not necessarily refer to the same dynamics – bulk OM adheres to different soil particles (for reasons discussed earlier), thus suggesting different biochemical processes. However, both isotope and pollen show some degree of similarity of patterns in the vegetation.

The bulk organic radiocarbon ages which revealed complex age discrepancies with older than expected ages and age reversals (mainly related to the proximal core) have been largely resolved and the true age of the organics and age of deposition elucidated. These problems are related to issues of different sources (marine and terrestrial) and different organics as it was not clear what was dated or the impact of hugely different flow rates in the OR. The proximal core H2 presented the more challenging chronology compared to the distal core H7 which has a much simpler, sensible chronology with a reasonably steady trend, probably due to the higher and consistent levels of marine OM.

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A major proportion of ORC sediment, including isotopes, the fluvial portion of pollen input and the bulk OM is sourced in the Upper catchment, as indicated by Maake and Compton (2007). The pollen, however appears to be sourced from a range of subregions of the ORC and is transported via both fluvial and aeolian means. The carbon isotopes are strongly consistent with a significant C_4- rich input from the ORC although the inland terrestrial content is more C_3 than expected, given the Upper catchment (certainly the high runoff and high organic rich area is C_4 rich. The surface is more C_3 and this may be related to algae or perhaps indicate an increase in sour grass (over sweeter C_4-rich grass) and therefore reduction in summer rainfall referred to by Scott and Vogel (2000) who suggested this to have increased from 1200 ending 420 years ago. There is nothing in the pollen to conclusively confirm this other than some general indicators of aridity (Asteraceae-1 and Cyperaceae pollen decrease towards the surface) and some of these reduced water levels and indicators may be consistent with increased impoundment.

This exploration of the character of the Namaqualand mudbelt represents a unique record of inland change, valuable to elucidating the timing and extent of palaeoenvironmental change of a large portion of southern Africa. While the data is sometimes difficult to interpret and lacks clarity on aspects of depositional age, being the product of multiple factors and driving forces determining deposition of the organic fraction and proxy components, this synthesis of the proxy data does accord well with established inland palaeoenvironmental records, human induced land use change in the ORC and, in future, might offer some insight into possible additional fluctuations not yet observed in the inland record.

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APPENDICES

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APPENDIX A

Relevance of the name, "Orange" River

The "Orange" River was officially named in 1777 by Colonel Robert Gordon, garrison commander of the Dutch East India Company, in honour of the Dutch House of Orange. (Cullinan 1992). However, the earliest name given to the Orange (above its confluence with the Vaal River) by the indigenous Khoi (or Khoe), in their native language, was "!Gariep", meaning "Great River" (Dicey 2004). Above this confluence, the river was called the "Nu !Gariep" (Black River) and the Vaal known as the "Ky !Gariep" (Yellow River). A hundred years prior to being named the "Orange", the river was named by Commander van der Stel (V.O.C. Commander at the Cape) as the "Vigiti Magna", after the mythical city (Williams 1902). Local Dutch colonists had otherwise referred to it as the "Groote" (Great) River.

It is important to mention the significance of a possibly controversial place name used in this thesis. Until recently, the name "Orange" River was freely used in literature, but some researchers now argue that the original and more "historically correct" name, Gariep (or Great River) be used. This is relevant, given the post-democracy place name revision that is taking place in South Africa. Indeed some popular local South African literature makes use of "Gariep" in place of "Orange" and thus creates a discrepancy with the now renamed, Gariep dam (previously the H.F. Verwoerd Dam), a major dam of the Orange. However, this name has not officially changed at the time of writing. The term, "Orange" is preferred as it is well established in both literature and the international context. The mudbelt itself is still known as the Orange River or Namaqualand mudbelt.

Historical land use in southern Africa: Past to present (Late Quaternary)

According to current studies, there is evidence that hunter gatherers were present in Southern Africa since Early Stone Age times and earlier (Scott and Lee Thorp 2004). Farmers (and transhumant Khoisan pastoralists) arrived in the southern African context at about 2000 years BP, bringing with them agriculture and domestic animals such as sheep and cattle (Scott and Lee Thorp 2004). They followed a semi-settled lifestyle, moving in response to climate and societal needs. Iron Age farmers arrived in the East and central region of southern Africa, farming sorghum and millet C_4 crops (which favoured a summer rainfall) (Scott and Lee Thorp 2004). Prior to the arrival of the farmers, hunter gatherers seemed to expand in terms of their presence on the landscape, evidenced by increased numbers of archaeological sites at about 7.5k BP in response to increased moisture and the consequent increased food availability. There is much still to be understood in this regard and limited records of land use dynamics indicate that what we know of the intensity of past land use trends are tentative at best.

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Ranking	River Name	Country	Catchment Area (106 km2)	Water Discharge (km3.yr-1)	Sediment Discharge (106t.yr-1)	Turbidity Ratio (sediment discharge/water discharge)
WORLD'S LARGEST						
1	Ganges	Bangladesh	1.48	971	1670	1.7
2	Hwang Ho (Yellow)	China	0.77	49	1080	22.0
3	Amazon	Brazil	6.15	6300	900	0.1
4	Yangtze	China	1.94	900	478	0.5
5	Irrawaddy	Burma	0.43	428	265	0.6
AFRICA'S LARGEST						
1	Congo	Democratic Republic of Congo	3.82	1250	43	0
2	Niger	Nigeria	1.21	192	40	0.2
3	Zambezi	Mozambique	1.20	223	20	0.1
4	***Orange***	***South Africa***	***0.89***	***11***	***17***	***1.5***
5	Nile		2.96	30	0	0

Table A1 Comparative table of major ranking world rivers: the Orange River is an important river within southern Africa, although it does not compare well with major world rivers in terms of high volume, it does compare well by virtue of its large catchment area and high turbidity ratio (from Bremner *et al.* 1990).

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APPENDIX B

HODSA Coring Operation - Ships Log

CORES H2 and H7 Orange Prodelta. Protea. Latitude S28°52'31.8" Longitude E16°21'17.3"

DEPTH (cm)	SAMPLE NUMBER	COMMENTS
		Section G (grab) Depth 116 m
		Landward end of DBM pinger profile (± 5m Holocene)
0 - 5.0	H2 - G2	Soft olive / brown clay.
5.0 - 10.0	H2 - G1	Stiff olive / grey-brown clay.
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 7
0 - 4.5	H2 - 7 - 4	Mottled soft light and dark brown clay.
4.5 - 9.0	H2 - 7 - 3	
9 - 13.5	H2 - 7 - 2	
13.5 - 15.75	H2 - 7 - 1b	
15.75 - 18.0	H2 - 7 - 1a	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 6
18.0 - 22.5	H2 - 6 - 12	Soft laminated greyish brown clay with 0.7 cm rich black laminae.
22.5 - 27.0	H2 - 6 - 11	
27.0 - 31.5	H2 - 6 - 10	
31.5 - 36.0	H2 - 6 - 9	
36.0 - 40.5	H2 - 6 - 8	
40.5 - 45.0	H2 - 6 - 7	
45.0 - 49.5	H2 - 6 - 6	
49.5 - 54.0	H2 - 6 - 5	
54.0 - 58.5	H2 - 6 - 4	
58.5 - 63.0	H2 - 6 - 3	
63.0 - 68.5	H2 - 6 - 2	
68.5 - 72.0	H2 - 6 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 5 Depth 115 m
72.0 - 77.0	H2 - 5 - 20	Laminated and mottled light brown + brown to black softer clay.
77.0 - 82.0	H2 - 5 - 19	
82.0 - 87.0	H2 - 5 - 18	
87.0 - 92.0	H2 - 5 - 17	
92.0 - 97.0	H2 - 5 - 16	
97.0 - 102.0	H2 - 5 - 15	
102.0 - 107.0	H2 - 5 - 14	
107.0 - 112.0	H2 - 5 - 13	
112.0 - 117.0	H2 - 5 - 12	
117.0 - 122.0	H2 - 5 - 11	
122.0 - 127.0	H2 - 5 - 10	Light brown stiff clay.
127.0 - 132.0	H2 - 5 - 9	Light brown to darker brown mottled stiff clay.
132.0 - 137.0	H2 - 5 - 8	Light brown to black stiff clay with angular deformity (black).
137.0 - 142.0	H2 - 5 - 7	Light brown + black stiff clay.
142.0 - 147.0	H2 - 5 - 6	Finely laminated brown clay with black laminae and a patch of organic black material (148 - 150 cm depth).
147.0 - 152.0	H2 - 5 - 5	
152.0 - 157.0	H2 - 5 - 4	
157.0 - 162.0	H2 - 5 - 3	

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162.0 - 167.0	H2 - 5 - 2	
167.0 - 172	H2 - 5 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 4
172.0 - 177.0	H2 - 4 - 20	Light brown faintly laminated stiff clay.
177.0 - 182.0	H2 - 4 - 19	
182.0 - 187.0	H2 - 4 - 18	
187.0 - 192.0	H2 - 4 - 17	Coarser laminated (cf below) brown stiff clay.
192.0 - 197.0	H2 - 4 - 16	
197.0 - 202.0	H2 - 4 - 15	
202.0 - 207.0	H2 - 4 - 14	
207.0 - 212.0	H2 - 4 - 13	
212.0 - 217.0	H2 - 4 - 12	
217.0 - 222.0	H2 - 4 - 11	
222.0 - 227.0	H2 - 4 - 10	Finely laminated greyish-brown stiff clay. Gas expansion structures throughout, especially 252.0 to 272.0 cm.
227.0 - 232.0	H2 - 4 - 9	
232.0 - 237.0	H2 - 4 - 8	
237.0 -242.0	H2 - 4 - 7	
242.0 - 247.0	H2 - 4 - 6	
247.0 - 252.0	H2 - 4 - 5	
252.0 - 257.0	H2 - 4 - 4	
257.0 - 262.0	H2 - 4 - 3	
262.0 - 267.0	H2 - 4 - 2	
267.0 - 272.0	H2 - 4 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 3
272.0 - 277.0	H2 - 3 - 20	Greyish brown finely laminated clay.
277.0 - 282.0	H2 - 3 - 19	
282.0 - 287.0	H2 - 3 - 18	
287.0 - 292.0	H2 - 3 - 17	Greyish brown to black finely laminated clay.
292.0 - 297.0	H2 - 3 - 16	Light brown mottled (dark) stiff clay.
297.0 - 302.0	H2 - 3 - 15	Finely laminated greyish brown stiff clay.
302.0 - 307.0	H2 - 3 - 14	
307.0 - 312.0	H2 - 3 - 13	
312.0 - 317.0	H2 - 3 - 12	Dark grey to black laminated clay.
317.0 - 322.0	H2 - 3 - 11	Dark grey finely laminated stiff clay.
322.0 - 327.0	H2 - 3 - 10	
327.0 - 332.0	H2 - 3 - 9	
332.0 - 337.0	H2 - 3 - 8	
337.0 - 342.0	H2 - 3 - 7	Mottled greyish brown stiff clay (black mottles) non laminated towards top.
342.0 - 347.0	H2 - 3 - 6	
347.0 - 352.0	H2 - 3 - 5	
352.0 - 357.0	H2 - 3 - 4	
357.0 - 362.0	H2 - 3 - 3	
362.0 - 367.0	H2 - 3 - 2	Brown faintly laminated stiff clay.
367.0 - 372.0	H2 - 3 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 2 Depth 115 m .
		Latitude (S) 28°52'30.2" Longitude 16°21'17.9"
372.0 - 377.0	H2 - 2 - 20	Finely laminated (black) greyish brown clay.
377.0 - 382.0	H2 - 2 - 19	
382.0 - 387.0	H2 - 2 - 18	
387.0 - 392.0	H2 - 2 - 17	

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392.0 - 397.0	H2 - 2 - 16	Wavey laminae and lenses of black (organic) colour in stiff brown clay (light and dark.)
397.0 402.0	H2 - 2 - 15	
402.0 - 407.0	H2 - 2 - 14	
407.0 - 412.0	H2 - 2 - 13	
412.0 - 417.0	H2 - 2 - 12	
417.0 - 422.0	H2 - 2 - 11	
422.0 - 427.0	H2 - 2 - 10	
427.0 - 432.0	H2 - 2 - 9	
432.0 - 437.0	H2 - 2 - 8	
437.0 - 442.0	H2 - 2 - 7	
442.0 - 447.0	H2 - 2 - 6	
447.0 - 452.0	H2 - 2 - 5	
452.0 - 457.0	H2 - 2 - 4	
457.0 - 462.0	H2 - 2 - 3	
462.0 - 467.0	H2 - 2 - 2	
467.0 - 472.0	H2 - 2 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section 1
472.0 - 477.0	H2 - 1 - 20	Homogeneous brown stiff clay.
477.0 - 482.0	H2 - 1 - 19	Transition upwards to homogeneous brown clay.
482.0 - 487.0	H2 - 1 - 18	Mottled and laminated brown clay.
487.0 - 492.0	H2 - 1 - 17	Mainly homogeneous slightly mottled brown clay.
492.0 - 497.0	H2 - 1 - 16	Homogeneous olive-brown clay.
497.0 - 502.0	H2 - 1 - 15	
502.0 - 507.0	H2 - 1 - 14	
507.0 - 512.0	H2 - 1 - 13	
512.0 - 517.0	H2 - 1 - 12	
517.0 -522.0	H2 - 1 - 11	
522.0 - 527.0	H2 - 1 - 10	
527.0 -532.0	H2 - 1 - 9	
532.0 - 537.0	H2 - 1 - 8	
537.0 - 542.0	H2 - 1 - 7	
542.0 - 547.0	H2 - 1 - 6	
547.0 - 552.0	H2 - 1 - 5	
552.0 - 557.0	H2 - 1 - 4	
557.0 - 562.0	H2 - 1 - 3	
562.0 - 567.0	H2 - 1 - 2	
567.0 -572.0	H2 - 1 - 1	
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section Sp (Below 1)
572.0 - 577.0	H2 - Sp - 4	Stiff olive clay.
577.0 - 582.0	H2 - Sp - 3	Stiff olive clay.
582.0 - 587.0	H2 - Sp - 2	Mottled brown/olive stiff clay.
587.0 - 592.0	H2 - Sp - 1	Mottled brown/olive stiff clay.
		No archive for H2-Sp-1 to H2-Sp- 4.
DEPTH (cm)	**SAMPLE NUMBER**	**COMMENTS**
		Section CC
		No top valve used. Cutting edge mud fell out reloading.
592.0 - 597.0	H2 - CC - 2	Both stiffish dark olive clay.
597.0 - 602.0	H2 - CC - 1	

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CORE H7	Orange Protea. LatitudeS29°22'09.75" Longitude E17°00'42.6"	
		Due west of Buffels River (Kleinsee.)
DEPTH (cm)	SAMPLE NUMBER	COMMENTS
		Section G (grab). Depth 80 m
0 - 5.0	H7 - G2	Sloppy clay, greyish brown + dark grey patches.
5.0 - 10.0	H2 - G1	Greyish - brown clay.
DEPTH (cm)	SAMPLE NUMBER	COMMENTS
		Section 6 Box 31
0 - 5.0	H7 - 6 - 20	Dark olive green soft clay.
5.0 - 10.0	H7 - 6 - 19	Faintly laminated with dark grey.
10.0 - 15.0	H7 - 6 - 18	Dark olive green soft clay with clear patches of dark grey clay.
15.0 - 20.0	H7 - 6 - 17	
20.0 - 25.0	H7 - 6 - 16	Apparently homogeneous olive-green soft clay with sparse mollusc fragments. Lighter coloured laminae seem to be absent.
25.0 - 30.0	H7 - 6 - 15	
30.0 - 35.0	H7 - 6 - 14	
35.0 - 40.0	H7 - 6 - 13	
40.0 - 45.0	H7 - 6 - 12	
45.0 - 50.0	H7 - 6 - 11	
50.0 - 55.0	H7 - 6 - 10	
55.0 - 60.0	H7 - 6 - 9	
60.0 - 65.0	H7 - 6 - 8	
65.0 - 70.0	H7 - 6 - 7	
70.0 - 75.0	H7 - 6 - 6	
75.0 - 80.0	H7 - 6 - 5	
80.0 - 85.0	H7 - 6 - 4	
85.0 - 90.0	H7 - 6 - 3	
90.0 - 95.0	H7 - 6 - 2	
95.0 - 100.0	H7 - 6 - 1	
DEPTH in Cms.	SAMPLE NUMBER	COMMENTS
		Section 5 Box 30
100.0 - 105.0	H7 - 5 - 20	0 to 125 cms. As below but lighter coloured laminae common.
105.0 - 110.0	H7 - 5 - 19	
110.0 - 115.0	H7 - 5 - 18	
115.0 - 120.0	H7 - 5 - 17	
120.0 - 125.0	H7 - 5 - 16	
125.0 - 130.0	H7 - 5 - 15	As below but faint laminations revealed by rare laminae of lighter coloured clay.
130.0 - 135.0	H7 - 5 - 14	
135.0 - 140.0	H7 - 5 - 13	
140.0 - 145.0	H7 - 5 - 12	
145.0 - 150.0	H7 - 5 - 11	
150.0 - 155.0	H7 - 5 - 10	
155.0 - 160.0	H7 - 5 - 9	160 cms. Apparently homogeneous soft olive-green clay with molluscs and mollusc fragments. No gas expansion.
160.0 - 165.0	H7 - 5 - 8	
165.0 - 170.0	H7 - 5 - 7	
170.0 - 175.0	H7 - 5 - 6	
175.0 - 180.0	H7 - 5 - 5	
180.0 - 185.0	H7 - 5 - 4	
185.0 - 190.0	H7 - 5 - 3	
190.0 - 195.0	H7 - 5 - 2	
195.0 - 200.0	H7 - 5 - 1	

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DEPTH in Cms.	SAMPLE NUMBER	COMMENTS
		Section 4 Box 29.
200.0 - 205.0	H7 - 4 - 20	
205.0 - 210.0	H7 - 4 - 19	
210.0 - 215.0	H7 - 4 - 18	
215.0 - 220.0	H7 - 4 - 17	
220.0 - 225.0	H7 - 4 - 16	
225.0 - 230.0	H7 - 4 - 15	
230.0 - 235.0	H7 - 4 - 14	Apparently homogeneous soft olive-green clay with mollusc fragments.
235.0 - 240.0	H7 - 4 - 13	
240.0 -245.0	H7 - 4 - 12	
245.0 - 250.0	H7 - 4 - 11	
250.0 - 255.0	H7 - 4 - 10	
255.0 - 260.0	H7 - 4 - 9	Consistency becomes softer towards the top of this section.
260.0 - 265.0	H7 - 4 - 8	
265.0 - 270.0	H7 - 4 - 7	
270.0 - 275.0	H7 - 4 - 6	
275.0 - 280.0	H7 - 4 - 5	
280.0 -285.0	H7 - 4 - 4	
285.0 - 290.0	H7 - 4 - 3	
290.0 - 295.0	H7 - 4 - 2	
295.0 -300.0	H7 - 4 - 1	
DEPTH in Cms.	SAMPLE NUMBER	COMMENTS
		Section 3 Box 28.
300.0 - 305.0	H7 - 3 - 20	
305.0 - 310.0	H7 - 3 - 19	
310.0 - 315.0	H7 - 3 - 18	
315.0 - 320.0	H7 - 3 - 17	
320.0 - 325.0	H7 - 3 - 16	
325.0 -330.0	H7 - 3 - 15	Apparently homogeneous soft olive-green clay with sparse shell fragments. Gas expanded clay declines upwards.
330.0 - 335.0	H7 - 3 - 14	
335.0 - 340.0	H7 - 3 - 13	
340.0 -345.0	H7 - 3 - 12	
345.0 - 350.0	H7 - 3 - 11	
350.0 - 355.0	H7 - 3 - 10	
355.0 - 360.0	H7 - 3 - 9	
360.0 - 365.0	H7 - 3 - 8	
365.0 - 370.0	H7 - 3 - 7	
370.0 - 375.0	H7 - 3 - 6	
375.0 - 380.0	H7 - 3 - 5	
280.0 - 385.0	H7 - 3 - 4	
385.0 - 390.0	H7 - 3 - 3	
390.0 - 395.0	H7 - 3 - 2	
395.0 - 400.0	H7 - 3 - 1	
DEPTH in Cms.	SAMPLE NUMBER	COMMENTS
		Section 2 Box 27.
400.0 - 402.5	H7 - 2 - 21 (20B)	20A and 20B assumed to be 2.5 cm samples.
402.5 - 405.0	H7 - 2 - 20 (20A)	
405.0 - 410.0	H7 - 2 - 19	
410.0 - 415.0	H7 - 2 - 18	
415.0 - 420.0	H7 - 2 - 17	
420.0 - 425.0	H7 - 2 - 16	

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425.0 - 430.0	H7 - 2 - 15	Apparently homogeneous soft olive-green clay with sparse
430.0 - 435.0	H7 - 2 - 14	shell fragments.
435.0 - 440.0	H7 - 2 - 13	Gas expanded clay in sections 1 and 2 throughout.
440.0 - 445.0	H7 - 2 - 12	
445.0 - 450.0	H7 - 2 - 11	
450.0 - 455.0	H7 - 2 - 10	
455.0 - 460.0	H7 - 2 - 9	
460.0 - 465.0	H7 - 2 - 8	
465.0 - 470.0	H7 - 2 - 7	
470.0 - 475.0	H7 - 2 - 6	
475.0 - 480.0	H7 - 2 - 5	
480.0 - 485.0	H7 - 2 - 4	
485.0 - 490.0	H7 - 2 - 3	
490.0 - 495.0	H7 - 2 - 2	
495.0 500.0	H7 - 2 - 1	
DEPTH in Cms.	**SAMPLE NUMBER**	**COMMENTS**
		Section 1 Box 26
500.0 - 502.5	H7 - 1 - 22 (20B)	19A to 20B arbitrarily assumed to be 2.5 cm samples.
502.5 - 505.0	H7 - 1 - 21 (20A)	
505.0 - 507.5	H7 - 1 - 20 (19B)	
507.5 - 510.0	H7 - 1 - 19 (19A)	
510.0 - 515.0	H7 - 1 - 18	
515.0 - 520.0	H7 - 1 - 17	
520.0 - 525.0	H7 - 1 - 16	
525.0 - 530.0	H7 - 1 - 15	Apparently homogeneous "crumbly" olive-green clay with
530.0 - 535.0	H7 - 1 - 14	sparse shell fragments.
535.0 - 540.0	H7 - 1 - 13	
540.0 - 545.0	H7 - 1 - 12	
545.0 - 550.0	H7 - 1 - 11	
550.0 555.0	H7 - 1 - 10	
555.0 - 560.0	H7 - 1 - 9	
560.0 - 565.0	H7 - 1 - 8	
565.0 - 570.0	H7 - 1 - 7	
570.0 - 575.0	H7 - 1 - 6	
575.0 - 580.0	H7 - 1 - 5	
580.0 - 585.0	H7 - 1 - 4	
585.0 - 590.0	H7 - 1 - 3	
590.0 - 595.0	H7 - 1 - 2	
595.0 - 600.0	H7 - 1 - 1	
DEPTH in Cms.	**SAMPLE NUMBER**	**COMMENTS**
		Section CC
600.0 - 605.0	H7 - CC - 2	Crumbly olive clay with sparse shells.
605.0 - 610.0	H7 - CC - 1	
DEPTH in Cms.	**SAMPLE NUMBER**	**COMMENTS**
		Section CE
610.0 - 615.0	H7 - CE	"Gas expanded" soft olive clay. Assumed to be 10 cm thick.

Table B1 HODSA Coring Operation - Ships Log indicating sample number, depth and core lithology.

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BIOME	Subtype	Family	applicable?	broad description	listed species	common name		
Forest	1.Coastal Forest		n/a					
	2.Afromontane Forest							
	3.Sand Forest		n/a					
Thicket			n/a					
Savanna				grasssy, woody				
	9.Mopane Shrubveld							
	10Mopane Bushveld							
	11Soutpansberg arid Mountain Bushveld							
	12							
	13							
	14 Clay thorn bushveld	Fabaceae			*A. tortilis*	(hairy umbrella thorn)		
		Fabaceae			*A. nilotica*	scented thorn		
		Fabaceae			*A. Karroo*	Sweet thorn		
		Fabaceae			*A. tenuispina*			
		Fabaceae			*A. gerrardii*			
		Fabaceae			*A. nigrescens*			
		Fabaceae			*A. robusta*			
		Rhamnaceae			*Ziziphus mucronata*	Buffalo thorn		
		Fabaceae		woody spp.	*Dichrostachys cinerea*	sicklebush		
		Tiliaceae			*Grewia flava*	wild raisin		
		Poaceae		principle grass	*Ischaemum afrum*	turf grass		
		Poaceae			*Sehima galpinii*	Deck grass		
		Poaceae			*Setaria incrassata*	Canary millet		
		Poaceae			*Panicum coloratum*		overgrazing, deterioration	
		Poaceae			*Bothriochloa insculpta*	pinhole grass		
		Poaceae			*Aristida bipartita*	three-awn rolling grass		
		Poaceae			*Brachiaria eruciformis*	sweet signalgrass		
	15 subarid thorn bushve	Poaceae			*Sorghum versicolor*			
	16 Eastern Thorn Bushveld							
	17 Sweet Bushveld	Combretacea	Y	short shrubby/trees		Silver Clusterleaf		
		Bignoniaceae			*Rhigozum obovatum*	Yellow Pomegranate		
		Poaceae			*Grewia flava*	Wild Raisin		
		Fabaceae			*Acacia tortilis*			
		Poaceae			*Eragrostis pallens*	Broom Grass		

Table B2 Partial list of flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 1/22).

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	SS SS	Poaceae			*Schmidtia pappophoroid*	Kalahari Sand Quick		
		Poaceae			*Eragrostis trichophora*	Hairy Love Grass		
		Poaceae			*Brachiaria nigropedata*			
		Poaceae			*Loudetia simplex*			
		Poaceae			*Aristida stipitata*			
		Buseraceae		Shallower/drier soils	*Commiphora pyracanth*	Common Corkwood		
		Capparaceae			*Boscia albitrunca*	Shepherd's Tree		
		Combretaceae			*Combretum apiculatum*			
		Fabaceae		Dense/impenetrable	*Acacia erubescens*	Blue Thorn		
		Fabaceae			*A. mellifera*	Black Thorn		
					Dychrostachys cinerea	Sicklebush		
		Poaceae			*Panicum maximum*	Guinea Grass		
		Poaceae			*P. Coloratum*	Small Panicum	Poorly conserved	
		Poaceae			*Cenchrus ciliaris*	Blue Buffalo Grass		
		Poaceae			*Anthephora pubescens*			
					Enneapogon scoparius			
					Urochloa mosambicensis			
Savanna	18.Mixed Bushveld	Poaceae		Tree layer	*Combretum apiculatum*	Red Bushwillow	Shallow soils	
		Fabaceae			*Acasia cafra*	Common Hookthorne		
		Fabaceae			*Dichrostachys cinerea*	Sicklebush		
		Anacardiaceae			*Lannea discolor*	Live-long		
		Anacardiaceae			*Sclerocarya birrea*		dominated by grasses.	
		Poaceae		Grass Layer	*Digitaria eriantha*	Fingergrass		
		Poaceae			*Schmidtia pappophoroid*	Kalahari Sand Quick		
		Poaceae			*Anthephora pubesens*	Wool Grass		
		Poaceae			*Stipagrostis uniplumis*	Silky Bushman grass		
		Combretaceae			*Terminalia sericia*	Silver Clusterleaf	Deeper/sandy soil	
		Ochnaceae		Woody species	*Ochna pulchra*	Peeling Plane		
		Tiliaceae			*Grewia flava*	Wild Raisin		
		Fabaceae			*Peltophorum africanum*			
		Fabaceae			*Burkea africana*			
		Poaceae		Grass Layer scanty	*Eragrostis pallens*	Broom Grass		
		Poaceae			*Perotis patens*	Purple Spike Cat'stail		
Savanna	19.Mixed Lowveld Bushveld							

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 2/22).

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Savanna	20.Sweet Lowveld Bushveld		n/a					
Savanna	21.Sour Lowveld Bushveld		n/a					
Savanna	22.Subhumid Lowveld Bushveld		n/a					
Savanna	23.Coastal Bushveld Grassland		n/a					
Savanna	24.Coastal Hinterland Bushveld		n/a					
Savanna	25.Natal Central Bushveld		n/a					
Savanna	26.Natal Lowveld Bushveld		n/a					
Savanna	27.Thorny Kalahari Dur	Fabaceae		Sparse Trees	*Acasia erioloba*	Camel Thorn		
		Fabaceae			*Acasia leuderitzii*	Belly Thorn		
		Capparaceae			*Boschia albitrunca*	Shepherd's Tree		
		Combretaceae			*Terminalia sericea*	Silver Clusterleaf		
		Solanaceae		Shrub Layer	*Lycium bosciifolium*	Honeythorn		
		Tiliaceae			*Grewia retinervis*	Bastard Roughleaf Raisin		
		Anacardiaceae			*Rhus tenuinervis*	Kalahari Currant		
		Poaceae		Grass Layer	*Eragrostis lehmanniana*	Lehmann's Lovegrass		
		Poaceae			*Schmidtia kalihariensis*	Sour Bushmangrass		
		Poaceae			*Stipagrostis amabilis*	Kalahari Coach		
Savanna	28.Scrubby Kalahari Du	Fabaceae		Shrubs	*Acasia haematoxylon*	Grey Camel Thorn		Scattered
		Fabaceae			*Acasia erioloba*	Camel Thorn		
		Capparaceae			*Boscia albitrunca*	Shepherd's Tree		
		Tiliaceae			*Grewia retinervis*	Bastard Roughleaf Raisin		Widely scattered
		Anacardiaceae			*Rhus tenuinervis*	Kalahari Currant		Widely scattered
		Poaceae		Grass Layer	*Stipagrostis amabilis*	Kalahari Coach		Well developed - c
		Poaceae			*Eragrostis lehmanniana*	Lehmann's Lovegrass		
		Poaceae			*Aristida meridionalis*	Giant Stick Grass		
		Poaceae			*Centropodia glauca*			
Savanna	29.Karroid Kalahari Bus	Fabaceae		Tree Layer [sparse]	*Acacia erioloba*	Camel Thorn		Very sparse
		Capparaceae			*Boscia albitrunca*	Shepherd's Tree		Very sparse
		Chenopodiaceae		Shrub Layer	*Salsola tuberculata*	Cauliflowerbush		Moderately
		Asteraceae			*Eriocephalus spinescen*	Thornkapok		
		Bignoniaceae			*Rhigozum tricotomum*	Threethorn		
		Asteraceae			*Rosenia humulis*			
		Scrophulariaceae			*Aptosimum spinescens*			
		Asteraceae			*Eriocephalus pubescens*			
		Poaceae		Grass Layer	*Stipagrotis obtusa*	Small Bushman Grass		Poorly developed

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 3/22).

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		Poaceae			*Stipagrotis ciliata*	Tall Bushman Grass		
		Poaceae			*Enneapogon desvauxii*	Eightday Grass		Less general occu
		Poaceae			*Eragrostis annulata*	Ring Windgrass		
		Poaceae			*E. porosa*	Blue Windgrass		
		Poaceae			*E. homomalla*			
		Poaceae			*Tragus racemosus*			
		Poaceae			*Schmidtia kalihariensis*			
Savanna	30.Kalahari Plains Thor	Fabaceae		Tree Layer	*Acacia erioloba*	Camel Thorn		Fairly well develop
		Capparaceae			*Boscia albitrunca*	Shepherd's Tree		
		Fabaceae			*Acacia Luederitzii*	Belly Thorn		Scattered
		Combretaceae			*Terminalia sericea*	Silver Clusterleaf		
		Fabaceae		Shrub Layer	*Acacia mellifera*	Black Thorn		
		Fabaceae			*A. hebeclada*	Weeping Candle Thorn		
		Solanaceae			*Lycium hirsutum*	Karee-thorn		
		Tiliaceae			*Grewia flava*			
		Fabaceae			*Acacia haematoxylon*			
		Poaceae		Grass Layer	*Eragrostis lehmanniana*	Lehmann's Lovegrass		rainfall dependent
		Poaceae			*Schmidtia kalihariensis*	Sour Bushmangrass		
		Poaceae			*Stipagrostis uniplumis*	Silky Bushman grass		
Savanna	31.Kalahari Mountain B	Asteraceae		Tree Layer	*Tarchonanthus campho*	Camphor Tree		
		Anacardiaceae		Shrub Layer	*Rhus undulata*	Kunibush		
		Anacardiaceae			*Rhus dregeana*	Broom Karee		
		Oleaceae		Tree Layer poor	*Olea europaea subsp.a*	Wild Olive		Poorly dev.
		Fabaceae			*Acacia mellifera subsp.*	Black Thorn		
		Poaceae		Grass Layer	*Diheteropogon amplecte*	Broadleaf Bluestem		
		Poaceae			*Andropogon schirensis*	Hairy Bluegrass		
		Poaceae			*Brachiaria serrata*	Velvet Signalgrass		
		Poaceae			*Aristida diffusa*	Copperwire Grass		
		Poaceae			*Eragrostis lehmanniana*	Lehmann's Lovegrass		
		Poaceae			*Fingerhuthia africana*	Thimblegrass		
		Poaceae			*Digitaria eriantha*			
Savanna	32.Kimberley Thorn Bus	Fabaceae		Tree Layer	*Acacia tortillis*	Umbrella Thorn		Open Savanna
		Fabaceae			*A.erioloba*	Camel Thorn		
		Capparaceae		TreeLayer scattered	*Boscia albitrunca*	Shepherd's Tree		Scattered
		Fabaceae			*Acacia karroo*	Sweet Thorn		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 4/22).

		Asteraceae		Shrub Layer	*Tarchonanthus campho*	Camphor Tree		
		Fabaceae			*Acacia mellifera*	Spike-flowered Black Thorn		
		Tiliaceae			*Grewia flava*	Wild Raisin		
		Solanaceae			*Lycium hirsutum*			
		Poaceae		Grass Layer	*Themeda triandra*	Redgrass		
		Poaceae			*Enneapogon cenchroide*	Common Nine-awn Grass		Fairly well develop
		Poaceae			*Eragrostis lehmanniana*	Lehmann's Lovegrass		
		Poaceae			*Elionurus muticus*			
Savanna	33.Kalahari Plateau Bus	Asteraceae			*Cymbopogon plurinodis*			
		Bignoniaceae		Shrub Layer	*Tarchonanthus campho*	Camphor Tree		
		Boraginaceae			*Rhigozum tricotomum*	Threethorn		
		Tiliaceae			*Ehretia rigida*	Puzzle Bush		
		Celastraceae			*Grewia flava*			
		Oleaceae			*Maytenus heterophylla*			
		Fabaceae		Tree layer (sparse)	*Olea europaea subsp.a*	Wild Olive		not dominant
		Capparaceae			*Acacia tortilis*	Umbrella Thorn		
		Poaceae			*Boscia albitrunca*	Shepherd's Tree		
		Poaceae		Grass Layer	*Themeda triandra*	Redgrass		by nature tall
		Poaceae			*Aristuda diffusa*	Copperwire Grass		
		Anacardiaceae			*Stipagrostis uniplumis*	Silky Bushman grass		
		Fabaceae		Association	*Rhus ciliata*	Fringed Karee		Karoo dwarf shrub
		Fabaceae			*Acacia mallifera subsp.*	Spike-flowered Black Thorn		
Grasslan	34.Rocky Highveld Gras	Poaceae			*A.tortilis*	Umbrella Thorn		
		Poaceae		Grass Layer	*Trachypogon spicatus*	Giant Speargrass		
		Poaceae			*Diheteropogon amplecte*	Broadleaf Bluestem		
		Poaceae			*Schidzachyrium sangui*	Red autumngrass		
		Poaceae			*Andropogon schirensis*			
		Poaceae			*Loudetia simplex*			
		Poaceae			*Tristachya leucothrx*			
		Poaceae			*Panicum natalense*			
		Poaceae			*Bewsia biflora*			
		Poaceae			*Digitaria tricholaenoides*			
		Poaceae			*D.monodactyla*			
		Fabaceae		dicotyledonous forbs	*Sporobolus pectinatus*			
					Sphenostylis angustifoli	Wild Sweetpea		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 5/22).

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		Lamiaceae			*Acrotome hispida*	Rough-hair Sage		
		Asteraceae			*Senecio venosus*			
		Asteraceae			*S. coronatus*			
		Acanthaceae			*Justicia anagalloides*			
		Rubiaceae			*Pentanisia augustifolia*			
		Fabaceae			*Pearsonia cajanifolia*			
		Fabaceae			*Indigofera comosa*			
		Velloziaceae			*Xerophyta retinervis*			
		Euphorbiaceae			*Acalypha angustata*			
		Goodeniaceae			*Vernonia oligocephala*			
		Adiantaceae			*Cheilanthes hirta*	Parsley Fern		
		Crassulaceae			*Crassula lanceolata*	succulent		
		Poaceae		Drakensberg affinity	*Harpochloa faix*	Caterpillar Grass		
		Poaceae		(Afromontane)	*Ctenium concinnum*	Sickle Grass		
		Poaceae			*Rendlia altera*	Toothbrush Grass		
		Poaceae			*Alloteropsis semialata*			
		Poaceae			*Monocymbium ceresiiform*			
		Hyacinthaceae		Non grassy forbs	*Scilla nervosa*	Wild Squill		
		Anacardiaceae			*Rhus rehmanniana*	Bluntleaf Currant		
		Anacardiaceae			*R.discolor*	Gwarrie		
		Asteraceae			*Vernonia natalensis*			
		Asteraceae			*Berkheya setifera*			
		Asteraceae			*Helichrysum oreophilum*			
		Fabaceae		Woody vegetation	*Acacia caffra*	Common Hook Thorn		
		Anacardiaceae		Zambezian Afro-	*Rhus leptodictya*	Mountain Karee		
		Anacardiaceae		montane affinity	*R. pyroides*	Common Wild Currant		
		Anacardiaceae			*R.rigida*			
		Anacardiaceae			*R. magalismontana*			
		Anacardiaceae			*R. zeyheri*			
		Boraginaceae			*Ehretia rigida*			
		Celastraceae			*Maytenus heterophylla*			
		Ebenaceae			*Euclea crispa*			
		Rutaceae			*Zanthoxylum capense*			
		Sterculiaceae			*Dombeya rotundifolia*			
		Proteaceae			*Protea caffra*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 6/22).

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		Ulmaceae			*Celtis africana*			
		Rhamnaceae			*Ziziphus mucronata*			
		Rubiaceae			*Tapiphyllum parvifolium*			
		Rubiaceae			*Vangueria infausta*			
		Rubiaceae			*Canthium gilfillanii*			
					Englerophytum magalismontanum			
		Combretaceae			*Combretum molle*			
		Apocynaceae			*Ancylobotrys capensis*			
		Oleaceae			*Olea europaea subsp.africana*			
		Tiliaceae			*Grewia occidentalis*			
Grasslan	35 Moist Clay Highveld	Poaceae		Grass Layer	*Themeda triandra*	Redgrass		Dominates areas
		Poaceae			*Aristida bipartita*	Three-awn Rolling Grass		
		Poaceae			*Digitaria termata*	Blackseed Fingergrass		
		Poaceae			*Setaria nigrirostris*	Largeseed Setaria		
		Poaceae			*S. incrasata*			
		Poaceae			*Panicum coloratum*			
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		Other important sp
		Poaceae			*Heteropogon contortus*	Speargrass		
		Poaceae			*Setaria Sphacelata*	Golden Setaria		
		Poaceae			*Elionurus muticus*			
		Poaceae			*Microchloa caffra*			
		Poaceae			*Brachiaria serrata*			
		Poaceae			*Eragrostis plana*			
		Poaceae			*Chloris virgata*	Feathered Chloris		
		Poaceae			*Cynodon dactylon*	Couchgrass		
		Poaceae			*Aristida congesta*	Tassel Bristlegrass		
		Asteraceae		Dicotyledonous forbs	*Berkheya pinnatifida*	Dicotyledonous forbs		Prominent
		Acanthaceae			*Crabbea acaulis*	Flower-in-a-cage		
		Acanthaceae			*Chaetacanthus costatus*	Hairflower		
		Lamiaceae			*Salvia repens*			
		Asteraceae			*Pseudognaphalium luteo-album*			
		Cyperaceae			*Abildgaardia ovata*			
		Rubiaceae			*Anthospernum pumilum*			
		Euphorbiaceae			*Chamaesyce inaequilatera*			
		Cyperaceae			*Bulbostylus contexta*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 7/22).

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		Convolvulaceae			*Evolvulus alsinoides*			
Grasslan	36. Dry Clay Highveld G	Poaceae		Grass species	*Panicum coloratum*	White Buffalograss		
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		
		Poaceae			*E.plana*	Fan lovegrass		
		Poaceae			*Setaria nigrirostis*			
		Poaceae			*Themeda triandra*			
		Poaceae			*Aristida bipartita*	Three-awn Rolling Grass		
		Asteraceae		Dwarf shrubs	*Pentzia globosa*	Bitterkaroo		
		Asteraceae			*Felicia muricata*	Bloublommetjie		
		Asteraceae			*F.filifolia*	Ghombos		
		Solanaceae			*Lycium cinereum*			
		Poaceae		Grasses	*Eragrostis obtusa*			
		Poaceae			*Sporobolus ludwigii*	Saltpan Grass		
		Poaceae			*Tragus racemosus*	Carrotseed Grass		
		Asphodelaleae			*Bulbine narcissifolia*	Yellow Snakehead		Geophyte
Grasslan	37 Dry Sandy Highveld	Fabaceae	Y	Tree layer	*Acacia karroo*	Sweet Thorn		Occasionally along
		Fabaceae		Grass layer	*Eragrostis lehmanniana*	Lehmann's Lovegrass		Diagnostic grasse
		Fabaceae			*E.obtusa*			
		Fabaceae			*Panicum coloratum*	Small Buffalograss		
		Fabaceae			*Stipagrostis uniplumis*			
		Asteraceae		Dwarf shrub	*Pentzia globosa*	Bitterkaroo		Karroid
		Poaceae		Grass species	*Themeda triandra*	Redgrass		
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		
		Poaceae			*E. trichophora*	Hairy Lovegrass		
		Poaceae			*Anthephora pubescens*			
		Poaceae			*Aristida congesta*			
		Poaceae			*Digitaria eriantha*			
		Poaceae			*Cynodon dactylon*			
		Fabaceae		Forbs	*Chamaecrista mimosoides*			Dicotyledonous
		Lamiaceae			*Solanumpanduriforme*	Poison Apple		
		Asteraceae			*Dicoma anomala*	Tummy Bitterroot		
		Asteraceae			*Helichrysum callicomum*			
		Asteraceae			*H.cerastioides*			
		Amaranthaceae			*Kyphocarpa augustifolia*			
		Lamiaceae			*Leucas capensis*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 8/22).

		Thymelaeaceae			*Gnidia capitata*			
		Acanthaceae			*Blepharis angusta*			
		Rubiaceae			*Anthospermum hispidulum*			
		Euphorbiaceae			*Acalypha angustata*			
		Anacardiaceae		Dwarf shrubs	*Rhus ciliata*	Fringed Karee		Bfx.Karoo affinity
		Asteraceae			*Pentzia incana*	Anchorkaroo		
		Asteraceae			*Chrysocoma ciliata*	Bitterbush		
		Asteraceae			*Helichrysum pentziodes*			
		Chenopodiaceae			*Salsola kali*			
		Asteraceae			*Felicia muricata*			
		Selaginaceae			*Walafrida dsnsiflora*			
		Selaginaceae			*W.saxatilis*			
		Rubiaceae			*Nenax microphylla*			
Grasslan	38 Moist Sandy Highvel	Poaceae		Grass Layer	*Eragrostis plana*	Fan Lovegrass		
		Poaceae			*E.curvula*	Weeping Lovegrass		
		Poaceae			*Heteropogon contortus*	Speargrass		
		Poaceae			*Trachypogon spicatus*			
		Poaceae			*Themeda triandra*	Redgrass		Dominates entirely
Grasslan	39 Moist Cool Highveld	Poaceae		Grasses	*Themeda triandra*	Redgrass		Dominates entirely
		Poaceae			*Triraphis andropogonoid*	Broom Needlegrass		
		Poaceae			*Eragrostis superba*	Sawtooth Lovegrass		
		Poaceae			*Brachiaria serrata*	Velvet Signalgrass		
		Poaceae			*Elionurus muticus*			
		Poaceae			*Heteropogon contortus*			
		Poaceae			*Cymbopogon plurinodis*			
		Poaceae			*Setaria spacelata*			
		Fabaceae		Forbs	*Tephrosia semiglabra*	Fishbean		
		Convolvulaceae			*Ipomoea obscura*	Wild Petunia		
		Scrophulariaceae			*Sutera atropurpurea*	Brown Saffronbush		
		Apiaceae			*Deverra burchellii*			
		Asteraceae			*Helichrysum rugulosum*			
		Asteraceae			*H. caespititium*			
		Asteraceae			*H. dregeanum*			
		Acanthaceae			*Crabbea acaulis*			
		Malvaceae			*Hermannia depressa*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 9/22).

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		Fabaceae			*Rhynchosia totta*			
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		Becomes dominan
		Asteraceae		Karroid shrubs	*Pentzia globosa*	Bitterkaroo		
		Asteraceae			*Stroebe vulgaris*	Bankruptbush		
		Asteraceae			*Osteospermum scariosu*	Small Bietou		
		Selaginaceae			*Walafrida densiflora*			
		Rhamnaceae		Woody dwarf shrubs	*Zizphus zeyheriana*	Dwarf Buffalothorn		
		Fabaceae			*Elephantorrhiza elephar*	Elephant`s Root		
		Poaceae		Grass species	*Aristida congesta*	Tassel Bristlegrass		
		Poaceae			*Cynodon dactylon*	Couchgrass		
		Poaceae			*Eragrostis obtusa*			
		Poaceae			*Aristida canescens*			
		Poaceae			*Michrochloa caffra*			
		Poaceae			*Tragus berteronianus*			
		Euphorbiaceae		Forbs	*Chamaesyce prostrata*			
		Malvaceae			*Hibiscus trionum*	Bladderweed		
		Acanthaceae			*Blepharis integrifolia*	Rattlebush		
Grasslan	40. Moist Cold Highvelc	Poaceae		Grassland	*Cymbopogon plurinodis*	Bushveld Turpentinegrass		Moderately dense
		Poaceae			*Themeda triandra*	Redgrass		
		Poaceae			*Setaria Sphacelata*	Small Creeping Foxtail		
		Poaceae			*Elionurus muticus*			
		Poaceae			*Eragrostis curvula*			
		Poaceae		Grasses	*Aristida junciformis*	Ngongoni Bristlegrass		Typical
		Poaceae			*Eragrostis capensis*	Heartseed Lovegrass		
		Poaceae			*Tristachya leucothrix*	Hairy Tridentgrass		
		Poaceae			*Andropogon appendiculatus*			
		Poaceae			*Helictotrichon turgidulum*			
		Poaceae			*Microchloa caffra*			
		Poaceae			*Eragrostis plana*			
		Rubiaceae		Prominent forbs	*Anthospermum rigidum*	Kleinjakkelstert		
		Asteraceae			*Helichrysum rugulosum*	Veld Everlasting		
		Sterculiaceae			*Hermannia geniculata*			
		Asteraceae			*Senecio erubescens*			
		Asteraceae			*Conyza podocephala*			
		Asteraceae			*Berkheya onopordifolia*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 10/22).

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		Asteraceae			*B. pinnatifida*			
		Asteraceae		Karoo bush invasion	*Pentzia globosa*	Bitterkaroo		May occur
		Asteraceae			*Felicia muricata*	Bloublommetjie		
Grasslan	41. Wet Cold Highveld	Rosaceae		Woody Layer	*Leucosidea sericea*	Oldwood		Dense thickets
		Ebenaceae		Small-leaf	*Euclea undulata*	Guarri		
		Ebenaceae			*Diospyros Whyteana*	Bladdernut		
		Myrsinaceae			*Myrsine africana*	Cape Myrtle		
		Anacardiaceae			*Rhus dentata*			
		Poaceae		Grasses	*Hyparrhenia hirta*	Common Thatchgrass		Hot, dry, north-fac
		Poaceae			*Aristida diffusa*	Copperwire Grass		
		Poaceae			*A. congesta*	Tassel Bristlegrass		
		Poaceae			*Aristida junciformis*	Ngongoni Bristlegrass		
		Poaceae			*Themeda triandra*	Redgrass		
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		
		Poaceae			*Cymbopogon plurinodis*			
		Poaceae			*Tristachya leucothrix*			
		Poaceae			*Harpochloa faix*			
		Poaceae		non-grassy herb-	*Poa annua*	Annual Bluegrass		Moist, steep, cool
				aceous layer				
		Scrophulariaceae		Forbs	*Sutera polelensis*	Wild Phlox		
		Lamiaceae			*Stachys kuntzei*	Woundwort		
		Araceae			*Zantedeschia albomacu*	Small Arum Lily		
		Rubiaceae			*Rubia horrida*	Sticky Madder		
		Ranunculaceae			*Clematis oweniae*	Traveller`s Joy		
		Asparagaceae			*Myrsiphyllum asparagoi*	Cape Waitabit		
		Lamiaceae			*Leonitis dysophylla*	Wild Dagga		
		Euphorbiaceae			*Clutia pulchella*	Lightningbush		
		Adiantaceae			*Cheilanthes quadripinna*	Parsley Fern		
Grasslan	42.Moist Upland Grassl	Poaceae		Grass layer	*Themeda triandra*	Redgrass		Some
		Poaceae			*Heteropogon contortus*	Speargrass		of
		Poaceae			*Tristachya leucothrix*	Hairy Tridentgrass		the
		Poaceae			*Eragrostis curvula*			dominant
		Poaceae			*Elionurus muticus*			species
		Poaceae			*Hyparrhenia hirta*	Common Thatchgrass		Tall growing
		Poaceae			*Sporobolus pyramidalis*	Catstail Dropseed		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 11/22).

		Selaginaceae		Hardy forbs	*Walafrida densiflora*			Diagnostic species
		Cucurbitaceae			*Cucumus Zeyheri*	Spiky Cucumber		
		Cucurbitaceae			*C. hirsutus*	Wild Cucumber		
		Asteraceae			*Berkheya onopordifolia*			
		Rubiaceae			*Spermacoce natalensis*			
		Rubiaceae			*Kohautia cynanchica*			
		Fabaceae			*Tephrosia macropoda*			
		Fabaceae			*T. multijuga*			
		Asteraceae			*Conyza obscura*			
		Tiliaceae			*Corchorus confusus*			
		Euphorbiaceae			*Phyllanthus glaucophyllus*			
		Rubiaceae			*Richardia brasiliensis*			
		Amaranthaceae			*Gomphrena celosioides*			
		Asteraceae			*Aster bakerianus*			
		Fabaceae			*Alysicarpus rugosus*			
		Asteraceae			*Helichrysum coriaceum*			
		Asteraceae			*H. rugulosum*			
		Celastraceae		Trees and shrubs	*Maytenus heterophylla*	Common Spikethorn		
		Rutaceae			*Zanthoxylum capense*	Small Knobwood		
		Rhamnaceae			*Ziziphus mucronata*	Buffalo Thorn		
		Anacardiaceae			*Rhus rehmanniana*			
		Fabaceae			*Acacia sieberiana*			
		Poaceae			*Elionurus muticus*	Wire Grass		Overgrazing enco
		Asteraceae		Herbaceous weeds	*Senecio retrorsus*	Staggersweed		unpalatable Wire
		Asteraceae			*Helichrysum argyrophyl*	Doll Rose		
		Myrsinaceae			*Rapanea melanophloeo*	Cape Beech		Fire-protected are
		Rosaceae			*Cliffortia spp.*	Fynbos species		
		Ericaceae			*Erica spp.*	Heaths		
		Asteraceae			*Metalasia muricata*	Blombos		
		Rubiaceae			*Anthospermum aethiopi*	Jakkelsstert		
Grasslan	43. North-eastern Moun	Liliaceae		Grassland-endemic	*Liliaceae*	Lilies		
		Iridaceae			*Iridaceae*	Irises		
		Asteraceae			*Asteraceae*	Daisies		
		Laniaceae			*Lamiaceae*	Mints		
		Orchidaceae			*Orchidaceae*	Orchids		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 12/22).

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									Typical species
		Poaceae		Grasses	*Loudetia simplex*	Common Russetgrass			
		Poaceae			*Trachypogon spicatus*	Giant Speargrass			
		Poaceae			*Diheteropogon filifolius*	Threadleaf Bluestem			
		Poaceae			*Aristida junciformis*				
		Poaceae			*Tristachya leucothrix*				
		Poaceae			*Alloteropsis semialata*				
		Poaceae			*Eragrostis racemosa*				
		Poaceae			*Sporobolus pectinatus*				
		Poaceae			*Microchloa caffra*				
		Fabaceae		Forbs	*Aeschynomene nodulosa*				
		Fabaceae			*Eriosema augustifolium*	Geelkeurtjie			
		Dennstaedtiaceae			*Pteridium aquilinum*	Bracken			
		Asteraceae			*Berkheya echinacea*				
		Fabaceae			*Pearsonia sessilifolia*				
		Crassulaceae			*Crassula alba*				
		Asteraceae			*Vernonia centaurioides*				
		Asteraceae			*V. natalensis*				
		Euphorbiaceae			*Clutia monticola*				
		Poaceae			*Stiburus alopecuroides*				
		Asteraceae			*Helichrysum wilmsii*				
		Asteraceae			*H. cephaloideum*				
		Asteraceae			*H. acutatum*				
		Asteraceae			*H. pilosellum*				
		Poaceae		Mist belt peaks/	*Festuca costata*	Tussock Fescue			
		Poaceae		summits	*Randlia altera*	Toothbrush Grass			
		Asteraceae			*Helichrysum platypterur*	Everlasting			
		Asteraceae			*H. umbraculigurum*				
		Asteraceae			*H. mariepscopicum*				
		Selaginaceae			*Selago hyssopifolia*				
		Lamiaceae			*Rabdociella calycina*				
		Lobeliaceae			*Lobelia flaccida*				
		Hyacinthaceae			*Scilla nervosa*				
		Campanulaceae			*Craterocapse tarsodes*				
		Campanulaceae			*Wahlenbergia squamifolia*				
		Crassulaceae			*Crassula vaginata*				

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 13/22).

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		Lamiaceae			*Hemizygia subvolutina*			
		Poaceae		Grass Species	*Panicum natalens*	Natal Panic		Lower altitudes
		Poaceae			*Ctenium concinnum*	Sicklegrass		
		Poaceae			*Koeleria capensis*	Junegrass		
		Poaceae			*Eulalia villosa*			
		Asteraceae		Forbs	*Helichrysum oreophilum*	Everlasting		
		Thymelaeaceae			*Gnidea caffra*			
		Fabaceae			*Indigofera sanguinea*			
		Geraniaceae			*Monsonia attenuata*			
				Woody species	*Faurea rochetiana*	Broadleaf Beechwood		
		Proteaceae			*Protea caffra*	Common Sugarbush		
		Proteaceae			*P. gaguedi*	African Sugarbush		
		Acanthaceae		Escarpment edge	*Psychotria capensis*	Bastard Lemonwood		Forest related
		Myricaceae			*Myrica pilulifera*	Broadleaf Waxberry		
		Myrsinaceae			*Rapanea melanophloeo*	Cape Beech		
		Ericaceae			*Vaccinium exul.*	Blueberry		
		Rosaceae			*Cliffortia serpyllifolia*			
		Acanthaceae			*Psydrax livida*			
		Proteaceae			*Protea roupelliae*			
		Anacardiaceae			*Rhus tumulicola*			
		Asphodelaceae			*Aloe arborescens*			
		Thymelaeaceae			*Passerina montana*			
		Meliaceae			*Ekebergia pterophylla*			
		Ericaceae			*Erica cafforum*			
					Englerophytum magalismontanum			
Grasslan	44 South-eastern Moun	Poaceae		Sweet Grass	*Themeda triandra*	Redgrass		
		Poaceae			*Pennisetum sphacelatu*	Bullgrass		volcanic soils
		Poaceae			*Tetrachne dregei*	Robies cocksfoot		Plateau
		Poaceae		Karoo Mtns.	*Merxmuellera disticha*	Wire Grass		Winterberg Range
		Poaceae		Grass Species	*Ehrharta calycina*	Common Ehrharta		
		Poaceae			*Melica decumbens*	Staggers Grass		
		Poaceae			*Karoochloa purpurea*	Purple Danthonia		
		Poaceae			*Helictotrichon hirtulum*			
		Poaceae			*Pentaschistis spp*			
		Poaceae			*Bromus leptoclados*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 14/22).

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		Scrophulariaceae		Dicotyledonous forb	*Diascia capsularis*	Longspur		
		Scrophulariaceae			*Sutera macrosiphon*			
		Caryophyllaceae			*Dianthus caespitosus*	Wild Pink		
		Asteraceae			*Othonna auriculifolia*			
		Euphorbiaceae			*Euphorbia epicyparissias*			
		Poaceae		Short dense grass	*Themeda triandra*	Redgrass		Higher rainfall area
		Poaceae			*Festuca costata*	Tussock Fescue		
		Poaceae			*F. scabra*	Munnik Fescue		
		Poaceae			*Elionurus muticus*	Wire Grass		
		Ericaceae		Fynbos	*Erica caffra*	Water Heath		Dry grassy Fynbos
		Rosaceae			*Cliffortia spp.*			patches
		Restionaceae			*Restio spp.*			
		Asteraceae		Karroid Species	*Chrysocoma ciliata*	Bitterbush		Rocky bare sparse
		Asteraceae			*Felicia filifolia*	Ghombos		succulent vegetati
Grasslan	45 Afro Mountain Grass	Poaceae		Grass Species	*Elionurus muticus*	Wire Grass		
		Poaceae			*Eragrostis curvula*	Weeping Lovegrass		
		Poaceae			*Hyparrhenia hirta*	Common Thatchgrass		
		Poaceae			*H. pilosissima*			
		Poaceae			*Themeda triandra*	Redgrass		
		Poaceae			*Heteropogon contortus*	Speargrass		
		Poaceae			*Aristida junciformis*	Ngongoni Bristlegrass		
		Poaceae			*A. congesta*	Tassel Bristlegrass		
		Poaceae			*Cymbopogon marginatus*			
		Poaceae			*C. dieterlenii*			
		Poaceae			*Festuca caprina*			
		Poaceae			*Rendlia altera*	Toothbrush Grass		
		Poaceae			*Koeleria capensis*	Junegrass		
		Poaceae			*Digiteria sanguinalis*			
		Poaceae			*Harpochloa faix*			
		Asteraceae		Forbs	*Helichrysum pilosellum*			
		Asteraceae			*H. cephaloideum*			
		Asteraceae		Genus Helichrysum	*Helichrysum*	Everlastings		
		Asteraceae			*H. cerastioides*			
		Asteraceae			*H. oreophilum*			
		Asteraceae			*H. aureonitens*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 15/22).

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		Asteraceae			*H. spiralepis*			
		Asteraceae			*H. subluteum*			
		Asteraceae			*H. acutatum*			
		Asteraceae			*H. pilosellum*			
		Asteraceae			*Haplocarpha scaposa*			
		Euphorbiaceae			*Euphorbia striata*			
		Anacardiaceae			*Rhus discolor*			
		Selaginaceae			*Selago galpinii*			
		Asteraceae			*Berkheya cirsiifolia*			
		Asteraceae			*B. echinacea*			
		Rubiaceae			*Anthospermum herbaceum*			
		Euphorbiaceae			*Acalypha schenzii*			
		Euphorbiaceae			*Clutia monticola*			
		Gentianaceae			*Sebaea sedoides*			
		Asteraceae			*Senecio coronatus*			
		Fabaceae			*Indigofera dregeana*			
		Hypoxidaceae			*Hypoxis obtusa*	Geophytic Star Lily		
		Poaceae		Grasses	*Stiburus alopecuroides*			Higher plateau
		Poaceae			*Eragrostis caesia*	Blackpatch Lovegrass		endemic species
		Poaceae			*Merxmuellera spp.*			
		Poaceae			*Rendlia altera*	Toothbrush Grass		
		Fabaceae			*Lotononis eriantha*	Three-leaf Pea		
		Selaginaceae			*Selago compacta*			
		Lamiaceae			*Syncolostemon concinnus*			
		Asteraceae		Dwarf Shrubs	*Felicia filifolia*	Ghombos		Karoo affinity
		Asteraceae			*Pentzia incana*	Anchor Karoo		
		Anacardiaceae			*Rhus erosa*	Broom Karee		
		Asteraceae			*Chrysocoma ciliata*			
Grasslan	46 Alti Mountain Grass	Poaceae		Grass layer	*Merxmuellera disticha*	Mountain Wiregrass		Tussock grasses a
		Poaceae			*M. drakensbergensis*	Drakensberg Danthonia		ericoid dwarf shru
		Poaceae			*Festuca caprina*	Goat Fescue		
		Poaceae			*Harpochloa faix*			
		Poaceae			*Rendlia altera*	Toothbrush grass		
		Poaceae			*Poa binata*			
		Poaceae			*Eragrostis caesia*			

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 16/22).

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		Poaceae			*Pentaschistis galpinii*			
		Poaceae			*Agrostis barbuligera*			
		Poaceae			*Pennisetum thunbergii*			
		Poaceae			*Bromus speciosus*			
		Cypheraceae		The Sedges	*Carex clavata*			
		Cypheraceae			*Scirpus falsus*			
		Asteraceae		The forbs	*Helichrysum flanaganii*			
		Asteraceae Asteraceae			*H. trilineatum* *H. subsubglomeratum*			
		Asteraceae			*H. cephaloideum*			
		Asteraceae			*H. marginatum*			
		Asteraceae			*H. witbergense*			
		Asteraceae			*H. stolonifernum*			
		Ericaceae		Dwarf Heaths	*Erica algida*			
		Ericaceae			*E. dominans*			
		Ericaceae			*E. frigida*			
				Afromontane veg.	*Passerina monticola*			
				affiliated to Fynbos	*Anthospermum monticola*			Patches
		Ericaceae			*Erica maesta*			restricted to Platea
		Selaginaceae			*Selago galpinii*			
		Rosaceae			*Cliffortia nitidula*			
		Ebenaceae			*Euclea coriacea*			
		Asteraceae			*Metalasia muricata*			
		Polygalaceaer			*Muraltia alticola*			
		Iridaceae			*Watsonia densiflora*			
		Iridaceae			*Dierama robusta*			
		Poaceae		Prominent grasses	*Andropogon appendicul*	Vlei Bluegrass		
		Poaceae			*Cymbopogon dieterlenii*			
		Poaceae		Bogs common	*Agrostis subulifolia*			
		Scrophulariaceae		Lesotho Diagnostic	*Limosella longiflora*	Runner		
		Cyperaceae		species	*Isolepsis fluitans*			
		Ranunculaceae			*Ranunculus meyerii*			
		Poaceae		Other species	*Koeleria capensis*	Junegrass		
		Poaceae			*Poa binata*	Bog Bluegrass		
		Poaceae			*Festuca caprina*	Goat Fescue		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 17/22).

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		Poaceae			*Merxmuellera disticha*	Mountain Wiregrass		
		Asteraceae			*Haplocarpha nervosa*			
		Asteraceae			*Cotula hispida*			
		Asteraceae			*Helichrysum bellum*			
		Asteraceae			*Athrixia fontana*			
		Santalaceae			*Thesium nigrum*			
		Caryophyllaceae			*Cerastium arabidis*			
		Cyperaceae			*Carex monotropa*			
		Gentianaceae			*Sebaca marlothii*			
		Asteraceae			*Senecio cryptolanatus*			
		Aponogetonaceae			*Aponogeton junceus*			
Grasslan	47 Short Mistbelt Grass	Not necessary			*Not necessary*			
Grasslan	48 Coastal Grassland	Not necessary			*Not necessary*			
Nama Ka	49 Bushmanland Nama	Chenopodiaceae		Annuals and non-	*Salsola tuberculata*	Cauliflower Ganna		Common in sandy
		Poaceae		succulent shrubs	*Stipagrostis obtusa*	Small bushman Grass		summer rains
		Poaceae			*S. ciliata*	Tall Bushman Grass		
		Asteraceae		Rocky areas	*Eriocephalus spinescen*	Thorny Kapokbush		rocky areas
					Eberlanzia spinescens	Thorn Vygie		
		Bignoniaceae			*Rhigozum trichotomum*	Threethorn		
		Asteraceae		Annuals	*Pentzia annua*			Annuals
		Zygophyllaceae			*Zygophyllum simplex*	Brakspekbos		
Nama Ka	50 Upper Nama Karoo	Asteraceae		Shrubs	*Eriocephalus ericoides*	Kapokbush		stony plains
		Aizoaceae Part B			*Plinthus karooicus*	Silverkaroo		
		Asteraceae			*Rosenia humilis*	Perdekaroo		
		Poaceae		Grasses	*Aristida congesta*	Tassel Bristlegrass		After good rains th
		Poaceae			*Eragrostis lehmanniana*	Lehmann's Lovegrass		
		Anacardiaceae			*Rhus undulata*	Kunibush		Hilly regions
		Solanaceae			*Lycium spp.*	Kareethorn		
		Bignoniaceae			*Rhigozum trichotomum*	Threethorn		
		Poaceae			*Merxmuellera disticha*	Mountain Wiregrass		higher mountains
Nama Ka	51 Orange River Nama	Asphodelaceae			*Aloe dichotoma*	Quiver Tree		rocky and 'broken'
		Euphorbiaceae			*Euphorbia avasmontana*	Bushman Prison Tree		
		Euphorbiaceae		Trees and shrubs	*E. gregaria*	Aggenys Milkbush		steep slopes
		Fabaceae			*Acacia mellifera*	Spike-flowered Black Thorn		On the pediments
		Bignoniaceae			*Rhigozum trichotomum*	Threethorn		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 18/22).

		Capparaceae			*Boscia albitrunca*	Shepherd's Tree		
		Capparaceae			*B.foetida*	Stink Shepherd's Tree		
		Poaceae		Grass layer	*Stipagrostis uniplumis*	Silky Bushman Grass		Dominates plains
		Tamaricaceae			*Tamarix usneoides*	Wild Tamarisk		Abundant thickets
		Rhamnaceae			*Ziziphus mucronata*	Buffalo Thorn		
		Fabaceae			*Acacia eriobola*	Camel Thorn		dry river beds
Nama Ka	52 Eastern Mixed Nama	Asteraceae		Shrub layer	*Pentzia incana*	Bitterkaroo		A complex mix
		Asteraceae			*Eriocephalus ericoides*	Kapokbush		
		Asteraceae			*E. spinescens*	Thornkapok		
		Sterculiaceae			*Hermannia spp*			
		Poaceae		Grass layer	*Aristida spp*			
		Poaceae			*Eragrostis spp*			
		Poaceae			*Themeda triandra*	Redgrass		
		Fabaceae			*Acacia karroo*	Sweet Thorn		Trees not abunda
Nama Ka	53 Great Nama Karoo	Poaceae		Grass layer	*Aristida diffusa*	Copperwire Grass		Perennial grasses
		Poaceae			*Stipagrostis uniplumis*	Bushman Grass		
		Poaceae			*Fingerhuthia africana*	Thimblegrass		
		Asteraceae		Dwarf shrubs	*Pentzia incana*	Anchorkaroo		Region dominated
		Bignoniaceae			*Rhigozum obovatum*	Wild Pomegranate		
		Asteraceae			*Felicia filifolia*	Ghombos		
		Ebenaceae			*Euclea undulata*	Small-leaf Guarri		widespread.
		Anacardiaceae			*Rhus undulata*	Kunibush		
Nama Ka	54 Central Lower Nama	Bignoniaceae		Dwarf shrubs	*Rhigozum obovatum*	Wild Pomegranate		
		Asteraceae			*Pentzia incana*	Anchorkaroo		
		Mesembryanthemaceae		Succulents	*Delosperma spp.*			Greater incidence
		Mesembryanthemaceae			*Eberlanzia ferox*	Thorn Vygie		
		Mesembryanthemaceae			*Ruschia spp.*			
		Euphorbiaceae			*Euphorbia ferox*	Noorsdoring		
		Poaceae		Grass layer	*Eragrostis lehmanniana*	Lehmann's Lovegrass		gd summer rains
		Poaceae			*Aristida spp.*			
		Poaceae			*Digiteria spp.*			
		Fabaceae		Tree layer	*Acacia karoo*	Sweet Thorn		dry river beds
Succulen	55 Strandveld Succulent Karoo							
		Lamiaceae		Small trees	*Salvia lanceolata*	Sage		scattered low shru
					Nylandtia spinosa	Tortoise Berry		

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 19/22).

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		Zygophyllaceae	Succulent low shrub	*Zygophyllum morgsana*	Tortoisebush		
		Euphorbiaceae		*Euphorbia mauritanica*	Poison Milkbush		
		Euphorbiaceae		*E.burmannii*	Fragmenting Milkbush		
		Restionaceae (Part B)	Fynbos	*Restionaceae*	Cape Reed Family		
Succuler	56 Upland Succulent Karoo						
		Asphodelaceae	Tree layer	*Aloe dichotoma*	Quiver Tree		Characterises
		Mesembryanthemaceae	Succulent dwarf shr	*Eberlanzia ferox*	Thorn Vygie		dominant
		Mesembryanthemaceae		*Ruschia spp.*			
		Poaceae	Grass layer	*Ehrharta calycina*	Ehrharta		not common
		Asteraceae	Annuals	*Asteraceae*	Daisy		Many annuals
		Mesembryanthemaceae		*Mesembryanthemaceae*	Vygie		
Succuler	57 Lowland Succulent Karoo						
		Mesembryanthemaceae	Succulents	*Ruschia spp.*	Vygie Family		Round termiteria c
		Mesembryanthemaceae		*Drosanthemum spp.*	Vygie Family		domi. lowland
		Mesembryanthemaceae		*Malephora spp.*	Vygie Family		
		Mesembryanthemaceae		*Delosperma spp.*	Vygie Family		
		Aizoaceae (Part B)		*Galenia africana*	Kraalbos		Old lands and oth
		Asteraceae	Non succulent shrub	*Osteospermum sinuatum*			These palatable, r
Succuler	58 Little Succulent Karo	Not Necessary					
Fynbos E	59 North-western Mountain Renosterveld						
		Asteraceae	Dominant species	*Elytropappus rhinocerot*	Renosterbos		Dominant
		Asteraceae		*Eriocephalus africanus*	Wild Rosemary		Also common.
		Asteraceae		*Euryops lateriflorus*	Resinbush		
		Polygalaceae		*Nylandtia spinosa*	Tortoisebush		
Fynbos E	60 Escarpment Mounta	Not Necessary					
Fynbos E	61 Central Mountain Re	Not Necessary					
Fynbos E	62 West Coast Renosterveld						
		Asteraceae	Shrubs dominant	*Elytropappus rhinocerot*	Renosterbos		Overstory dom.
		Asteraceae		*Eriocephalus africanus*	Wild Rosemary		Subdominant
		Asteraceae		*Leysera gnaphalodes*	Dune Teabush		Subdominant
		Rubiaceae		*Anthospermum aethiopi*	Jakkals stert		Subdominant
		Asteraceae		*Athanasia trifurcata*			Subdominant

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 20/21).

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		Asteraceae			*Felicia filifolia*	Ghombos		Subdominant
		Asteraceae			*Metalasia muricata*			Subdominant
		Asteraceae			*Stoebe spiralis*			Subdominant
		Poaceae		Grass cover	*Ehrharta*	Ehrharta		Understory
		Poaceae			*Pentaschistis*			
		Poaceae			*Merxmuellera*			
		Poaceae			*Tribolium*			
		Poaceae			*Cymbopogon*			
		Poaceae			*Eragrostis*			
		Poaceae			*Themeda triandra*	Redgrass		Locally abundant.
		Poaceae			*Cymbopogon marginatu*	Terpentinegrass		
		Iridaceae		Geophytes	*Iridaceae*	Irises		characteristic
		Lilliaceae			*Lilliaeceae*	Lillies		
		Oxalidacea			*Oxalidaceae*	Sorrels		
		Poaceae		Grasses	*Avena*	Oats		Mediterranean
		Poaceae			*Briza*	Quaking Grass		
		Poaceae			*Lolium*	Ryegrass		
		Oleaceae		Bush clumps	*Olea europaea subsp.ai*	Wild Olive		dom. Bush clumps
		Anacardiaceae			*Rhus laevigata*	Dune Taaibos		
		Ebenaceae			*Euclea racemosa*	Bush Guarri		
Fynbos B	63 South and South-we	rveld						
Fynbos B	64 Mountain Fynbos							
								fragmentary
Fynbos B	65 Grassy Fynbos	/						
Fynbos B	66 Laterite Fynbos	/						
Fynbos B	67 Limestone Fynbos	/						
Fynbos B	68 Sand Plain Fynbos							

Table B2 Flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 21/22).

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		Asteraceae			*Asteraceous Fynbos*			Typical vegetation
					Proteoid			
		Ericaceae			*Heaths*			Seldom dom.
		Restionaceae			*Reeds*			dominate
		Proteaceae			*Sugarbushes*			
					Erica mammosa	Ninepin Heath		Sand Plain Fynbo
		Rhamnaceae			*Phylica cephalantha*	Starface		
		Rhamnaceae			*P. stipularis*	Baboon face		
		Restionaceae			*Thamnochortis obtuses*	restoids		
		Restionaceae			*T. punctatus*	Sandveld Thatching Reed		dom. south

Table B2 Partial list of flowering plants relevant to the pollen assemblage of the OR Mudbelt (data from Rutherford and Westfall 1986) (page 22/22).

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Sample	Description
JKB A /AC	Jakkalsberg A above charcoal lens
JKB A /BC	Jakkalsberg A below charcoal lens
JKB A /CL	Jakkalsberg A charcoal lens (20 cm depth)
JKB A /CL2	Jakkalsberg A charcoal lens (20 cm depth)
JKB O /L1	Jakkalsberg O layer 1 (silt)
JKB O /L2	Jakkalsberg O layer 2 (organic rich soil –sheep/goat dung) (70 cm)
JKB O /BL2	Jakkalsberg O below layer 2 (silt)
JKB O /L3	Jakkalsberg O layer 3 (silt)
JKB O /L3	Jakkalsberg O layer 3 (silt)
JKB O /BL3(2)	Jakkalsberg O below layer 3 (silt)
JKB O /BL3M	Jakkalsberg O below layer 3, above layer 4 (silt)
JKB O /L4	Jakkalsberg O layer 4 (organic rich soil – sheep/goat dung) (90 cm)
JKB O /AAL1	Jakkalsberg O above ash lens 1 (silt)
JKB O /A1	Jakkalsberg O ash lens 1
JKB O /AAL2	Jakkalsberg O above ash lens 2
JKB O /BAL2	Jakkalsberg O below ash lens 2
JKB O /C2	Jakkalsberg O ash lens 2 (charcoal)
JKB O /AL2	Jakkalsberg O ash lens 2
JKB O /AL3	Jakkalsberg O ash lens 3
JKB O /AL3 (2)	Jakkalsberg O ash lens 3
JKB N	Jakkalsberg N ostrich egg shell (OES) scattered on surface of flood plain at site
BLD 32 CL1 (102 cm)	Bloedrift site 32 charcoal lens 1 (102 cm)
BLD 32 CL (72 cm)	Bloedrift site 32 charcoal layer (72 cm)

Table B3 Jakkalsberg sites JKB O, A, N and site Bloeddrift 32 samples: collated list of samples analysed. Refer Figures 2. 16 – 2.18.

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Clay Type	%
Illite	33
Smectite	24
Vermiculite	18
Other	25
	100

H2

Clay Type	%
Illite	33
Smectite	24
Kaolinite	15
Clorite	8
Plagioclase	7
Vermiculite	6
Other	7
	100

H7

Clay Type	%
Plagioclase	19.9
Smectite	18.8
Illite	2.9
Kaolinite	0.7
Other	57.7
	100

LX

Table B4 % representation of clay types in H2, H7 and Lower Xobies.

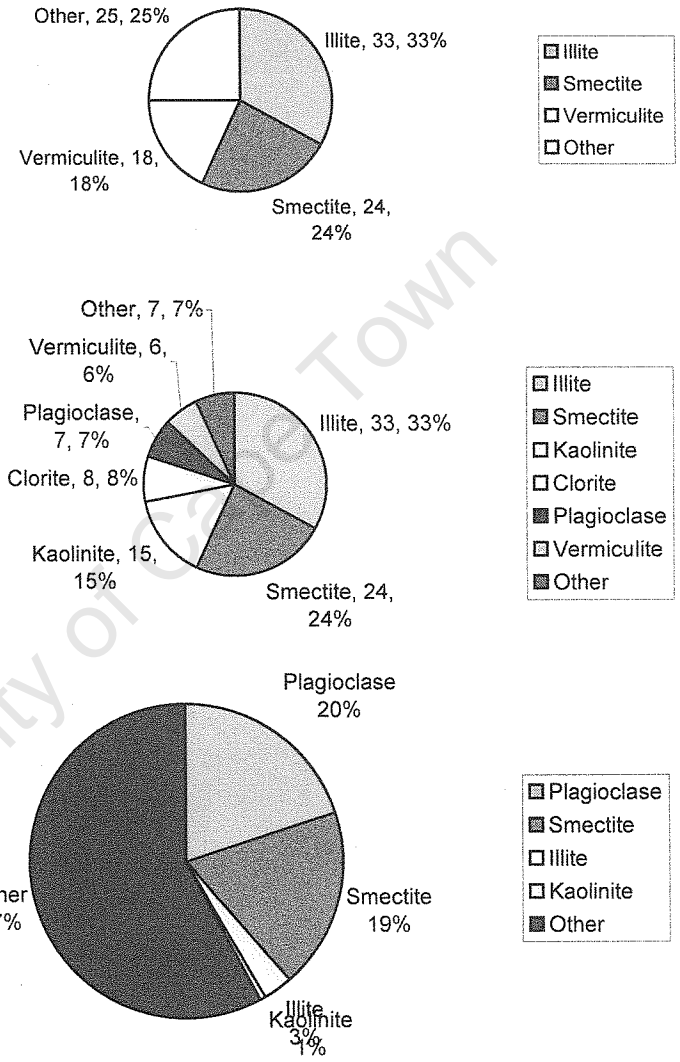

Figure B1 Percentage representation of clay types in gravity cores (H2, H7) and Lower Xobies sites (after Zawada et al. 1996 and Mabote 1996).

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APPENDIX C

Chemical processing of the sample for pollen analysis and microscopy

During the pilot phase of the pollen preparation, 100 g sub-samples of mudbelt sediment were utilised (Gray 1996), but this proved to be unnecessarily large and a smaller sample of 30 g was subsequently used. Due to the clayey consistency of the sediments, gravimetric rather than volumetric sub-sampling was utilised. The 6 m long gravity cores had already been sub-sampled at 5 cm intervals, so the 20 cm sampling interval was obtained through taking samples at appropriate intervals.

Clay-rich marine sediments require prolonged processing in preparation for pollen analysis. One of many obstacles to rapid progress in this study was the intense repetitive treatment of hydrofluoric acid that the samples required due to the exceptionally high clay fraction in the mudbelt sediments. These clay-rich mudbelt sediments make up the bulk of the samples, although samples from other sites in the Richtersveld analysed produced individual treatment problems (e.g. processing of goat dung).

Removal of clay minerals

During the pilot study (Gray 1996), sieving to retain pollen fraction in the sediment was discounted due to both the large clay fraction present in the sediment and the absence of fine mesh sieves in the laboratory at the time. However, given the prolonged hydrofluoric acid treatment, other options, including heavy liquid separation and fine mesh sieving were re-considered.

At first, heavy liquid separation was deemed to be the more efficient, renewable and safe means of removing the clay fraction and retaining the pollen fraction. There are numerous advantages to using this method. However, the procedure proved disadvantageous in the mudbelt samples due to the following reasons:

- The sodium polytungstate powder required was too expensive given the poor exchange rate and cost of import. In addition, the vagaries of the recycling

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process proved problematic in terms of making up the liquid and maintaining correct specific gravity during successive treatments (Rogers pers. comm.).

- Evidence from Dr Andy Baxter (pers. comm.) indicated the difficulty in properly mixing clay-rich sediments and preventing flocculation, while simultaneously attempting heavy liquid separation using heavy liquid mediums such as $ZnCl_2$ or sodium polytungstate (Baxter 1996).
- The additional cost of setting up a filtration and evaporation system for reclaiming and purifying the liquid allows for many more opportunities for contamination. In addition, there are logistical problems in acquiring suitable affordable equipment and funding was a limiting factor.
- Some sources point to loss of grains using heavy liquid separation (Moore *et al.* 1991).
- In a trial using $ZnCl_2$ for heavy liquid separation the processing was not successful as half the sample was lost and the sample flocculated and proved difficult to separate. The remaining sample was at a premium and in order to reduce loss, further investigation using this method was halted in favour of preserving the samples and preventing further delay.

A very fine mesh sieve of about 7 µm was used.[1] This sieve allows clay particles (smaller than 2 µm) and fine silt less than 7 µm through, but leaves the majority of polleniferous material on the surface of the mesh (Cwynar *et al.* 1979 after Moore, Webb and Collinson 1991). This size is favoured over other sieves such as the 10 µm and 15 µm sieve size as these sieves allow smaller- size fraction pollen through; use of an even smaller sieve size is not effective. The 7 µm size sieve is a popular choice in other international palynology laboratories where clay-rich samples are often processed and heavy liquid separation is found to be difficult. Of particular relevance in this regard were the sieving procedures followed by Dr Lydie Dupont

[1]A square metre of NITEX was procured from which a single sieve was made up by a commercial firm, but this quickly broke due to inferior workmanship. Therefore, a DIY sieve was made using a 110mm diameter PVC pipe. Two cylinders were cut to clamp the mesh, which was then bound with twine and glued in place. This could then be placed over the standard size 1 L glass beaker to collect the filtrate. The prototype DIY sieve worked well. One problem faced in the manufacture of these sieves was finding the correct tension for the mesh. Through correspondence with both the Canadian and Swiss branches of SEFAR, it was discovered that the company could not recommend a tension in order to achieve the 7µm mesh size. I devised a method by which the finished product (mesh pulled across the sieve cylinder, tied and glued) was checked for mesh width under a light microscope. The tension was just sufficient to create a taut mesh across the screen. The mesh size appeared to be a minimum of 5 µm in diameter with the material at right angles to the light path of the light binocular microscope (used for pollen analysis). However, the type of lattice mesh arrangement suggested that the true mesh width was closer to the 7 µm width.

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(pers. comm.) of Bremen University and Professor K Gajewski of Ottawa University, University of Toronto and the Palynology laboratory of the Centre for Climatic Research, University of Wisconsin.

A number of methods of sieving were considered (including sonication, vacuum sieving and hand sieving using both hands where small quantities of sediment were "massaged" in a hand held pouch of fine mesh and sieving without the use of these methods). The latter sieving method causing least disturbance to the pollen grains was selected for the following reasons:

1. Sonicating is favourable only for short periods of time, as it easily ruptures the pollen exine. These clay-rich mudbelt samples would require prolonged sonication, which was not a viable option.
2. Vacuum sieving is known to pull smaller pollen grains through the mesh, thus creating a net loss of pollen.
3. Hand-held pouches of mesh material would mean that the edge mesh openings, (where folds and bunching of the material occur) would be stressed and enlarged, thus allowing larger grains through. Also, hand massaging the pouch with both hands would increase chances of human error and sediment loss.

Eight sieves were made in order that a number of samples could be processed simultaneously. Individual samples required a minimum of eight hours hands-on sieving, the sample being sieved until the filtrate appeared clear. The sieves proved easy to maintain. Additional glue was required after a few samples had been sieved, as the glue began to lift off the sieve material. No further problems were experienced after the second application of glue. The samples were all hand sieved using warmed dilute sodium pyrophosphate ($Na_2P_2O_7$) and hastened by tapping the PVC sieve edge with a metal spoon and rubbing or by "tickling" of the sieve underside with the back of the spoon to assist the process. Thereafter, the sample was returned to the centrifuge tubes for additional processing.

Sodium pyrophosphate ($Na_2P_2O_7$) was used as a clay deflocculant (Bates *et al.* 1978). Over 24 treatments using this deflocculant were recorded in some samples, although most

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required at least 18 treatments. Comparative treatments with sodium pyrophosphate before and after the sieving showed that sodium pyrophosphate prior treatment reduced overall sieving and deflocculating time (often by a few hours). Calgon (sodium hexametaphosphate), another deflocculant commonly used in the laboratory, was used in a few test samples but yielded similar results to sodium pyrophosphate- treated samples.

Removal of humic acids

A 0.1M sodium hydroxide solution (NaOH) was used to remove unsaturated soil colloids (humic acids) from the sediment. Potassium hydroxide (KOH) is an alternative, sometimes used in conjunction with NaOH (Moore *et al.* 1989). This was used to compliment NaOH treatments in this way in less than half the samples, but was considered to be redundant as only one of the two chemicals mentioned proved necessary. Neither chemical was considered to have a superior result so the remaining samples were treated with NaOH, which was well-stocked in the laboratory. As these samples are rich in humic acids, a number of repetitions of NaOH and or KOH treatment were necessary. Most of the mudbelt samples required at least 14 treatments but some samples needed up to 23 treatments. Treatment with either NaOH or sodium pyrophosphate first, gave similar results. However, in certain cases a sodium pyrophosphate treatment, followed by washing with water, a hydrochloric acid treatment, then water treatment appeared to improve the efficacy of the sodium pyrophosphate step and reduce the number of repetitions of NaOH treatments necessary.

Removal of carbonates

A 10% solution of hydrochloric acid (HCl) was used to treat the samples for removal of calcium carbonates. HCl was used to pre-treat the sample for hydrofluoric acid (HF), as calcium and water (rinsing) react violently with HF. Only one treatment was necessary due to low carbonate content.

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Removal of extraneous siliceous material

The use of extremely hazardous hydroflouric acid (HF) is well-documented in palynological analysis, and numerous precautions have to be made during preparation, processing and storage. The initial pilot study indicated that a minimum of three repetitions of this treatment were necessary, although most samples still required treatment as they appeared grainy and required additional treatments to remove the fine siliceous material. The additional time required for sieving (removal of remaining clay fraction) was considered useful in reducing additional repeated treatments with HF. Samples were treated with 40% HF, either overnight at room temperature, or over a 3 hour treatment period in a warming bath at ± 40°C. Once the sieving step was incorporated into the processing protocol, the method of reducing the fine silica content was much improved and samples were cleaner, thus facilitating easier pollen counting. This proved to be the more environmentally friendly method (less waste material to neutralise and dispose), as fewer treatments with HF were necessary and as a result less opportunity for accidental exposure.

Removal of organic compounds (cellulose) by acid digestion

Another important treatment is the removal of cellulose and other organic compounds through the process of acetolysis (acid digestion). In this procedure, the sample must first be treated with glacial acetic acid in order to remove water from the sample before being treated with acid. Acetolysis mixture is made up of an acetic anhydride and sulphuric acid solution mixed in a ratio of 9:1. This mixture is poured into the sample and treated for 3 minutes in a warming bath, before the reaction is stopped with glacial acetic acid, centrifuged, the supernatant poured off and then the sample is treated once again with glacial acetic acid.

Summary of pollen processing

Initial processing during the pilot study proved time consuming and indicated that pollen concentration was not excessively high in the six samples (Gray 1996). In addition, the samples required a new approach to processing as the samples were poor in quality,

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showing significant amount of detritus and fine grained sediment, and cleaner processing would assist in a more rapid identification and counting process. However, the improved protocol was still a slow procedure, given the poor sample condition and low pollen count. It is important to note that cost of chemicals and laboratory equipment was a determining factor in many of the processing choices made. In terms of the processing, the method was improved and therefore sample quality was enhanced through the following:

- Sieving with 7μm mesh size NITEX sieves proved highly beneficial. As a result, the samples were cleaner than those processed during the pilot study. However, this method was labour intensive, requiring a minimum of 8 hours hands on attention per sample.
- NITEX mesh required minimal stretching in order to achieve the 7μm mesh size. This was achieved through simple clamping during production of the sieves. No special analyses and measuring were required to achieve this, apart from initially checking the mesh size using a light microscope. Comparison between pollen counts of the pilot study and the subsequent counts for this study of the same samples was completed in order to achieve consistency. Despite initial processing problems, these counts proved remarkably similar and consistent.
- HF treatment was significantly shortened because of fine mesh sieving. Another advantage was that less waste was produced. This proved more environmentally friendly and resulted in less exposure of pollen grains to HF.
- An initial purchase of sodium polytungstate for heavy liquid separation proved excessively expensive, given the disadvantageous exchange rate at the time. As further purchase was impossible, this treatment option was abandoned and $ZnCl_2$ considered as a more cost effective option.
- $ZnCl_2$ heavy liquid separation proved difficult. The excess quantity of clay flocculated and the initial attempt using this method resulted in sample loss. Therefore, this otherwise favourable and more rapid method was abandoned.
- Allowances had to be made for individual processing requirements of the mudbelt samples; these samples required vastly differing treatment regimes (repetitions of treatment), depending on the material. Although up to 12 samples were processed

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concurrently, this meant that some samples required additional processing before samples could be taken to the next processing step.

- Richtersveld samples were processed more quickly than the mudbelt samples, given the large proportion of the coarse fraction in the former, compared with the predominantly clay- and silt-size mudbelt fraction of the latter.
- KOH treatment, recommended by Faegri *et al.* (1989) as an alternative for NaOH treatment (in order to remove humic acid) proved unnecessary. In addition, treatment with KOH did not result in a noticeable decrease in pollen grain size.
- Faegri *et al.* (1989) and others have noted that certain types of chemical processes produce changes in pollen grain size. Hydrochloric acid is known to degrade the pollen exine. Hydrofluoric acid, acetolysis, storage in a wet environment (marine in this case) and glycerol are known to increase the size of the pollen grain. Potassium hydroxide (KOH) is known to decrease grain size. However, although KOH was used in less than half the samples, it was considered to be unnecessary and therefore not used in later sample runs. The change in grain size was not noticeable and is not considered to detract from pollen identification in this study.
- Minimal amounts of carbonate were found in the sample and a single treatment with hydrochloric acid was required for the purpose of removal.
- Glycerol and TBA silicon were both used as a preservative medium and were associated with both advantages and disadvantages. Glycerol was easy to use, but is not favoured for long-term archival purposes. Silicon preservation was advantageous for archival purposes, but silicon preservation of a number of samples produced 'sludging', possibly related to TBA treatment, which I considered disadvantageous.
- Use of either calgon (sodium-hexametaphosphate) or sodium pyrophosphate proved equally useful, but I favoured sodium pyrophosphate, as the dry chemical pellets were more easily obtainable through local suppliers.

Sample preservation

Once the now pollen-rich sample was considered to be reasonably clean, the sample was stained with aqueous safranin dye and preserved in either glycerol or silicon. Half of the

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samples were treated with TBA (Tert-Butyl Alcohol otherwise known as 2-Methyl-2-propanol) before being preserved in silicon and the other half were preserved in glycerol. Silica oil was initially favoured due to the relatively long preservation life compared to glycerol (minimum 2 years) but it was concluded that the samples preserved in glycerol (as in the case of the pilot samples) were more easily counted as some TBA-treated samples exhibited "sludging" and, as a result, were difficult to count for pollen. There is anecdotal evidence from several palynology laboratories to suggest that TBA is responsible for this sludging (Booth pers. comm.). Another problem experienced with TBA during winter processing was the winter-time room temperature being well below TBA melting point of 25°C. This meant leaving the samples in the warming bath for prolonged periods to evaporate the remaining TBA.

The major processing improvement since the pilot study was the incorporation of the sieving method. This greatly improved on the quality of the pilot study samples, which had previously hampered identification and counting because of excess grainy, silt-rich matter. This also meant that the period of potential exposure to HF was much reduced, smaller volumes of expensive HF had to be ordered and smaller volumes of toxic HF-waste subsequently processed by waste disposal. Although this process was still lengthy (even more so with the sieving), the end results were favourable.

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Microscopy: slide preparation, pollen identification and the reference collection

Samples were preserved in either silicon or glycerol, although glycerol was later favoured for reasons outlined above. Glycerol-preserved slides were sealed at the edges using a porous glycerol jelly sealant that was then painted with a clear nail varnish so as to discourage water absorption and thus prevent swelling of the pollen grains. However, silicon-preserved slides were not sealed. In addition, these were left on the slide warmer up to 30 minutes prior to placing the cover slip over the assembly, to allow any remaining TBA to evaporate. This prolonged warming was not necessary in glycerol-preserved samples. 0.1ml aliquots of sample were used on each slide.

The University of Cape Town Collection of Pollen (UCTCP) pollen reference collection housed in the Department provides an excellent reference collection of pollen sample slides from the Western Cape, West Coast region and some inland areas of South Africa. Due to the extensive nature of the Orange River drainage catchment area, the making of an additional complementary modern pollen reference collection from this large area was considered unnecessary due to the abundance of pollen reference books and manuals in the laboratory, and the comprehensive, complementary nature of the laboratory pollen reference collection already in existence.

Slides were analysed and pollen grains identified to the lowest taxonomic level possible (usually family). Where possible, genus and species-level identification was made, but this was usually the exception, given the size of the flora and the fact that the light microscope method of identification was used. Three light microscopes were used during the identification: a Zeiss Light Microscope with an attached 35 mm film camera (Olympus BH2) at the UCT laboratory, subsequently fitted with a Zeiss digital camera, and two Leitz Laborlux S microscopes (a Nikon Coolpix 950 zoom digital camera was fixed to one of these microscopes). All these microscopes were fitted with 40 x lenses which magnification was used almost exclusively for pollen scanning while the 60 x magnification lens was used occasionally to complement the 40 x lens. Photography required occasional use of a 100 x lens for detailed digital photographs.[2]

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[2]Photographs were taken of pollen (either on film or digitally) for reference. Some difficult pollen grains were later identified in this way. Photographs taken using black and white photographic film were more successful than the commercial colour print results as there is more control over the finished product in the darkroom. Indeed, these proved to be of better quality than the subsequent digital photography system. Most of the black and white film used was processed and enlarged in a home darkroom.

APPENDIX D

Core	Depth (cm)	^{210}Pb	Prec. Pb	^{137}Cs	Prec. Cs	^{210}Pb	Prec.	Run #
H5	0	135	13	*	*	161	11	2
H5	4	96	12	5.3	2	122.5	12	3
H5	7	102	11	Yes	*	*	*	1
H5	12	22	10	4.9	1	66.2	10	3
H5	16	32	8	4.3	1	54.7	8	3
H5	20	16	7	0	0	37.2	7	3
H5	24	38	9	*	*	57	8	2
H5	26	31	10	no	*	*	*	1
H7	0	144	14	*	*	177	12	2
H7	4	69	10	10	1	93.9	10	3
H7	7	77	12	yes	*	*	*	1
H7	12	26	14	6.5	2	101.8	14	3
H7	16	43	9	0	0	73.5	8	3
H7	20	26	10	0	0	70	10	3
H7	24	125	7	5.1	1	151.7	7	3
H7	24	21	9	*	*	55	8	2
H7	26	26	14	no	*	*	*	1
H2	0	106	14	*	*	135	12	2
H2	4	76	10	8.7	2	102.5	10	3
H2	7	95	8	Yes	*	*	*	1
H2	12	46	8	7.2	1	68.5	8	3
H2	16	43	9	7.4	2	68.4	9	3
H2	24	52	8	*	*	71	7	2
H2	26	32	9	no	*	*	*	1
OR	None	66	10	0	0	102.3	10	3
H5 3.6	4.5	88	11	*	*	108	10	2
H5 2.1	122	38	10	no	*	*	*	1
H7 G2	0	66	11	Yes	*	*	*	1
H7 6.2	85	64	11	*	*	96	10	2
H7 6.1	95	33	10	no	*	*	*	1
H2 7.4	0	80	11	*	*	106	10	2

Table D1 Results for ^{210}Pb and ^{137}Cs analysis for Namaqualand Mudbelt gravity and box cores (measure in Bq/kg). Box cores analysed unless gravity cores are indicated by the annotation e.g. H5.3.6. Box and gravity cores separate [prec.=precision].

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APPENDIX E

Results of $\delta^{13}C$, $\delta^{15}N$ analysis for mudbelt, Richtersveld and modern Orange River sediment data

This section includes the following tables:

- Table E1 Namaqualand Mudbelt $\delta^{13}C$, $\delta^{15}N$ results for box cores.
- Table E2 Richtersveld, Jakkalsberg and modern OR sediment $\delta^{13}C$, $\delta^{15}N$ results.
- Table E3 Lower Xobies palaeoflood $\delta^{13}C$ and $\delta^{15}N$ results.
- Table E4 Namaqualand Mudbelt core H7 - $\delta^{13}C$ and $\delta^{15}N$ results. (3 pages).
- Table E5 Namaqualand Mudbelt core H2 - $\delta^{13}C$ and $\delta^{15}N$ results. (4 pages).

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Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N
0	A30-0	-19.688	7.712493	1.05754	0.262229	3.813454	4.03288
2.5	A30-2.5	-19.5988	5.832623	1.032087	0.233947	4.27447	4.411624
5	A30-A5-N	—	7.261596	—	0.161134	6.206008	—
5	A30-5-N	—	6.540783	—	0.260664	3.83635	—
7.5	A30-7.5	-19.3949	10.62423	1.019303	0.238624	4.190696	4.271589
10	A30-10	-19.6642	6.505822	0.920499	0.207236	4.825423	4.441797
12.5	A30-12.5	-19.7928	—	0.777916	—	—	—
15	A30-15	-20.1607	5.328912	0.99973	0.236247	4.23285	4.231706
17.5	A30-17.5 REPEAT 2	-20.3826	—	2.067871	—	—	—
20	A30-20	-20.1855	—	1.036459	—	—	—
22.5	A30-22.5	-20.5779	7.036687	1.139984	0.152236	6.568749	7.488265
25	A30-25	-22.1352	10.0459	0.930796	0.152134	6.573169	6.118282
28	A30-28	-21.9068	7.982269	0.84508	0.165902	6.027647	5.093846
	Std Deviation	0.949133	1.705946	0.344703	0.04511	1.153669	1.204976
	Mean	-20.3695	7.487131	1.075206	0.207035	5.054881	5.011249
0	A37-0	-18.8468	5.155511	0.786348	0.199932	5.001703	3.933079
5	A37-5	-18.7925	-1.64524	0.683958	0.134822	7.417177	5.073039
10	A37-10	-18.6532	14.71814	0.650751	0.107269	9.322389	6.066557
15	A37-15 REPEAT 2	-18.9606	10.98039	1.404549	0.121506	8.230075	11.55955
20	A37-20	-17.3083	4.714191	0.676772	0.14363	6.962355	4.711924
21	A37-21-N	—	2.411212	—	0.167382	5.974358	—
25	A37-25	-17.5615	1.461189	0.714582	0.094658	10.5644	7.549128
27	A37-27 REPEAT 2	-18.2359	—	1.863308	—	—	—
	Std Deviation	0.661573	5.665411	0.475308	0.036135	1.913745	2.78238
	Mean	-18.337	5.399342	0.96861	0.138457	7.638922	6.482212
0	A49-0	-19.2541	4.778275	0.981217	0.218465	4.577395	4.491417
5	A49-5	-19.4533	10.13534	0.936897	0.191088	5.233182	4.902955
10	A49-10-N	—	2.565312	—	0.176041	5.680486	—
15	A49-15	-19.0839	-1.40018	0.748481	0.113388	8.819289	6.601075
20	A49-20	-17.2696	—	0.713817	—	—	—
25	A49-25	-17.2028	2.785967	0.656556	0.125712	7.954663	5.222684
27	A49-27	-18.5273	7.66523	0.913876	0.132529	7.545544	6.895693
	Std Deviation	1.000831	4.081897	0.135214	0.041818	1.700097	1.064844
	Mean	-18.4652	4.421659	0.825141	0.159537	6.635093	5.622765
Total	Std Deviation	1.286768	3.940517	0.353834	0.050408	1.871813	1.838287
Total	Mean	-19.2765	6.052029	0.981599	0.173773	6.253558	5.636689

Table E1 Namaqualand Mudbelt $\delta^{13}C$, $\delta^{15}N$ results for box cores.

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Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N
R/C/99	-20.6281	9.196867	0.278481	0.052202	19.15638	5.33469
WT/1/#1	-18.7746	—	0.250227	—	—	—
WT/1/BPM	-21.2706	—	0.180735	—	—	—
WT/1/LNCH	-24.7714	-0.50316	0.204356	0.025126	39.79984	8.133318
WT/13/#3	-21.4455	—	0.131709	—	—	—
WT/13/#4	-23.0077	—	0.191843	—	—	—
WT/1/#2	-23.1195	—	0.500912	—	—	—
WT/2/SC	-20.9552	—	0.147711	—	—	—
WT/2POT	-21.3921	—	0.204418	—	—	—
WT/4/NO3	-23.4103	—	0.102363	—	—	—
WT/4/R2	-17.7193	—	0.244033	—	—	—
Std Deviation	2.051683	6.858954	0.106526	0.019146	14.59713	1.978929
Mean	-21.4995	4.346854	0.221526	0.038664	29.47811	6.734004
JKB A /AC	-24.0999	15.83802	0.228037	0.043834	22.81348	5.202317
JKB A /BC	-22.0508	13.68529	0.163444	0.029413	33.99813	5.556798
JKB A /CL	-22.8682	12.35869	0.425719	0.03277	30.51598	12.99124
JKB A /CL2	-23.4558	10.74962	0.495365	0.085316	11.72116	5.806254
JKB O /L1	-18.3963	11.09099	0.439206	0.094009	10.63731	4.671967
JKB O /L2	-20.6566	10.21397	0.469255	0.071426	14.00049	6.569803
JKB O /BL2	-22.7241	7.232056	0.178254	0.044862	22.29036	3.973348
JKB O /L3	-24.2035	12.64265	0.696125	0.052875	18.91268	13.1656
JKB O /L3	-21.3804	—	0.307347	—	—	—
JKB O /BL3	-21.5522	—	0.113665	—	—	—
JKB O /BL3M	-21.0523	—	0.31354	—	—	—
JKB O /L4	-22.3978	6.277608	0.312103	0.026278	38.05424	11.87684
JKB O /AAL1	-21.2953	—	0.049824	—	—	—
JKB O /A1	-21.267	—	0.039937	—	—	—
JKB O /AAL2	-23.6874	—	0.301093	—	—	—
JKB O /BAL2	-20.8704	4.485682	0.069445	0.050249	19.90075	1.382009
JKB O /C2	-20.9201	—	0.3449	—	—	—
JKB O /AL2	—	7.984369	—	0.029837	33.51551	—
JKB O /AL3	—	11.12615	—	0.040766	24.5302	—
JKB O /AL3(2)	—	14.56299	—	0.062407	16.02372	—
Std Deviation	1.486336	3.352275	0.179702	0.02166	8.912629	7.420964
Mean	-21.934	10.63447	0.291015	0.05108	22.83954	7.119617

Table E2 Richtersveld, Jakkalsberg and modern Orange River sediment $\delta^{13}C$, $\delta^{15}N$ results.

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Height (cm)	Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N
600	0	S1X/ SURFACE	-19.0167	—	0.320565	—	—	—
560	40	S1X/P1	-19.1451	—	0.28492	—	—	—
550	50	S1X/P2 45CM	-19.587	7.329209	0.504782	0.05449	18.35189	9.2637
545	55	S1X/P3	-19.2371	7.936593	0.271791	0.037987	26.32514	7.154932
568	32	S1X/P4	—	4.102426	—	0.027811	35.95762	—
530	70	S1X/P5 (30)	-19.677	8.763239	0.44742	0.115163	8.683307	3.885085
515	85	S1X/P5	-19.3793	5.458145	0.233757	0.049846	20.06179	4.68958
500	100	S1X/N1	-18.7699	—	0.301269	—	—	—
492	108	S1X/N2	-18.7921	9.397307	0.28074	0.098835	10.11792	2.840509
486	114	S1X/N3	-17.4213	5.927929	0.269906	0.021356	46.82586	12.63857
478	122	S1X/N4 O BASE	-18.0817	5.304945	0.430979	0.029195	34.25245	14.76207
460	140	S1X/L	-20.1157	—	0.251352	—	—	—
450	150	S1X/K	-20.7122	3.045796	0.210798	0.016689	59.92128	12.63128
430	170	S1X/J	-20.1795	—	0.426969	—	—	—
425	175	S1X/I	-17.3435	2.078036	0.486832	0.026743	37.39321	18.20421
425	175	S1X/I	-18.6803	—	0.303187	—	—	—
385	215	S1X/H TOP	-19.1115	—	0.226195	—	—	—
370	230	S1X/4 MID(5CM)	-19.5325	—	0.288842	—	—	—
365	235	S1X/H/0	-18.5724	—	0.175722	—	—	—
360	240	S1X/G1	-18.1143	—	0.290727	—	—	—
340	260	S1X/G2	-19.0783	3.824835	0.433762	0.01904	52.52007	22.7812
315	285	S1X/62V G3(V)	-18.5244	—	0.578137	—	—	—
264	336	S1X/63	—	-1.21239	—	0.016864	59.29696	—
296	304	S1X/B8(45)	—	7.198313	—	0.045029	22.20805	—
290	310	S1X/1F	-18.2256	—	0.418444	—	—	—
280	320	S1X/E	-18.4487	—	0.072167	—	—	—
275	325	S1X/D	-19.4072	—	0.195027	—	—	—
200	400	S1X1/C1-15	-21.1196	3.191661	0.251553	0.032687	30.5932	7.695803
200	400	S1X/C1	-19.1547	—	0.109396	—	—	—
120	480	S1X/C3	-19.3974	5.582937	0.175457	0.043771	22.84644	4.008562
168	432	S1X/C4 (30)	-19.7322	5.883553	0.190803	0.050913	19.64121	3.747606
152	448	S1X/C5	-19.5059	7.365048	0.097779	0.053128	18.82235	1.84043
144	456	S1X/C6	-19.7272	—	0.068316	—	—	—
136	464	S1X/C7	-19.9859	5.351057	0.101777	0.045534	21.96177	2.235196
128	472	S1X/C8(45)	-19.0558	—	0.089183	—	—	—
120	480	S1X/C9	-18.7938	6.44674	0.100347	0.044421	22.51209	2.259021
104	496	S1X/CO	—	7.660417	—	0.04793	20.86381	—
72	528	S1X/C10	-20.3141	6.958488	0.173142	0.048506	20.61622	3.56953
60	540	S1X/A1 60CM FROM IV	—	6.836289	—	0.046703	21.41187	—
5	595	S1X/5	—	2.782199	—	0.025888	38.62855	—
		Std Deviation	0.837324	2.445779	0.135389	0.023621	14.32881	6.254012
		Mean	-19.1747	5.53099	0.266531	0.043414	29.12231	7.894547

Table E3 Lower Xobies palaeoflood site $\delta^{13}C$ and $\delta^{15}N$ results.

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Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
595	H7-1-1	-19.65	6.90	4.12	0.44	2.26	9.31		✓
590	H7-1-2	-19.60	6.88	4.24	0.44	2.29	9.70		✓
582	H7-1-3	-19.65	7.10	4.36	0.48	2.10	9.15		✓
580	H7-1-4	-19.62	6.97	3.62	0.46	2.16	7.81	✓	
575	H7-1-5	-19.80	7.18	4.31	0.46	2.16	9.31		✓
570	H7-1-6	-19.59	7.18	4.12	0.47	2.14	8.82	✓	
565	H7-1-7	-19.69	6.44	4.20	0.45	2.20	9.24		✓
560	H7-1-8	-19.65	7.32	3.89	0.47	2.14	8.33	✓	
555	H7-1-9	-19.05	7.19	4.56	0.47	2.15	9.79		✓
550	H7-1-10	-19.78	7.03	4.13	0.46	2.17	8.96	✓	
545	H7-1-11	-19.41	7.08	4.44	0.46	2.19	9.74		✓
540	H7-1-12	-19.59	8.92	3.56	0.44	2.26	8.06	✓	
535	H7-1-13	-20.08	6.92	4.66	0.37	2.70	12.55		✓
535	H7-1-13	-19.98	—	3.32	—	—	—	—	—
530	H7-1-14	-21.27	7.34	2.30	0.26	3.78	8.69	✓	
525	H7-1-15	-21.11	7.03	2.26	0.31	3.22	7.28	✓	
520	H7-1-16	-20.34	7.54	3.12	0.37	2.68	8.34	✓	
515	H7-1-17	-20.08	6.77	3.60	0.36	2.74	9.89	·	✓
510	H7-1-18	-20.84	6.55	3.32	0.38	2.63	8.73	✓	
507.5	H7-1-19	-19.72	6.77	4.57	0.44	2.28	10.43	·	✓
505	H7-1-20	-21.04	6.96	2.70	0.33	3.05	8.24	✓	
502.5	H7-1-21	-20.22	7.23	3.59	0.39	2.56	9.18	·	✓
500	H7-1-22	-19.71	6.81	3.98	0.41	2.42	9.62	·	✓
495	H7-2-1	-19.49	7.02	4.25	0.44	2.27	9.66	·	✓
590	H7-2-2	-20.54	7.22	2.74	0.44	2.25	6.17	✓	
485	H7-2-3	-19.61	6.63	4.28	0.44	2.29	9.80		✓
480	H7-2-4	-19.59	6.90	4.15	0.44	2.29	9.50		✓
475	H7-2-5	-19.69	7.22	4.16	0.45	2.22	9.25	·	✓
470	H7-2-6	-19.42	6.99	4.51	0.46	2.19	9.86		✓
465	H7-2-7	-19.55	7.15	4.14	0.48	2.09	8.63	✓	
460	H7-2-8	-19.99	6.62	3.83	0.43	2.33	8.91	✓	·
455	H7-2-9	-20.29	6.16	4.57	0.33	2.99	13.64		✓
450	H7-2-10	-20.25	7.48	3.78	0.38	2.65	10.01		✓
445	H7-2-11	-19.89	7.16	4.26	0.47	2.13	9.05		✓
440	H7-2-12	-19.74	7.03	4.82	0.48	2.10	10.11	·	✓
435	H7-2-13	-20.06	6.78	4.88	0.49	2.06	10.04		✓
430	H7-2-14	-19.64	6.96	5.09	0.49	2.05	10.44		✓
425	H7-2-15	-19.44	6.24	5.26	0.49	2.06	10.83	·	✓
420	H7-2-16	-19.34	6.86	5.15	0.48	2.09	10.74		✓
415	H7-2-17	-19.86	7.25	4.90	0.48	2.07	10.16		✓
410	H7-2-18	-19.70	6.81	4.58	0.48	2.08	9.54	·	✓
405	H7-2-19	-19.84	6.61	4.23	0.42	2.39	10.12	·	✓
402.5	H7-2-20	-19.96	7.14	4.07	0.42	2.37	9.65		✓
400	H7-2-21	—	7.12	—	0.44	2.29	—	—	—
395	H7-3-1	-19.87	6.65	3.82	0.41	2.43	9.27		✓
390	H7-3-2	-19.63	7.26	4.33	0.46	2.17	9.41		✓
385	H7-3-3	-19.66	7.10	4.29	0.45	2.22	9.53	·	✓
380	H7-3-4	-19.72	6.98	4.40	0.44	2.25	9.90		✓
375	H7-3-5	-19.40	7.05	4.49	0.48	2.10	9.43	·	✓

Table E4 Namaqualand Mudbelt core H7 - $\delta^{13}C$ and $\delta^{15}N$ results. (page 1/3).

University of Cape Town

Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
370	H7-3-6	-19.59	6.28	4.57	0.45	2.24	10.25	·	✓
365	H7-3-7	-19.70	7.04	4.64	0.48	2.07	9.59	·	✓
360	H7-3-8	-19.36	6.78	4.95	0.47	2.12	10.51	·	✓
355	H7-3-9	-19.79	6.80	3.75	0.45	2.24	8.41	✓	
350	H7-3-10	-16.84	7.14	2.19	0.46	2.20	4.80	✓	
345	H7-3-11	-19.68	7.22	4.56	0.46	2.16	9.85		✓
340	H7-3-12	-19.52	6.81	5.01	0.44	2.25	11.30	·	✓
335	H7-3-13	-19.91	6.98	3.90	0.45	2.20	8.60	✓	
330	H7-3-14	-20.40	7.05	3.51	0.37	2.72	9.53		✓
325	H7-3-15	-19.82	7.00	3.88	0.40	2.52	9.76		✓
320	H7-3-16	-20.15	6.99	3.80	0.36	2.78	10.55		✓
315	H7-3-17	-20.14	7.29	4.09	0.39	2.55	10.42	·	✓
310	H7-3-18	-19.85	7.02	3.14	0.42	2.37	7.44	✓	
305	H7-3-19	-20.28	6.89	3.14	0.41	2.46	7.70	✓	
300	H7-3-20	-20.34	6.93	4.01	0.43	2.30	9.23		✓
295	H7-4-1	-19.82	6.70	3.79	0.44	2.26	8.57	✓	
290	H7-4-2	-19.80	6.96	4.42	0.45	2.24	9.90		✓
285	H7-4-3	-19.75	6.92	3.48	0.44	2.26	7.88	✓	
280	H7-4-4	-20.65	6.80	3.17	0.43	2.31	7.32	✓	
275	H7-4-5	-19.79	6.75	4.41	0.43	2.35	10.35	✓	
270	H7-4-6	-20.00	6.51	4.25	0.43	2.33	9.89		✓
265	H7-4-7	-19.75	6.68	3.43	0.43	2.35	8.06	✓	
260	H7-4-8	-20.01	6.55	4.09	0.41	2.45	10.01		✓
255	H7-4-9	-20.17	—	3.83	—	—	—	—	—
250	H7-4-10	-19.37	6.54	3.91	0.38	2.64	10.32		✓
245	H7-4-11	-19.28	6.31	3.34	0.39	2.57	8.59	✓	
240	H7-4-12	-23.45	6.31	3.95	0.42	2.39	9.45		✓
235	H7-4-13	-20.08	5.76	3.82	0.40	2.49	9.49		✓
230	H7-4-14	-20.51	6.22	4.02	0.41	2.42	9.73		✓
225	H7-4-15	-19.85	6.34	4.02	0.42	2.38	9.58		✓
220	H7-4-16	-21.35	6.15	3.14	0.45	2.23	7.01	✓	·
215	H7-4-17	-19.60	6.71	4.27	0.44	2.26	9.62	—	✓
210	H7-4-18	-19.90	6.71	4.09	0.45	2.21	9.02	—	✓
205	H7-4-19	-19.55	—	4.17	—	—	—	—	—
200	H7-4-20	-19.60	6.82	3.83	0.45	2.23	8.54	✓	
195	H7-5-1	-20.34	6.73	4.48	0.45	2.22	9.96		✓
190	H7-5-2	-20.22	6.45	3.31	0.44	2.29	7.58	✓	
185	H7-5-3	-20.06	6.09	3.05	0.43	2.35	7.18	✓	
180	H7-5-4	-20.39	5.84	3.43	0.42	2.40	8.26	✓	
175	H7-5-5	-22.00	6.05	3.51	0.42	2.36	8.28	✓	
170	H7-5-6	-19.84	5.39	3.49	0.39	2.58	8.99	✓	
165	H7-5-7	-19.80	6.45	2.94	0.44	2.29	6.73	✓	
160	H7-5-8	-21.03	5.74	3.31	0.41	2.46	8.16	✓	
155	H7-5-9	-19.89	6.45	4.03	0.42	2.40	9.65		✓
150	H7-5-10	-19.82	6.55	4.04	0.47	2.15	8.68	✓	
145	H7-5-11	-21.05	5.74	3.85	0.40	2.47	9.52		✓
140	H7-5-12	-19.64	6.53	4.11	0.45	2.23	9.16	·	✓
135	H7-5-13	-19.61	6.55	4.25	0.43	2.30	9.78		✓

Table E4 Namaqualand Mudbelt core H7 - $\delta^{13}C$ and $\delta^{15}N$ results. (page 2/3).

University of Cape Town

Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
130	H7-5-14	-19.51	6.40	3.45	0.46	2.17	7.50	✓	
125	H7-5-15	-19.77	6.47	4.01	0.46	2.18	8.76	✓	
120	H7-5-16	-19.95	6.17	3.18	0.47	2.15	6.84	✓	
115	H7-5-17	-19.78	6.55	4.40	0.46	2.19	9.62		✓
110	H7-5-18	-20.18	6.28	2.94	0.45	2.21	6.49	✓	
105	H7-5-19	-20.77	6.30	4.16	0.45	2.24	9.31		✓
100	H7-5-20	-20.68	6.15	3.90	0.41	2.45	9.57		✓
95	H7-6-1	-19.70	6.59	4.18	0.43	2.34	9.76		✓
90	H7-6-2	-20.40	6.56	4.42	0.43	2.34	10.32		✓
85	H7-6-3	-19.70	6.24	4.36	0.43	2.31	10.06		✓
80	H7-6-4	-20.30	6.44	4.21	0.44	2.26	9.53	·	✓
75	H7-6-5	-21.30	6.45	4.32	0.46	2.20	9.48		✓
70	H7-6-6	-19.80	6.42	4.53	0.45	2.22	10.05		✓
65	H7-6-7	-21.00	6.44	4.28	0.44	2.28	9.74		✓
60	H7-6-8	-20.00	6.47	3.69	0.37	2.68	9.89		✓
55	H7-6-9	-20.50	6.30	3.82	0.40	2.49	9.51		✓
50	H7-6-10	-21.10	6.32	3.06	0.40	2.47	7.55	✓	
45	H7-6-11	-21.50	6.47	2.96	0.42	2.41	7.13	✓	
40	H7-6-12	-20.00	6.60	2.76	0.37	2.72	7.51	✓	
35	H7-6-13	-20.00	6.54	2.73	0.36	2.79	7.62	✓	
30	H7-6-14	-19.60	6.50	2.84	0.39	2.54	7.20	✓	
25	H7-6-15	-19.50	6.47	3.70	0.38	2.63	9.74		✓
20	H7-6-16	-19.00	6.98	3.14	0.32	3.10	9.75		✓
15	H7-6-17	19.95	8.09	3.21	0.27	3.71	11.92		✓
15	H7-6-17	-19.70	—	4.28	—	—	—	—	—
10	H7-6-18	-19.60	6.74	3.46	0.36	2.81	—	—	—
5	H7-6-19	-19.80	6.43	3.74	0.39	2.53	—	—	—
0	H7-6-20	-19.60	6.49	3.63	0.41	2.44	—	—	—
0	H7-6-20	-19.89	—	3.06	—	—	—	—	—
	Std Deviation	3.633672	0.460276	0.62293	0.042753	0.28899	1.255932	·	
	Mean	-19.66	6.74	3.89	0.43	2.38	9.17	·	

Table E4 Namaqualand Mudbelt core H7 - $\delta^{13}C$ and $\delta^{15}N$ results. (page 3/3).

University of Cape Town

Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
572	H2.1.1	-19.74	6.38	2.26	0.29	3.41	7.69	✓	
572	H2-1-1	-19.30	—	2.28	—	—	—	—	—
572	H2-1-1	-19.64	—	2.59	—	—	—	—	—
567	H2.1.2	-19.92	6.50	2.02	0.24	4.15	8.37	✓	
562	H2.1.3	-20.11	6.40	2.59	0.31	3.21	8.30	✓	
562	H2-1-3	-20.34	—	2.42	—	—	—	—	—
562	H2-1-3	-19.84	—	2.08	—	—	—	—	—
557	H2.1.4	-19.56	6.37	2.93	0.36	2.79	8.18	✓	
552	H2.1.5	-19.81	6.14	2.62	0.35	2.83	7.43	✓	
547	H2.1.6	-19.00	6.19	3.01	0.35	2.82	8.48	✓	
542	H2.1.7	-18.96	6.21	1.95	0.32	3.17	6.18	✓	
542	H2-1-7	-19.21	—	2.24	—	—	—	—	—
542	H2-1-7	-18.72	—	2.10	—	—	—	—	—
542	H2-1-7	-18.38	—	2.69	—	—	—	—	—
537	H2.1.8	-19.28	6.47	2.29	0.35	2.84	6.52	✓	
532	H2.1.9	-18.97	6.20	2.88	0.34	2.96	8.55	✓	
527	H2.1.10	-18.40	6.18	2.03	0.32	3.09	6.27	✓	
522	H2.1.11	-17.65	6.32	1.88	0.26	5.09	7.12	✓	
517	H2.1.12	-18.47	5.75	1.84	0.24	4.08	7.50	✓	
512	H2.1.13	-17.91	5.85	1.27	0.23	4.41	5.62	✓	
507	H2.1.14	-17.27	5.44	1.75	0.22	4.52	7.90	✓	
502	H2.1.15	-17.48	5.23	1.48	0.21	4.69	6.97	✓	
497	H2.1.16	-17.59	5.82	1.75	0.20	4.76	8.72	✓	
492	H2.1.17	-18.51	6.31	1.28	0.24	5.08	5.43	✓	
487	H2.1.18	-18.04	6.24	1.77	0.23	4.97	7.69	✓	
482	H2.1.19	-16.86	6.07	1.26	0.22	4.71	5.84	✓	
477	H2.1.20	-18.20	5.52	1.49	0.17	5.87	8.74	✓	
472	H2.2.1	-14.50	4.95	1.61	0.17	6.01	9.66		✓
467	H2.2.2	-16.30	4.77	1.29	0.16	6.21	8.00	✓	
462	H2.2.3	-18.70	5.83	1.80	0.22	4.33	8.31	✓	
457	H2.2.4	-17.78	5.34	2.06	0.20	5.01	10.31		✓
452	H2.2.5	-17.20	5.63	1.41	0.18	5.53	7.80	✓	
447	H2.2.6	-16.48	5.24	1.41	0.20	5.03	7.08	✓	
442	H2.2.7	-15.94	6.19	0.38	0.20	4.90	1.95	—	—
437	H2.2.8	-16.52	4.75	1.46	0.17	6.06	8.86	✓	
432	H2.2.9	-16.01	5.15	2.37	0.19	5.36	12.73		✓
427	H2.2.10	-17.50	4.68	1.62	0.18	5.60	9.06		✓
422	H2.2.11	-17.37	5.34	1.47	0.17	5.86	8.60	✓	
422	H2-2-11	-18.16	—	1.63	—	—	—	—	—
422	H2-2-11	-17.53	—	1.38	—	—	—	—	—
417	H2.2.12	-16.76	5.63	1.10	0.15	4.54	7.34	✓	
417	H2.1.13	-17.45	6.17	1.41	0.20	4.86	7.00	✓	
412	H2.2.14	-16.74	5.22	1.73	0.18	5.52	9.58		✓
407	H2.2.15	-17.78	5.36	1.18	0.17	5.78	6.82	✓	
402	H2.2.16	-17.07	6.20	1.96	0.20	4.96	9.73		✓
392	H2.2.17	-17.09	5.84	1.71	0.22	4.62	7.92	✓	
387	H2.2.18	-16.58	5.66	1.39	0.21	4.82	6.71	✓	
387	H2-2-18	-17.39	—	1.76	—	—	—	—	—

Table E5 Namaqualand Mudbelt core H2 - $\delta^{13}C$ and $\delta^{15}N$ results (page 1/4).

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Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
382	H2.2.19	-16.22	5.73	1.62	0.20	5.13	8.28	✓	
372	H2.3.1	-18.79	6.14	2.00	0.25	3.99	7.98	✓	
367	H2.3.2	-18.97	6.12	1.69	0.27	3.76	6.37	✓	
362	H2.3.3	-17.48	5.99	1.94	0.26	3.81	7.38	✓	
357	H2.3.4	-18.28	6.28	1.55	0.22	5.03	7.17	✓	
352	H2.3.5	-16.85	5.80	1.24	0.17	5.90	7.33	✓	
347	H2.3.6	-15.93	5.53	1.85	0.21	4.83	8.95	✓	
342	H2.3.7	-17.10	6.10	1.57	0.20	4.98	7.81	✓	
337	H2.3.8	-18.61	6.56	2.14	0.33	5.47	6.50	✓	
332	H2.3.9	-16.23	5.32	1.50	0.20	4.88	7.31	✓	
332	H2-3-9	-15.84	—	2.53	—	—	—	—	—
327	H2.3.10	—	6.09	—	0.24	4.74	—	—	—
322	H2.3.11	-17.07	5.90	1.73	0.20	5.06	8.78	✓	
317	H2.3.12	-15.23	5.83	2.57	0.21	4.72	12.13		✓
317	H2-3-12	-16.17	—	2.32	—	—	—	—	—
317	H2-3-12	-17.02	—	2.42	—	—	—	—	—
312	H2.3.13	-17.12	5.42	1.97	0.23	4.29	8.47	✓	
307	H2.3.14	-14.33	6.13	2.42	0.22	4.62	11.20		✓
302	H2.3.15	-16.60	5.88	1.67	0.24	4.15	6.94	✓	
297	H2.3.16	-16.63	5.85	1.74	0.19	5.23	9.08		✓
292	H2.3.17	-16.48	5.88	1.48	0.17	5.86	8.65	✓	
287	H2.3.18	-17.63	6.03	1.94	0.23	4.99	8.50	✓	
282	H2.3.19	-17.48	5.82	2.15	0.19	5.14	11.03		✓
277	H2.3.20	-16.90	5.13	1.46	0.17	5.91	8.63	✓	
272	H2.3.21	-13.86	6.05	2.20	0.21	4.83	10.61	—	—
272	H2.4.1	-16.20	6.27	1.96	0.23	5.02	9.39		✓
267	H2.4.2	-16.78	6.33	1.86	0.24	5.11	7.83	✓	
262	H2.4.3	-16.66	5.53	1.97	0.20	5.01	9.89		✓
257	H2.4.4	-16.56	5.50	1.55	0.20	5.11	7.91	✓	
252	H2.4.5	-13.76	5.19	2.22	0.19	5.28	11.74		✓
247	H2.4.6	-16.62	5.68	1.80	0.20	4.97	8.95	✓	
242	H2.4.7	-18.18	5.85	1.84	0.20	4.97	9.13		✓
242	H2-4-7	-17.29	—	1.85	—	—	—	—	—
242	H2-4-7	-16.60	—	1.69	—	—	—	—	—
237	H2.4.8	-16.86	5.96	1.97	0.20	4.97	9.76		✓
232	H2.4.9	-18.22	5.80	1.96	0.23	4.73	8.52	✓	
227	H2.4.10	-18.21	5.67	2.14	0.24	4.15	8.88	✓	
222	H2.4.11	-17.17	6.16	1.86	0.26	4.84	7.17	✓	
217	H2.4.12	-15.65	5.51	2.15	0.18	4.41	12.12		✓
212	H2.4.13	-18.54	5.60	1.83	0.20	5.02	9.17		✓
207	H2.4.14	-17.33	5.68	2.06	0.21	4.80	9.87		✓
202	H2.4.15	-16.97	5.57	2.31	0.21	4.69	10.85		✓
197	H2.4.16	-17.37	5.39	2.31	0.21	4.84	11.16		✓
192	H2.4.17	-16.09	5.88	2.29	0.20	4.98	11.44		✓
187	H2.4.18	-17.42	5.69	1.55	0.19	5.28	8.16	✓	
182	H2.4.19	-17.94	5.68	1.63	0.19	5.21	8.50	✓	
177	H2.4.20	-16.98	6.00	1.77	0.21	4.85	8.56	✓	
175	H2.4.21	-17.51	6.05	1.39	0.18	5.53	7.71	·	

Table E5 Namaqualand Mudbelt core H2 - $\delta^{13}C$ and $\delta^{15}N$ results (page 2/4).

University of Cape Town

Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
175	H2-4-21	-18.19	—	1.41	—	—	—	—	—
175	H2-4-21	-17.43	—	1.38	—	—	—	—	—
172	H2.5.1	-15.81	5.92	2.33	0.21	4.69	6.54	✓	
167	H2.5.2	-16.87	5.96	1.52	0.22	4.45	6.75	✓	
162	H2.5.3	-15.28	5.79	2.08	0.21	4.75	9.86		✓
157	H2.5.4	-16.81	5.29	1.62	0.20	4.91	7.95	✓	
152	H2.5.5	-16.81	5.30	1.34	0.18	5.44	7.27	✓	
147	H2.5.6	-17.60	5.64	1.79	0.19	5.27	9.42		✓
142	H2.5.7	-17.07	4.59	1.39	0.14	7.18	9.98		✓
137	H2.5.8	-18.35	5.54	2.47	0.24	4.23	10.44		✓
132	H2.5.9	-16.63	5.65	1.52	0.18	4.56	8.54	✓	
127	H2.5.10	-17.81	6.32	2.17	0.26	5.10	8.45	✓	
122	H2.5.11	-16.99	5.24	1.59	0.17	5.84	9.31		✓
117	H2.5.12	-17.58	5.62	1.72	0.20	4.96	8.53	✓	
117	H2-5-12	-18.35	—	2.15	—	—	—	—	—
117	H2-5-12	-17.96	—	1.72	—	—	—	—	—
112	H2.5.13	-17.46	5.93	1.84	0.18	4.88	10.11		✓
107	H2.5.14	-17.41	5.93	1.60	0.19	5.38	8.58	✓	
102	H2.5.15	-17.59	6.23	1.37	0.21	4.96	6.40	✓	
97	H2.5.16	-15.28	6.02	2.14	0.22	4.58	9.79		✓
92	H2.5.17	-17.37	5.98	1.89	0.24	4.16	7.88	✓	
87	H2.5.18	-18.02	6.05	1.96	0.25	3.93	7.71	✓	
82	H2.5.19	-17.94	5.32	2.07	0.19	5.34	11.06		✓
77	H2.5.20	-17.71	6.04	1.73	0.20	5.03	8.68	✓	
72	H2.6.1	-17.20	6.44	2.55	0.23	5.27	8.25	✓	
72	H2-6-1	-18.09	—	1.88	—	—	—	—	—
69	H2.6.2	-16.91	5.39	1.43	0.17	5.79	8.29	✓	
63	H2.6.3	-16.78	5.99	1.76	0.18	5.51	10.28		✓
63	H2-6-3	-20.37	—	1.59	—	—	—	—	—
63	H2-6-3	-14.59	—	1.86	—	—	—	—	—
59	H2.6.4	-17.33	6.28	1.49	0.23	5.04	6.57	✓	
54	H2.6.5	-17.56	5.94	1.68	0.20	4.90	8.72	✓	
54	H2-6-5	-17.29	—	1.83	—	—	—	—	—
54	H2-6-5	-18.27	—	1.71	—	—	—	—	—
50	H2.6.6	-17.86	5.88	1.80	0.21	4.71	7.57	✓	
50	H2-6-6	-17.14	—	1.90	—	—	—	—	—
50	H2-6-6	-17.34	—	1.61	—	—	—	—	—
45	H2.6.7	-15.38	5.78	1.80	0.21	4.72	8.57	✓	
41	H2.6.8	-17.31	5.38	1.72	0.20	4.91	8.46	✓	
36	H2.6.9	-16.49	5.92	1.58	0.19	5.13	8.11	✓	
32	H2.6.10	-17.21	5.66	1.67	0.19	5.18	6.86	✓	
32	H2-6-10	-15.54	—	1.80	—	—	—	—	—
32	H2-6-10	-17.00	—	1.32	—	—	—	—	—
27	H2.6.11	-17.82	5.81	1.81	0.19	5.26	9.51		✓
23	H2.6.12	-17.41	4.94	1.59	0.19	5.32	8.46	✓	
18	H2.6.13	-17.20	5.50	1.58	0.17	5.77	9.13	·	
18	H2-6-13	-15.73	—	1.73	—	—	—	—	—
18	H2-6-13	-17.78	—	1.58	—	—	—	—	—
18	H2.7.1	-16.72	5.56	1.42	0.17	5.79	8.25	✓	

Table E5 Namaqualand Mudbelt core H2 - $\delta^{13}C$ and $\delta^{15}N$ results (page 3/4).

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Depth (cm)	Sample	$\delta^{13}C$	$\delta^{15}N$	%C	%N	1/N	C/N	5-9 C/N	>9 C/N
14	H2.7.2	-18.12	5.47	1.73	0.19	5.25	9.08		✓
14	H2-7-2	-17.27	—	1.58	—	—	—	—	—
14	H2-7-2	-17.85	—	1.92	—	—	—	—	—
9	H2.7.3	-17.88	5.45	1.82	0.20	4.97	9.05		✓
5	H2.7.4	-19.00	6.07	1.80	0.25	5.04	7.15	✓	
	Standard Deviation	1.214466	0.41452	0.3943	0.04413	0.7495	1.5596		
	Mean	-17.39	5.78	1.83	0.22	4.86	8.43		

Table E5 Namaqualand Mudbelt core H2 - $\delta^{13}C$ and $\delta^{15}N$ results (page 4/4).

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APPENDIX F

Results of pollen analysis for the OR mudbelt, Richtersveld and modern OR sediment data.

This section includes the following data sheets:

- Raw pollen count sheets: Namaqualand Mudbelt gravity cores:
  - Table F1 H2 data (4 pages).
  - Table F2 H7 data (4 pages).
- Box core data pollen count:
- Table F1 A 30 (0 cm and 10 cm).
- Table F1 A 49 (0 cm and 10 cm).
- Table F3 Box cores, H2 and H7 pollen represented as a relative percentage (2 pages).
- Table F4 Box and gravity core data showing 7 main pollen types as relative percentage.
- Table F5 Modern Orange River pollen count as a relative percentage.
- Table F6 Table of raw pollen counts: Richtersveld samples, JKB/L2, JKBO/DROL (goat pellets) and Lower Xobies surface SIX/SURF.

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- Table F7 Table of inert (pollen) samples in gravity cores (depths indicated in cm), H2 and H7.

- Table F8 Table of modern Orange River sediment pollen - raw count.

- Table F9 DCA Detrended Correspondence Analysis. This data was used for DCA, PCA in 'PAST' statistical package (2 pages).

- Table F10 Correspondence Analysis Scores relating to Figures 6.8 and 6.9 using PAST statistical package. (2 pages).

- Table F11 PCA correlation matrix (not co-variance) of H2, H7 and inland Orange River data. (2 pages).

- Figure F1 Histogram comparing box and gravity core data at depths of 0 cm, 10 cm for 7 main pollen types as relative percentage. Note: this differs from the 6 main pollen types used in the DCA and PCA analysis.

- Figure F2 Pollen Diagram Histogram of Namaqualand Mudbelt off Orange River (H2, top) and Buffels River (H7, below).

- Figure F3 Correspondence Analysis (no detrending) scores for Axis 1 and 2.

- Figure F4 Correspondence Analysis (no detrending) scores for Axis 2 and 3.

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depth (cm)	0	10	20	40	80	100	120	140
Indeterminate	3	5	22	39	13	40	8	26
Unknown	5	6	4	14	7	4	0	8
Acacia (Mimosaceae)	1	0	1	0	0	0	0	1
Acanthaceae undiff.	0	1	9	1	15	5	1	4
Acanthaceae retic.	0	0	0	0	0	0	0	0
Aceraceae	3	0	0	0	0	5	0	1
Amaryllidaceae	0	0	0	0	0	0	0	0
Anacardiaceae	0	1	9	0	5	0	3	2
Apiaceae	0	0	3	0	7	1	1	7
Aster- 1	9	14	76	49	75	67	51	69
Aster - 2	0	2	0	2	2	3	2	0
Aster - 4	0	0	0	0	1	2	1	2
Bignoniaceae	0	0	3	5	0	0	1	0
Boraginaceae	0	0	0	0	0	4	0	1
Brassicaceae	1	1	4	3	0	0	2	0
Campanulaceae	0	0	0	1	0	0	0	1
Caryophyllaceae	9	2	35	20	20	26	18	23
Celastraceae	5	1	0	0	1	0	1	7
Chenopodiaceae/Amaranth	2	2	31	26	45	47	16	23
Convolvulaceae	0	0	0	0	0	0	0	0
Crassulaceae	2	1	1	0	2	1	0	0
Cruciferaceae	0	0	0	0	0	0	0	1
Cyperaceae	3	5	24	46	20	46	34	28
Ebenaceae	0	0	1	0	0	0	0	0
Ericaceae	1	0	2	1	1	1	0	0
Euphorbiaceae	0	2	2	2	2	3	2	4
Fabaceae - undiff.	1	0	1	0	0	0	0	7
Geraniaceae	0	0	4	0	0	3	0	0
Iridaceae	0	0	8	3	0	1	1	1
Juncaceae	1	3	2	10	0	0	10	12
Liliaceae	0	1	4	1	3	1	2	0
Malvaceae	6	1	4	0	4	2	3	0
Mesembryanthemaceae	0	0	5	0	0	0	0	0
Myrtaceae	0	0	2	0	0	0	0	0
Oleaceae	0	0	0	1	0	0	0	0
Orchidaceae	0	0	0	0	0	0	0	0
Pinaceae - undiff.	0	0	0	0	0	0	0	0
Plumbaginaceae	0	0	0	0	0	0	0	1
Poaceae undiff.	20	29	47	53	55	19	120	47
Podocarpus	0	0	0	0	0	0	0	0
Polygonaceae	0	0	0	0	4	0	7	3
Portulacaceae	0	0	1	1	0	0	0	2
Potamogeton	0	2	3	0	0	0	0	0
Restionaceae	23	27	12	82	36	76	25	51
Rosaceae	0	0	0	0	0	0	0	0
Rubiaceae	0	0	0	0	0	0	4	1
Rutaceae	0	0	0	1	3	0	0	4
Scrophulariaceae	0	0	0	0	0	0	0	0
Solanaceae	0	0	0	0	0	0	1	0
Spore (monolete)	0	0	0	0	0	0	0	0
Spore (trilete)	0	0	1	0	0	0	0	0
Thymelaeaceae	0	0	1	0	1	18	0	1
Verbenaceae	0	0	0	0	0	0	0	0
Zygophyllaceae	0	0	1	0	0	0	0	0

Table F1 H2 raw pollen count (page 1/4). Box core data included on page 4.

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depth (cm)	160	180	190	220	230	260	300	360
Indeterminate	8	15	28	29	18	3	23	6
Unknown	0	8	12	0	5	0	20	0
Acacia (Mimosaceae)	0	0	0	0	0	0	0	0
Acanthaceae undiff.	1	0	1	1	3	2	4	4
Acanthaceae retic.	0	0	0	0	0	0	0	0
Aceraceae	0	0	0	2	5	0	0	0
Amaryllidaceae	0	0	0	0	0	0	0	0
Anacardiaceae	1	0	0	4	7	4	0	3
Apiaceae	1	1	0	3	3	0	0	2
Aster- 1	50	55	18	48	59	57	37	69
Aster - 2	2	0	0	0	2	0	1	8
Aster - 4	5	0	0	2	0	2	0	0
Bignoniaceae	0	0	0	4	3	4	2	0
Boraginaceae	0	0	0	0	0	0	0	0
Brassicaceae	0	0	0	0	3	4	0	4
Campanulaceae	1	2	0	0	0	0	3	0
Caryophyllaceae	11	18	4	8	30	29	9	28
Celastraceae	4	0	0	6	2	2	0	0
Chenopodiaceae/Amaranth	25	22	30	29	61	40	31	27
Convolvulaceae	0	0	0	0	0	0	0	0
Crassulaceae	3	0	0	0	2	0	2	0
Cruciferaceae	0	0	0	0	0	0	0	0
Cyperaceae	28	23	34	51	38	50	20	33
Ebenaceae	0	0	0	0	0	0	5	0
Ericaceae	1	0	0	1	2	4	0	1
Euphorbiaceae	2	2	0	4	4	4	4	3
Fabaceae - undiff.	0	0	0	0	0	0	1	2
Geraniaceae	0	0	1	0	6	0	0	2
Iridaceae	2	0	0	1	3	2	1	6
Juncaceae	11	0	1	14	0	7	26	11
Liliaceae	1	0	0	4	0	1	2	1
Malvaceae	2	4	0	1	0	0	5	2
Mesembryanthemaceae	2	0	0	1	0	2	0	4
Myrtaceae	0	0	0	0	0	0	0	0
Oleaceae	0	0	0	0	2	0	3	0
Orchidaceae	0	0	0	0	0	0	0	1
Pinaceae - undiff.	0	0	0	0	0	2	0	0
Plumbaginaceae	0	0	1	0	0	2	0	0
Poaceae undiff.	110	134	7	62	46	81	47	79
Podocarpus	0	0	1	0	0	0	1	0
Polygonaceae	1	0	1	1	0	0	5	6
Portulacaceae	0	1	0	0	0	0	0	1
Potamogeton	0	1	0	0	0	0	5	0
Restionaceae	36	32	37	50	30	10	75	7
Rosaceae	1	0	0	0	0	0	0	1
Rubiaceae	0	0	0	0	0	1	0	0
Rutaceae	3	0	0	0	0	0	1	2
Scrophulariaceae	0	0	0	0	2	0	0	0
Solanaceae	1	0	0	1	0	1	0	0
Spore (monolete)	0	0	4	0	0	0	0	0
Spore (trilete)	0	0	8	0	0	0	0	0
Thymelaeaceae	2	0	0	4	2	1	0	2
Verbenaceae	0	0	0	0	0	0	0	0
Zygophyllaceae	0	0	0	0	0	0	0	0

Table F1 H2 raw pollen count (page 2/4).

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depth (cm)	380	400	420	460	520	530	540	560
Indeterminate	12	19	0	4	15	42	11	25
Unknown	1	12	0	0	5	0	0	11
Acacia (Mimosaceae)	1	1	0	0	2	1	0	2
Acanthaceae undiff.	1	0	0	3	8	0	5	6
Acanthaceae retic.	0	1	0	0	0	0	0	0
Aceraceae	0	0	2	0	0	0	1	0
Amaryllidaceae	0	0	0	0	0	1	0	0
Anacardiaceae	0	1	0	0	6	0	0	0
Apiaceae	0	0	0	5	6	1	2	2
Aster- 1	43	60	88	51	83	3	79	52
Aster - 2	4	0	1	10	1	6	7	3
Aster - 4	0	3	0	1	0	4	10	0
Bignoniaceae	2	0	0	2	0	1	5	0
Boraginaceae	0	0	0	0	0	6	0	0
Brassicaceae	0	2	0	0	0	0	1	0
Campanulaceae	0	0	0	0	0	0	0	0
Caryophyllaceae	14	26	23	28	37	1	34	30
Celastraceae	0	6	1	7	1	0	9	1
Chenopodiaceae/Amarantl	45	40	63	49	65	15	61	33
Convolvulaceae	0	0	0	0	1	1	0	0
Crassulaceae	0	1	0	0	0	0	3	0
Cruciferaceae	0	0	0	0	0	0	0	0
Cyperaceae	57	23	12	43	32	5	34	21
Ebenaceae	0	4	0	0	0	0	0	0
Ericaceae	2	0	0	1	0	0	0	3
Euphorbiaceae	12	8	14	4	1	0	3	6
Fabaceae - undiff.	0	1	0	0	0	0	0	0
Geraniaceae	0	0	0	3	0	1	3	1
Iridaceae	3	4	1	2	3	1	1	3
Juncaceae	13	10	0	14	0	2	2	0
Liliaceae	2	2	3	0	2	1	0	3
Malvaceae	5	3	1	1	3	1	0	0
Mesembryanthemaceae	3	4	2	5	0	1	5	0
Myrtaceae	0	2	0	0	0	0	0	0
Oleaceae	2	0	6	0	5	0	0	0
Orchidaceae	0	0	0	0	1	0	2	0
Pinaceae - undiff.	0	0	0	0	0	0	1	0
Plumbaginaceae	0	0	0	0	3	1	0	1
Poaceae undiff.	76	46	40	51	23	19	28	98
Podocarpus	0	0	0	0	0	0	0	0
Polygonaceae	0	0	1	0	0	4	4	5
Portulacaceae	0	5	0	0	1	6	0	0
Potamogeton	0	0	3	0	0	1	0	5
Restionaceae	17	35	37	26	34	0	2	19
Rosaceae	0	0	0	0	0	0	0	0
Rubiaceae	0	0	2	0	0	0	0	0
Rutaceae	0	1	2	0	7	2	0	2
Scrophulariaceae	1	0	0	0	0	0	0	0
Solanaceae	0	0	0	0	0	0	1	0
Spore (monolete)	0	0	0	0	0	0	0	0
Spore (trilete)	0	3	0	0	0	0	0	0
Thymelaeaceae	0	5	0	0	0	2	1	2
Verbenaceae	0	6	0	0	0	1	0	0
Zygophyllaceae	0	0	1	0	0	0	0	0

Table F1 H2 raw pollen count (page 3/4).

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depth (cm)	570	600
Indeterminate	2	12
Unknown	4	4
Acacia (Mimosac	0	0
Acanthaceae und	1	0
Acanthaceae reti	0	0
Aceraceae	1	0
Amaryllidaceae	0	0
Anacardiaceae	1	0
Apiaceae	2	0
Aster- 1	36	19
Aster - 2	3	0
Aster - 4	0	0
Bignoniaceae	6	1
Boraginaceae	0	0
Brassicaceae	3	2
Campanulaceae	0	0
Caryophyllaceae	55	13
Celastraceae	2	0
Chenopodiaceae/	58	12
Convolvulaceae	0	0
Crassulaceae	0	2
Cruciferaceae	0	0
Cyperaceae	37	5
Ebenaceae	0	0
Ericaceae	1	0
Euphorbiaceae	2	1
Fabaceae - undiff	1	0
Geraniaceae	1	0
Iridaceae	4	0
Juncaceae	3	4
Liliaceae	0	0
Malvaceae	3	0
Mesembryanthen	7	3
Myrtaceae	0	0
Oleaceae	0	0
Orchidaceae	0	0
Pinaceae - undiff.	0	0
Plumbaginaceae	1	0
Poaceae undiff.	50	26
Podocarpus	0	0
Polygonaceae	2	0
Portulacaceae	0	0
Potamogeton	0	1
Restionaceae	18	20
Rosaceae	0	0
Rubiaceae	0	0
Rutaceae	2	0
Scrophulariaceae	1	0
Solanaceae	6	0
Spore (monolete)	0	0
Spore (trilete)	0	0
Thymelaeaceae	2	0
Verbenaceae	1	0
Zygophyllaceae	0	0

depth (cm)	A30 (0cm)	A30 (10cm)	A49 (0 cm)	A49(10cm)
Indetermin	9	4	5	13
Unknown	4	2	3	0
Acacia (Mi	0	1	0	0
Acanthacea	2	1	5	5
Acanthacea	0	0	1	0
Aceraceae	0	1	0	0
Amaryllida	0	0	0	0
Anacardiac	1	0	0	0
Apiaceae	1	1	1	1
Aster- 1	104	61	86	88
Aster - 2	6	2	7	0
Aster - 4	4	0	0	0
Bignoniace	0	0	4	0
Boraginace	0	1	1	3
Brassicacea	0	1	5	0
Campanula	0	0	1	1
Caryophyll	20	19	30	23
Celastracea	1	2	1	2
Chenopodi	51	35	17	38
Convolvula	0	0	0	0
Crassulace	0	0	1	4
Cruciferac	0	0	1	1
Cyperaceae	25	31	33	51
Ebenaceae	1	2	0	1
Ericaceae	1	2	2	1
Euphorbiac	4	3	2	7
Fabaceae -	0	3	0	0
Geraniacea	0	0	4	2
Iridaceae	2	2	1	2
Juncaceae	3	31	15	8
Liliaceae	1	3	2	0
Malvaceae	14	9	0	3
Mesembrya	0	1	6	3
Myrtaceae	0	0	0	0
Oleaceae	1	1	6	2
Orchidacea	1	1	0	0
Pinaceae -	0	0	0	0
Plumbagina	0	0	0	0
Poaceae un	48	52	46	38
Podocarpus	1	0	0	1
Polygonace	1	0	6	0
Portulacace	6	0	1	1
Potamogeto	4	6	0	1
Restionacea	13	17	5	15
Rosaceae	0	0	0	0
Rubiaceae	0	4	0	0
Rutaceae	1	3	2	3
Scrophular	0	2	0	0
Solanaceae	0	1	0	3
Spore (mon	0	0	0	0
Spore (trile	0	0	0	0
Thymelaea	0	3	1	1
Verbenacea	0	0	0	0
Zygophylla	0	0	0	0

Table F1 H2 raw pollen count (page 4/4). Box core pollen count.

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depth (cm)	0	1	10	40	80	100	180	200	240	260	280	320	340
Indeterminate	18	5	32	18	0	48	25	10	31	4	21	9	44
Unknown	18	1	5	0	0	8	12	24	12	3	12	8	9
Acacia (Mimosaceae)	0	0	0	0	0	0	1	0	0	0	2	0	0
Acanthaceae undiff.	2	0	2	2	1	5	0	7	0	0	7	2	3
Acanthaceae retic.	0	0	0	0	0	0	0	0	0	0	0	0	0
Aceraceae	0	0	0	2	0	0	4	0	2	0	1	0	0
Anacardiaceae	0	0	0	0	0	4	2	0	1	1	2	1	0
Apiaceae	0	0	2	3	3	0	1	0	5	0	4	11	5
Aster- 1	115	8	121	92	63	118	51	26	73	71	77	109	58
Aster - 2	1	0	3	9	6	4	11	10	11	5	3	5	2
Aster - 4	0	0	3	0	1	3	1	34	0	1	3	0	0
Bignoniaceae	1	0	0	0	0	0	6	5	1	1	5	1	0
Boraginaceae	0	0	5	2	2	2	1	0	0	0	4	11	0
Brassicaceae	2	0	0	2	3	0	4	1	0	5	4	0	0
Campanulaceae	2	0	1	0	0	2	0	0	0	0	1	0	0
Caryophyllaceae	20	0	62	42	4	21	23	21	30	23	33	20	32
Celastraceae	0	0	1	0	0	1	10	0	2	0	4	0	0
Chenopodiaceae/Amaranthacea	27	4	63	90	48	48	39	78	34	29	44	47	34
Convolvulaceae	0	0	0	0	0	0	0	8	0	0	0	0	0
Crassulaceae	3	0	0	8	0	0	1	0	0	1	4	0	0
Cruciferaceae	0	0	0	0	0	0	0	0	0	0	0	0	0
Cucurbitaceae	0	0	2	0	0	1	0	0	0	0	0	0	0
Cupressaceae	0	0	0	0	0	0	0	5	0	0	0	0	0
Cyperaceae	9	0	2	14	3	9	38	16	26	35	25	18	19
Ebenaceae	0	0	0	4	0	2	0	1	0	0	0	3	0
Ericaceae	0	1	0	1	0	0	0	2	0	3	4	0	1
Euphorbiaceae	4	0	4	17	18	9	7	8	3	12	10	7	0
Fabaceae - undiff.	1	0	0	0	1	2	0	0	3	1	3	1	0
Geraniaceae	0	0	0	0	0	0	0	0	0	0	0	1	0
Iridaceae	3	0	1	0	0	2	0	0	0	2	4	0	1
Juncaceae	6	0	5	0	1	13	7	5	5	8	12	6	3
Liliaceae	4	0	2	0	1	6	0	0	0	0	2	0	1
Malvaceae	2	0	0	0	1	4	3	0	1	6	0	0	0
Mesembryanthemaceae	4	0	1	0	0	3	1	4	2	8	1	1	0

Table F2 H7 raw pollen count (page 1/4).

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Myrtaceae	0	0	0	0	0	0	0	0	0	0	0	0	0
depth (cm)	**0**	**1**	**10**	**40**	**80**	**100**	**180**	**200**	**240**	**260**	**280**	**320**	**340**
Oleaceae	2	1	0	4	0	1	0	4	2	0	7	2	0
Oliniaceae	0	0	0	0	0	0	0	0	0	0	0	0	0
Orchidaceae	0	0	0	0	0	0	1	0	0	1	1	3	0
Plumbaginaceae	2	0	1	0	0	0	0	0	0	0	1	0	2
Poaceae undiff.	34	0	15	18	29	74	56	40	45	45	46	24	27
Podocarpus	0	0	2	0	0	0	0	0	0	0	0	0	0
Polygalaceae	0	0	0	0	0	0	0	0	0	1	0	0	0
Polygonaceae	0	0	0	0	0	0	1	0	1	0	2	1	0
Portulacaceae	1	0	1	0	0	9	0	0	0	0	2	0	0
Potamogeton	10	0	3	0	0	0	0	0	0	7	1	8	2
Restionaceae	29	0	22	1	2	19	33	5	40	43	33	47	115
Rhamnaceae	0	0	2	0	0	0	0	0	0	0	0	0	0
Rosaceae	0	0	1	0	0	0	0	0	0	0	0	0	0
Rubiaceae	0	0	0	0	0	0	0	2	2	3	2	0	0
Rutaceae	2	0	7	0	0	3	1	0	1	0	0	6	3
Scrophulariaceae	0	0	0	0	0	0	0	21	0	0	0	0	0
Solanaceae	4	0	0	0	0	0	3	0	0	0	0	0	0
Spore (monolete)	0	0	0	0	0	4	0	5	0	0	0	0	0
Spore (trilete)	2	0	1	0	0	20	0	11	2	0	0	0	0
Thymelaeaceae	0	0	4	0	0	0	0	1	3	0	0	0	0
Tiliaceae	0	0	2	0	0	0	0	0	0	0	0	0	0
Verbenaceae	0	0	0	0	0	8	0	11	0	0	0	0	0
Zygophyllaceae	0	0	2	0	0	2	0	3	0	0	0	0	0

Table F2 H7 raw pollen count (page 2/4).

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depth (cm)	360	380	400	420	440	460	500	540	580	600	610
Indeterminate	6	35	0	0	105	20	56	14	17	0	7
Unknown	1	2	13	5	4	0	18	5	3	2	8
Acacia (Mimosaceae)	1	1	0	0	0	4	0	0	2	0	0
Acanthaceae undiff.	8	4	4	0	4	5	1	0	10	5	1
Acanthaceae retic.	0	0	0	0	0	0	0	11	0	0	0
Aceraceae	2	1	0	0	0	1	0	1	7	0	0
Anacardiaceae	1	0	0	0	11	2	2	2	0	0	0
Apiaceae	3	2	1	3	11	3	0	2	4	2	1
Aster- 1	52	49	48	51	92	41	128	61	54	37	30
Aster - 2	1	5	6	9	8	2	0	1	5	0	3
Aster - 4	0	6	0	2	0	3	7	4	6	0	0
Bignoniaceae	3	1	6	0	0	6	3	0	7	0	1
Boraginaceae	5	2	1	0	0	2	2	1	0	3	0
Brassicaceae	0	1	0	1	1	2	0	1	9	0	0
Campanulaceae	0	1	0	0	2	0	0	0	1	0	0
Caryophyllaceae	15	22	1	24	28	23	38	34	17	7	5
Celastraceae	1	11	1	0	0	5	5	0	11	0	0
Chenopodiaceae/Amaranthacea	21	32	72	27	49	26	33	23	39	9	11
Convolvulaceae	0	0	0	0	0	0	2	0	0	0	0
Crassulaceae	1	2	0	0	0	2	4	0	6	0	0
Cruciferaceae	0	0	0	1	0	1	0	0	0	0	0
Cucurbitaceae	0	0	0	0	0	0	0	0	0	0	0
Cupressaceae	0	0	0	0	0	0	0	0	0	0	0
Cyperaceae	10	45	31	24	13	25	12	36	26	5	1
Ebenaceae	5	0	6	6	0	5	22	5	1	4	0
Ericaceae	0	1	0	1	2	1	0	2	7	0	1
Euphorbiaceae	8	7	3	9	2	4	4	4	6	0	1
Fabaceae - undiff.	0	0	0	2	0	1	2	0	0	0	0
Geraniaceae	0	1	0	1	0	1	1	2	1	0	0
Iridaceae	1	5	1	5	21	0	1	2	4	0	0
Juncaceae	0	5	8	11	0	10	1	2	0	0	4
Liliaceae	0	3	1	6	6	1	14	1	3	1	0
Malvaceae	1	0	0	5	2	0	16	0	0	1	0
Mesembryanthemaceae	0	3	2	0	0	1	2	66	1	0	1

Table F2 H7 raw pollen count (page 3/4).

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Myrtaceae	0	0	0	0	0	0	0	1	0	0	0
depth (cm)	**360**	**380**	**400**	**420**	**440**	**460**	**500**	**540**	**580**	**600**	**610**
Oleaceae	2	0	3	0	11	4	1	0	0	0	1
Oliniaceae	1	0	0	0	0	4	0	0	0	0	0
Orchidaceae	1	1	0	1	0	1	2	0	3	0	0
Plumbaginaceae	0	0	0	0	1	0	0	0	0	0	1
Poaceae undiff.	41	41	39	42	16	54	26	62	28	22	24
Podocarpus	0	0	1	0	0	0	0	1	0	0	0
Polygalaceae	0	0	0	0	0	0	1	0	0	0	0
Polygonaceae	0	0	1	0	0	0	3	0	1	0	0
Portulacaceae	0	0	0	2	6	5	2	0	3	0	0
Potamogeton	5	0	6	0	1	11	0	2	0	0	4
Restionaceae	24	45	23	44	25	45	2	27	28	1	10
Rhamnaceae	0	0	0	0	0	0	0	0	0	0	0
Rosaceae	0	0	0	0	0	1	0	0	0	1	0
Rubiaceae	1	0	1	3	0	2	1	0	0	0	0
Rutaceae	1	4	3	0	7	0	3	3	2	0	1
Scrophulariaceae	1	0	3	2	0	0	0	0	2	0	0
Solanaceae	2	2	0	1	0	2	5	0	0	0	0
Spore (monolete)	0	0	0	0	0	0	6	0	0	0	0
Spore (trilete)	0	0	1	10	0	0	0	0	0	0	0
Thymelaeaceae	0	0	0	0	0	1	2	1	4	0	0
Tiliaceae	0	0	0	0	0	0	0	0	0	0	0
Verbenaceae	0	1	0	4	0	0	1	1	0	0	0
Zygophyllaceae	0	0	0	0	0	0	0	0	0	0	0

Table F2 H7 raw pollen count (page 4/4).

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depth (cm)	% A30 (0)	% (A30 (10)	% A49 (0)	% A49 (10)
Indetermin	3	1	2	4
Unknown	1	1	1	0
Acacia (Mi	0	0	0	0
Acanthacea	1	0	2	2
Acanthacea	0	0	0	0
Aceraceae	0	0	0	0
Amaryllida	0	0	0	0
Anacardiac	0	0	0	0
Apiaceae	0	0	0	0
Aster- 1	32	20	29	27
Aster - 2	2	1	2	0
Aster - 4	1	0	0	0
Bignoniace	0	0	1	0
Boraginace	0	0	0	1
Brassicacea	0	0	2	0
Campanula	0	0	0	0
Caryophyll	6	6	10	7
Celastracea	0	1	0	1
Chenopodia	15	11	6	12
Convolvula	0	0	0	0
Crassulace	0	0	0	1
Cruciferac	0	0	0	0
Cyperaceae	8	10	11	16
Ebenaceae	0	1	0	0
Ericaceae	0	1	1	0
Euphorbiac	1	1	1	2
Fabaceae -	0	1	0	0
Geraniacea	0	0	1	1
Iridaceae	1	1	0	1
Juncaceae	1	10	5	2
Liliaceae	0	1	1	0
Malvaceae	4	3	0	1

Box cores

depth (cm)	% (0 cm)	% (10 cm)
Indetermin	3	5
Unknown	5	6
Acacia (Mi	1	0
Acanthacea	0	1
Acanthacea	0	0
Aceraceae	3	0
Amaryllida	0	0
Anacardiac	0	1
Apiaceae	0	0
Aster- 1	9	13
Aster - 2	0	2
Aster - 4	0	0
Bignoniace	0	0
Boraginace	0	0
Brassicacea	1	1
Campanula	0	0
Caryophyll	9	2
Celastracea	5	1
Chenopodia	2	2
Convolvula	0	0
Crassulace	2	1
Cruciferac	0	0
Cyperaceae	3	5
Ebenaceae	0	0
Ericaceae	1	0
Euphorbiac	0	2
Fabaceae -	1	0
Geraniacea	0	0
Iridaceae	0	0
Juncaceae	1	3
Liliaceae	0	1
Malvaceae	6	1

H2 (gravity core)

depth (cm)	% (0 cm)	% (10 cm)
Indetermin	5	10
Unknown	5	2
Acacia (Mi	0	0
Acanthacea	1	1
Acanthacea	0	0
Aceraceae	0	0
Anacardiac	0	0
Apiaceae	0	1
Aster- 1	35	37
Aster - 2	0	1
Aster - 4	0	1
Bignoniace	0	0
Boraginace	0	2
Brassicacea	1	0
Campanula	1	0
Caryophyll	6	19
Celastracea	0	0
Chenopodia	8	19
Convolvula	0	0
Crassulace	1	0
Cruciferac	0	0
Cucurbitac	0	1
Cupressace	0	0
Cyperaceae	3	1
Ebenaceae	0	0
Ericaceae	0	0
Euphorbiac	1	1
Fabaceae -	0	0
Geraniacea	0	0
Iridaceae	1	0
Juncaceae	2	2
Liliaceae	1	1

H7 (gravity core)

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Table F3 Box core, H2 and H7 pollen count as a relative perentage. (page 1/2).

depth (cm)	% A30 (0)	% (A30 (10)	% A49 (0)	% A49 (10)
Mesembrya	0	0	2	1
Myrtaceae	0	0	0	0
Oleaceae	0	0	2	1
Orchidacea	0	0	0	0
Pinaceae -	0	0	0	0
Plumbagina	0	0	0	0
Poaceae un	15	17	15	12
Podocarpus	0	0	0	0
Polygonace	0	0	2	0
Portulacace	2	0	0	0
Potamogeto	1	2	0	0
Restionacea	4	6	2	5
Rosaceae	0	0	0	0
Rubiaceae	0	1	0	0
Rutaceae	0	1	1	1
Scrophular	0	1	0	0
Solanaceae	0	0	0	1
Spore (mon	0	0	0	0
Spore (trile	0	0	0	0
Thymelaeac	0	1	0	0
Verbenacea	0	0	0	0
Zygophylla	0	0	0	0

Box cores

depth (cm)	% (0 cm)	% (10 cm)
Mesembrya	0	0
Myrtaceae	0	0
Oleaceae	0	0
Orchidacea	0	0
Pinaceae -	0	0
Plumbagina	0	0
Poaceae un	21	27
Podocarpus	0	0
Polygonace	0	0
Portulacace	0	0
Potamogeto	0	2
Restionacea	24	25
Rosaceae	0	0
Rubiaceae	0	0
Rutaceae	0	0
Scrophular	0	0
Solanaceae	0	0
Spore (mon	0	0
Spore (trile	0	0
Thymelaeac	0	0
Verbenacea	0	0
Zygophylla	0	0

H2 (gravity core)

depth (cm)	% (0 cm)	% (10 cm)
Malvaceae	1	0
Mesembrya	1	0
Myrtaceae	0	0
Oleaceae	1	0
Oliniaceae	0	0
Orchidacea	0	0
Plumbagina	1	0
Poaceae un	10	5
Podocarpus	0	1
Polygalacea	0	0
Polygonace	0	0
Portulacace	0	0
Potamogeto	3	1
Restionacea	9	7
Rhamnacea	0	1
Rosaceae	0	0
Rubiaceae	0	0
Rutaceae	1	2
Scrophular	0	0
Solanaceae	1	0
Spore (mon	0	0
Spore (trile	1	0
Thymelaeac	0	1
Tiliaceae	0	1
Verbenacea	0	0
Zygophylla	0	1

H7 (gravity core)

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Table F3 Box core, H2 and H7 pollen count as a relative perentage. (page 2/2).

	A30 (0)	A30 (10)	A49 (0)	A49 (10)	H2 (0)	H2 (10)	H7 (0)	H7 (10)
Aster- 1	32	20	29	27	9	13	35	37
Cary	6	6	10	7	9	2	6	19
Cheno	15	11	6	12	2	2	8	19
Cyp	8	10	11	16	3	5	3	1
Euphorb	1	1	1	2	0	2	1	1
Poaceae	15	17	15	12	21	27	10	5
Restio	4	6	2	5	24	25	9	7

Table F4 Box and gravity core data showing 7 main pollen types as relative percentage.

	WT POT (%)	WT13#4 (%)	WT13#5 (%)
Aster1	42	37	30
Aster2	1	0	0
Cary	7	9	9
Euph	9	2	2
Poa	30	44	50
Rest	11	7	9

Table F5 Modern Orange River pollen count as a relative perentage.

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HODSA	SIX/SURF	JKB/L2	JKBO/DROL
Indeterminable	90	132	0
Acacia (Fabaceae)	0	0	118
Acanthaceae Undiff	3	0	0
Acanthaceae Reticulate	1	0	0
Anacardiaceae	1	0	0
Asteraceae - 1 Asteroideae	16	0	0
Campanulaceae	2	0	10
Caryophyllaceae	6	2	0
Chenopodiaceae/ Amaranthaceae - undiff.	97	2	35
Cyperaceae	13	0	71
Ebenaceae	3	1	3
Fabaceae - undiff.	0	1	0
Iridaceae	3	0	0
Liliaceae	3	0	0
Poaceae Undiff.	38	0	0
Restionaceae	9	0	6
Rutaceae	2	0	4
Spore (monolete)	0	5	0
Spore (trilete)	4	0	3
Thymelaeaceae	2	0	0
Total	293	143	132

Table F6 Raw pollen counts: Various Richtersveld samples: Lower Xobies surface (SIX/SURF), Jakkalsberg L2 (JKB L2) and JKBO/DROL.

H2 Depth (cm)	H7 Depth (cm)
0	20
60	60
200	120
240	140
280	160
320	220
340	300
440	480
480	520
580	560

Table F7 Samples found to be inert (pollen) in gravity cores, H2 and H7. Depth indicated in cm.

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HODSA	WT POT	WT13#3	WT13#4
Indeterminable	0	0	0
Unknown	0	0	1
Acanthaceae Undiff	0	9	0
Acanthaceae Reticulate	3	0	2
Aceraceae	2	0	1
Anacardiaceae	7	5	11
Apiaceae	2	2	7
Asteraceae - 1	79	76	48
Asteraceae - 2	1	1	0
Bignoniaceae	8	3	3
Campanulaceae	0	0	3
Caryophyllaceae	14	18	15
Celastraceae	0	5	2
Chenopodiaceae/Amaranthac	8	23	24
Convolvulaceae	1	0	0
Crassulaceae	1	4	1
Cyperaceae	31	16	33
Ebenaceae	1	3	0
Ericaceae	1	1	0
Euphorbiaceae	17	5	4
Fabaceae - undiff.	0	3	2
Geraniaceae	2	2	1
Iridaceae	1	1	1
Juncaceae	4	5	8
Liliaceae	4	1	0
Malvaceae	0	2	3
Mesembryanthemaceae	0	6	12
Oleaceae	2	0	0
Orchidaceae	1	0	0
Plumbaginaceae	1	1	2
Poaceae Undiff.	56	90	80
Polygonaceae	1	3	6
Portulacaceae	0	1	0
Potamogeton - type	6	1	8
Restionaceae	20	14	14
Rhamnaceae	3	0	9
Rosaceae	0	0	4
Rubiaceae	3	1	4
Rutaceae	4	11	3
Solanaceae	0	0	5
Thymelaeaceae	0	2	0

Table F8 Table of modern Orange River sediment pollen - raw count

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	Aster 1	Aster2	Cary	Euph	Poa	Rest
H2-0	15	0	15	0	33	38
H2-10	18	3	3	3	38	36
H2-20	44	0	20	1	27	7
H2-40	24	1	10	1	25	39
H2-80	39	1	11	1	29	19
H2-100	35	2	13	2	10	39
H2-120	23	1	8	1	55	11
H2-140	36	0	12	2	24	26
H2-160	24	1	5	1	52	17
H2-180	23	0	7	1	56	13
H2-190	27	0	6	0	11	56
H2-220	28	0	5	2	36	29
H2-230	35	1	18	2	27	18
H2-260	31	0	16	2	45	6
H2-300	21	1	5	2	27	43
H2-360	36	4	14	2	41	4
H2-380	26	2	8	7	46	10
H2-400	34	0	15	5	26	20
H2-420	43	0	11	7	20	18
H2-460	30	6	16	2	30	15
H2-520	46	1	21	1	13	19
H2-530	10	21	3	0	66	0
H2-540	52	5	22	2	18	1
H2-560	25	1	14	3	47	9
H2-570	22	2	34	1	30	11
H2-600	24	0	16	1	33	25
H7-0	57	0	10	2	17	14
H7-1	100	0	0	0	0	0
H7-10	53	1	27	2	7	10
H7-40	51	5	23	9	10	1
H7-80	52	5	3	15	24	2
H7-100	48	2	9	4	30	8

Table F9 DCA Detrended Correspondence Analysis (page 1/2).

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H7-180	28	6	13	4	31	18
H7-200	24	9	19	7	36	5
H7-240	36	5	15	1	22	20
H7-260	36	3	12	6	23	22
H7-280	38	1	16	5	23	16
H7-320	51	2	9	3	11	22
H7-340	25	1	14	0	12	49
H7-360	37	1	11	6	29	17
H7-380	29	3	13	4	24	27
H7-400	40	5	1	3	33	19
H7-420	28	5	13	5	23	25
H7-440	54	5	16	1	9	15
H7-460	24	1	14	2	32	27
H7-500	65	0	19	2	13	1
H7-540	32	1	18	2	33	14
H7-580	39	4	12	4	20	20
H7-600	55	0	10	0	33	1
H7-610	41	4	7	1	33	14
WTPOT	42	1	7	9	30	11
WT13#4	37	0	9	2	44	7
WT13#5	30	0	9	2	50	9

Table F9 DCA Detrended Correspondence Analysis (page 2/2). This data used for DCA, PCA in 'PAST' statistical package.

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Treatment of raw pollen data for statistical analysis (DCA, PCA):

- 6 families of pollen identified for statistical analysis
- 26 x H2 samples
- 24 x H7 samples
- 3 x modern pollen samples
- 53 samples plotted on PCA
- all converted to relative %
- fluvial influences removed
- removed 5% or less pollen representatives (anywhere in the assemblage)
- re-scaled %, thus producing a relative %. Therefore calculate a correlation not a co-variance due to re-scaling.

	Axis 1	Axis 2	Axis 3
Aster1	1.81E-50	0.41674	0.57918
Aster2	0.81914	2.8414	1.5396
Cary	0.96364	0.13236	-1.171
Euph	0.2555	0.86578	3.1992
Poa	1.4728	1.7239	0.28021
Rest	2.2697	-0.55374	1.1261
H2-0	1.4783	0.43648	0.42732
H2-10	1.4237	0.63956	0.71598
H2-20	0.75941	0.65171	0.20921
H2-40	1.3605	0.36535	0.5785
H2-80	0.97511	0.60889	0.43967
H2-100	1.1676	0.19173	0.60638
H2-120	1.1591	1.0412	0.36859
H2-140	1.0643	0.453	0.49199
H2-160	1.2106	0.94602	0.46498
H2-180	1.1898	1.0072	0.38654
H2-190	1.4909	-4.43E-14	0.74753
H2-220	1.2417	0.60065	0.59503
H2-230	0.98313	0.57545	0.3462
H2-260	0.95823	0.91023	0.24983
H2-300	1.4496	0.37093	0.70941
H2-360	0.85883	0.97445	0.32679
H2-380	1.0261	0.98385	0.55873
H2-400	0.99419	0.54231	0.4793

Table F10 CA Scores (page 1/2).

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H2-420	0.83535	0.50452	0.60901
H2-460	1.0007	0.77588	0.39972
H2-520	0.82755	0.37175	0.31513
H2-530	1.173	1.7801	0.53104
H2-540	0.54587	0.70998	0.24622
H2-560	1.0578	0.94699	0.32856
H2-570	1.0381	0.65844	-6.29E-14
H2-600	1.2224	0.56598	0.36123
H7-0	0.66961	0.48364	0.4823
H7-1	0	0.41674	0.57918
H7-10	0.60355	0.36764	0.2024
H7-40	0.46017	0.63619	0.43459
H7-80	0.50203	0.88642	0.90364
H7-100	0.72945	0.7686	0.50052
H7-180	1.0498	0.77376	0.51984
H7-200	0.91839	1.0344	0.4362
H7-240	0.97578	0.59508	0.43301
H7-260	0.97414	0.56645	0.60618
H7-280	0.88591	0.5648	0.45728
H7-320	0.78788	0.38272	0.60746
H7-340	1.4178	0.085811	0.57588
H7-360	0.93315	0.64844	0.55993
H7-380	1.1264	0.52217	0.56117
H7-400	0.96587	0.79184	0.69241
H7-420	1.0961	0.58316	0.59883
H7-440	0.67071	0.46904	0.4285
H7-460	1.2323	0.56643	0.44815
H7-500	0.40236	0.53192	0.26565
H7-540	0.99054	0.69429	0.30406
H7-580	0.91629	0.5664	0.56178
H7-600	0.61119	0.81395	0.30826
H7-610	0.90656	0.79382	0.49918
WTPOT	0.79015	0.7469	0.67254
WT13#4	0.90782	0.91232	0.37879
WT13#5	1.0325	0.96638	0.3738

	Eigenvalue
Axis 1	0.1179
Axis 2	0.07839
Axis 3	0.02789
Axis 4	0.01764

Table F10 CA Scores relating to Figures 6.8 and 6.9 using PAST statistical package (page 2/2).

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PC	Eigenvalue	% variance
1	36.5524	69.88
2	7.68695	14.696
3	6.35917	12.157
4	1.48735	2.8435
5	0.221323	0.42312
6	5.37E-11	1.03E-10
7	1.49E-11	2.84E-11
8	1.12E-11	2.15E-11
9	7.16E-12	1.37E-11
10	1.80E-12	3.44E-12
11	1.10E-12	2.10E-12
12	8.55E-13	1.63E-12
13	6.85E-13	1.31E-12
14	4.69E-13	8.97E-13
15	4.13E-13	7.89E-13
16	3.40E-13	6.50E-13
17	2.67E-13	5.11E-13
18	2.33E-13	4.45E-13
19	2.27E-13	4.34E-13
20	1.71E-13	3.26E-13
21	1.43E-13	2.72E-13
22	1.23E-13	2.35E-13
23	1.06E-13	2.04E-13
24	9.64E-14	1.84E-13
25	6.40E-14	1.22E-13
26	5.95E-14	1.14E-13
27	5.13E-14	9.81E-14
28	3.99E-14	7.63E-14
29	2.47E-14	4.72E-14
30	5.93E-15	1.13E-14
31	-1.86E-15	-3.55E-15
32	-5.44E-15	-1.04E-14
33	-1.61E-14	-3.08E-14

Table F11 PCA correlation matrix (1/2).

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34	-2.51E-14	-4.80E-14
35	-3.49E-14	-6.67E-14
36	-5.00E-14	-9.56E-14
37	-6.30E-14	-1.20E-13
38	-7.28E-14	-1.39E-13
39	-8.19E-14	-1.57E-13
40	-1.16E-13	-2.22E-13
41	-1.60E-13	-3.07E-13
42	-1.82E-13	-3.48E-13
43	-2.12E-13	-4.06E-13
44	-3.17E-13	-6.07E-13
45	-3.86E-13	-7.37E-13
46	-5.17E-13	-9.88E-13
47	-6.17E-13	-1.18E-12
48	-7.63E-13	-1.46E-12
49	-9.60E-13	-1.84E-12
50	-1.88E-12	-3.59E-12
51	-5.55E-12	-1.06E-11
52	-1.20E-11	-2.29E-11
53	-3.44E-11	-6.59E-11

	Axis 1	Axis2	Axis3	Axis 4	Axis 5	Axis6
Aster1	8.429	3.8788	0.52303	-0.55948	-0.05219	-1.16E-1
Aster2	-6.4834	0.31096	0.98536	-0.65446	-0.75323	1.51E-11
Cary	-1.7272	0.86316	0.62146	2.4116	0.061635	2.63E-12
Euph	-6.0951	0.64554	0.8996	-0.91582	0.72956	5.91E-13
Poa	5.4161	-4.5661	2.0043	-0.16427	0.020804	-1.33E-1
Rest	0.46071	-1.1323	-5.0338	-0.11758	-0.00659	4.54E-12

Table F11 PCA correlation matrix (not co-variance) of H2, H7 and inland Orange River data (page 2/2).

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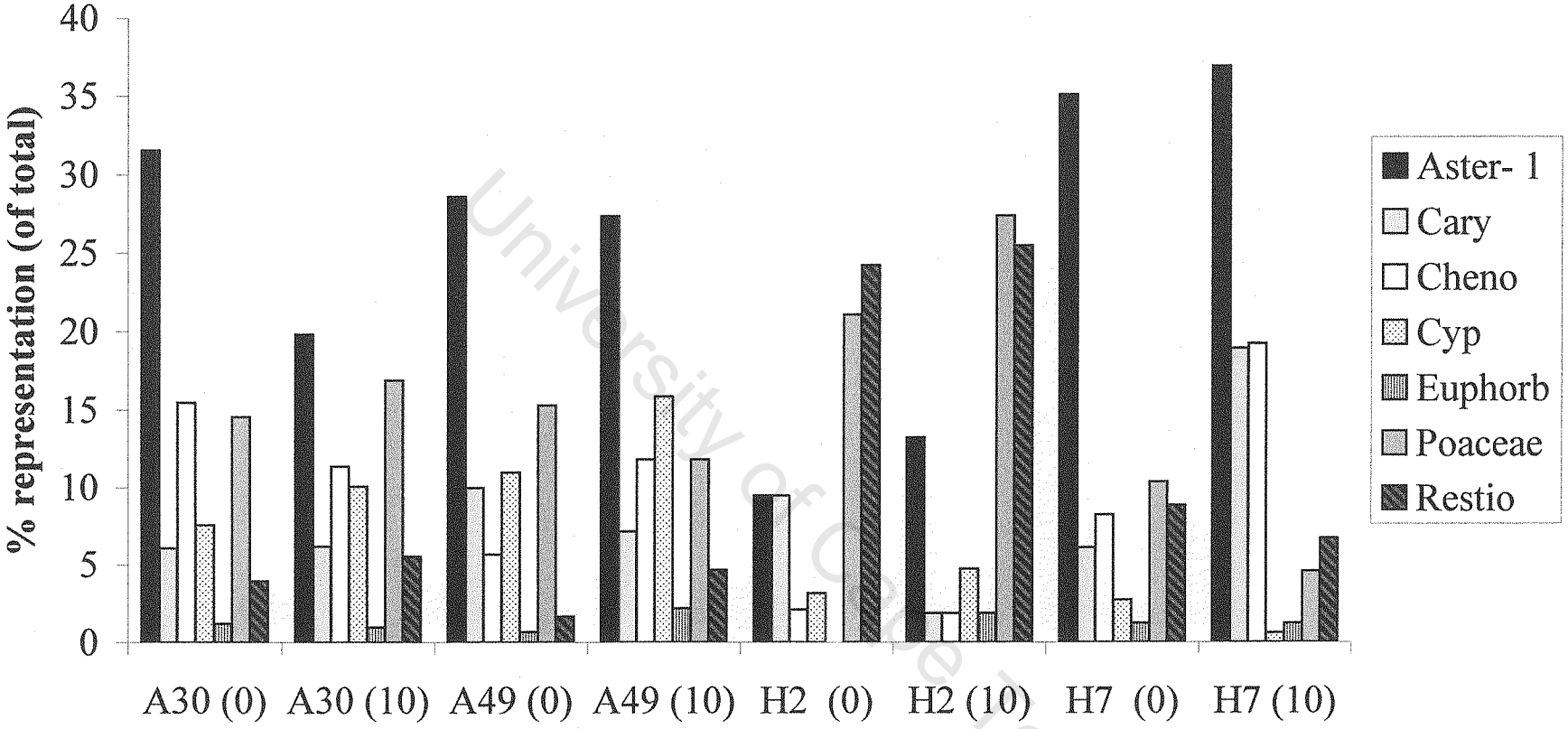

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Figure F1 Histogram comparing box and gravity core data at depths of 0 cm and 10cm for 7 main pollen types as a relative percentage.

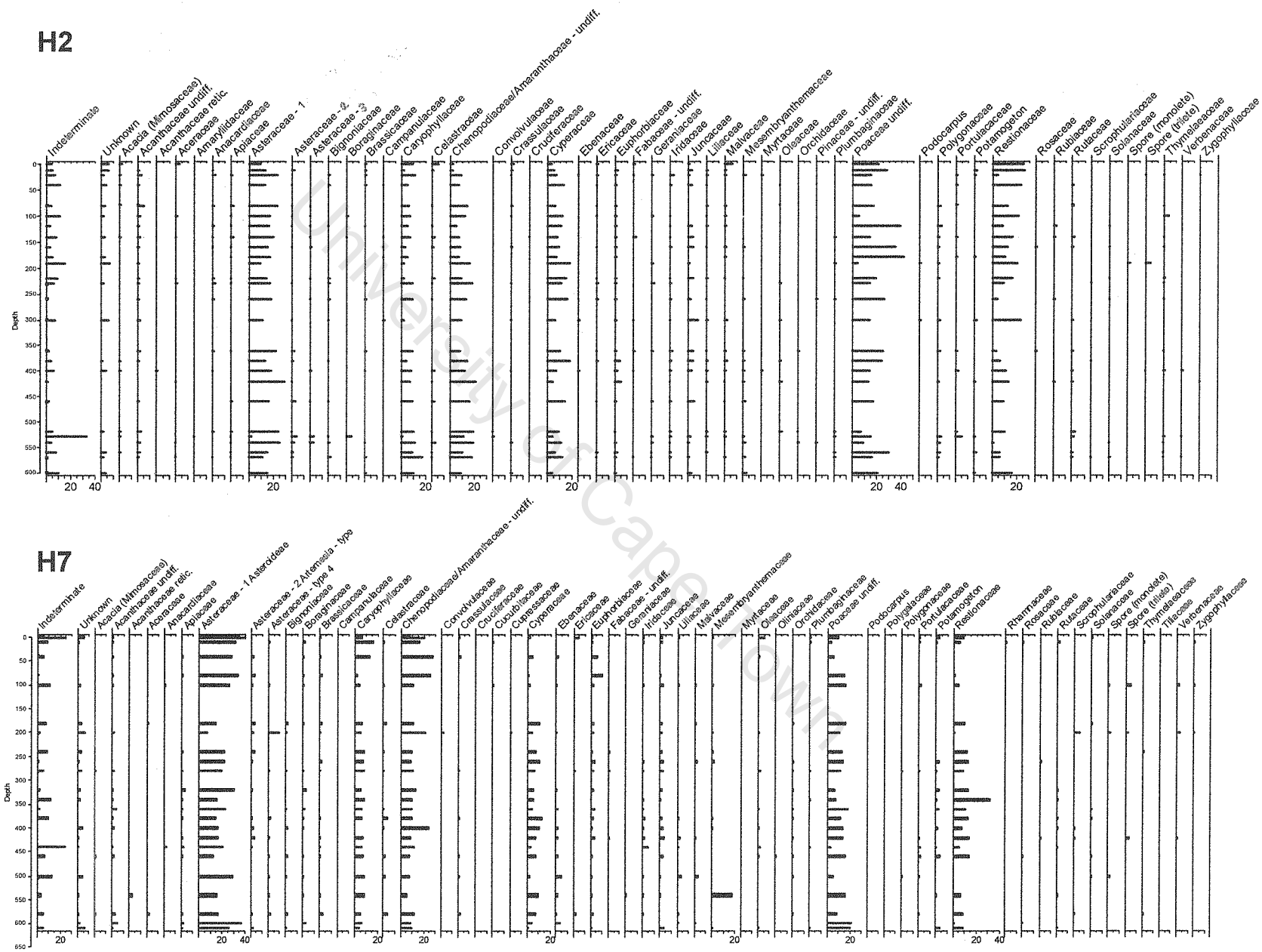

Figure F2 Pollen Diagram histogram of Namaqualand Mudbelt off Orange River (H2, top) and Buffels River (H7, below).

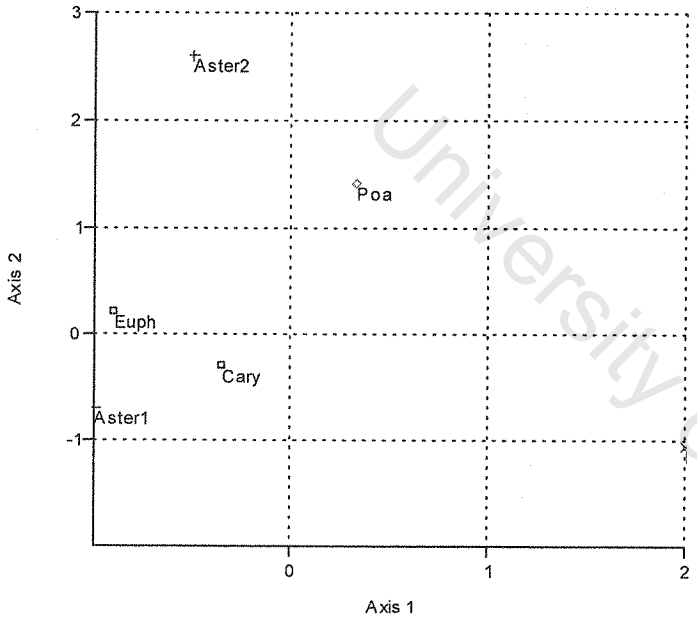

Figure F3 Correspondence Analysis (no detrending) scores for Axis 1 and 2.

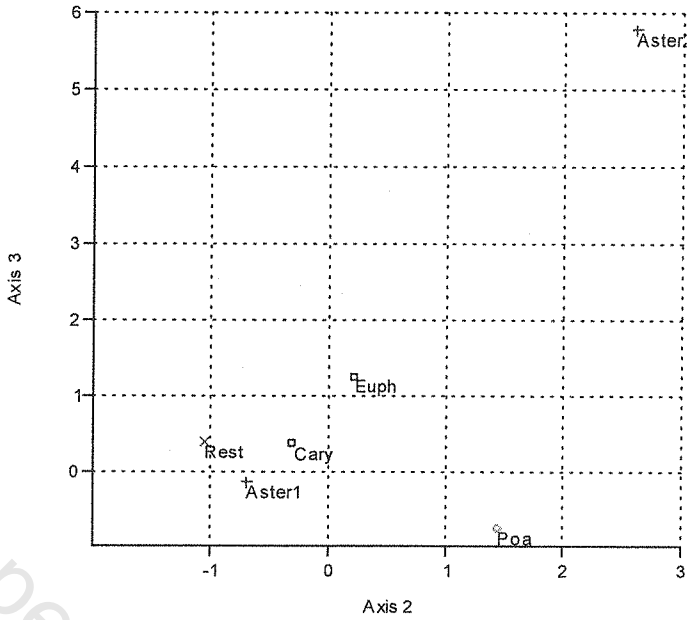

Figure F4 Correspondence Analysis (no detrending) scores for Axis 2 and 3.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMS	- Accelerator Mass Spectrometry
BLD	- Bloeddrift, Richtersveld
BRC	- Buffels River Catchment, West Coast
CAM	- Crassulacean Acid Metabolism (photosynthetic pathway)
CSIR	- Council for Scientific and Industrial Research (South Africa)
DCA	- Detrended Correspondence Analysis
DWAF	- Department of Water Affairs and Forestry (South Africa)
ENSO	- El Niño and the Southern Oscillation
HODSA	- Holocene Denudation of South Africa (research group)
IRSL	- Infrared-stimulated Luminescence
JKB	- Jakkalsberg, Richtersveld
LGM	- Last Glacial Maximum
LOI	- Loss on ignition
LX	- Lower Xobies, Richtersveld
OES	- Ostrich egg shell
OM	- Organic matter
OR	- Orange River
ORC	- Orange River Catchment
ORM	- Orange River Mouth
OSL	- Optically Stimulated Luminescence
PCA	- Principal Component Analysis
PDB	- Pee Dee Belemnite Marine carbonate standard
SELUCSA	- Soil Erosion and Land Use Change in South Africa (research group)
SEM	- Scanning electron microscope
SST	- Sea Surface Temperature
TOC	- Total organic carbon
UCT	- University of Cape Town
WT	- Modern Orange River samples analysed in this thesis

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