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The fluvial history of the lower Vaal River catchment

Ryan James Gibbon

A thesis submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2009

Declaration

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this __ day of _____ 20__

_____

Ryan James Gibbon

Abstract

Cosmogenic nuclide burial dating was used to determine the age of ancient alluvial terrace deposits in the lower Vaal River catchment, and thus provide an absolute fluvial chronology. A poor chronological framework has been the primary shortcoming of previous fluvial history studies as there was no accurate way to evaluate or correlate the proposed driving mechanisms with the fluvial events themselves. Cosmogenic nuclide burial dating has shown that there have been three periods, each of both river incision and alluvial gravels and fines aggradation, in the Pliocene. Burial dating determined that periods of bedrock incision have occurred relatively rapidly over short periods of time, following lengthy periods of net aggradation. It has been proposed that the lower Vaal River catchment provided the ideal situation for rapid bedrock incision to proceed sporadically. The Vaal River in its lower reaches is largely confined to pre-Karoo valleys that are filled with soft, easily erodible Karoo rocks. When these rocks are at least partially exposed along the river channel/valley, rapid bedrock erosion and incision occurs through the action of saltating resistant clasts abrading the channel. It has been argued that these incision events occur only when suitable climatic conditions develop that allow for the complete erosion of alluvial gravel deposits lining the Vaal River channel/valley (i.e. frequent and large formative discharges are needed to achieve this). Periods of gravel aggradation have been attributed to an increase in coarse sediment supply, primarily through the erosion of older alluvial deposits in the valley during periods of reduced vegetation cover. Periods of fine sediment aggradation are the net result of a reduction in the capacity of formative discharges, a direct result of a drying climate. It is thus apparent that climate change has played the most important role in controlling the fluvial evolution of the Vaal River.

Climate controls fluvial events by determining the Vaal River's net transport ability. Various combinations of changes in transport and erosion potentials, in both the river and surrounding landscape, have resulted in varying fluvial outcomes. In conclusion, the fluvial evolution of the lower Vaal River catchment is unique due to a number of aspects. The structure of the pre-Karoo surface and readily available resistant clasts from older terrace deposits and tillite, in conjunction with climate change, have proved crucial in shaping the Vaal River's fluvial history.

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Chapter 1

Introduction

A geochronological and geomorphological study was conducted into the fluvial history of the lower Vaal River catchment (see Figure 2.1 for the location of the study area). Research focused on the fluvial remnants preserved within the lowermost 300 kilometres of the Vaal River valley, where the deposits have been extensively exposed by diamond mining operations. The aim of this study was to provide an absolute chronology for the alluvial terrace deposits through the application of cosmogenic nuclide burial dating (Granger & Muzikar 2001). With the establishment of an absolute chronology, consideration could then be given to achieving an improved understanding of the processes driving the Vaal River's fluvial evolution.

The ancient alluvial terrace deposits of the lower Vaal River have long been the focus of research due to the diamonds, fossils and Stone Age artefacts contained within them (van Riet Lowe 1937, Cooke 1949, van Riet Lowe 1952*b*, Partridge & Brink 1967, Butzer *et al.* 1973, Helgren 1977*a*, Helgren 1977*b*, Helgren 1978, Helgren 1979). See Helgren (1979) and de Wit *et al.* (2000) for a summary of research to date. The fluvial history models which have come out of these studies have, however, been debated largely due to the poor chronological framework for the fluvial events (Partridge & Brink 1967, Helgren 1979). Absolute dating techniques have been unavailable, and dating using the very sparse fauna contained within these deposits is fraught with difficulties and imprecision (Helgren 1977*b*). Without absolute ages for the various terrace deposits, or even an idea of the time that each deposit may

represent, conclusions could only remain tentative.

In terms of the various fluvial history models, there has been debate over the years as to the factors which led to the formation and preservation of the various fluvial deposits within the lower Vaal River valley, and thus about the geomorphic history of the Vaal River catchment. Climatic factors have dominated the interpretations (van Riet Lowe 1952*b*, Helgren 1979), while others have abandoned climatic explanations in favour of other geomorphic processes such as tectonics, river capture, variable lithologies and the cyclic passage of knickpoints (Partridge & Brink 1967). All these studies have suffered from the poor chronological framework, as the timing of the proposed driving mechanisms could not be correlated with any certainty to the fluvial events themselves. A direct comparison between climatic changes, tectonic processes, and the sequence of fluvial events or major features of the deposits, was simply not possible.

A key component of the current study was thus to provide an absolute chronology of the preserved deposits. Several key localities containing representative deposits were dated using *in situ* cosmogenic nuclides (Granger & Muzikar 2001). With an absolute chronology, previous conclusions on the stratigraphy, and associations between the various deposits, could be reassessed and augmented. This is essential as a complete understanding of the deposits, within both space and time, is needed before one can draw conclusions about ancient geomorphic environments or processes driving the Vaal River's fluvial evolution.

Cosmogenic nuclide burial dating was used to determine the age of terrace deposits. This dating technique is based on the relative radioactive decay of ^{26}Al and ^{10}Be produced in quartz grains by exposure to secondary cosmic rays near the ground surface prior to burial (Granger & Muzikar 2001). Subsequent to burial, the quartz is shielded from cosmic radiation, and radioactive decay lowers the ^{26}Al/^{10}Be ratio over time (Granger & Muzikar 2001). The key to burial dating is that production rates of ^{26}Al and ^{10}Be decline rapidly beneath

the surface (Granger & Muzikar 2001). If samples are deeply buried then further production of cosmogenic nuclides effectively ceases. The inherited ^{26}Al and ^{10}Be within the quartz then decay. Because ^{26}Al has a shorter half-life than ^{10}Be, the ratio ^{26}Al/^{10}Be decreases exponentially over time. The measured ^{26}Al/^{10}Be ratio thus indicates the time at which the quartz was buried (Granger *et al.* 2001).

This absolute dating technique was initially used to date cave-deposited river sediments (Granger *et al.* 1997). Caves provided the ideal situation for burial dating as once the sediment had been washed into the cave the overlying rock provided complete shielding, preventing further production of the two radionuclides. Subsequent radioactive decay of the ^{26}Al and ^{10}Be allowed for an age determination of when sediment was washed into the cave. With all-around improvements in the dating technique in the subsequent years, such as advances in constraining production rates in shallowly buried sediments (for a complete summary see Chapter 3), it is now possible to date open air alluvial terrace deposits of only five metres in thickness. The burial age obtained provides the time at which the alluvial deposit was aggraded. Cosmogenic nuclide burial dating thus provides a means to date alluvial deposits that are beyond the range of dating techniques such as radio carbon and luminescence dating. The range of burial dating is roughly two hundred thousand to five million years (Granger & Muzikar 2001) making it ideal for the old terrace deposits along the lower Vaal River catchment, which are beyond the age limits of the younger dating techniques.

In the current study, burial dating of the ancient deposits along the lower Vaal River has provided an accurate chronology of fluvial events over the Pliocene. The absolute chronology is markedly different from previous ones based on faunal estimates. The determined chronology provided a means to compare and evaluate previously proposed driving mechanisms to the sequence of fluvial events and major features of the deposits. It is proposed that climate change has played the most important role in controlling the fluvial evolution of the lower Vaal River. Conclusions of the present study differ from those of the previous studies in many ways. This is due to both the determined absolute

chronological framework and a much improved palaeoclimatic record for the Pliocene, allowing for an improved understanding of the processes driving the Vaal River's fluvial evolution. It is concluded that the fluvial evolution of the lower Vaal River catchment is unique from a number of aspects. Specific geological features, in conjunction with climate change, have proved crucial in shaping the Vaal River's fluvial history.

The thesis is set out as follows. The following chapter (i.e. Chapter 2) provides an overview of research on the fluvial history of the lower Vaal River catchment. This is followed in Chapter 3 by a discussion on the theory behind cosmogenic nuclide burial dating, while Chapter 4 provides the burial dating results for the various alluvial terrace deposits. Chapter 5 provides the key discussion on the revised fluvial history of the lower Vaal River catchment. Chapter 6 then provides a short discussion on the implications of both the burial dating and the revised fluvial history model in terms of human evolution. Finally, Chapter 7 provides a summary of, and highlights the most important conclusions of, the current study. It is important to note that certain paragraphs/sections of this thesis are taken from Gibbon *et al.* (in press).

Chapter 2

Overview of research on the fluvial history of the lower Vaal River catchment

2.1 Introduction

Study of the fluvial history of the lower Vaal River catchment has been the focus of scientific investigation for over a century, with continuous re-evaluation and changing models of terrace development and river geomorphic evolution (van Riet Lowe 1937, Sohnge *et al.* 1937, van Riet Lowe 1952*b*, Partridge & Brink 1967, Butzer *et al.* 1973, Helgren 1977*a*, Helgren 1979). Several levels of terrace development above the modern Vaal River and it's tributaries have been recognised (Partridge & Brink 1967, Helgren 1979). The Vaal River alluvial gravel deposits have been divided into 'older' and 'younger gravels' on the basis of lithological and topographical observations (Helgren 1979, de Wit *et al.* 2000). At the type-site at Windsorton and nearby surrounds (Figure 2.1), the 'older gravel' deposits occur at elevations of 21 to 60 metres above river level and have been grouped into the Windsorton Formation (South African Committee for Stratigraphy (SACS) 1980, de Wit *et al.* 2000). This is followed by the 'younger gravels', which includes the Rietputs and Riverton Formations at lower elevations.

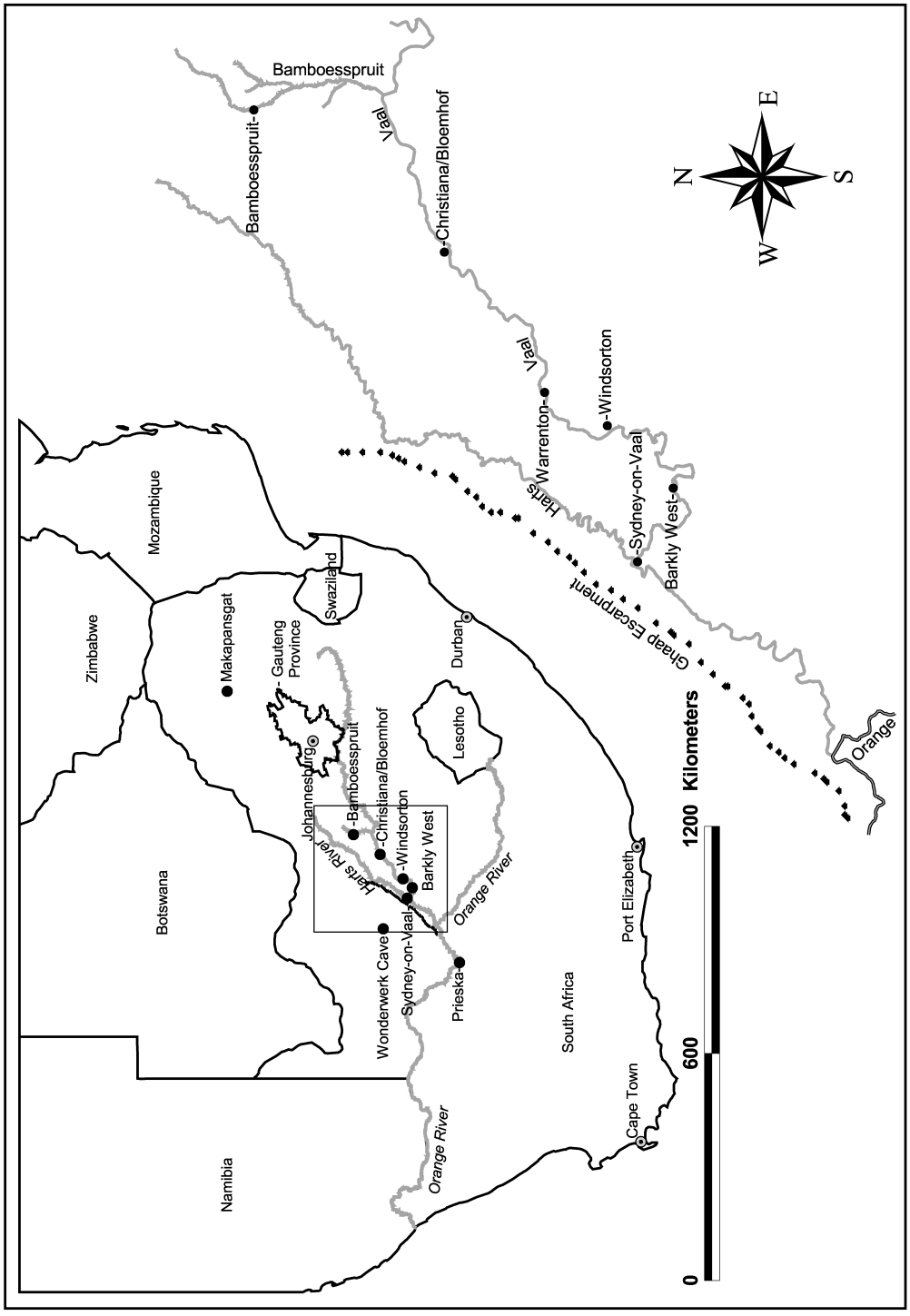


Figure 2.1: Map of South Africa and a blow-up of the study area showing locations of sites referred to in the text.

The most current and generally accepted fluvial history model is summarized below. This model is by no means definitive, but does provide a testable framework for the current study. In addition, the most comprehensive study to date on the fluvial history of the lower Vaal River by Helgren (1979) is also summarized. Helgren's study provides more detail on all aspects of the drainage evolution, such as the processes which led to the alluvial deposits formation, preservation and alteration, as well as, the evolution of geomorphic environments. The conclusions of this study are also in need of re-evaluation.

2.2 Geological setting

Before proceeding with a discussion on the fluvial history of the Vaal River a brief description of the geological setting is needed. The information below was obtained from the South African Geological Survey 1:250 000 series, geological maps 2824 Kimberley of 1993 and 2724 Christiana of 1994. The lower Vaal River basin is dominated by rocks of the Ventersdorp Supergroup and the Karoo Sequence, with the Griqualand West Sequence outcropping in the Vaal-Harts River valley in the east of the catchment (Figure 2.2). Figure 2.2 has been taken from Helgren (1979, 70) and modified only in that the geological names have been updated. Helgren's map still provides a good generalised geological overview.

Outcrops of the Ventersdorp Supergroup are dominated by the andesitic Allanridge Formation. These rocks are referred to in this study as Ventersdorp lava, a term commonly used throughout the last century. The Karoo Sequence in the catchment consists of Prince Albert Formation shale and varvite and Dwyka tillite. The Griqualand West Sequence consists of the Campbell Group consisting of the dolomites and limestones that form the Ghaap escarpment and plateau. The Karoo Sequence has been intruded in many places by Jurassic age dolerites which provide most of the relief in the landscape today due to their greater resistance to erosion.

Both the Ventersdorp Supergroup and the Griqualand West Sequence underlie

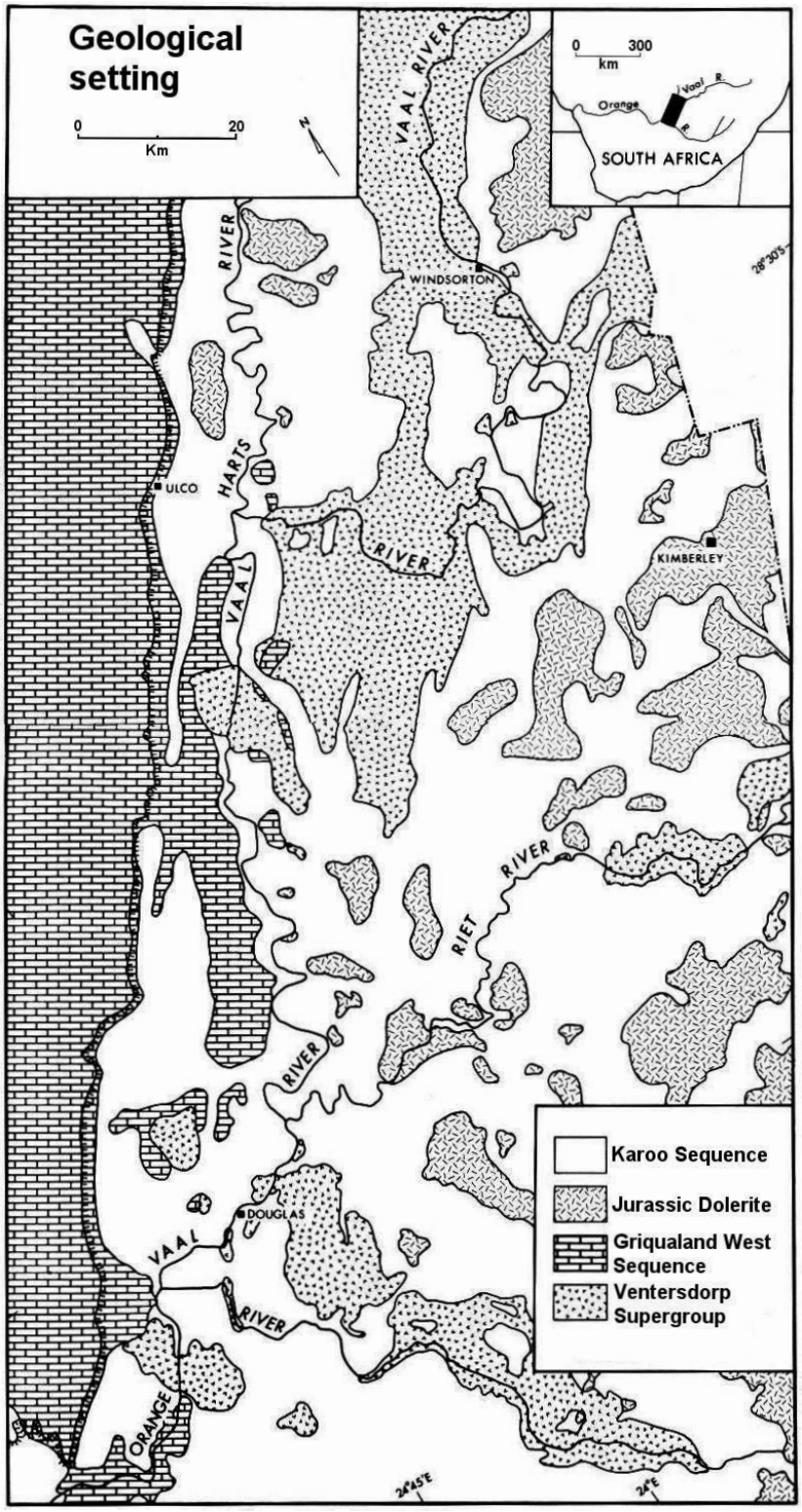


Figure 2.2: Generalised geology of the lower Vaal River catchment taken from Helgren (1979, 70). Helgren's map is unmodified from its original form and still provides an accurate generalised geological overview. Only the geological names have been updated. The pre-Karoo surface is prominently exposed where the Vaal River flows over the Ventersdorp Supergroup.

a major Proterozoic to late Carboniferous unconformity (de Wit *et al.* 2000). This unconformity has been re-excavated from beneath flat-lying, easily erodible Karoo rocks exposing both the relief and structure of this ancient surface. This pre-Karoo surface is prominently exposed where the Vaal River flows over the Ventersdorp Supergroup (Figure 2.2). Further discussion on the geological setting follows.

2.3 Current fluvial history model

The current fluvial history model is outlined below. Research has been focused on the fluvial remnants preserved within the lowermost 300 kilometres of the Vaal River valley, where the deposits have been extensively exposed by diamond mining operations. The highest and oldest deposits (Nooitgedacht and Droogeveld gravels) occur between 75 and 200 metres above the present Vaal River, spread across a pre-Karoo platform of Ventersdorp lava, and are believed to be Upper Cretaceous in age (Helgren 1979, Spaggiari *et al.* 1999, de Wit *et al.* 2000). The more important terrace deposits of the 'older gravels' for the current study include the well preserved, primary fluvial deposits at elevations between 60 to 21 metres (Partridge & Brink 1967, Helgren 1979). The oldest of these deposits is the 60 metre Holpan terrace, which is believed to be of early Miocene age (de Wit *et al.* 2000). This terrace is followed by the Proksch Koppie and Wedburg terraces, occurring at 30 to 45 metres and 21 to 30 metres respectively (de Wit *et al.* 2000). These terraces are well preserved in places and occur from Windsorton to the confluence with the Orange River. The Wedburg terrace is believed to be between 4.5 to 3.5 million years old, based on palaeontological evidence (Helgren 1977*b*, de Wit *et al.* 2000). The Proksch Koppie terrace thus lies somewhere between the two in a rather large time span. These three ancient terrace deposits form the Windsorton Formation.

The 'younger gravel' deposits consist of the Rietputs and Riverton Formations (South African Committee for Statigraphy (SACS) 1998, de Wit *et al.* 2000).

The Rietputs Formation (+12 to 14 metres) has not been formally recognised by the South African Committee for Stratigraphy but has been divided into three members by Helgren and has been traced over substantial reaches of the lower Vaal River valley (Helgren 1979). The Rietputs Formation contains both stone artefacts and fossils and has been assigned a middle Pleistocene age (Klein 2000). The Rietputs Formation is followed by the Riverton Formation deposits which occur as a proposed five-fold cut and fill sequence of sand and silts with a few gravel lenses (Helgren 1979). These deposits are believed to be of late Pleistocene to Holocene in age.

North bank tributary deposits of the Vaal River (e.g. Bamboesspruit) occur in the North-West Province (Marshall 1990). These deposits have been divided into four fluvial units (Marshall 1990). It is believed that these deposits are time equivalent, less extensive analogues of the 'older' and 'younger gravels' of the lower Vaal River (de Wit *et al.* 2000).

In summary, the macro-scale fluvial evolution of the Vaal River catchment since the Cretaceous is said to include two major periods of river rejuvenation (Partridge & Maud 2000, de Wit *et al.* 2000). It is believed that tectonic uplift events, in combination with relatively wet climatic conditions, resulted in these two major periods of river rejuvenation/incision (de Wit *et al.* 2000). The first, in the Miocene resulted in major changes in the drainage net, producing a network roughly the same as the present (de Wit *et al.* 2000). At this time it is believed that the 40 to 60 metre terraces developed along the Vaal. The Vaal terraces include the Holpan terrace near Windsorton and corresponding terraces along the Bamboesspruit (Marshall 1990). The arid late Miocene then saw the development of major duricrusts (Partridge & Maud 1987, Partridge & Maud 2000). After this aridity late Pliocene rivers again incised their valleys and gravel sequences were deposited. Along the Vaal River these took the form of the 12 to 30 metre terraces (de Wit *et al.* 2000). Subsequently, it is believed that oscillating climates during the Pleistocene constrained the development of the gravels and overbank deposits of the Rietputs Formation, as well as, the finer fluvial sediments of the Riverton Formation (de Wit *et al.* 2000).

It must be emphasized that this is a tentative fluvial history model. This model has been constructed by correlating terrace heights across great distances, which can only be used as a rough guide. Without a chronological framework for the different terraces, or even an idea of the time that each terrace may represent, one is unable to provide an absolute chronology of the fluvial history of the catchment.

In addition, there has been much debate over the years as to the factors which led to the formation and preservation of the various alluvial deposits within the lower Vaal River valley, and thus about the geomorphic evolution of the catchment. Climatic factors have dominated the interpretations (van Riet Lowe 1952*b*, Helgren 1979), while others have abandoned climatic explanations in favour of other geomorphic processes such as tectonics, river capture, variable lithologies and the cyclic passage of knickpoints (Partridge & Brink 1967). All of these studies have suffered from a poor chronological framework, as the timing of the proposed driving mechanisms could not be correlated with any certainty to the results (i.e. the deposits themselves). A direct comparison between climatic changes, tectonic processes, and the sequence of fluvial events or major features of the deposits, has not been possible.

In the next section a more thorough discussion of the various alluvial deposits and geomorphic evolution is presented. This discussion is based on the work of Helgren (1979). Helgren's research has formed the basis of our current understanding on the fluvial history of the lower Vaal River catchment. However, recent advances in radiometric dating techniques of alluvial deposits and a substantial increase in our knowledge of the climate of the last five million years, has highlighted that there is a need for a re-evaluation of many of the conclusions reached in his study.

2.4 Helgren's fluvial history model

Discussion will only focus on fluvial deposits of the Holpan, Proksch Koppie, and Wedburg terraces, as well as, the Rietputs Formation. The older Cretaceous deposits and younger Riverton Formation deposits do not form part of the current study. The discussion in this section has been obtained from Helgren (1979) unless otherwise referenced.

2.4.1 The pre-Karoo surface

Helgren's study found that the modern river valleys of the lower Vaal River catchment owe most of their characteristics (relief and structure) to the re-excavation of valleys within the pre-Karoo surface (Proterozoic to late Carboniferous unconformity) (see Figure 2.2). Where river channels are confined to valleys of this pre-Karoo surface, terrace deposits are best preserved, as the rivers were not able to move laterally across a floodplain but have rather cut through the soft Karoo rocks that filled the valleys. Helgren's investigation concluded that the large platforms upon which both Holpan and Proksch Koppie terrace deposits had been preserved, must be regarded as pre-Karoo features that were slightly modified by later river drainages. The importance of the recognition of the re-excavation of the resistant pre-Karoo surface from beneath the softer Karoo rocks is a crucial concept for the understanding of the Vaal River drainage evolution.

2.4.2 Holpan terrace deposits

Primary fluvial remnants are preserved across large areas of the Holpan platform near Windsorton (Figure 2.1). A palaeo-channel that is between 75 and 400 metres wide has been identified on the platform and is covered by 4 to 12 metres of calcrete (de Wit *et al.* 2000). Helgren identified that primary alluvial gravels rested either upon Ventersdorp lava (exposed pre-Karoo surface) or on isolated remnants of Karoo rocks (tillite). He identified several episodes

of colluvial filling above the alluvial deposits and attributed these, as well as pedogenic features of the deposits, to changing geomorphic environments. A Miocene age for the Holpan terrace deposit is based upon the calcretisation of the deposits that has been attributed to a period of aridity during the late Miocene which saw the development of major duricrusts (de Wit *et al.* 2000).

2.4.3 Proksch Koppie terrace deposits

The next major terrace deposit is situated on the Proksch Koppie platform. These deposits are again found throughout the lower basin. Helgren identified primary alluvial deposits that were covered by several episodes of colluvial fills. Environmental fluctuations were again suggested to explain both the deposits and associated pedogenic features. The greatest changes in environmental conditions were identified as fluctuations between calcrete formation and corrosion, and between stability and movement of the colluvial deposits. Helgren suggested a Vaal River with high discharges occurring in an semiarid to arid environment. He was not certain whether the coarse clasts of the alluvial gravel deposit could provide information on the environment at the time.

2.4.4 Wedburg terrace deposits

The final terrace deposit of the 'older gravels' is the Wedburg terrace. Helgren has identified this terrace as a morpho-stratigraphic marker throughout the lower Vaal River basin and indicated that it was not an exhumed pre-Karoo platform, such as the Holpan and Proksch Koppie platforms. He also identified parallel terraces along the Riet, Harts and Orange Rivers. Available exposures showed the deposits to consist of basal gravels which were in some areas covered by alluvial sands. At least one unit of colluvial fill capped the alluvial deposits. Helgren noted that the Wedburg terrace residuals were so substantial around Windsorton that one could speculate that alluvial deposits as large and complex as the 'younger gravels' may have once been present. Helgren believed that the terrace deposits indicated that the Vaal River was

capable of carrying boulder-grade gravels, thus indicating a high energy river. He noted, however, that the preservation of derived calcrete clasts within the deposits suggested a relatively arid local environment.

Helgren concluded that the Wedburg terrace demarcated a major stage in the denudation of the region. After abandonment of the Proksch Koppie terrace the Vaal River cut down and then remained static at Wedburg levels for a substantial period of time during which extended plains were eroded at this level throughout the basin.

2.4.5 'Older gravels' dating

Helgren noted that, although one can say clearly that at any one location, such as at Windsorton, Holpan deposits are without any doubt older than those of Proksch Koppie deposits, and similarly Wedburg deposits are still younger, problems arise when trying to correlate deposits in adjacent reaches along the river. He concluded that correlating terraces other that Wedburg, in different reaches of the valley was no more than speculative. He also noted that deposits are too limited in extent and spatially discontinuous to allow meaningful conclusions to be drawn on longitudinal gradients of these palaeo-rivers. Dating of the older gravels above the Wedburg terrace was thus not attempted by Helgren.

Based on fossil evidence Helgren assigned an age of 4.3 to 3.2 Ma for the Wedburg terrace. Although the provenance of the fossils was poorly known with most coming out of the 'younger gravels', Helgren concluded that it was most reasonable to associate them with the Wedburg terrace. He believed that they had been eroded out of Wedburg deposits and then had been reincorporated into the 'younger gravels'. An age was then obtained from a comparison with fossils from the better dated East African faunal deposits (Helgren 1977*b*).

2.4.6 Denudation conclusions

Helgren concluded that one had to consider the Holpan and Proksch Koppie terraces apart from the Wedburg terrace. The older terraces and associated deposits were identified as being located on progressively lower pre-Karoo slopes, which argued for the dismissal of the possibility of cyclic denudation occurring during the Cenozoic. Helgren rather viewed these older gravels as erratic, infrequently preserved depositional residues of a long period of continuing erosion. He did not exclude climate change as being the driving mechanism for this continuing erosion, but did not see it as a primary cause.

Helgren identified an episode of valley incision preceding Wedburg terrace formation. This was then followed by a period of stability with little net deposition as lateral planation eroded valley shoulders to produce the Wedburg platform identified throughout the basin. This was again followed by a period of valley incision before the deposition of the Rietputs Formation. Helgren believed that climatic changes provided the most suitable explanation for this sequence of events. He dismissed tectonic and river capture explanations. Helgren envisaged incision occurring when the discharge was so great that the Vaal River continuously had excess energy to deepen and widen the channel. A balance between erosion and deposition would have kept base levels constant in order to produce the Wedburg platform. He pointed to other climatic indicators within the basin to support this conclusion. Both tufa deposits and terraces above the Sand River were used as evidence for climate change, although he did conclude that the exact climatic relationships with valley incision and development were not clear. The age relationships of the Wedburg terrace, the tufa deposits and the Sand River terraces were also not clear.

2.4.7 Sources of the Vaal River gravel clasts

Before discussing the Rietputs Formation of the 'younger gravels' it is important to discuss the sources of the Vaal River gravels, as put forward by Helgren (1979). Helgren identified three primary sources and one secondary source.

2.4.7.1 Primary sources

Dwyka tillites and dropstone beds Helgren saw these as the most important primary source providing 'ready made' clasts.

Siliceous clasts These clasts consist of the most resistant materials from various lithologies throughout the basin and were believed to have moved across the subcontinent since the early Mesozoic.

Karoo rocks These consisted of shale, hornfels, dolerites and fossil wood clasts.

2.4.7.2 Secondary source

'Older gravel' deposits Helgren saw these as the most important with each younger deposit receiving most of its clasts from it's most immediate older deposit. In this way he believed that most of the clasts in the various deposits were introduced as a result of denudation of the adjoining hillslopes and not by gravel surges introduced from upstream drainage or obtained from erosion of the resistant pre-Karoo bedrock.

2.4.8 Rietputs Formation deposits

2.4.8.1 Bedrock incision

Helgren's study indicated that a period of river incision occurred throughout the lower Vaal River basin following the formation of the Wedburg platform and the deposition of associated alluvium. Erosion in some areas of the catchment was in excess of 25 metres and reached the base of the coincident, pre-Karoo channels. Helgren noted that, between Windsorton and Sydney-on-Vaal (Figure 2.1), this incision stopped with the exhumation of the pre-Karoo surfaces. From Sydney-on-Vaal to the confluence with the Orange River, as well as in the Harts, Riet and Orange River valleys, this incision was halted before all

Karoo sediments had been removed. Aggradation of the Rietputs Formation 'younger gravel' deposits commenced thereafter.

2.4.8.2 Basis of the Rietputs Formation geomorphic model

Helgren based his identification of the various units of the Rietputs Formation on five key exposures at the type-site at Windsorton and nearby surrounds (Figure 2.1). It was from this identification and classification that all remaining deposits within the catchment were categorised. These five sites provided the morphological, depositional, erosional, and pedogenic framework for the study.

On this basis Helgren identified three different members of the Rietputs Formation, designated A, B, and C. He also identified periods of erosion occurring after the aggradation of each of these members. Post-depositional pedogenic processes such as calcretisation and rubification were also identified and used to define and distinguish the members.

In his study of the 'younger gravels', Helgren also identified Rietputs Formation equivalent deposits and associated features along the Harts, Riet and Orange Rivers. He thus concluded that there was substantial evidence that similar, broadly synchronous events occurred along similar reaches of several streams in the region across variable bedrocks, with indicators occurring relatively continuous for substantial distances, even when stream sources were in different precipitation zones. It was this region-wide sequence of events that was used to construct a geomorphic environmental model to explain the deposits and drainage evolution of the lower Vaal River basin. Each member and intervening non-depositional/erosional event was then attributed to varying climatic conditions or transitions.

2.4.8.3 Rietputs Formation members

Member A Helgren's study identified member A as a massive deposit of coarse gravels that filled the newly incised valley. The deposits comprised subrounded, pebble to boulder-grade gravels with inhomogeneous sandy matrices.

In several localities member A was found to be more than 40 metres in depth. Down stream of Sydney-on-Vaal, as well as along Vaal River tributaries and along the Orange River, member A deposits were represented by rock-cut platforms and related alluvium. Along the Harts River, as well as, along the Vaal River at Sydney-on-Vaal and at the confluence with the Orange River, member A deposits are inter-fingered with limestone tufa deposits (Figure 2.1). These tufas were deposited by streams draining the distant (7 to 15 kilometres) karstic terrain of the Ghaap escarpment. Helgren noted that small modern streams at these sites were extremely ephemeral and do not deposit tufas under the current climatic regime (Helgren 1978).

Member B Helgren's study concluded that, following the deposition of member A, rivers throughout the region incised the member A terraces and associated deposits. He believed that at this time a rubefied weathering zone developed on the surface of the member A deposits. A second period of aggradation followed, but this was much less extensive than the first. These member B deposits were rarely more than five metres thick, and consisted of reworked member A clasts, with frequent sandy interbeds. At several sites Helgren identified sediment free benches cut into bedrock with no associated gravel deposits preserved. An important characteristic of member B deposits identified by Helgren is that they were generally calcreted. Helgren also believed that it was during this interval that large amounts of sand were deflated out of the Vaal River channel. These sands (Hutton sands) are widespread throughout the region today.

Member C Helgren's study also concluded that, following member B aggradation, there was another period of stream incision followed by the aggradation of member C deposits. These deposits, which are up to six metres thick, consist of cobble gravels with irregular sandy matrices. They are found in or near the modern Vaal River channel. Helgren noted that they were typically cemented at the surface by either calcrete or ferro-manganese compounds.

Helgren noted that the gravel facies of all of the members were virtually

identical, and that the erosional contact between them was poorly demarcated. Helgren went on to say that "*it is an understatement to say that the stratigraphy in these exposures is complex. Individual beds are often capped by steeply dipping unconformities and facies may change rapidly, so that very different exposures may be found in adjacent pits*" (Helgren 1979, 184).

2.4.8.4 Chronology of the Rietputs Formation

Table 2.1 presents Helgren's record of events that occurred during the span of the Rietputs Formation at the type-site at Windsorton, as well as his synthesis for the region as a whole. This information is taken from Helgren (1979) page 219 for the Rietputs Formation at Windsorton and pages 302 to 303 (Table 10.1 - 'Record of the Rietputs Formation') for the synthesis. Table 2.1 provides a good summary of Helgren's key findings from his study. These findings provide the basis for his climatic interpretation of the Rietputs Formation (discussed below).

Table 2.1: Record of the Rietputs Formation (after Helgren 1979)

Vaal River at Windsorton	**Vaal River main channel and tributary features**
Stage 1: Abandonment of the Wedburg terrace and incision of the Karoo sediments to irregularly expose a pre-Karoo valley. The floodplain-margin sediments were silts and sands of the 'Basal Fines' at Riverview I. River levels: from +21 metres to somewhat below present level	Major valley incision and valley widening. Wedburg Terrace abandoned. Tributary valleys incise. Scarps of the Wedburg Terrace begin to retreat. Rubefied palaeosols develop on some 'Older Gravels' outcrops.

Table 2.1: Record of the Rietputs Formation (after Helgren 1979) (continued)

Vaal River at Windsorton	**Vaal River main channel and tributary features**
Stage 2: Aggradation of Rietputs Formation, Member A, a complex valley fill of coalescing and merging mid-channel bars, combined with tributary gravels from coeval hillslope erosion. River levels: from below present level to above +12 metres	Deposition of Rietputs Member A (massive valley-fill of coarse gravels). Channel lengthening at Vaal-Harts confluence. Tributary channels aggrade coarse sediments derived from erosion of Older Gravels and tillites. Massive interdigitation of Ghaap Escarpment tufas with fluvial sediments along Vaal-Harts valley. Shale plains re-grade to the local base-levels provided by the Rietputs-A fill.
Stage 3: Floodplain incision, followed by development of the rubefied weathering zone on Rietputs A. Still later, the eroded gravel surfaces in the incised channels in the eastern sector of the valley fill were calcreted. River levels: from above +12 metres to near present level.	Valley and valley-fill incision. Widespread erosion of Rietputs-A deposits. Tributary channels incise. Rubefied palaeosol develops on Rietputs-A surfaces. Corrosion and solution of tufa surfaces. During later phases throughflow calcretes intrude Rietputs A.

Table 2.1: Record of the Rietputs Formation (after Helgren 1979) (continued)

Vaal River at Windsorton	**Vaal River main channel and tributary features**
Stage 4: Aggradation of Rietputs Formation, Member B (with gravel and sand facies), coincident with local erosion of Rietputs A and stripping of surficial sediments from the surrounding slopes, to be re-sorted in the channelways. Repetitive calcretion of sediments in and along the channels of the eastern valley-fill area. Calcretion also followed alluviation. River levels: from present level to at least +12 metres.	Aggradation of Rietputs B (mosaics of gravel with sandy interbeds in channels, sandy floodplain margins). Continued erosion of Rietputs-A fills. Coincident calcretion of Rietputs-B sediments. Massive fluvial sands first appear in Lower Vaal Basin. Cyclic sedimentation at Riverview Estates (Windsorton) and Winter's Rush. Floodplain deflation.
Stage 5: Fill cutting and then aggradation of Rietputs Formation, Member C along and near the axis of the modern Vaal. River levels: from above +12 metres to below the present level. Followed by calcretion.	Erosion of Rietputs-B deposits and creation of associated terrace morphology. Deposition of Rietputs C, lining the modern channel. Channel lengthening at Vaal-Harts confluence. Erosion of earlier Rietputs alluvia. Throughflow calcretes develop in valley alluvia.

2.4.8.5 Climatic interpretations

Rietputs Formation member A environments Helgren identified three geomorphic environmental phases related to the valley incision preceding aggradation, the aggradation of Rietputs Formation member A, as well as, the valley incision following member A deposition. The initial valley incision through the Karoo rocks was explained in terms of frequent, high-magnitude discharges

in a humid geomorphic environment. The Vaal River at this time was transporting the largest clasts provided from erosion of the tillites, 'older gravels' and dolerites, leading Helgren to conclude that the competence and capacity was well beyond that of the modern Vaal. Helgren suggested that this phase may represent the most humid environment in the late Cenozoic history of the catchment.

The aggradation of Rietputs Formation member A deposit was seen as a period of humid aggradation. Helgren noted that never before had the Vaal River deposited such large masses of gravels and neither had the Ghaap Escarpment tufas reached the Vaal River is such large volumes. He concluded that although the climate may have been less humid than the previous period with more erratic discharges, a humid environment was still indicated.

Evidence used to support this humid environment comes from the deposition of the tributary limestone tufa deposits. As already mentioned these tufas were deposited by streams draining the distant (7 to 15 kilometres) karstic terrain of the Ghaap escarpment. Helgren noted that small modern streams at these sites were extremely ephemeral and do not deposit tufas under the current climatic regime, and that a significantly more humid environment would be needed to generate these deposits today. Further evidence used to corroborate climatic conditions came from tributary facies of Rietputs Formation member A age. These colluvial gravels, which merge with the alluvial deposits, were said to suggest that member A deposition was a result of greatly increased hillslope erosion. Helgren attributed this erosion to increased frost-induced, mass-wasting processes. He consequently believed that the humid environment was a response to both high precipitation and decreased evapotranspiration.

Helgren concluded that the coarse gravels of member A documented repeated and frequent high magnitude discharges from the upper basin, while the tufa and colluvial deposits indicated a humid climate and persistent, high discharges in the lower Vaal River basin. Based on palaeo-discharge calculations he suggested that the member A Vaal River discharge was four to five times that of today.

The incision that followed the aggradation of member A was believed by Helgren to be accompanied by the development of the rubefied palaeosol on member A deposits. The member A deposits were eventually calcreted towards the end of this incisional phase, believed to indicate a change to semiarid or even an arid environment prior to the deposition of member B.

Rietputs Formation member B environments The Rietputs Formation member B deposits were said by Helgren to show episodic gravel mobilisation, with stream competences generally in the sand grades. The cyclic layers of the finer sediments were said to record desiccation along tributary channels and in peripheral flood basins. Helgren notes that this greater aridity is reinforced by the persistent calcretion of the alluvium. He concluded that the environment was arid, with highly periodic discharges, provided primarily from the upper basin.

During this period Helgren concludes that there is a major change in the geomorphic history of the catchment. It is during this period that the Hutton sands are introduced to the region creating a permeable land surface that changed subsequent patterns of hillslope erosion. An arid environment was needed for the mobilisation of the sands. Vaal River floodplain deflation would have contributed to the body of sand. Other sources of sand were believed to be derived from within and outside of the basin.

Rietputs Formation member C environments Helgren believed that several geomorphic environments were probably formative in the valley incision and aggradation of member C. Continuing semiarid conditions were identified by calcretion of member A and B deposits. However, humid environments were also identified, for example by the mobilisation of iron and manganese as represented by the oxide cements of member C deposits, as well as the channel lengthening that occurred at the Vaal-Harts confluence. Helgren thus concluded that member C deposits indicated a long interval of intermediate, sub-arid to sub-humid environments, with average conditions similar to those of the present.

2.4.8.6 Dating of the Rietputs Formation

The ages of the various Rietputs Formation members were approximated by Helgren through external correlation of included fossils and stone artefacts, as well as generalized lengths of time that geological events recognised from the Rietputs Formation implied. As mentioned earlier, based on fossil evidence Helgren assigned an age of 4.3 to 3.2 Ma for Wedburg terrace. The following period of substantial valley incision was believed to be in the order of a million years.

A collection of over a 1000 mammal fossils, most coming from Rietputs Formation member C, were also identified as being of later middle Pleistocene age (Helgren 1977*b*). Helgren believed these fossils could provide only a general dating inference for the Rietputs Formation. Acheulean stone artefacts found in all the members indicated that the members could be as old as 1.4 Ma in comparison with East African collections.

In conclusion, Rietputs Formation member A was said to span a few hundred thousand years during the early Pleistocene. The erosional period between members A and B was said to be of similar duration. Member B deposition was thought to span tens of thousands of years during the lower Pleistocene or middle Pleistocene. Member C deposition was thought to span several hundred thousand years during the middle Pleistocene.

2.5 Conflicting interpretations between the fluvial history models

Below is a brief outline of how the fluvial history models discussed above differ. Helgren's fluvial history model generally invokes climatic changes to understand the formation and preservation of the various alluvial deposits and associated features, and thus to explain the fluvial history of the lower Vaal River catchment. Other authors, however, have criticised climatic interpretations indicating that there is no unequivocal evidence for climate change within

the sequence of terrace deposits (Partridge & Brink 1967, de Wit *et al.* 2000).

Similarly to Helgren, early studies (Sohnge *et al.* 1937) invoked climatic explanations, with periods of incision, gravel aggradation and sand aggradation explained by a climate wetter than present that began to wane after initial incision. Cooke (1947), however, favoured non-climatic explanations to explain periods of increased erosive activity that resulted in incision. He did, however, attribute the calcified sands which lie above the gravel deposits to a drying climate.

Partridge and Brink (1967) criticised climatic explanations proposing that the vertical and lateral variations within the alluvial deposits were compatible with deposits normally found in a floodplain of a mature river subject to a given range of climatic conditions. These authors attributed the sequences of terraces and associated deposits along the Vaal River rather to either tectonics, river capture, variable lithologies and the cyclic passage of knickpoints. It was believed that the deposits of the lower Vaal River could be explained by an initial increase in gradient resulting from local axial warping during the Pliocene, followed by successive stages of the headward advance of knickpoints across rock-barriers (Partridge & Brink 1967). The Rietputs Formation was seen as a semi-arid accumulation showing the imprint of periodic humid episodes (Partridge & Brink 1967).

2.6 North bank tributary deposits

In addition to alluvial deposits along the lower Vaal River, alluvial deposits are also preserved along right-bank tributaries (e.g. the Bamboesspruit) in the North West Province (Marshall 1990). This feeder catchment is located between Christiana/Bloemhof and the Harts River and just upstream of the present Bamboesspruit (Figure 2.1). These deposits are crucial to the understanding of the fluvial history of the lower Vaal River catchment and are thus outlined below. The following discussion has been derived from the work of Marshall (1990) unless otherwise referenced.

Mapping and analysis of these deposits has indicated that they comprise four alluvial units, and one derived gravel unit. The oldest deposits that have been termed A0 gravels, represent the earliest phase of alluvial deposition and are believed to be late Cretaceous to early Neogene in age (de Wit *et al.* 2000). The later A1 deposits are developed both outside of, and within, the present valleys. They occur in channels up to 30 metres wide and consist of clast supported, granule-to-cobble gravels. It has been noted that there has been substantial calcretisation of these deposits, as a result of a desiccating climate. Thus a Miocene age has been proposed, linked to a period of aridity during the late Miocene which saw the development of major duricrusts in the region (de Wit *et al.* 2000).

Marshall's study found that the A2 deposits are located along the length of numerous dry streams in the area, of which the Bamboesspruit is one (Figure 2.1). The deposits consist of a basal granule-to-coarse cobble gravel up to two metres thick, with limited boulder-size clasts. The deposits are poorly sorted and generally matrix supported. The deposit fines upwards with the gravels overlain by up to seven metres of finer grained alluvial sands and muds, which have been variably calcretised, oxidised or reduced, depending on their location to the modern water table. These A2 deposits are found between three to ten metres below the modern drainage, indicating that aggradation has dominated since their deposition. The A2 gravels are believed to be Rietputs Formation equivalents. A3 deposits occur along the Vaal River and are believed to be Riverton Formation equivalents.

Focus will now be concentrated on the A2 deposits and drainage. Prior to aggradation of these deposits it has been argued that tectonic uplift was the driving mechanism for incision through the older gravels into the land surface. When incision stopped the streams began to aggrade the coarse A2 gravel deposits. Marshall's study of the A2 right bank tributaries, upstream of Windsorton, indicated that the modern drainage basin and pattern of these tributaries has not changed since Rietputs Formation (A2) times. Clast composition and roundness indicated that the gravels had been derived from local lithologies within the catchment. In addition, a surface texture classification scheme for

kimberlitic indicator-minerals, in which texture characteristics were related to relative distance travelled in a fluvial system, also indicate a similar modern basin size.

Marshall's study of the A2 gravel deposits also indicated that palaeo-channel width was about 30 metres, as opposed to 10 metres at present. Channel depth was around six to seven metres. Gravels up to 200 metres in width have been found, which probably represent lateral channel migration of the streams. Study of the meander wavelength of the palaeo-channel compared to the present drainage indicates that a higher volume of water was flowing in A2 streams. It has thus been argued that there was a higher discharge out of this catchment during Rietputs Formation times into the Vaal River.

It has also been argued by Marshall that there has been extensive desiccation of the climate since A2 gravel times, which resulted in the deposition and calcretisation of the finer-grained sediments on top of the gravel deposits, just as is found along the Vaal River. In addition, pans now occupy many of these dry channels, with gravels occurring at a depth of five to eight metres. As the pans lie within dry channels and there is no evidence for tectonic disruption of the A2 drainage, it is argued that this is evidence of a drying climate. At present the right bank tributaries of the Vaal River consist of small, dry, insignificant streams that only flow during extensive flooding, remaining dry for periods of up to 10 years.

* * *

This overview of previous research on the fluvial history of the lower Vaal River catchment (which summarises the consensus to date on current models of terrace development and river geomorphic evolution), will be re-evaluated in light of a new radiometric dating technique available for dating of alluvial deposits. Cosmogenic nuclide burial dating of the fluvial remnants in the catchment forms the basis of the current study. The theory behind this absolute dating technique is discussed in the following chapter.

Chapter 3

Cosmogenic nuclide burial dating

3.1 Introduction

The cosmogenic nuclide burial dating technique is based on the relative radioactive decay of ^{26}Al ($t_{1/2}$ = 0.717±0.017 Ma) and ^{10}Be ($t_{1/2}$ = 1.34±0.07 Ma) produced in quartz grains by exposure to secondary cosmic rays near the ground surface prior to burial (Granger & Muzikar 2001). Subsequent to burial, the quartz is shielded from cosmic radiation, and radioactive decay lowers the ^{26}Al/^{10}Be ratio over time (Granger & Muzikar 2001). The quartz is assumed to have been exposed to the secondary cosmic rays for sufficient time to acquire suitable cosmogenic nuclide concentrations (Granger & Muzikar 2001).

Both ^{26}Al and ^{10}Be are produced by energetic nucleons and muons that penetrate the uppermost few metres of earth's surface (Granger 2006). Although production rates of these two nuclides vary geographically as a function of elevation, depth beneath the surface, and geomagnetic field strength over time, the ratio of the two production rates remains nearly constant (Granger & Muzikar 2001). Thus, the ratio ^{26}Al/^{10}Be can be accurately estimated for quartz that has been exposed near the ground surface, even if the absolute values of the concentrations cannot.

The key to burial dating is that production rates of ^{26}Al and ^{10}Be decline

rapidly beneath the surface (Granger & Muzikar 2001). If samples are deeply buried, by more than about five to ten metres, then further production of cosmogenic nuclides effectively ceases. The inherited ^{26}Al and ^{10}Be within the quartz then decay. Because ^{26}Al has a shorter half-life than ^{10}Be, the ratio ^{26}Al/^{10}Be decreases exponentially over time. The measured ^{26}Al/^{10}Be ratio thus indicates the time at which the quartz was buried (Granger *et al.* 1997, Granger *et al.* 2001, Partridge *et al.* 2003). The specifics of the method are discussed further below. This method is also reviewed in detail by Granger and Muzikar (2001) and Granger (2006). These papers form the basis for the discussion that follows.

3.2 Production of cosmogenic nuclides in quartz

The *in situ* production of ^{26}Al and ^{10}Be in quartz, at or below the surface varies with depth. At the surface and shallow depths production is dominated by nucleon (neutrons and protons) spallation (Granger & Muzikar 2001). Nucleons are rapidly attenuated with depth, however, decreasing exponentially with a penetration length L_0 of 160 g cm^{-2}, or about 60 cm in rock of density 2.6 g cm^{-3} (Gosse & Phillips 2001). With increasing depth production is dominated by negative muon capture and then by fast muon reactions (Granger & Smith 2000). Slow negative muons captured by ^{28}Si and ^{16}O nuclei produce ^{26}Al and ^{10}Be by subsequent nucleon loss (Granger & Smith 2000). Fast muons penetrate the deepest and produce ^{26}Al and ^{10}Be as by-products of nuclear cascades generated by bremsstrahlung, pair production, ionisation loss, and electromagnetic interactions (Granger & Smith 2000).

At the surface of the earth production by nucleon spallation accounts for over 97% of production while negative muon capture and fast muon reactions acount for the rest (Granger & Smith 2000). For quartz buried at depth, production by muons becomes increasingly important. An example is given by Granger and Muzikar (2001, 271).

"Though production by muons is dwarfed at the surface, for a clast buried at

a depth of, say, 10 m, nuclide production due to nucleons has been reduced by a factor of 10^{-7} from its surface value, while production from muons is still about 15% of its surface value."

For any rock exposed to cosmic rays, the concentration (N_i) of a cosmogenic nuclide i reflects a balance between production and decay (Granger & Muzikar 2001).

$$dN_i/dt = P_i(t) - N_i/\tau_i \tag{3.1}$$

In equation 3.1, t represents time, $P_i(t)$ is the time-varying production rate of cosmogenic nuclide i, and τ_i is its radioactive meanlife (meanlife=halflife/ln(2)).

The production of ^{26}Al and ^{10}Be by nucleon spallation as a function of depth can be determined by equations 3.2 and 3.3,

$$P_{26}(z) = A_0 e^{-\rho z/L_0} \tag{3.2}$$

$$P_{10}(z) = B_0 e^{-\rho z/L_0} \tag{3.3}$$

where P is the production rate of each nuclide, z is the depth below the surface, ρ is the density of the deposit and the nucleon decay length is given by L_0. The prefactors A_0 and B_0 depend on latitude and altitude (Granger & Muzikar 2001). Reasonable estimates for sea-level, high latitude are $A_0 \approx 30$ and $B_0 \approx 4.5$, in units of atoms per gram of quartz per year (Gosse & Phillips 2001).

Attenuation lengths of muons are somewhat more complicated than that of nucleons (Stone *et al.* 1998, Heisinger *et al.* 2002*b*, Heisinger *et al.* 2002*a*). The production rate can be fit as the sum of three exponentials (Granger & Smith 2000), with penetration lengths L_1 (738 g cm^{-2}), L_2 (2688 g cm^{-2}), and L_3 (4360 g cm^{-2}). The total production rate of ^{26}Al and ^{10}Be in a piece of quartz can then be described by equations 3.4 and 3.5 (Granger & Muzikar 2001).

$$P_{26}(z) = A_0 e^{-\rho z/L_0} + A_1 e^{-\rho z/L_1} + A_2 e^{-\rho z/L_2} + A_3 e^{-\rho z/L_3} \tag{3.4}$$

$$P_{10}(z) = B_0 e^{-\rho z/L_0} + B_1 e^{-\rho z/L_1} + B_2 e^{-\rho z/L_2} + B_3 e^{-\rho z/L_3} \tag{3.5}$$

The prefactors A_1 to A_3 and B_1 to B_3 depend on latitude, altitude and time (e.g. Stone 2000, Gosse and Phillips 2001). For sea-level, high-latitude again,

$A_1 \approx 0.72$, $A_2 \approx 0.16$, $A_3 \approx 0.19$, $B_1 \approx 0.08$, $B_2 \approx 0.02$, and $B_3 \approx 0.02$, all in units of atoms per gram of quartz per year.

The second and third terms in equations 3.4 and 3.5 describe production due to negative muon capture (Granger & Smith 2000). The fourth terms describe fast muon reactions and are the most difficult to fit (Granger & Muzikar 2001). A reasonable fit is, however, obtained up to depths of about $5000/\rho$ cm (Granger & Smith 2000).

3.3 Burial dating

Determining the burial age of a piece quartz from within a river terrace or cave deposit requires certain assumptions concerning the exposure of the piece of quartz to cosmic rays prior to burial (Granger & Muzikar 2001). Various models can be used to determine the initial concentrations of the two nuclides which are needed to determine a burial age (Granger & Muzikar 2001). The model most appropriate for dating of alluvial deposits is discussed below. However, it is pertinent at this time to discuss how the concentrations of ^{26}Al and ^{10}Be in quartz, measured by accelerator mass spectrometry (AMS), are related to the burial age for a piece quartz within a deep deposit.

In the simplest form of burial dating one assumes that a piece of quartz has been exposed to cosmic rays and subsequently acquired certain concentrations of both ^{26}Al and ^{10}Be. The quartz was then buried so that the production of the nuclides stops. ^{26}Al and ^{10}Be both then decay. Their concentrations are then measured by AMS at the present time. The present concentrations of ^{26}Al and ^{10}Be are related to their burial time t by equations 3.6 and 3.7 (Granger & Muzikar 2001),

$$N_{26}(t) = N_{26inh} e^{-t/\tau_{26}} \tag{3.6}$$

$$N_{10}(t) = N_{10inh} e^{-t/\tau_{10}} \tag{3.7}$$

where $N_{26}(t)$ and $N_{10}(t)$ are the measured concentrations of ^{26}Al and ^{10}Be respectively, N_{26inh} and N_{10inh} are the initial concentrations of the nuclides prior to burial and τ_{26} and τ_{10} are the mean lives of the nuclides. The initial concentrations of ^{26}Al and ^{10}Be are unknown and thus the equations cannot as yet be solved. The solution of these equations relies on the fact that the initial concentrations of ^{26}Al and ^{10}Be are related, since the two nuclides were produced in the same piece of quartz, by the same cosmic rays, over the same period of time (Granger & Muzikar 2001). Thus one has to use a model to describe the buildup of ^{26}Al and ^{10}Be prior to burial in order to solve equations 3.6 and 3.7, and determine the burial age of the quartz (Granger & Muzikar 2001).

The most appropriate model to describe the buildup of ^{26}Al and ^{10}Be prior to burial assumes that the quartz comes from a landscape that is eroding. As the landscape erodes, the quartz is exhumed to the surface and then buried thereafter (Granger & Muzikar 2001). Simpler models assume that the production rates of the nuclides are constant prior to burial. The landscape of South Africa is continuously eroding and thus production rates will not be constant. As a piece of quartz is brought nearer to the surface during the processes of weathering and erosion, the production rates within the piece of quartz increase. As a result these simpler models are not appropriate for use in the South African landscape.

For a rock near the ground surface that is eroding at a constant rate ε, depth can be substituted for time and equations 3.1, 3.4 and 3.5 can be solved for the steady-state concentration of ^{26}Al or ^{10}Be (Lal 1991).

$$N_{26} = \sum_{j=0}^{3} \frac{A_j}{\frac{1}{\tau_{26}} + \frac{\rho\varepsilon}{L_j}} \tag{3.8}$$

$$N_{10} = \sum_{j=0}^{3} \frac{B_j}{\frac{1}{\tau_{10}} + \frac{\rho\varepsilon}{L_j}} \tag{3.9}$$

The ratio ^{26}Al/^{10}Be depends only on the local erosion rate and constants that are known. This erosion rate ε can be referred to as the 'inherited' erosion rate, as it is the erosion experienced by a piece of quartz during its accumulation of ^{26}Al and ^{10}Be before the piece of quartz is buried (Granger & Muzikar 2001).

Once a piece of quartz has been buried within an alluvial deposit, the ratio $^{26}Al/^{10}Be$ then decays according to (Granger & Muzikar 2001),

$$N_{26}/N_{10} = (N_{26}/N_{10})_{inh} e^{-t/\tau_{eff}} \tag{3.10}$$

where the inherited ratio is given by equations 3.8 and 3.9 and τ_{eff} is given by (Granger & Muzikar 2001),

$$\tau_{eff} = 1/(1/\tau_{26} - 1/\tau_{10}) \tag{3.11}$$

The ratio $^{26}Al/^{10}Be$ therefore depends only on the local erosion rate prior to burial, and on the duration of burial. Equations 3.8, 3.9 and 3.10 can be solved simultaneously for both of these variables in order to determine the burial age of the quartz (Granger *et al.* 1997)(for reviews see Granger and Muzikar 2001 and Granger 2006).

The above model assumes that erosion has proceeded at a constant rate for a long period of time (Granger & Muzikar 2001). A constant erosion rate of a landscape may not always be realistic. However, it has been found that accounting for variations in erosion rates seldom affects burial dates significantly (Granger & Muzikar 2001). Where erosion rates are above roughly 0.6m/Ma radioactive decay can be ignored and the initial nuclide ratio is unaffected by even large variations in the erosion rate (Granger & Muzikar 2001).

Equation 3.10 is strictly valid only for samples that are deeply buried. If samples are buried by only a few metres, then post-burial production of ^{26}Al and ^{10}Be cannot be ignored. Post-burial production is both depth- and time-dependent (Granger 2006). In this case, the concentration of each radionuclide after burial follows equation 3.12,

$$N_i(z,t) = N_{i,inh} e^{-t/\tau_i} + \int_0^t [P_n(z+\rho\varepsilon_{pb}t') + P_{\mu^-}(z+\rho\varepsilon_{pb}t') + P_{\mu^{fast}}(z+\rho\varepsilon_{pb}t')] e^{-t'/\tau_i} dt' \tag{3.12}$$

where z is the current depth of the sample, ε_{pb} is the post-burial erosion rate of the sedimentary deposit, P_n, P_{μ^-} and $P_{\mu^{fast}}$ are production rates by nucleon spallation, negative muon capture, and fast muon reactions respectively, and t' is a dummy variable of integration. Equation 3.12 contains at least three unknowns; these are the burial age, the inherited ^{26}Al and ^{10}Be concentrations, and the time dependence of the post-burial production rate (Granger 2006). The post-burial production rate is equivalent to the erosion rate (ε_{pb}) in steady state (Granger 2006). Equation 3.12 cannot be solved uniquely using only a single sample.

There are two approaches that can be taken for dating samples with post-burial accumulation. The first approach is to compute minimum and maximum ages by assuming endmember erosion histories (Gibbon *et al.* in press). The minimum age is calculated assuming that the sample was deeply buried in the past, but has recently been brought near the surface by erosion. This is the solution of equation 3.10 ignoring post-burial production. The maximum age can be calculated assuming that the sample has always been exposed at its present depth (z), i.e., that there has been no erosion of the alluvial deposit. The current concentrations of each nuclide are then given by equations 3.13 and 3.14 (Granger & Muzikar 2001).

$$N_{26}(t) = N_{26inh}e^{-t/\tau_{26}} + P_{26}(z)\tau_{26}(1 - e^{-t/\tau_{26}}) \tag{3.13}$$

$$N_{10}(t) = N_{10inh}e^{-t/\tau_{10}} + P_{10}(z)\tau_{10}(1 - e^{-t/\tau_{10}}) \tag{3.14}$$

Equations 3.13 and 3.14 are a set of two equations for two unknowns, where the one unknown in the burial age t and the other is the erosion rate ε (Granger & Muzikar 2001). The initial concentrations are determined by equations 3.8 and 3.9.

The second approach to dating shallowly buried sediments is to analyse multiple samples from different depths in a vertical profile (Wolkowinsky & Granger 2004). In this case, one must assume that all of the samples have the same burial age, i.e., that the deposit being dated has a single age; however, it is not necessary that each sample have the same inheritance (Granger & Muzikar

2001, Granger 2006). Each sample will also have the same post-burial erosion rate of the sedimentary deposit (ε_{pb}) (Wolkowinsky & Granger 2004). Because the depth-dependence of cosmogenic nuclide production is well-constrained, one can evaluate the integral in equation 3.12 uniquely for multiple samples at different depths (Wolkowinsky & Granger 2004). Samples should be taken from sufficiently different depths so that there are significant differences in post-burial production of each sample (Granger 2006). The burial age of the deposit is determined using equation 3.12 to reproduce the AMS measured concentrations of the nuclides in every sample (Granger 2006). The best-fit age can then be determined by chi-square minimisation (χ^2) (Granger 2006). Profile dating is appropriate in many situations where sediment is rapidly deposited or buried, e.g., glacial outwash terraces (Wolkowinsky & Granger 2004) or rapidly buried palaeosols (Balco *et al.* 2005*a*, Balco *et al.* 2005*b*).

As numerical integration of equation 3.12 is tedious, Granger and Smith (2000) developed a simple analytical approximation that is suitable for estimating alluvial terrace deposit ages. Granger and Smith (2000) incorporated the exponential approximations of the last three terms of equations 3.4 and 3.5 into equation 3.12. The measured concentrations of ^{26}Al and ^{10}Be in a deposit undergoing constant erosion are then given by equation 3.15 (Granger & Smith 2000),

$$\begin{aligned} N_i = {} & N_{i,inh} e^{-t/\tau_i} \\ & + [P_n e^{-\rho z/L_0} / (1/\tau_i + \rho\varepsilon_{pb}/L_0)][1 - e^{-t(1/\tau_i + \rho\varepsilon_{pb}/L_0)}] \\ & + [Y_i A_1 e^{-\rho z/L_1} / (1/\tau_i + \rho\varepsilon_{pb}/L_1)][1 - e^{-t(1/\tau_i + \rho\varepsilon_{pb}/L_1)}] \\ & + [Y_i A_2 e^{-\rho z/L_2} / (1/\tau_i + \rho\varepsilon_{pb}/L_2)][1 - e^{-t(1/\tau_i + \rho\varepsilon_{pb}/L_2)}] \\ & + [B_i e^{-\rho z/L_3} / (1/\tau_i + \rho\varepsilon_{pb}/L_3)][1 - e^{-t(1/\tau_i + \rho\varepsilon_{pb}/L_3)}] \end{aligned} \tag{3.15}$$

where $A_1 = 170.6$ and $A_2 = 36.75$ at sea-level and high-latitude, $Y_{Al} = 4.24 \times 10^{-3}$ and $B_{Al} = 0.192$ for ^{26}Al and $Y_{Be} = 4.91 \times 10^{-4}$ and $B_{Be} = 0.023$ for ^{10}Be (Wolkowinsky & Granger 2004). These constants are adjusted for a ^{10}Be half-life of 1.34 Ma (Wolkowinsky & Granger 2004). The cosmogenic

nuclide concentrations can then be modelled by the use of the well constrained production rates and penetration lengths, and the variables t, z, N_{inh} and ε_{pb} (Granger & Smith 2000).

For a profile of samples taken from an alluvial terrace deposit the profile is then fit by χ^2 minimisation, solving for terrace age, the terrace erosion rate, and the inheritance of each sample (Wolkowinsky & Granger 2004). Deviations from this fit can be normalised by using the measurement uncertainties of the nuclides (Wolkowinsky & Granger 2004). A suitable way to display the goodness of fit between the data and the model is by plotting the χ^2 surface as a function of the model terrace deposit age and the model terrace erosion rate (Wolkowinsky & Granger 2004). The advantages of this approach are outlined by Granger (2006, 11):

1. *"The best-fit age and erosion rate are apparent by the minimum on the chi-square surface. Trade-offs between age and erosion rate are immediately apparent.*

2. *The reduced chi-square value can be used to quantitatively estimate the likelihood that the model fully explains the data. If a poor fit is obtained, then it is likely that the profile does not match the assumptions in the model. For example, the profile may consist of two separate deposits of different age.*

3. *The curvature of the chi-square surface can be used to reveal the uncertainty in the modelled age and erosion rate."*

One standard error of uncertainty is circumscribed on the χ^2 surface where it increases by one from its lowest value (Bevington & Robinson 2003, Granger 2006).

Accounting for post-burial production, as discussed above, is crucial in order to determine the true burial age of a piece of quartz. The importance of post-burial production depends on the inherited cosmogenic nuclide concentrations, depth of burial, and the age of the sample (Granger & Muzikar 2001). The longer the pre-burial exposure the smaller the effects of post-burial production

(Granger & Muzikar 2001). In South Africa quartz is normally exposed for a long period near the ground surface due to the very slow erosion rate, so inherited concentrations are high. For samples dating to the early and middle Pleistocene, a depth of five to ten metres is often sufficient (Gibbon *et al.* in press). For older samples, or in locations with high erosion rates, the burial depths must be greater.

3.4 Cosmogenic nuclide half-lives

Knowing the half-lives of both ^{26}Al and ^{10}Be with some degree of certainty is crucial for burial dating. Specifically, the uncertainty in the half-life of ^{10}Be has seriously affected the accuracy of burial dating in the past. The half-life of ^{26}Al is, however, more certain and is firmly established to within three percent (Granger 2006). For further discussion on the ^{26}Al half-life see Granger (2006).

Consensus on the ^{10}Be half-life has until recently not been achieved. Two values for the half-life have been adopted by the scientific community. The first is the ICN (ICN Chemical and Radioisotope Division) standard which is 1.51±0.06 Ma (Hofmann *et al.* 1987). The second is the NIST (National Institute of Standards and Technology) standard of 1.34±0.07 Ma (Granger 2006). Granger (2006) provides a complete discussion on the history of these two standards and suggests that the shorter half-life is more correct. Granger (2006) makes the important point that, when a decision is made to use the shorter half-life, all of the measurements must be changed as well, because they were measured against standards calibrated to the longer half-life. Hence all ^{10}Be concentrations must be lowered by 14% and similarily the ^{26}Al/^{10}Be ratio must be raised by 14% (Granger 2006).

Recently, there has been absolute calibration of the ^{10}Be AMS standards which has laid to rest the uncertainty (Nishiizumi *et al.* 2007). Nishiizumi *et al.* (2007) provided an independent calibration of the ^{10}Be standards by implanting a known number of ^{10}Be atoms in both Si detectors and Be foil targets. The ^{10}Be concentrations in these targets were then measured by AMS and the

results were compared with both of the standards. These authors found that the $^{10}Be/^{9}Be$ isotopic ratio of the ICN standard, which is based on the longer half-life, was 1.106±0.012 times lower than the nominal value (Nishiizumi *et al.* 2007). It was concluded that, since the decay rate of the ICN standard was well determined, the decrease in the $^{10}Be/^{9}Be$ ratio required that the ^{10}Be half-life be reduced to 1.36±0.07 Ma (Nishiizumi *et al.* 2007). Nishiizumi *et al.* (2007) also found that their measurement of the NIST standard agreed to within measurement of error of the certified value. Adjustment of the ^{10}Be half-life thus brings the $^{10}Be/^{9}Be$ ratios of the ICN standard into agreement with the NIST standard (Nishiizumi *et al.* 2007).

The shorter half-life of ^{10}Be ($t_{1/2}$ = 1.34±0.07 Ma) is thus adopted in this study, as the longer half-life no longer seems plausible in light of the recent absolute calibration. All data presented are thus corrected for use of the shorter half-life.

3.5 Uncertainties and limits of burial dating

The largest source of error in burial dating is given approximately by the fractional uncertainty in ^{26}Al and ^{10}Be measurement by AMS. The $^{26}Al/^{10}Be$ ratio is determined by measuring $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ with AMS (Granger & Muzikar 2001). Chemical methods are used to determine the concentration of the stable isotopes ^{27}Al and ^{9}Be. The analytical uncertainty in burial dating is given by the fractional uncertainty in the measured $^{26}Al/^{10}Be$ ratio multiplied by τ_{eff} (Granger & Muzikar 2001). For typical measurement uncertainties of 3 to 5%, this would lead to a 7% uncertainty in the nuclide ratio and an absolute uncertainty of 150 000 years. For this reason it is difficult to achieve an analytical uncertainty less than about 100 000 years except by analysing many samples. In addition, the chemistry used in sample processing introduces additional uncertainty. A different type of uncertainty is introduced by physical constants such as the radioactive meanlives. At present, the meanlives are known only to about 3 to 5%, leading to a systematic uncertainty of about

100 000 years (Granger 2006). The production rates, which vary with time, are also not known to better than several percent (Granger & Muzikar 2001). Together, these sources of uncertainty place a limit of about 100 000 years on the precision of burial dating.

The maximum range of burial dating is limited by radioactive decay of ^{26}Al. Its half-life is 0.717±0.017 Ma; after five million years the inherited ^{26}Al has decayed to less than 1% of its original value, making measurement difficult. As mentioned, for burial depths less than about thirty metres, nuclide production continues after burial due to the action of muons; thus after enough time radioactive decay will be balanced by production (Granger & Muzikar 2001). A range of four to five million years is thus the limit of the method.

In terms of dating alluvial terrace deposits, reworking of sediment in an alluvial setting can be problematic for burial dating, particularly when deposits are surrounded by other older alluvial sediments, each with its own unique burial history and associated cosmogenic nuclide concentrations (Gibbon *et al.* in press). Massive slumping of older deposits into a river and incorporation of that sediment into a terrace without re-exposure to cosmic radiation can cause burial dates to overestimate the age of the younger deposit (Balco *et al.* 2005*a*, Balco *et al.* 2005*b*). Similarly, reworking of sediment in a floodplain over time could provide misleading ages. To help overcome this problem numerous samples from the same deposit can be taken, including samples of individual large clasts (pebbles or cobbles), samples of sand that contain thousands of grains, as well as amalgamated samples of sands and larger clasts. In samples of sand or amalgamated gravels, even if a small percentage of the grains have had a complicated burial history, this will then be averaged out in the larger sample. Consistency among samples taken from the same deposit, comprised of varying clast categories, provides confidence in the ages and indicates that reworking is not a major problem. Dating of the older deposits is also helpful as a check for sediment reworking, and dating of modern river sediment can indicate whether sediment is being reworked at the present day.

3.6 Sample processing procedure

The procedure to process sediment samples from alluvial deposits for burial dating is summarised below. Sample processing initially involves purifying quartz through a series of chemical and physical treatments. The Al and Be are then extracted and separated out. Samples consist of sands; amalgamated sands or larger clasts; and individual large clasts obtained from the alluvial deposits. The procedure is outlined below and follows Wolkowinsky and Granger (2004):

1. Clasts larger than the sand fraction are firstly crushed to 0.25 to 0.5 mm.
2. Samples are then sieved in order to separate into the different size fractions. 0.25 to 0.5 mm is the ideal grain size for the subsequent chemistry, so this fraction is separated out at this time.
3. Samples are then rinsed in deionised water in a beaker. This step removes a large portion of the lighter materials (clays and organic matter) that remain in suspension immediately after rinsing. This material is then poured off before it has time to settle.
4. Samples are then leached in aqua regia. This involves soaking the sample in a diluted solution of HCl/HNO_3 (usually 1:1, acid to water) in order to remove carbonates.
5. Mafic minerals are then separated magnetically, using a magnetic separator.
6. Heavy minerals are then separated from the quartz in lithium metatungstate (Heavy Liquid).
7. All samples are then leached in a 1% solution of HF/HNO_3, and agitated on commercial hot-dog rollers.
8. Samples are subsequently leached in the same solution in an ultrasonic bath. Both this and the previous step remove aluminosilicates and meteoric ^{10}Be (Kohl & Nishiizumi 1992).

9. A purified sample of 25 to 50 g quartz is then dissolved in 5:1 HF/HNO_3.

10. This solution is then spiked with 0.4 to 0.8 mg Be in a carrier solution prepared from beryl.

11. An aliquot is taken from this solution for aluminium determination by absorption spectrophotometry. As discussed above, determination of the concentration of the stable isotopes ^{27}Al and ^{9}Be is by chemical methods.

12. Once the solution has been dried down on a hotplate, fluorides are removed by repeated fuming in H_2SO_4.

13. Iron is then removed by ion exchange in 10 N HCl.

14. Al and Be are then separated using ion chromatography in oxalic acid on a cation exchange column.

15. Al and Be are then precipitated as hydroxides and rinsed in water, and then oxidised at 1100°C in a furnace.

16. Al_2O_3 and BeO are then mixed with silver and niobium, respectively, for AMS analyses.

17. $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ ratios are then measured by AMS at PRIME Lab, Purdue University.

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In the next chapter, the burial ages of the fluvial remnants preserved in the lower Vaal River catchment, determined using the cosmogenic nuclide burial dating technique, are presented.

Chapter 4

Dating of the alluvial deposits of the lower Vaal River catchment

4.1 Introduction

In this chapter the cosmogenic nuclide burial dating data are presented for the various Vaal River alluvial terrace deposits. Sampling was focused at the type-site at Windsorton, although other locations were also sampled (Figures 4.1 and 4.2). Study of the deposits at Windsorton has formed the basis for all previous findings on the fluvial history, thus sampling needed to be focused here. However, terrace deposits both up- and downstream, as well as tributary deposits, were also sampled to investigate the larger catchment-wide timing of fluvial events. As discussed in the previous chapter, various clast categories were sampled to test for reworking of older alluvium into younger deposits. Duplicate samples were only taken in the form of stratigraphic sampling of a specific deposit. These samples should be close in age and in stratigraphic order. This sampling strategy allows for verification of the technique, as well as generating as much data as possible given the expense of burial dating. This approach eliminates the need to duplicate a single sample.

Burial ages were determined following procedures outlined in the previous chapter and are discussed further below. Tables 4.2, 4.3, 4.4 and 4.5, at the end of this chapter, provide all data for each cosmogenic nuclide burial dating

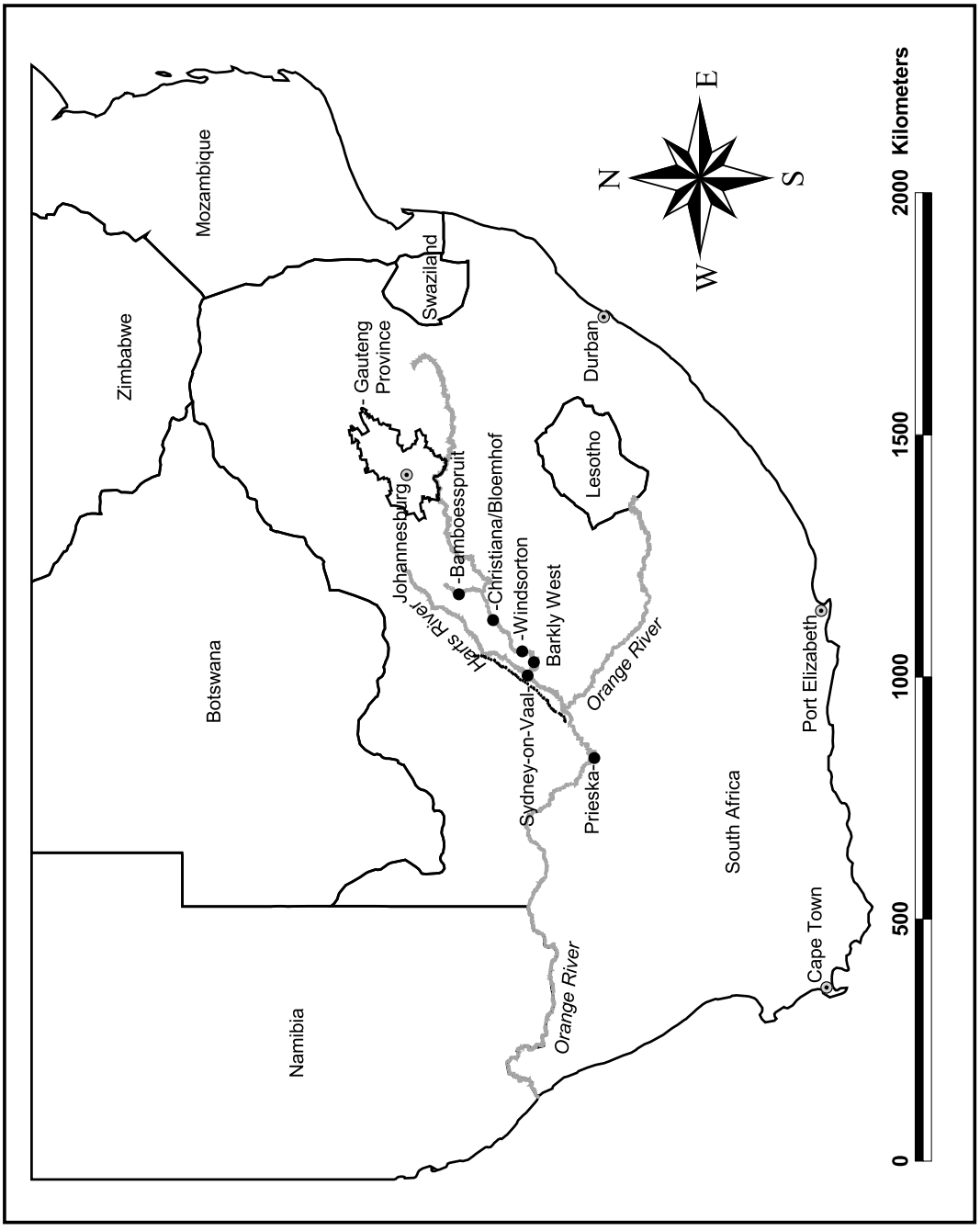


Figure 4.1: Map of South Africa and neighbouring countries showing locations of sites referred to in the text. Cosmogenic nuclide burial dating samples were collected from the Bamboesspruit; Christiana/Bloemhof; Windsorton; Barkly West; Sydney-on-Vaal; and along the middle Orange River between the Vaal/Orange confluence and Prieska.

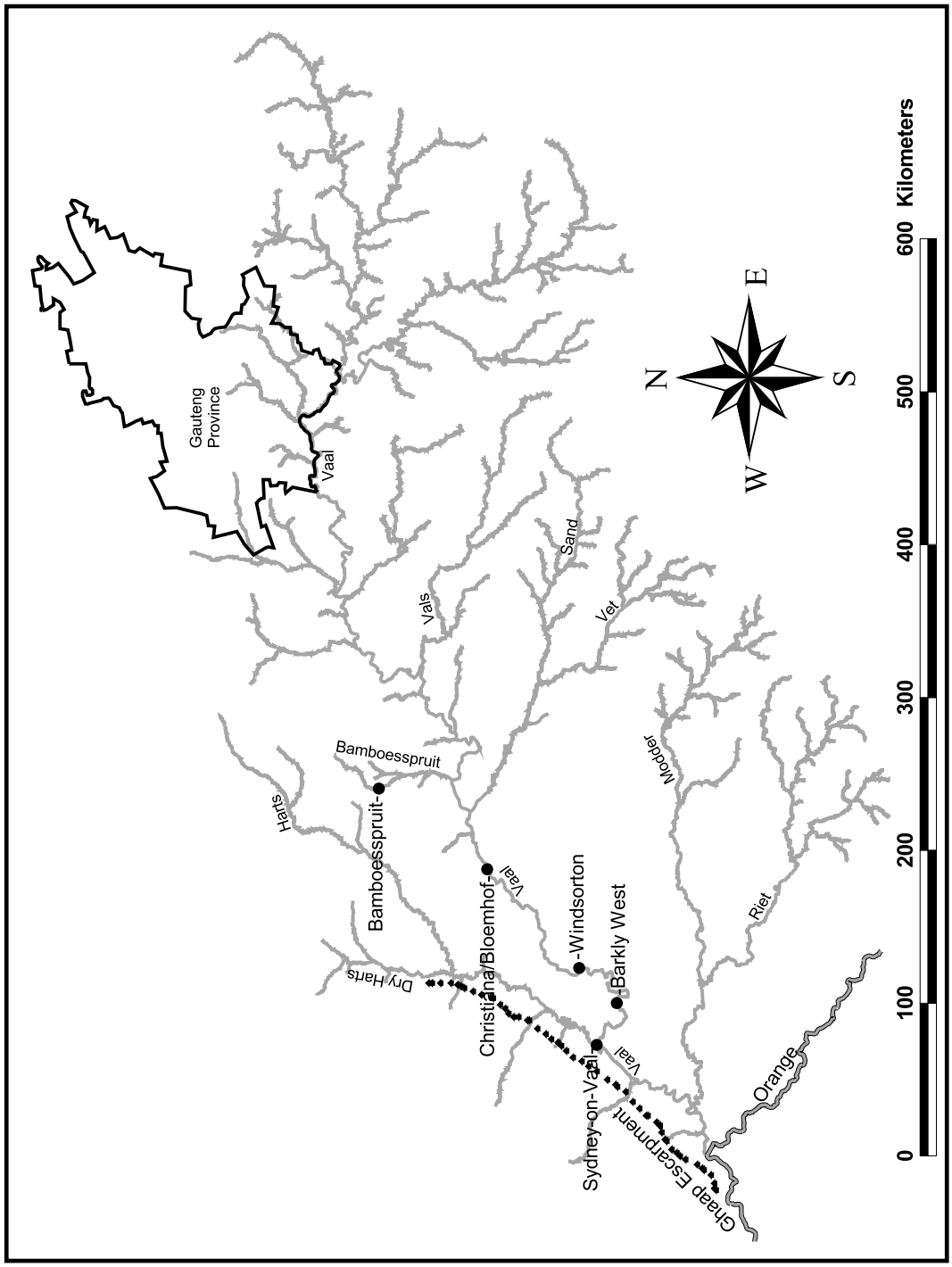


Figure 4.2: The Vaal River catchment showing locations of sites referred to in the text. Cosmogenic nuclide burial dating samples were collected from the Bamboesspruit; Christiana/Bloemhof; Windsorton; Barkly West; and Sydney-on-Vaal.

sample. In addition, section photographs (Figures 4.10 to 4.22) of each pit within the alluvial terrace deposits from which dating samples were collected, are similarly displayed at the end of the chapter. At this time, however, it is important to briefly discuss the data provided in each of the tables.

Table 4.2 This table firstly defines sample names which are used in the other tables. These names are also used for reference in the text. In addition, information on the site location, and a description of the nature of the sample is also provided. Cosmogenic nuclide burial dating samples consisted of either sands; amalgamated sands or larger clasts; or individual large clasts obtained from the alluvial deposits (see Figure 4.9 at the end of the chapter). Finally, one column indicates if the sample is problematic in terms of the burial age obtained.

Table 4.3 This table provides a description of each sample's location within the alluvial deposit, as well as the depth of the sample below the modern surface. In addition, the measured concentrations of both ^{26}Al and ^{10}Be by AMS, as well as the errors, are provided. The concentration of ^{10}Be was measured against standards prepared by Kuni Nishiizumi and normalized for a ^{10}Be half-life of 1.34 Ma (as discussed in the previous chapter). The final two columns provide the measured ^{26}Al/^{10}Be ratio and measurement error for each sample. ^{26}Al/^{27}Al and ^{10}Be/^{9}Be ratios used to determine the concentrations of each nuclide were measured by AMS at PRIME Lab, Purdue University.

Table 4.4 This table provides the maximum and minimum ages for each sample, following procedures discussed in the previous chapter. Ages were calculated using ^{10}Be half-life of 1.34 Ma and ^{26}Al half-life of 0.72 Ma. Uncertainties reflect measurement error only. To calculate systematic errors related to half-lives add 6% uncertainty in quadrature. It is assumed that samples were deposited with ^{26}Al and ^{10}Be concentrations in equilibrium with erosion rates in the watershed, and that the gravel and sand was buried quickly with respect to radioactive decay. The percentage of nuclides in each sample produced by post-burial production, assuming

no erosion of the alluvial deposit since aggradation, is also provided in this table.

Table 4.5 This table provides the bedrock depth for each pit from which dating samples were obtained, in relation to bedrock height above the modern river level. Similarly, the alluvial terrace surface height is given in relation to the modern river level. Heights were determined from 1:10 000 ortho-photos where available, and were supplemented by 1:50 000 topographic maps where necessary, and should only be used as a rough guide. Surface production rates of both ^{26}Al and ^{10}Be for each site were calculated following procedures discussed in the previous chapter. Production rates of the nuclides were scaled to each sample's location, in respect to latitude and elevation, following Stone (2000). Production rates of each nuclide, the latitude of each site, and height above sea level is thus provided in the table. The estimated density of each alluvial deposit is also provided and incorporated into the burial dating calculations. A density of 1.9 g/cm^3 has been assigned to deposits with an overburden of fine alluvium, while a density of 2.1 g/cm^3 has been assigned to deposits composed of larger clast fractions (pebbles, cobbles and boulders) bounded by a sand matrix. Finally, the calculated average inherited erosion rate for each sample is given.

Burial dating samples were only obtained from alluvial deposits of the Holpan, Proksch Koppie, and Wedburg terraces, as well as the Rietputs Formation. The older Cretaceous deposits and younger Riverton Formation deposits do not form part of the current study.

4.2 Rietputs Formation

4.2.1 Introduction

Previous attempts to date the Rietputs Formation have been based on relative dating techniques. The Rietputs Formation contains both stone artefacts and

fossils and has previously been assigned a middle Pleistocene age (Klein 2000) based largely on the presence of *Elephas recki* (Reck's Elephant) and *Metridiochoerus andrewsi* (giant warthog). However, locations of most fossils within the gravels are poorly documented (Helgren 1977*b*). Moreover, recent work (Todd 2005) has highlighted the potential unsuitability of *E. recki* for faunal dating, rendering the age assignment uncertain, and *M. andrewsi* is now known to be late Pliocene/Early Pleistocene in age, with a range of 1.6 to 2.95 Ma in East Africa (White 1995).

Cosmogenic nuclide burial dating of the Rietputs Formation was specifically focused on the type-site at Windsorton. Extensive sampling undertaken at the type-site provides a good age model for the Rietputs Formation; thus these burial ages are presented separately from samples collected both up- and downstream. Similarly, samples from Rietputs Formation equivalent deposits, located along a north bank tributary (Marshall 1990), are presented separately. All of these other sites are then compared to the type-site at Windsorton.

4.2.2 Windsorton type-site

Table 4.1 contains data obtained from Tables 4.3 and 4.4. The dating samples in Table 4.1 provide the age model for the type-site and thus are presented in a separate table. Three other Rietputs Formation samples (w6a, w1b and w5b) from the type-site produced problematic ages. These three samples are presented separately, with discussions provided to explain the problematic results.

Exposures from active diamond mining near the town of Windsorton show that the Rietputs Formation includes a lower coarse gravel and sand unit, covered by laminated and cross-bedded fine alluvium with laterally discontinuous palaeosols (Figures 4.10 to 4.13a) (Gibbon *et al.* in press). The gravels range up to seven metres thick, with the total deposit reaching depths locally up to 19 metres to bedrock (Figure 4.3).

Five pits (numbered 1 to 5), opened for diamond mining within an area of

Figure 4.3: A section through the Rietputs Formation at the type-site at Windsorton showing the older lower coarse alluvium capped by the younger upper fine alluvium. Note person for scale near bottom left.

Table 4.1: Cosmogenic nuclide concentrations and burial ages for the type-site at Windsorton.

Sample name	**Sample depth (m)**	**[^{26}Al] 10^6 at/g**	**[^{10}Be] 10^6 at/g**	**Max Age (Ma)**	**Min Age (Ma)**	**Sampling location description**
w1a	7	2.07±0.16	0.75±0.02	1.89±0.19	1.72±0.16	LCA*
w2a	10	3.07±0.26	0.86±0.02	1.26±0.19	1.19±0.17	UFA$^\diamondsuit$
w2b	13.5	3.03±0.20	0.86±0.03	1.27±0.15	1.22±0.14	top of LCA
w2c	15.3	2.91±0.30	0.85±0.03	1.34±0.22	1.29±0.21	LCA
w2d	16	2.92±0.23	0.90±0.03	1.42±0.17	1.37±0.16	LCA
w3a	7.7	3.33±0.23	0.92±0.03	1.24±0.16	1.16±0.15	UFA
w3b	14	2.66±0.23	0.91±0.04	1.64±0.20	1.57±0.19	LCA
w4a	12	2.73±0.19	0.97±0.02	1.72±0.15	1.64±0.14	LCA
w5a	15	1.26±0.12	0.35±0.01	1.43±0.23	1.32±0.21	LCA
*LCA - lower coarse alluvium $^\diamondsuit$UFA - upper fine alluvium						

about five square kilometres, were sampled for dating (Figure 4.4). Seven sand, one amalgamated pebbles and cobbles, and one individual cobble sample (Table 4.2) were collected at depths ranging from 7 to 16 metres. Six samples from the lower coarse alluvium have an average burial age of 1.57±0.22 Ma and three samples date the upper fine alluvium to 1.26±0.10 Ma (Figure 4.5, Table 4.1) (Gibbon *et al.* in press). The quoted uncertainties include both measurement error and the standard deviation of the data, added in quadrature. The standard deviation is reported rather than the smaller standard error of the mean because it is believed that the spread in the data reflects true variability in the age of the deposit associated with a prolonged period of gravel deposition. Burial dates from each pit are in stratigraphic order (Figure 4.5a). However, the spread in burial ages among different pits suggests that sediment deposition occurred over a time span of several hundred thousand years. A cumulative probability density function of the burial ages is shown in Figure 4.5b. The data indicate that gravel deposition dominated from *ca* 1.8 to 1.35 Ma,

with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma (Gibbon *et al.* in press).

Table 4.1 provides a maximum and minimum age for each of the samples. The maximum age calculation assumes that the depth of burial of the sample has not changed since aggradation of the alluvial deposits. The current depth is then used to calculate the influence of secondary cosmic ray muons, and the age is calculated using equations 3.13 and 3.14. The average contribution of post-burial nuclide production is 7.5% for all the samples, with values ranging from 4.3 to 16% for individual samples (see Table 4.4). The minimum age calculation assumes that the top of the deposit has undergone fast and continuous erosion since deposition, such that the sample's depth of burial is much reduced today, following equation 3.10. In effect, this calculation disregards post-burial production and follows the simplest burial history model that assumes that production ceases with burial, followed only by decay. The maximum and minimum ages are within measurement error of each other; however, the maximum ages will be closer to the true age. There is no evidence that the terrace deposits have undergone much erosion, so it is more appropriate to use the more conservative maximum age for the deposits. The ages are consistent with the presence of *M. andrewsi* in the gravels, with its last appearance date in East Africa of 1.6 Ma (White 1995).

Figure 4.6 shows a scatter plot of the measured concentrations of ^{26}Al and ^{10}Be for each burial dating sample. Figure 4.7 shows a scatter plot of the measured ratio of ^{26}Al/^{10}Be to ^{10}Be concentrations for each burial dating sample. These two plots provide a useful means of evaluating the integrity of the nuclide data. Samples w1a, w2a-d, w3a-b and w4a all contain similar concentrations of the nuclides (Figure 4.6). These samples, except for w4a, consisted of sand, either obtained from the upper fine alluvium or from the sand matrix that surrounds the larger clasts in the lower coarse alluvium (Figure 4.9). Sample w4a consisted of amalgamated pebbles and cobbles. Sample w5a, which was an individual cobble, contains much lower concentrations of the nuclides (Figure 4.6), indicating that it had a different inherited erosional history prior to burial compared to the other samples. This can be seen quite clearly in

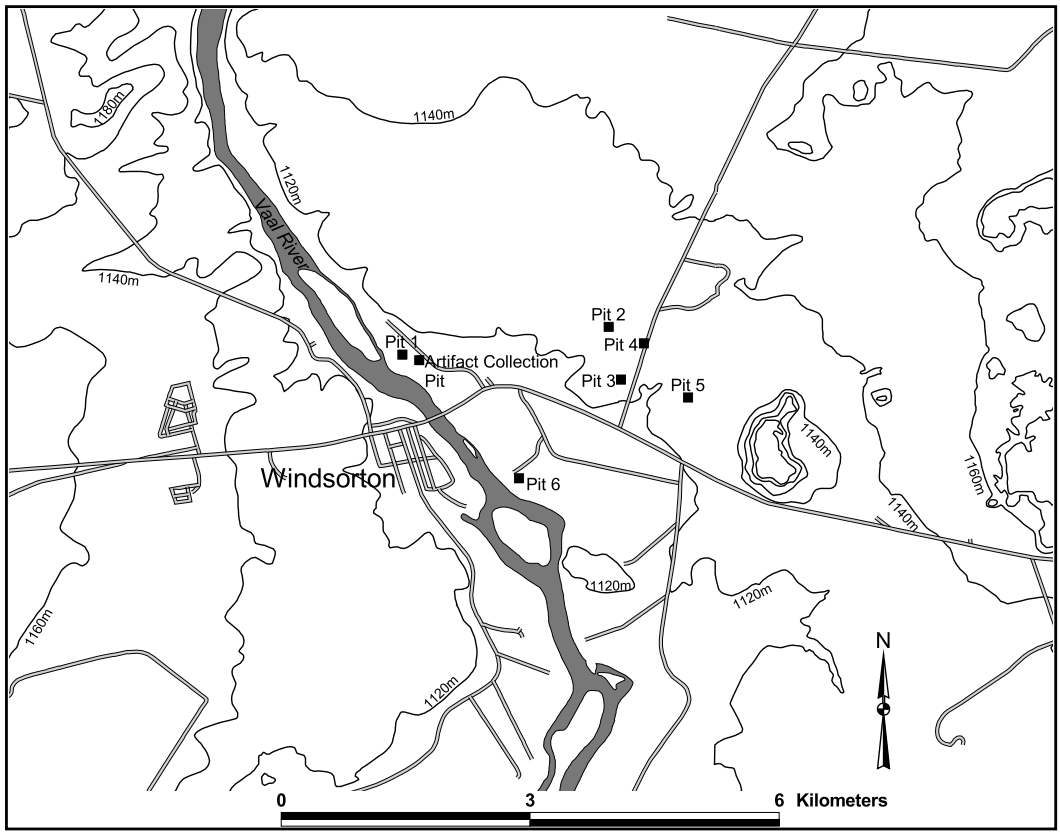
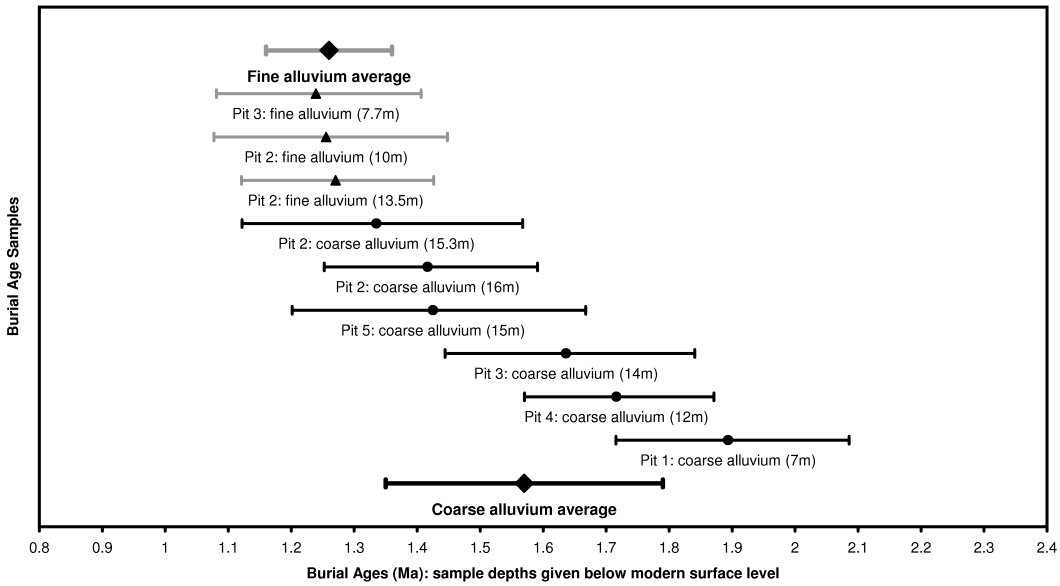
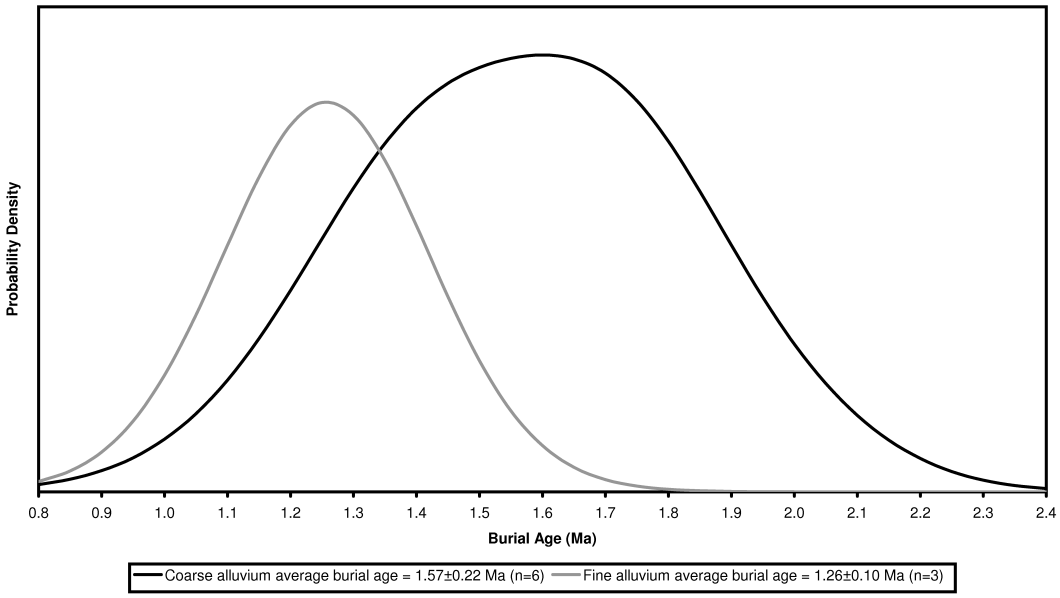


Figure 4.4: Type-site of the Rietputs Formation near to the town of Windsorton, Northern Cape Province, South Africa. The Rietputs Formation occurs along both sides of the river but is more extensive on the east. Riverton Formation deposits are situated along the immediate river banks. The 'older gravel' deposits are found to the west of the river at increasing altitudes, with a few remnants of the Wedburg terrace deposits sitting on bedrock pedestals above the Rietputs and Riverton Formations on the east bank. Mining pits from which cosmogenic nuclide burial dating samples were obtained are numbered, as well as the pit from which stone artefacts were collected (discussed later).



(a) Burial ages showing errors for the Rietputs Formation. Ages are in stratigraphic order for individual pits. The average burial age for both the fine and coarse alluvium is shown.



(b) Cumulative probability density function showing that coarse gravel deposition dominated from *ca* 1.8 to 1.35 Ma, with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma.

Figure 4.5: Cosmogenic nuclide burial data for the type-site at Windsorton

Table 4.5, where the calculated inherited erosion rate for w5a is approximately three times higher than for the rest of the samples. Most likely the w5a cobble was eroded more rapidly from one of the older alluvial terrace deposits near to the river, in comparison to the slower erosion of quartz bearing bedrock within the catchment. This would explain the lower concentrations of the nuclides. The alluvial sand samples, and the amalgamated pebbles and cobbles sample, however, were most likely derived from the slow erosion of quartz rich rocks higher in the catchment. Their slower erosion and subsequent transport to streams and eventually down the Vaal River allowed for suitable time for higher concentrations of the nuclides to be produced prior to burial.

Figure 4.7 which plots the ratio of $^{26}Al/^{10}Be$, and thus essentially compares the ages of each sample, shows that although the nuclide concentrations of w5a were lower prior to burial the cobble still has the same burial age as the rest of the samples. Even though w5a started with lower concentrations of the nuclides, the post-burial component is not high as this sample was deeply buried and thus well protected from secondary cosmic ray muons (see Table 4.4 and Figure 4.13a).

In terms of the calculated inherited erosion rate for each of the samples (excluding w5a) values range from 189 to 286 cm/Ma (Table 4.5), with an average of 249 cm/Ma. The data are very consistent and indicate that during the span of the Rietputs Formation the Vaal River catchment was eroding at an approximate rate of 2.5 metres per million years.

In conclusion, although there are large errors associated with cosmogenic nuclide burial dating at the type-site, the data indicates that the gravel deposits of the lower coarse alluvium were deposited from *ca* 1.8 to 1.35 Ma, with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma. This age model will be used as the basis of the timing of the Rietputs Formation aggradation, with samples collected from other locations along the Vaal River and a tributary, compared to this data in the following sections.

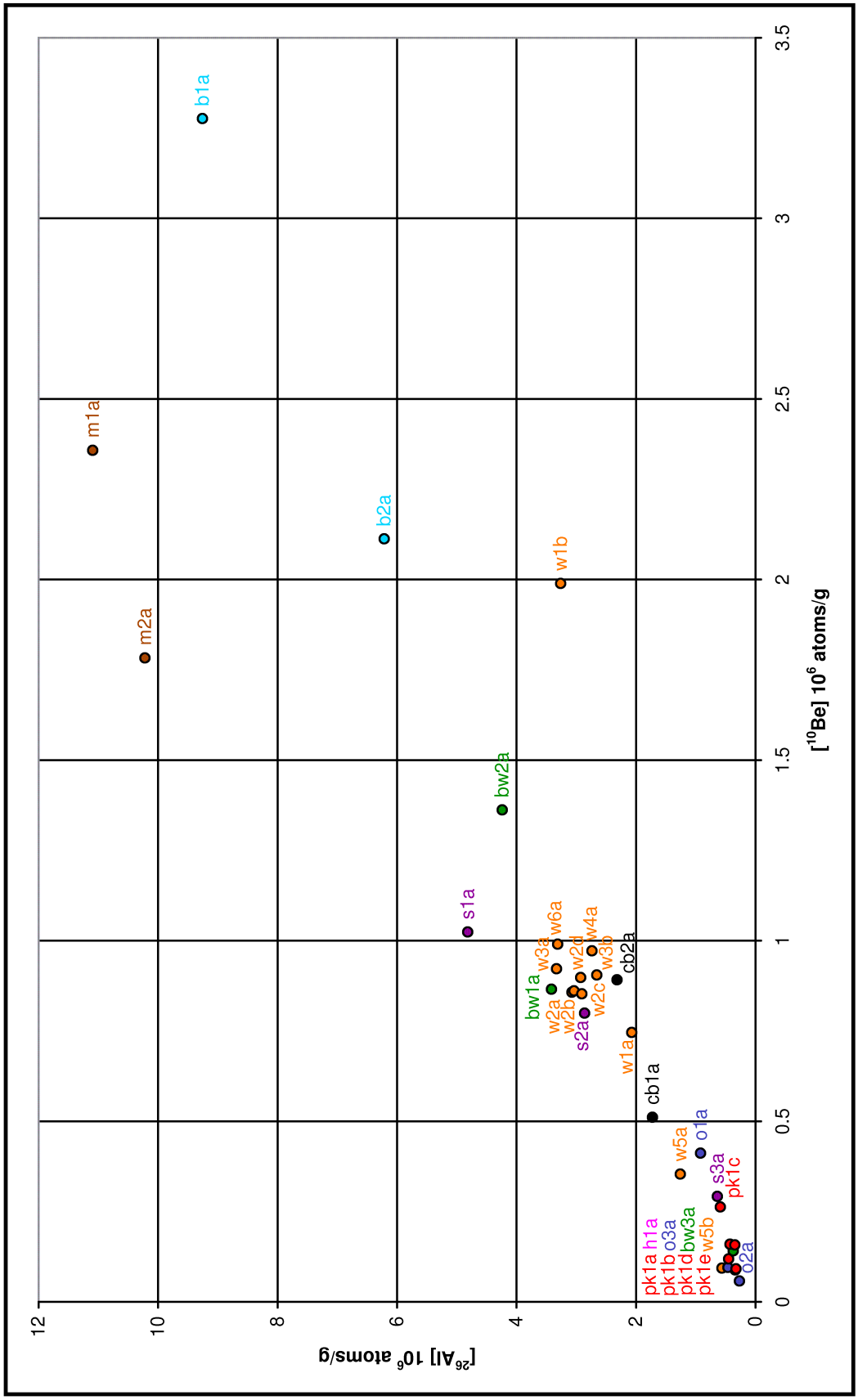


Figure 4.6: Scatter plot of the measured concentrations of ^{26}Al and ^{10}Be for each burial dating sample.

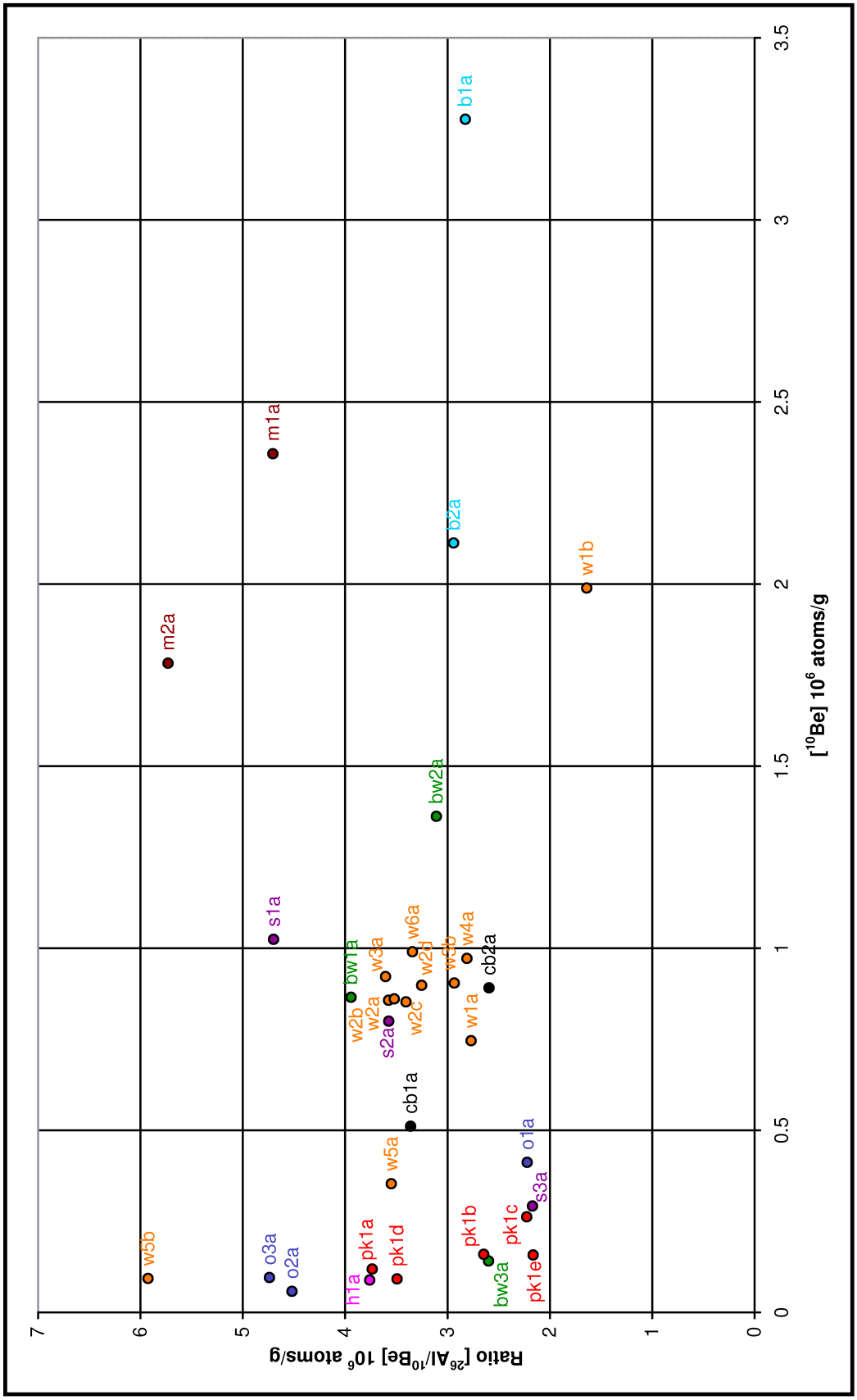


Figure 4.7: Scatter plot of the measured ratio of ^{26}Al/^{10}Be to ^{10}Be concentrations for each burial dating sample.

4.2.2.1 Windsorton type-site problematic burial ages

Windsorton sample w6a This sample was collected at Pit 6 from the type-site (Figure 4.4). It was collected from a depth of three metres below the top of the lower coarse alluvium (Figure 4.13b) and has a maximum age of *ca* 1.84±0.29 Ma and a minimum age of *ca* 1.30±0.16 Ma (Table 4.4). Unlike samples collected from Pits 2-5, where the lower coarse alluvium is capped by the younger upper fine alluvium, the lower coarse alluvium at Pit 6 is capped by the substantially younger Riverton Formation alluvial deposits or wind blown Hutton sands. In Figure 4.13b the trees in the background are located along the immediate banks of the modern Vaal River. The lower coarse alluvium continues to the river. Due to its location right next to the river, it appears that the upper fine alluvium has been eroded away by fluvial and colluvial activity in this higher erosional setting. Only a portion of the original lower coarse alluvium is probably preserved. At a later time the Riverton Formation deposits or Hutton sands have capped these Rietputs Formation gravels. A similar situation has occurred at Pit 1, which is also located near to the modern river (Figures 4.10 and 4.4). Although at Pit 1 the upper fine alluvium has also been eroded, the lower gravel deposits have been less eroded and are much thicker providing good shielding from cosmic radiation.

In determining the burial age from the w6a sample, a depth of three metres must be used to calculate the influence of secondary cosmic ray muons, as the precise burial history is not known. As a result the maximum and minimum ages are substantially different (Table 4.4), and the influence of post-burial production due to insufficient burial can clearly be seen. It can be seen in Table 4.4 that the percentage of nuclides from post-burial production is a very high 76%. This indicates that the burial age obtained is problematic and should probably not be used.

However, it can be seen in Figure 4.6 that the concentrations of the nuclides are very similar to the rest of the samples collected from the type-site. In addition, Figure 4.7 shows that the ratio of the nuclides is also similar to the other samples. It can thus be concluded that a general age determination

from sample w6a is possible, and that the true age of the deposit is most likely closer to the minimum age. The erosion of the upper fine alluvium and probably some of the lower coarse alluvium has likely occurred relatively recently (during Riverton Formation times). A general burial age (nearer to the minimum age) is consistent with the age model for the Rietputs Formation proposed above. In addition, the calculated inherited erosion rate for w6a (234 cm/Ma) is consistent with the rest of the samples from the type-site.

Windsorton sample w1b This sample was collected from Pit 1 and consisted of amalgamated pebbles and cobbles. It was collected from the base of the lower coarse alluvium (Figure 4.10) and has a maximum age of *ca* 2.52±0.25 Ma and a minimum age of *ca* 2.37±0.22 Ma (Table 4.4). These ages are clearly inconsistent with the Rietputs Formation age model. There are two possible explanations for this discrepancy.

Firstly, as this sample consisted of amalgamated pebbles and cobbles, it is possible that these larger clasts were quickly eroded from an older alluvial deposit lining the river bank. This could happen in a situation where there is massive collapse of the river bank and incorporation of the larger clasts into the aggrading alluvial deposit, without sufficient re-exposure to cosmic radiation. The lighter, finer sediments (i.e. sands and finer fractions) were most likely washed away. In this situation the burial age would overestimate the age of the deposit.

Secondly, if one examines the concentrations of the nuclides in the sample (Figure 4.6), it is apparent that w1b contains an ^{26}Al concentration that is consistent with the rest of the Rietputs Formation samples. However, the ^{10}Be concentration is elevated. Firstly, it is possible that during sample processing meteoric ^{10}Be in the sample, produced by exposure to rain water was not completely removed in the leaching process in the ultrasonic bath (Kohl & Nishiizumi 1992). The measured concentration thus consisted of both *in situ* produced ^{10}Be in the quartz and meteoric ^{10}Be adhering to minerals in the sample. Secondly, the sample may have been contaminated by meteoric ^{10}Be during sample processing. In either situation the result would be the same: an

incorrect ratio would be measured and an incorrect burial age obtained.

Windsorton sample w5b This sample consisted of an individual quartzite cobble obtained from Pit 5 lower coarse alluvium. This sample has a maximum age of *ca* 0.33±0.38 Ma and a minimum age of *ca* 0.28±0.27 Ma (Table 4.4). Clearly the burial age obtained in problematic, and at odds with sample w5a collected from the same pit. Sample w5b contains extremely low concentrations of both ^{26}Al and ^{10}Be (Figure 4.6), but a high ^{26}Al/^{10}Be ratio (Figure 4.7). A possible scenario explaining the data is provided below.

As discussed for sample w1b, it is possible that the w5b clast was rapidly exposed from an older alluvial terrace deposit such as the Proksch Koppie terrace. This could happen in a situation where there is massive collapse of the river bank. Sample w5b contains similar concentrations to the Proksch Koppie samples (Figure 4.6). After the clast was rapidly eroded it is possible that it was exposed at the surface for a short period of time. As the production rate of ^{26}Al is nearly seven times as much as ^{10}Be, this short exposure period pushed up the ratio compared to the Proksch Koppie samples (Figure 4.7); however concentrations still remained low. If the clast was rapidly eroded from the top few meters of a Proksch Koppie terrace deposit, then the ratio would have already been slightly elevated due to a reduced burial depth and increased production rates. An example of this would be the shallowest buried sample (pk1a) from the Proksch Koppie terrace (Figure 4.6 and 4.7). The w5b clast was subsequently buried deeply in the Rietputs Formation. It's measured concentrations have an elevated ratio when compared to the other Proksch Koppie samples due to the short time it was exposed which would have pushed up the ^{26}Al concentration. If one considers that sample processing chemistry and measurement errors may also have caused an increase in the measured ratio, then it becomes apparent that sample w5b is really not that different from the rest of the Proksch Koppie samples.

The possible scenario presented above, as well as presented for sample w1b, emphasises the fact that individual large clasts are not ideal for obtaining burial ages for alluvial deposits in the Vaal River catchment. When the larger clasts

have been eroded from older terrace deposits, which can occur very rapidly, then they may not have been exposed for a sufficient period of time at the surface to obtain suitable concentrations of nuclides. The burial ages obtained then either overestimate the age of the deposit, as in sample w1b, or provide an erroneously young age if the clast was obtained from a very old deposit, such as the Proksch Koppie terrace.

4.2.3 Evaluating problematic burial ages

At this point it is important to outline the procedure for evaluating and identifying problematic burial ages from accurate ones. This evaluation is needed as it must be demonstrated that the processes which have caused problematic results have not affected the accepted (accurate) ages in a similar way, although in this case it would be in a far more systematic way. Without this critical evaluation it is uncertain if these processes could have caused the error margins for all the cosmogenic nuclide burial dates to be increased.

The two key processes which affect the robustness and accuracy of burial dating are: the rapid reworking of clasts from older terrace deposits and burial depth change through erosive processes since the deposit was aggraded (i.e. depth of burial has decreased over time due to the erosion of the alluvial deposit). These two processes have been proposed to explain the Windsorton type-site problematic burial ages above.

In terms of burial depth change (i.e. insufficient burial depth), the effect of this process is easy to model and evaluate. The maximum age calculation models the post-burial component based on the samples current depth of burial from which it was collected. This calculation determines if the post-burial component is significant and indicates if an incorrect age has been obtained or if there is a larger error margin. As discussed in Chapter 3, the importance of post-burial production depends on the inherited cosmogenic nuclide concentrations, depth of burial, and the age of the sample (Granger & Muzikar 2001). The longer the pre-burial exposure the smaller the effects of post-burial production (Granger & Muzikar 2001). In a slowly eroding landscape (less than 5m/Ma)

quartz bearing bedrock will have high cosmogenic nuclide concentrations. If this quartz is subsequently buried in an alluvial deposit of younger than 2 Ma, an age determination would be possible even if the sample was buried by only five metres. On the other hand, in a landscape with high erosion rates (greater than 20m/Ma), an alluvial deposit of the same age would only be able to be dated if a sample could be obtained from a much deeper depth (i.e. over ten to fifteen metres).

It is thus clear that each sample taken for burial dating, which will invariable have different initial cosmogenic nuclide concentrations due to differing erosional histories, must be modelled to determine the percentage of nuclides due to post-burial production. This has been done for all the samples in this study and the data are presented in Table 4.4. As a rule of thumb if the percentage of nuclides from post-burial production is less than 20% then the date should be considered accurate as long as the post-burial component is accounted for in the burial age calculation. Higher than 20% and the age obtained must be considered with caution. In conclusion, the maximum age calculation provides an accurate means to demonstrate if a problematic burial age is obtained or not. As discussed above, the average contribution of post-burial nuclide production for the type-site samples is 7.5%, indicating that the ages obtained are robust and accurate.

Before proceeding with a discussion on how to evaluate the effect of rapid reworking of clasts from older terrace deposits, it is important at this point to state exactly how many cosmogenic nuclide burial dating samples are problematic in the study. In terms of the Rietputs Formation and equivalent deposits a total of 20 samples were collected. 15 of these are considered to be robust and accurate. Of the five problematic samples, two (w6a and cb2a) were collected from depths that were just too shallow for burial dating. In hindsight these samples should not have been collected. However, as discussed above, as one can only determine what a suitable depth of burial is, depending on both the age of the deposit being dated and the inherited cosmogenic nuclide concentrations, these samples were collected. Only after AMS analyses could it be determined that the depth of burial was insufficient for an age to be obtained.

Removing these two samples leaves a total of 18 with only three of these being problematic, a total of 17% of the samples. The remainder of all the burial dating samples which are problematic are the result of the samples coming from deposits that are older than the applicable age range of the dating technique using the single sample dating approach. The profile dating approach used for the Proksch Koppie terrace eliminates this problem. In hindsight again, these older deposits should probably not have be sampled, but as no reliable age determination was available they needed to be sampled for dating.

In demonstrating if there could have been rapid reworking of clasts from older terrace deposits which will have affected the ages obtained, one has to consider the cosmogenic nuclide data in conjunction with geological data, and in the case of the Rietputs Formation one also needs to consider the archaeological data. Samples w1b and w5b, discussed above, can be used to demonstrate this approach. w1b has a maximum age of *ca* 2.52±0.25 Ma and a minimum age of *ca* 2.37±0.22 Ma, while w5b has a maximum age of *ca* 0.33±0.38 Ma and a minimum age of *ca* 0.28±0.27 Ma. Firstly, these ages are inconsistent with the Stone Age archaeology preserved within the deposits. The Rietputs Formation contains Acheulean stone artefacts that are only found between *ca* 1.7 and 0.5 Ma on the African continent (Klein 2000). The age for w1b is thus clearly too old and similarly the age for w5b is too young. This is the first indication that the ages could be incorrect. If one then considers the cosmogenic nuclide data, it becomes apparent that both samples differ greatly from the rest of the Rietputs Formation samples (Figure 4.6 and 4.7). One does not expect the concentrations of the cosmogenic nuclides for each sample to be the same, in fact they will most of the time differ, but one does not expect them to differ so substantially if the all the samples were obtained from the same catchment, which would have undergone similar erosional rates. Sample w5b has very low concentrations of both ^{26}Al and ^{10}Be, while w1b has a high concentration of ^{10}Be. The very low concentrations of w5b indicate immediately that the sample was not exposed at the surface for a sufficient period of time in order to gain a suitable concentration of nuclides to make burial dating possible. Rapid reworking of clast from older terrace deposits provides the explanation as to

why the sample produced a problematic age. Normal erosion rates within the catchment are sufficiently slow so that if the w5b clast had come from normal bedrock erosion it would have had very high concentrations of the nuclides and would have been ideal for burial dating. Sample w1b on the other hand in more problematic to explain to a single process. As stated above it could be either rapid reworking of clasts or contamination of the sample during processing. In either case its nuclide concentrations are at odds with the rest of the catchment and thus the date obtained should be used with caution. It can thus be seen that one can evaluate the likelihood that a sample has undergone rapid reworking from an older terrace deposit which has resulted in an incorrect age being obtained.

In conclusion, it can be seen that it is simple to evaluate and demonstrate if the processes of the rapid reworking of clasts from older terrace deposits and burial depth change through erosive processes have affected a sample for burial dating. If either of these processes are identified then the age obtained must be considered with caution. If it is similarly identified that these processes have not been involved then it is appropriate to considered the age obtained robust and accurate, and there is no need to consider that there will be larger error margins for these samples.

4.2.4 Christiana/Bloemhof

Two samples were collected from Rietputs Formation deposits between the towns of Christiana and Bloemhof, approximately 110 kilometres upstream of the Windsorton type-site (Figure 4.2). Deposits here were similar to those found at Windsorton. A lower coarse gravel and sand unit was again covered by laminated and cross-bedded fine alluvium with laterally discontinuous palaeosols (Figure 4.14a and b). Burial dating data on each of the samples discussed below is given in Tables 4.2 to 4.5.

4.2.4.1 Christiana/Bloemhof sample cb1a

This sample was collected from the base of the lower coarse alluvium (Figure 4.14a) and has a maximum age of *ca* 1.65±0.23 Ma and a minimum age of *ca* 1.40±0.18 Ma. Prior to burial, the quartz in this sample, which consisted of sand, contained lower concentrations of the two nuclides compared to the samples collected at Windsorton (Figure 4.6). As a result of this the post burial contribution by muons is nearly 30% in the sample. This higher post-burial component causes the maximum and minimum ages to be quite different, even though the sample was collected from an appropriate depth of six metres below the surface. As discussed previously, the maximum age of the sample will be closer to the true age. Even though there are large errors associated with this sample, due to the effect of post-burial production, it is completely consistent with the age model for the Rietputs Formation proposed above.

The inherited erosion rate is higher than that of the samples from Windsorton (471 cm/Ma). The reason for this is not entirely clear. It is possible that the sand in this sample was derived from erosion of older alluvial deposits near to the river, with the sand subsequently buried relatively quickly thereafter. Erosion of these deposits, in this higher erosional setting, would be faster than the exhumation and erosion of quartz bearing bedrock from higher in the catchment. As a result, the concentration of the nuclides in the sample as a whole was lower, pushing up the inherited erosion rate.

4.2.4.2 Christiana/Bloemhof sample cb2a

This sample was collected from the top of the lower coarse alluvium (Figure 4.14b), providing an age for the capping upper fine alluvium. This sample has a maximum age of *ca* 2.46±0.26 Ma and a minimum age of *ca* 1.83±0.16 Ma (Table 4.4), clearly inconsistent with the rest of the Rietputs Formation ages. The reason for these problematic ages is the shallow depth of burial of only four metres from which the sample was obtained. The post-burial component is an extremely high 72%, indicating immediately that the age is incorrect

an should not be used. The concentrations of the two nuclides in the sample are, however, consistent with the samples collected at Windsorton (Figure 4.6) and indicate that if this sample had been more deeply buried an age consistent with the Rietputs Formation age model would have been obtained.

4.2.5 Sydney-on-Vaal

Two samples were collected from Rietputs Formation deposits at Sydney-on-Vaal, approximately 110 kilometres downstream from the Windsorton type-site (Figure 4.2). Deposits were again similar to those found at Windsorton (Figure 4.15a and b). Burial dating data on each of the samples discussed below are given in Tables 4.2 to 4.5.

4.2.5.1 Sydney-on-Vaal sample s1a

This sample was collected from the base of the lower coarse alluvium (Figure 4.15a) and has a maximum age of *ca* 0.64±0.14 Ma and a minimum age of *ca* 0.62±0.13 Ma. These ages are clearly inconsistent with the Rietputs Formation age model. The burial age data in Tables 4.2 to 4.5 appear to be consistent and no obvious problems are apparent. There are two possible explanations for the discrepancy.

Firstly, the deposit sampled could be a gravel member of the Riverton Formation, deposited later than the Rietputs Formation. Although this explanation is possible, it seems unlikely as the lower coarse alluvium appears to be a typical cobble to boulder grade gravel (Figure 4.15a), consistent with all the other exposures of the Rietputs Formation within the catchment. The Riverton Formation that follows is said to be mostly comprised of sands and silts, with only a few gravel lenses (Butzer *et al.* 1973), and only rare instances of limited (1.5 metre thick) basal gravel deposits occurring below the fines (Helgren 1979). The gravel deposit at this site is over six metres thick. Like the other Rietputs Formation deposits it is similarly capped by fine alluvium.

The second possibility is that either sample processing, or measurement errors,

have lead to the incorrect younger age. The ^{10}Be concentration is relatively consistent with the rest of the samples from Windsorton (Figure 4.6); however, the ^{26}Al concentration is elevated. It is impossible to say exactly from where the error could arise. It is important to note that out of the 33 burial dating samples (66 AMS measurements), one would expect at least a few measurements to fall outside of two standard deviations of the mean, leading to an error in the burial ages obtained. The only way to determine which one of the above two options is correct would be to run more dating samples at the site, on both the lower coarse alluvium and upper fine alluvium.

4.2.5.2 Sydney-on-Vaal sample s2a

This sample was collected from the base of the lower coarse alluvium (Figure 4.15b) and has a maximum age of *ca* 1.47±0.22 Ma and a minimum age of *ca* 1.20±0.15 Ma. This site is similar to Pit 1 and Pit 6 at Windsorton (Figures 4.10 and 4.13b). The upper fine alluvium has been eroded from the top of the lower coarse alluvium, due to the site's location right next to the Vaal River in a higher erosional setting (discussed previously). Only a portion of the original lower coarse alluvium is probably preserved. The gravels are now capped by younger Riverton Formation alluvial deposits or wind blown Hutton sands. In determining the burial age from the s2a sample, a depth of just over four metres must be used to calculate the influence of secondary cosmic ray muons, as the precise burial history is not known. As a result the maximum and minimum ages are quite different. The contribution of post-burial production accounts for a third of the nuclides in the sample due to insufficient burial. This high percentage indicates that caution is needed in accepting the age.

As with sample w6a, however, it can be seen in Figure 4.6 that the concentrations of the nuclides are very similar to the rest of the samples collected from the type-site. In addition, Figure 4.7 shows that ratio of the nuclides is similar to the other samples. It can thus similarly be concluded that a general age determination is possible. The erosion of the upper fine alluvium, and possibly some of the lower coarse alluvium, has likely occurred relatively recently.

A general burial age between the maximum and minimum ages is consistent with the age model for the Rietputs Formation. In addition, the calculated inherited erosion rate for s2a (289 cm/Ma) is consistent with the rest of the samples from the type-site.

4.2.6 Barkly West (Canteen Kopje)

Two samples were collected from Rietputs Formation deposits at Barkly West (Canteen Kopje), approximately 70 kilometres downstream of the Windsorton type-site (Figure 4.2). Deposits were again similar to those found at Windsorton (Figures 4.17 and 4.18a), consisting of massive coarse alluvium. At Canteen Kopje, however, there is no capping fine alluvium above the gravels, with younger Riverton Formation alluvial deposits or wind blown Hutton sands now capping the deposit. The upper fine alluvium has been eroded from the top of the lower coarse alluvium, due to the site's location right next to the Vaal River in a higher erosional setting (discussed previously). In addition, the clasts in the coarse alluvium are much more angular when compared to other Rietputs Formation deposits, and are dominated by Ventersdorp lava clasts derived from the surrounding koppies (hills) (Figures 4.17 and 4.18a). However, all clast lithologies found at other sites are represented, but to a lesser degree. Burial dating data on each of the samples discussed below are given in Tables 4.2 to 4.5.

4.2.6.1 Barkly West sample bw1a

This sample was collected from the base of the lower coarse alluvium (Figure 4.17) and has a maximum age of *ca* 1.06±0.19 Ma and a minimum age of *ca* 1.00±0.18 Ma. Although at the younger end of the age range for the Rietputs Formation, given burial dating uncertainties of 100 to 200 thousand years, this age is still consistent with the model. When considered in conjunction with the sample discussed below, collected 40 metres away in a separate pit, the indicated age of the gravels at Canteen Kopje is consistent with the

proposed age model (discussed below). The inherited erosion rate (311 cm/Ma) is also consistent with the other Rietputs Formation samples.

4.2.6.2 Barkly West sample bw2a

This sample was collected from the base of the lower coarse alluvium (Figure 4.18a), in a separate pit 40 metres from where bw1a was collected. It has a maximum age of *ca* 1.46±0.15 Ma and a minimum age of *ca* 1.37±0.14 Ma. Samples bw1a and bw2a essentially date the same deposit. There are two possible options to explain the discrepancy between the burial ages. The first invokes the coarseness of the burial dating technique, in terms of associated error margins of the data. With such large errors the dates are not inconsistent. The second invokes geological variables. It is quite possible that aggradation at site bw2a was either initially more rapid than at bw1a, or took place slightly earlier. It could be either of, or even a combination of, the above two options that explains the discrepancy in the ages.

Just as with sample bw1a, the inherited erosion rate (147 cm/Ma) is also fairly consistent with the other Rietputs Formation samples. In conclusion, it can be seen that the deposits at Canteen Kopje are consistent with the Rietputs Formation age model.

4.2.7 Bamboesspruit

Two samples were collected from Rietputs Formation equivalent deposits along the Bamboesspruit (Marshall 1990), a right bank tributary of the Vaal River (Figure 4.2). The Bamboesspruit joins the Vaal River approximately 180 kilometres upstream of Windsorton. Deposits here are similar to those found along the Vaal River. A lower coarse gravel and sand unit is covered by laminated and cross-bedded fine alluvium with laterally discontinuous palaeosols (Figure 4.19). Burial dating data on each of the samples discussed below is given in Tables 4.2 to 4.5.

4.2.7.1 Bamboesspruit sample b1a

Sample b1a consisted of sand collected from the top of the lower coarse alluvium, thus providing an age for the fines above. This sample has a maximum age of *ca* 1.34±0.11 Ma and a minimum age of *ca* 1.30±0.11 Ma. These ages are totally consistent with the age model for the Rietputs Formation along the Vaal River.

It is important to note that sample b1a contains very high concentrations of both nuclides (Figure 4.6). This indicates that the quartz sand of the sample was derived from a slowly eroding landscape. The calculated inherited erosion rate is 59 cm/Ma (Table 4.5), roughly five time slower than the erosion rate calculated for samples collected along the Vaal River. This inherited erosion rate is consistent with the relatively flat topography of the Bamboesspruit catchment (see the gentle slope leading to the interfluve in the background of Figure 4.19).

4.2.7.2 Bamboesspruit sample b2a

Sample b2a consisted of an isolated individual cobble collected from near the base of the upper fine alluvium. This sample has a maximum age of *ca* 1.47±0.15 Ma and a minimum age of *ca* 1.38±0.13 Ma. These ages are slightly older than the proposed age model. The difference could be the result of either measurement error; or that fines deposition started marginally earlier in the Bamboesspruit catchment. It is difficult to say which is more probable.

The calculated inherited erosion rate for sample b2a, even though it was from an individual large clast, is similarly low at 98 cm/Ma. This indicates that, even if the clast had been derived from erosion of an older terrace deposit, the erosion of this deposit was very slow, providing initial concentrations suitable to conduct burial dating.

4.2.8 Conclusion

It can be concluded that cosmogenic nuclide burial dating samples collected from Rietputs Formation alluvial deposits both up- and downstream of the type-site at Windsorton, as well as samples collected from equivalent deposits of a right bank tributary, are in agreement with the age model determined from the type-site. Although there are large errors associated with burial dating, the data indicate that the gravel deposits of the lower coarse alluvium were deposited from *ca* 1.8 to 1.35 Ma, with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma. It must be noted at this point, however, that during this period the palaeo-Vaal River would have most likely have been subject to fluctuating episodes of aggradation, non-deposition (equilibrium) and erosion. All that can be concluded is that there was a net aggradation of gravels over this period, followed by aggradation of the fines.

4.3 Wedburg terrace

4.3.1 Introduction

The Wedburg terrace was previously believed to be between 4.5 and 3.5 million years old, based on palaeontological evidence (Helgren 1977*b*, de Wit *et al.* 2000). Unfortunately, burial dating samples from the Wedburg terrace could not be collected from the type-site at Windsorton. Wedburg alluvial deposits have been almost completely mined away, with the only deposits preserved being too shallow for burial dating. Two sites downstream of Windsorton, that on terrace height above the modern river were assumed to be Wedburg equivalents, have produced problematic ages. Wedburg terrace deposits are said to occur at heights of 21 to 30 metres above modern river levels (de Wit *et al.* 2000). These two sites are discussed further below. Unfortunately at this time, an age determination for the Wedburg terrace has not been possible. Burial dating data on each of the samples discussed below is given in Tables 4.2 to 4.5. It must be noted at this point, however, that the previously

proposed age, based on palaeontological evidence, cannot be correct in light of cosmogenic nuclide burial dating of the Proksch Koppie terrace (discussed further below).

4.3.2 Sydney-on-Vaal sample s3a

One sample was collected from a Wedburg terrace alluvial deposit at Sydney-on-Vaal, based upon terrace surface height, occurring at approximately 30 metres above modern river level (Table 4.5). Bedrock depth is approximately 21 metres above river level. The site is approximately 110 kilometres downstream of the Windsorton type-site (Figure 4.2). This higher deposit is similar to the Rietputs Formation deposits found at Windsorton (Figure 4.16). Again, a lower coarse gravel and sand unit is covered by laminated and cross-bedded fine alluvium with laterally discontinuous palaeosols. A burial dating sand sample was collected from the base of the lower coarse alluvium. Sample s3a has a maximum age of *ca* 3.54 Ma and a minimum age of *ca* 2.34 Ma. However, when the contribution of post-burial production is calculated (Table 4.4), it is apparent that these ages are meaningless, as all of the nuclides within the sample can be accounted for by post-burial production. The deposit is clearly too old, in respect of the depth of burial cover, for an age determination to be feasible.

If one looks at the concentrations and ratios of the nuclides in this sample, s3a contains similar concentrations to Proksch Koppie terrace samples collected at Windsorton (Figures 4.6 and 4.7). It is unclear if this deposit is, in fact, a Wedburg or Proksch Koppie terrace equivalent. At the type-site at Windsorton, the Proksch Koppie terrace occurs at approximately 34 metres above modern river level, while bedrock depth is 26 metres. Terrace s3a is clearly lower, but as height can only be used as a very rough guide, the deposit could belong to either.

4.3.3 Barkly West sample bw3a

One sample was collected from a Wedburg terrace alluvial deposit near to Barkly West, based upon terrace surface height, occurring at approximately 28 metres above modern river level (Table 4.5). Bedrock depth is approximately 19 metres above river level. These heights are very similar to the Sydney-on-Vaal site discussed above. The site is approximately 70 kilometres downstream of the Windsorton type-site (Figure 4.2). This deposit is similar to the Rietputs Formation deposits found at Windsorton (Figure 4.18b): a lower coarse gravel and sand unit is capped by fine alluvium. A burial dating sand sample was collected from the base of the lower coarse alluvium. Sample bw3a has a maximum age of *ca* 10.85 Ma and a minimum age of *ca* 2.03 Ma. As with sample s3a above, when the contribution by post-burial production is calculated (Table 4.4), it is apparent that these ages are meaningless, as all of the nuclides within the sample can be accounted for by post-burial production. The concentrations and ratios of the nuclides in this sample are also similar to Proksch Koppie terrace samples collected at Windsorton (Figures 4.6 and 4.7). It is thus unclear if this deposit is in fact a Wedburg or Proksch Koppie terrace equivalent.

4.4 Proksch Koppie terrace

The profile dating approach was used to obtain a burial age for the Proksch Koppie terrace deposit at the type-site at Windsorton (Figure 4.2). This terrace deposit is said to occur at 30 to 45 metres above modern river level (de Wit *et al.* 2000). This higher deposit is similar to the Rietputs Formation and Wedburg terrace deposits. A lower coarse gravel and sand unit is covered by laminated and cross-bedded fine alluvium (Figure 4.20a). The profile approach to dating old, shallowly buried deposits uses the analyses of multiple samples from different depths in a vertical profile. This method is discussed in full in the previous chapter, with age determination following equations 3.12 and 3.15. For a profile of samples taken from the terrace deposit the profile is fit by χ^2

minimisation, solving for terrace age, the terrace erosion rate, and the inheritance of each sample (Wolkowinsky & Granger 2004). The most suitable way to display the goodness of fit between the data and the model is by plotting the χ^2 surface as a function of the model terrace deposit age and the model terrace erosion rate (Figure 4.8) (Wolkowinsky & Granger 2004).

The Proksch Koppie profile is best fit age with a burial age of 3.40±0.18 Ma and a terrace erosion rate of 852 cm/Ma. The goodness-of-fit of the terrace age is determined by the reduced χ^2 value (χ^2_r). A χ^2_r value near one indicates that the data are well explained by the model. The χ^2_r value for the Proksch Koppie terrace is 0.3, indicating a very reasonable model fit. The terrace erosion rate does not seem unreasonable (discussed further below).

Burial dating data on each of the profile samples is given in Tables 4.2 to 4.5. In Table 4.4 the maximum (4.05 Ma) and minimum (2.90 Ma) ages were determined by obtaining their values at one standard error of uncertainty on the χ^2 surface plot. In the case of the age of the Proksch Koppie deposit, the maximum and minimum ages reflect the uncertainty in the true age of the deposit due to various factors such as the terrace erosion rate, and not solely due to the influence of secondary cosmic ray muons, as with the single sample maximum and minimum ages. As such, the true age could be anywhere in this large time span. These values are thus used to show the large uncertainties, and are more appropriate than the best fit age with it's smaller errors, as they most accurately reflect the true uncertainty in the age of the deposit.

It can be seen clearly in Figure 4.8 that changes in the terrace erosion rate greatly affect the terrace age. The best fit model terrace erosion rate of 852 cm/Ma can be roughly evaluated by comparison with inherited erosion rates determined from the younger Rietputs Formation, as well as from the Proksch Koppie terrace itself. As discussed earlier, the average erosion rate for the Vaal River catchment during the aggradation of the Rietputs Formation was approximately 250 cm/Ma. The calculated inherited erosion rates for each of the Proksch Koppie samples are several fold higher than those for the Rietputs Formation (Table 4.5). Although highly variable, values range from 355 to

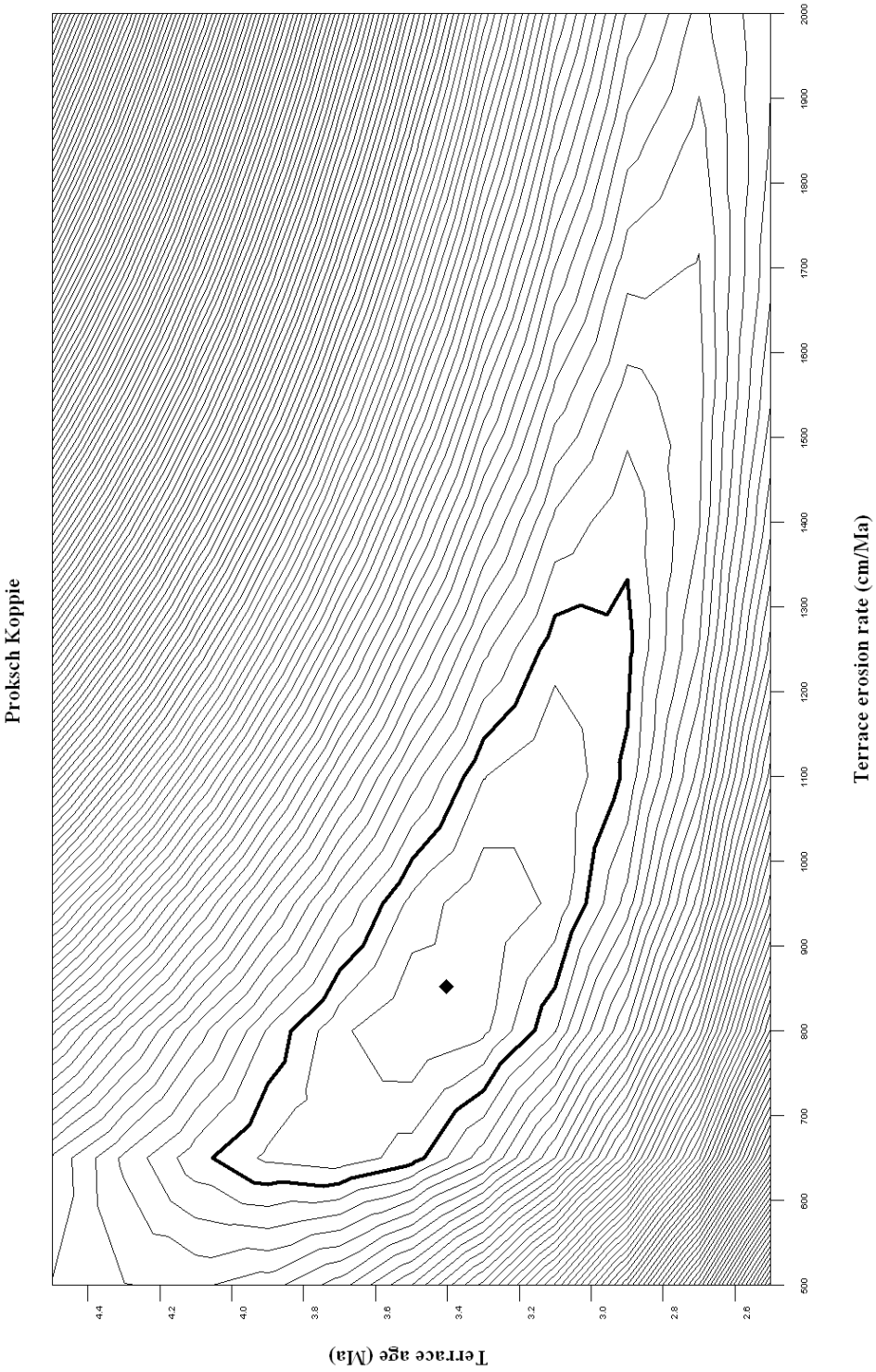


Figure 4.8: χ^2 contours shown as a function of the Proksch Koppie terrace deposit age and terrace deposit erosion rate. The minimum χ^2 value (=0.9) represents the best model fit and is shown as a diamond. The best fit age is 3.40±0.18 Ma, with a terrace erosion rate of 852 cm/Ma. The bold contour is at a value of one higher than the minimum and circumscribes one standard error in the model estimation. Contour interval is approximately 0.3.

1851 cm/Ma (average=1038 cm/Ma) indicating increased erosion rates within the catchment during this earlier time period. It can thus be seen that there was a decrease in erosion rates in the catchment over time. How these inherited erosion rates exactly relate to the Proksch Koppie terrace erosion rate is difficult to evaluate. The Proksch Koppie inherited erosion rates indicate that an erosion rate of 852 cm/Ma of the terrace is not unreasonable. The Rietputs Formation inherited erosion rates indicate that this value might be too high. However, if one considers that the Proksch Koppie terrace forms the crest/escarpment of the immediate valley surrounding the Vaal River and that slopes here are relatively steep in this higher erosional setting, then 852 cm/Ma is not unreasonable.

The above discussion shows clearly that the profile burial dating technique provides only a rough age estimate for the Proksch Koppie terrace. This is why the the maximum and minimum ages are given at their values at one standard error of uncertainty on the χ^2 surface plot. That being said, however, this rough age estimate can be used in conjunction with the burial age determination of the younger Rietputs Formation, as well as geological data, to provide a better chronology and understanding of the fluvial history of the lower Vaal River catchment (discussed below).

4.5 Holpan terrace

Determination of a burial age for the Holpan terrace near to Windsorton (Figure 4.2) was not possible due the the old age of the deposit concerned. The Holpan terrace is believed to be Miocene in age (de Wit *et al.* 2000). This older, higher (60 metre) deposit is, however, similar to the Rietputs Formation deposits found at Windsorton (Figure 4.20b). A lower coarse gravel and sand unit is covered by laminated and cross-bedded fine alluvium. A burial dating sand sample was collected from the base of the lower coarse alluvium, however, no burial age determination was possible (Tables 4.2 to 4.5). Sample

h1a contains very low concentrations of both nuclides, but a high ratio (Figures 4.6 and 4.7), consistent with a very old deposit that is slowing being eroded towards the surface.

4.6 Middle Orange River terraces

Three terrace deposits were sampled for burial dating along the middle Orange River (samples o1a, o2a and o3a)(Figure 4.1). Unfortunately, no low lying terrace deposits (Wedburg or Rietputs Formation equivalents), could be sampled due to the lack of suitable exposures. One terrace deposit situated 45 metres above the modern river (Figure 4.21a), and two located at 70 metres were sampled (Figures 4.21b and 4.22). Burial dating data on each of these sites is given in Tables 4.2 to 4.5.

As with the Holpan terrace, burial dating was not possible at any of these sites due to the excessive age of the deposits concerned. It is interesting to note that each of these deposits also consisted of a lower coarse gravel and sand unit covered by laminated and cross-bedded fine alluvium. All three samples contain very low concentrations of ^{26}Al and ^{10}Be (Figures 4.6). When one compares the ratios of these samples to the burial dating samples collected along the Vaal River (Figure 4.7), it is apparent that sample o1a has a similar ratio to the deepest Wedburg/Proksch Koppie samples, and sample o2a and o3a have similar ratios to the Holpan terrace. These data suggests similar ages for these deposits, although determination of an absolute age is not possible.

4.7 Modern Vaal River samples

As discussed in the previous chapter, burial dating of modern river sediment is a good test to see whether sediment is being reworked from older deposits in the present day. If it is, this could then indicate that reworking would similarly have taken place in the past and thus ages obtained for the older deposits could be problematic. As discussed above, it appears that some larger

clasts were in fact being eroded relatively quickly from older deposits and then buried quickly in younger deposits, without sufficient re-exposure to cosmic radiation, thus providing an overestimation of the age of the younger deposit. It has been argued, however, that the finer sand fraction did not experience this rapid burial and was most likely transported downstream in the alluvial system, and thus re-exposed to cosmic radiation for a sufficient period of time to acquire suitable concentrations of nuclides to make burial dating possible. In addition, the sand fraction from an older deposit would most likely also be mixed with the sand fraction produced from the slow erosion of bedrock within the catchment, thus eliminating the problem of reworking.

To test the above argument, two sand samples were collected from the modern Vaal River for burial dating. One sample was collected from between Sydney-on-Vaal and the Vaal/Orange confluence (sample m1a), and another was collected from near Christiana/Bloemhof (sample m2a) (Figure 4.2). If sediment reworking is not taking place one would expect these samples to have a burial age of zero and an $^{26}Al/^{10}Be$ ratio equal to the surface production rate ratio. The surface production rate ratio of $^{26}Al/^{10}Be$ for the Vaal River catchment is 6.79 (scaled with respect to latitude and elevation). Burial dating data on each of the samples discussed below are given in Tables 4.2 to 4.5.

4.7.1 Modern Vaal River sample m1a

Sample m1a has a burial age of 0.39±0.08 Ma and a ratio of $^{26}Al/^{10}Be$ of 4.70 (see Figure 4.7). These values clearly indicate that this sample contains reworked sediments from older deposits. In Figure 4.6 it can be seen that this sample contains high concentrations of both nuclides, indicating that at least a portion of the sample has been exposed near the surface recently. The explanation to this problematic burial age lies in the location from which the sample was collected. This sample was collected from between Sydney-on-Vaal and the Vaal/Orange confluence, downstream from the majority of the alluvial diamond mining operations along the Vaal River. These operations are currently mining the older terrace deposits along the Vaal River. During the

mining operations, vast quantities of alluvial fines (sands, silts and clays) are pumped into the modern river and invariably transported down stream. These large scale mining operations are thus rapidly reworking older sediments into the modern river. Mixing of these older sediments with current sediment produced by normal erosion processes, has produced a sample with a burial age of 0.39±0.08 Ma. It is very difficult or impossible to calculate the percentage of the sample that would be coming from reworked mining sediments. Terrace deposits of all ages are being mined. In addition, the younger Riverton Formation sediments are also excavated to get to the Rietputs Formation gravels below. It is thus apparent that a mixture of old sediments, with a variety of ages, would most likely have contributed to the modern river sediment sample, making an accurate percentage calculation impossible.

The calculated inherited erosion rate from the modern river sample should provide a current erosion rate for the catchment. The inherited erosion rate for sample m1a is 69 cm/Ma, much lower than that for the Rietputs Formation deposits. However, caution is needed in reading too much into this erosion rate due to the mixing of the older sediment into the sample.

4.7.2 Modern Vaal River sample m2a

Sample m2a has a burial age of 0.14±0.11 Ma and a ratio of $^{26}Al/^{10}Be$ of 5.73 (see Figure 4.7). This burial age and ratio are very close to what one would expect for a sample collected from the surface given measurement errors. This sample was collected from near Christiana/Bloemhof. There are fewer mining operations upstream from this location, although mining does still occur along both the Vaal River and right bank tributaries such as the Bamboesspruit. It appears that this sample may contain some older deposits, reworked into the younger sediments due to mining operations, but that the bulk of the sample consists of modern day sediments. Thus the calculated inherited erosion rate of 153 cm/Ma most likely reflects a true erosion rate for the catchment. This erosion rate is less than that during the aggradation of the Rietputs Formation, indicating that a reduction in erosion rates has taken place through time.

* * *

In the next chapter the cosmogenic nuclide burial ages for each of the various terrace deposits presented in this chapter, will be used to refine our current understanding of the fluvial history of the lower Vaal River catchment.

Table 4.2: Cosmogenic nuclide burial dating sample names, description and locations.

Sample name	**Location**	**Sample description**	**Problematic sample**	**GPS co-ordinates (decimal ° south and east)**
w1a	Windsorton Pit 1	sand	no	28.322367417000, 24.715595925200
w2a	Windsorton Pit 2	sand	no	28.319361582000, 24.737953897600
w2b	Windsorton Pit 2	sand	no	28.319361582000, 24.737953897600
w2c	Windsorton Pit 2	sand	no	28.319361582000, 24.737953897600
w2d	Windsorton Pit 2	sand	no	28.319361582000, 24.737953897600
w3a	Windsorton Pit 3	sand	no	28.325067731000, 24.739292319900
w3b	Windsorton Pit 3	sand	no	28.325067731000, 24.739292319900
w4a	Windsorton Pit 4	amalgamated pebbles and cobbles	no	28.321128823000, 24.741738578300
w5a	Windsorton Pit 5	individual cobble	no	28.327019336600, 24.746549371900
w6a	Windsorton Pit 6	sand	yes	28.335782820000, 24.728234158800
w1b	Windsorton Pit 1	amalgamated pebbles and cobbles	yes	28.322367417000, 24.715595925200

Table 4.2: Cosmogenic nuclide burial dating sample names, description and locations (continued).

Sample name	**Location**	**Sample description**	**Problematic sample**	**GPS co-ordinates (decimal ° south and east)**
w5b	Windsorton Pit 5	individual cobble	yes	28.327019336600, 24.746549371900
cb1a	Christiana/Bloemhof Pit 1	sand	no	27.775980000000, 25.317780000000
cb2a	Christiana/Bloemhof Pit 2	amalgamated pebbles and cobbles	yes	27.788600000000, 25.308650000000
s1a	Sydney-on-Vaal Pit 1	sand	yes	28.414250000000, 24.272130000000
s2a	Sydney-on-Vaal Pit 2	sand	no	28.421010000000, 24.285100000000
s3a	Sydney-on-Vaal Pit 3	sand	yes	28.455305560000, 24.279388890000
bw1a	Barkly West Pit 1 (Canteen Kopje)	sand	no	28.548750000000, 24.537610000000
bw2a	Barkly West Pit 2 (Canteen Kopje)	amalgamated sand and pebbles	no	28.548750000000, 24.537610000000
bw3a	Barkly West Pit 3	sand	yes	28.484870000000, 24.576040000000
b1a	Bamboesspruit Pit 1	sand	no	27.139001526000, 25.792560763700
b2a	Bamboesspruit Pit 2	individual cobble	no	27.000370000000, 25.907520000000

Table 4.2: Cosmogenic nuclide burial dating sample names, description and locations (continued).

Sample name	**Location**	**Sample description**	**Problematic sample**	**GPS co-ordinates (decimal ° south and east)**
h1a	Holpan Pit 1 (near Windsorton)	sand	yes	28.325091284000, 24.644986856700
o1a	Middle Orange River Pit 1 (between Vaal/Orange confluence and Prieska)	individual cobble	yes	29.535950000000, 22.989870000000
o2a	Middle Orange River Pit 2 (between Vaal/Orange confluence and Prieska)	individual cobble	yes	29.409340000000, 23.143440000000
o3a	Middle Orange River Pit 3 (between Vaal/Orange confluence and Prieska)	individual cobble	yes	29.318170000000, 23.252240000000
pk1a	Proksch Koppie Pit 1 (Windsorton)	amalgamated sand, pebbles and cobbles	no	28.348547369000, 24.717498282000
pk1b	Proksch Koppie Pit 1 (Windsorton)	amalgamated sand, pebbles and cobbles	no	28.348547369000, 24.717498282000
pk1c	Proksch Koppie Pit 1 (Windsorton)	amalgamated sand, pebbles and cobbles	no	28.348547369000, 24.717498282000

Table 4.2: Cosmogenic nuclide burial dating sample names, description and locations (continued).

Sample name	**Location**	**Sample description**	**Problematic sample**	**GPS co-ordinates (decimal ° south and east)**
pk1d	Proksch Koppie Pit 1 (Windsorton)	amalgamated sand, pebbles and cobbles	no	28.348547369000, 24.717498282000
pk1e	Proksch Koppie Pit 1 (Windsorton)	sand	no	28.348547369000, 24.717498282000
m1a	Modern Vaal River 1 (between Sydney-on-Vaal and Vaal/Orange confluence)	sand	yes	N/A, N/A
m2a	Modern Vaal River 2 (near Christiana/Bloemhof)	sand	no	N/A, N/A

Table 4.3: Cosmogenic nuclide concentrations.

Sample name	**Sampling location description**	**Sample depth (m)**	**[^{26}Al]* $\times$ 10^6 atoms/g**	**Error (±)**	**[^{10}Be]*† $\times$ 10^6 atoms/g**	**Error (±)**	**^{26}Al/^{10}Be**	**Error (±)**
w1a	LCA*	7	2.067222940000	0.1600097	0.7467619342591	0.0176169	2.7682489	0.2240024
w2a	UFA$^{\diamond}$	10	3.067572769278	0.2571007	0.8580151421845	0.0198221	3.5751965	0.3108209
w2b	top of LCA	13.5	3.032895186382	0.1978896	0.8619971261669	0.0308567	3.5184516	0.2618513
w2c	LCA	15.3	2.905034299158	0.2960261	0.8534964298324	0.0299123	3.4036865	0.3667794
w2d	LCA	16	2.922219745390	0.2272447	0.8989254767814	0.0262106	3.2507920	0.2699817
w3a	UFA	7.7	3.327385959645	0.2308014	0.9231361949391	0.0291956	3.6044367	0.2747807
w3b	LCA	14	2.654601378328	0.2344569	0.9055938973257	0.0375435	2.9313375	0.2860014
w4a	LCA	12	2.732642534714	0.1894447	0.9728372098554	0.0238202	2.8089412	0.2065230
w5a	LCA	15	1.256902918519	0.1146754	0.3542721311619	0.0142016	3.5478459	0.3535592
w6a	LCA	3	3.309853748148	0.2382038	0.9911376065751	0.0417614	3.3394493	0.2784938
w1b	LCA	6.2	3.258794148148	0.4323424	1.9900188451187	0.0338303	1.6375695	0.2190318
w5b	LCA	15	0.556680371111	0.0759988	0.0939826356916	0.0043240	5.9232258	0.8533335
cb1a	LCA	6	1.719601429722	0.1349724	0.5118717336966	0.0201136	3.3594381	0.2948814

Table 4.3: Cosmogenic nuclide concentrations (continued).

Sample name	**sampling location description**	**Sample depth (m)**	**[^{26}Al]* $\times$ 10^6 atoms/g**	**Error (±)**	**[^{10}Be]*† $\times$ 10^6 atoms/g**	**Error (±)**	**^{26}Al/^{10}Be**	**Error (±)**
cb2a	top of LCA	4	2.312872454806	0.1544300	0.8922529270551	0.0459120	2.5921713	0.2185119
s1a	LCA	7.7	4.814958015313	0.3003967	1.0249930116932	0.0265482	4.6975520	0.3173247
s2a	LCA	4.1	2.858181441825	0.2144690	0.8004385702832	0.0169522	3.5707693	0.2784071
s3a	LCA	7	0.634396535106	0.1251236	0.2926413353895	0.0098367	2.1678296	0.4337311
bw1a	LCA	7.5	3.413470333333	0.2575020	0.8661423305955	0.0447507	3.9410039	0.3603420
bw2a	LCA	6.3	4.235473333333	0.2917909	1.3630130621962	0.0436164	3.1074341	0.2360450
bw3a	LCA	7	0.369417934620	0.0422489	0.1422624880763	0.0051867	2.5967347	0.3117034
b1a	top of LCA	6	9.252849330791	0.5599906	3.2772085053520	0.0836504	2.8233935	0.1854499
b2a	UFA	5	6.211466118035	0.4361349	2.1136353488795	0.0617090	2.9387596	0.2234706
h1a	LCA	9.5	0.336140811761	0.0535683	0.0894324761241	0.0039225	3.7585990	0.6212515
o1a	LCA	5	0.916150545704	0.2173232	0.4126048752742	0.0104900	2.2204065	0.5297267
o2a	LCA	8.5	0.264006543417	0.0344514	0.0584310096740	0.0041955	4.5182608	0.6729701

Table 4.3: Cosmogenic nuclide concentrations (continued).

Sample name	**sampling location description**	**Sample depth (m)**	**[^{26}Al]* $\times$ 10^6 atoms/g**	**Error (±)**	**[^{10}Be]*† $\times$ 10^6 atoms/g**	**Error (±)**	**^{26}Al/^{10}Be**	**Error (±)**
o3a	LCA	6	0.456895182399	0.0659204	0.0964325124883	0.0037669	4.7379786	0.7082026
pk1a	LCA	3.6	0.447001155500	0.0466493	0.1197274503172	0.0065673	3.7334893	0.4401703
pk1b	LCA	4.6	0.424543408336	0.0430997	0.1606289705436	0.0101987	2.6430065	0.3164725
pk1c	LCA	5.55	0.585395508906	0.0871474	0.2632933510483	0.0140691	2.2233585	0.3516658
pk1d	LCA	5.6	0.323180666667	0.0425329	0.0925625439686	0.0038837	3.4914843	0.4822913
pk1e	LCA	6.5	0.342926400974	0.0572692	0.1586243826438	0.0047116	2.1618770	0.3667025
m1a	N/A	0	11.091341903704	0.7495664	2.3582783864237	0.0762972	4.7031521	0.3523893
m2a	N/A	0	10.217338798070	0.6335116	1.7836833970411	0.0509484	5.7282244	0.3910462

Table 4.3: Cosmogenic nuclide concentrations (continued).

Sample name	**sampling location description**	**Sample depth (m)**	**[^{26}Al]* $\times$ 10^{6} atoms/g**	**Error (±)**	**[^{10}Be]*† $\times$ 10^{6} atoms/g**	**Error (±)**	**^{26}Al/^{10}Be**	**Error (±)**

* Samples consisted of 25 to 50 g quartz spiked with 0.4 to 0.8 mg Be. † Measured against standards prepared by Kuni Nishiizumi and normalized for a ^{10}Be half-life of 1.34 Ma. * LCA - lower coarse alluvium. $^{\diamondsuit}$ UFA - upper fine alluvium.

Table 4.4: Cosmogenic nuclide burial ages and the percentage of post-burial production for each sample.

Sample name	**Max Age‡ (Ma)**	**Error (±)**	**Min Age‡ (Ma)**	**Error (±)**	**Percentage of nuclides from post-burial production assuming no erosion of the alluvial deposit**
w1a	**1.89**	0.19	**1.72**	0.16	16.0
w2a	**1.26**	0.19	**1.19**	0.17	6.4
w2b	**1.27**	0.15	**1.22**	0.14	4.7
w2c	**1.34**	0.22	**1.29**	0.21	4.4
w2d	**1.42**	0.17	**1.37**	0.16	4.3
w3a	**1.24**	0.16	**1.16**	0.15	7.7
w3b	**1.64**	0.20	**1.57**	0.19	5.9
w4a	**1.72**	0.15	**1.64**	0.14	6.9
w5a	**1.43**	0.23	**1.32**	0.21	11.5
w6a	**1.84**	0.29	**1.30**	0.16	76.2
w1b	**2.52**	0.25	**2.37**	0.22	12.2

Table 4.4: Cosmogenic nuclide burial ages and the percentage of post-burial production for each sample (continued).

Sample name	**Max Age‡ (Ma)**	**Error (±)**	**Min Age‡ (Ma)**	**Error (±)**	**Percentage of nuclides from post-burial production assuming no erosion of the alluvial deposit**
w5b	**0.33**	0.38	**0.28**	0.27	9.3
cb1a	**1.65**	0.23	**1.40**	0.18	27.3
cb2a	**2.46**	0.26	**1.83**	0.16	72.2
s1a	**0.64**	0.14	**0.62**	0.13	3.4
s2a	**1.47**	0.22	**1.20**	0.15	33.8
s3a	**3.54**	N/A	**2.34**	N/A	135.0
bw1a	**1.06**	0.19	**1.00**	0.18	7.1
bw2a	**1.46**	0.15	**1.37**	0.14	8.3
bw3a	**10.85**	N/A	**2.03**	N/A	27560.0
b1a	**1.34**	0.11	**1.30**	0.11	3.8

Table 4.4: Cosmogenic nuclide burial ages and the percentage of post-burial production for each sample (continued).

Sample name	**Max Age‡ (Ma)**	**Error (±)**	**Min Age‡ (Ma)**	**Error (±)**	**Percentage of nuclides from post-burial production assuming no erosion of the alluvial deposit**
b2a	**1.47**	0.15	**1.38**	0.13	8.5
h1a	**N/A**	N/A	**N/A**	N/A	N/A
o1a	**3.67**	N/A	**2.25**	N/A	185.1
o2a	**N/A**	N/A	**N/A**	N/A	N/A
o3a	**N/A**	N/A	**N/A**	N/A	N/A
pk1a	**4.05**	N/A	**2.90**	N/A	N/A
pk1b	**4.05**	N/A	**2.90**	N/A	N/A
pk1c	**4.05**	N/A	**2.90**	N/A	N/A
pk1d	**4.05**	N/A	**2.90**	N/A	N/A
pk1e	**4.05**	N/A	**2.90**	N/A	N/A

Table 4.4: Cosmogenic nuclide burial ages and the percentage of post-burial production for each sample (continued).

Sample name	**Max Age‡ (Ma)**	**Error (±)**	**Min Age‡ (Ma)**	**Error (±)**	**Percentage of nuclides from post-burial production assuming no erosion of the alluvial deposit**
m1a	**0.39**	0.08	**0.39**	0.08	N/A
m2a	**0.14**	0.11	**0.14**	0.11	N/A

‡ Ages calculated using ^{10}Be half-life of 1.34 Ma and ^{26}Al half-life of 0.72 Ma. Uncertainties reflect measurement error only. To calculate systematic errors related to half-lives add 6% uncertainty in quadrature.

Table 4.5: Cosmogenic nuclide burial dating sample information.

Sample name	**Sample depth (m)**	**Bedrock depth‡ (m)**	**Terrace surface height‡ (m)**	**Latitude (°S)**	**AMSL (m)**	**P_{26}* (at/g/yr)**	**P_{10}† (at/g/yr)**	**$\rho^{\star}$ (g/cm^3)**	**$\varepsilon^{\diamond}$ (cm/Ma)**
w1a	7	3.0	11	28.33	1120	56.53	8.32	2.1	242
w2a	10	1.0	18	28.33	1120	56.53	8.32	1.9	286
w2b	13.5	1.0	18	28.33	1120	56.53	8.32	1.9	279
w2c	15.3	1.0	18	28.33	1120	56.53	8.32	1.9	271
w2d	16	1.0	18	28.33	1120	56.53	8.32	1.9	244
w3a	7.7	2.5	17	28.33	1120	56.53	8.32	1.9	268
w3b	14	2.5	17	28.33	1120	56.53	8.32	1.9	214
w4a	12	5.0	20	28.33	1120	56.53	8.32	1.9	189
w5a	15	0.5	18	28.33	1120	56.53	8.32	1.9	689
w6a	3	1.0	10	28.33	1120	56.53	8.32	2.1	234
w1b	6.2	3.0	11	28.33	1120	56.53	8.32	2.1	41

Table 4.5: Cosmogenic nuclide burial dating sample information (continued).

Sample name	**Sample depth (m)**	**Bedrock depth‡ (m)**	**Terrace surface height‡ (m)**	**Latitude (°S)**	**AMSL (m)**	**P_{26}* (at/g/yr)**	**P_{10}† (at/g/yr)**	**$\rho^{\star}$ (g/cm^3)**	**$\varepsilon^{\diamond}$ (cm/Ma)**
w5b	15	0.5	18	28.33	1120	56.53	8.32	1.9	4716
cb1a	6	3.5	10	27.78	1210	59.65	8.78	1.9	471
cb2a	4	0.0	6	27.78	1210	59.65	8.78	1.9	191
s1a	7.7	4.0	14	28.42	1020	52.69	7.76	1.9	303
s2a	4.1	8.0	18	28.42	1020	52.69	7.76	1.9	289
s3a	7	21.0	30	28.46	1030	53.12	7.82	1.9	N/A
bw1a	7.5	4	12	28.32	1100	55.71	8.20	1.9	311
bw2a	6.3	4	12	28.32	1100	55.71	8.20	1.9	147
bw3a	7	19.0	28	28.49	1120	56.71	8.35	1.9	N/A
b1a	6	N/A	N/A	27.14	1360	65.53	9.65	1.9	59
b2a	5	N/A	N/A	27.00	1300	62.63	9.22	1.9	98

Table 4.5: Cosmogenic nuclide burial dating sample information (continued).

Sample name	**Sample depth (m)**	**Bedrock depth‡ (m)**	**Terrace surface height‡ (m)**	**Latitude (°S)**	**AMSL (m)**	**P_{26}* (at/g/yr)**	**P_{10}† (at/g/yr)**	**$\rho^{\star}$ (g/cm^3)**	**$\varepsilon^{\diamond}$ (cm/Ma)**
h1a	9.5	N/A	60	28.33	1165	58.38	8.60	1.9	N/A
o1a	5	38.0	45	29.94	970	52.36	7.71	1.9	N/A
o2a	8.5	N/A	70	29.41	1000	52.96	7.80	1.9	N/A
o3a	6	N/A	70	29.31	1020	53.62	7.90	1.9	N/A
pk1a	3.6	26.0	34	28.33	1120	56.53	8.32	1.9	1851
pk1b	4.6	26.0	34	28.33	1120	56.53	8.32	1.9	726
pk1c	5.55	26.0	34	28.33	1120	56.53	8.32	1.9	355
pk1d	5.6	26.0	34	28.33	1120	56.53	8.32	1.9	1580
pk1e	6.5	26.0	34	28.33	1120	56.53	8.32	1.9	677
m1a	0	N/A	N/A	28.70	1000	52.22	7.69	1.9	69
m2a	0	N/A	N/A	27.00	1200	58.32	8.59	1.9	153

Table 4.5: Cosmogenic nuclide burial dating sample information (continued).

Sample name	**Sample depth (m)**	**Bedrock depth**[‡] **(m)**	**Terrace surface height**[‡] **(m)**	**Latitude (°S)**	**AMSL (m)**	$\mathbf{P_{26}}^{*}$ **(at/g/yr)**	$\mathbf{P_{10}}^{\dagger}$ **(at/g/yr)**	$\rho^{\star}$ **(g/cm^3)**	$\varepsilon^{\diamondsuit}$ **(cm/Ma)**

[‡] Heights given above the modern river level. * Surface production rate of ^{26}Al. † Surface production rate of ^{10}Be. ⋆ Deposit density. ♢ Average inherited erosion rate.



Figure 4.9: Cosmogenic nuclide burial dating samples consisted of either sands; amalgamated sands or larger clasts; or individual large clasts obtained from the alluvial deposits.



Figure 4.10: Windsorton Pit 1. Dating samples collected from the base of the lower coarse alluvium.



(a) Windsorton Pit 2. Three dating samples were collected from the lower coarse alluvium. A fourth, was collected 1.5 metres above the coarse alluvium in the upper fine alluvium.



(b) Windsorton Pit 3. One dating sample was collected from the base of the lower coarse alluvium. A second, was collected 1.3 metres above the coarse alluvium in the upper fine alluvium.

Figure 4.11: Cosmogenic nuclide burial dating samples collected at Windsorton Pit 2 and 3.



Figure 4.12: Windsorton Pit 4. Dating sample collected from the base of the lower coarse alluvium.



(a) Windsorton Pit 5. Dating samples collected from the base of the lower coarse alluvium.



(b) Windsorton Pit 6. Dating sample collected from the base of the lower coarse alluvium.

Figure 4.13: Cosmogenic nuclide burial dating samples collected at Windsorton Pit 5 and 6.



(a) Christiana/Bloemhof Pit 1. Dating sample collected from the base of the lower coarse alluvium.



(b) Christiana/Bloemhof Pit 2. Dating sample collected from the top of the lower coarse alluvium.

Figure 4.14: Cosmogenic nuclide burial dating samples collected at Christiana/Bloemhof Pit 1 and 2.



(a) Sydney-on-Vaal Pit 1. Dating sample collected from the base of the lower coarse alluvium.



(b) Sydney-on-Vaal Pit 2. Dating sample collected from the base of the lower coarse alluvium.

Figure 4.15: Cosmogenic nuclide burial dating samples collected at Sydney-on-Vaal Pit 1 and 2.

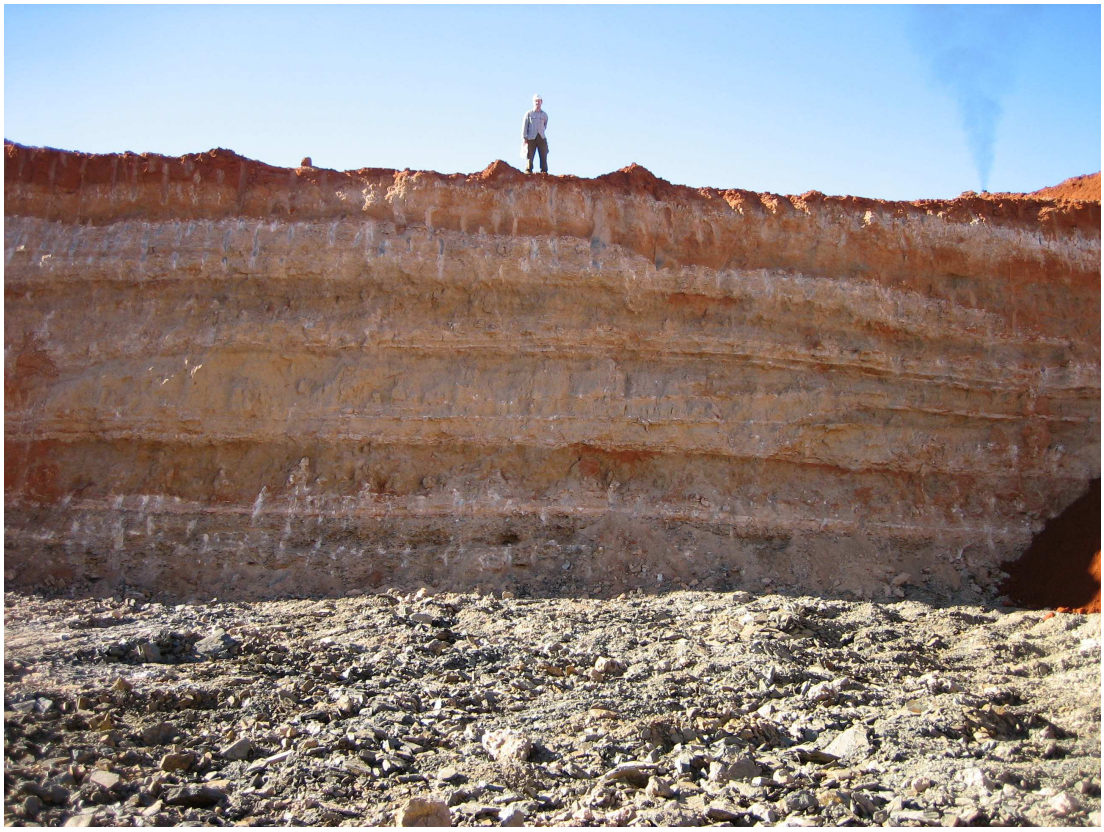


Figure 4.16: Sydney-on-Vaal Pit 3. Dating sample collected from the base of the lower coarse alluvium.



Figure 4.17: Barkly West Pit 1 (Canteen Kopje). Dating sample collected from the base of the lower coarse alluvium.



(a) Barkly West Pit 2 (Canteen Kopje). Dating sample collected from the base of the lower coarse alluvium.



(b) Barkly West Pit 3. Dating sample collected from the base of the lower coarse alluvium.

Figure 4.18: Cosmogenic nuclide burial dating samples collected at Barkly West Pit 2 (Canteen Kopje) and Pit 3.



Figure 4.19: Bamboesspruit Pit 1. Dating sample collected from the top of the lower coarse alluvium.



(a) Proksch Koppie Pit 1 (Windsorton). Profile dating samples collected upwards from the base of the lower coarse alluvium.



(b) Holpan Pit 1 (near Windsorton). Dating sample collected from the base of the lower coarse alluvium.

Figure 4.20: Cosmogenic nuclide burial dating samples collected at Proksch Koppie Pit 1 and Holpan Pit 1.



(a) Middle Orange River Pit 1. Dating sample collected from the base of the lower coarse alluvium.



(b) Middle Orange River Pit 2. Dating sample collected from the base of the lower coarse alluvium.

Figure 4.21: Cosmogenic nuclide burial dating samples collected at the middle Orange River Pit 1 and Pit 2 (between Vaal/Orange confluence and Prieska).



Figure 4.22: Middle Orange River Pit 3. Dating sample collected from the base of the lower coarse alluvium.

Chapter 5

Fluvial evolution of the lower Vaal River catchment

5.1 Introduction

In this chapter a revised fluvial history model for the lower Vaal River catchment is proposed. This model accounts for periods both of Vaal River aggradation and incision. The model is based upon the cosmogenic nuclide burial dated sequence of fluvial events, bedrock erosion mechanisms, and the palaeoclimatic record. The model highlights the uniqueness of the lower Vaal River catchment, and emphasises that characteristics of the catchment crucially influenced the fluvial evolution of the river.

5.2 Fluvial chronology

The chronological history of the fluvial evolution of the lower Vaal River catchment is outlined below. This chronological sequence was determined from cosmogenic nuclide burial dating of the various alluvial deposits within the catchment, outlined in the previous chapter. This sequence of events forms the basis for the construction of a revised fluvial history model outlined in this chapter. The fluvial chronology is primarily based on the absolute dating of alluvial deposits at the type-site at Windsorton. The age of each of the alluvial deposits

is summarised below, followed by an outline of the sequence of fluvial events.

Holpan terrace An absolute age determination for the Holpan terrace was not possible. The cosmogenic nuclide data are consistent with a very old deposit. A Miocene age, as proposed by others (de Wit *et al.* 2000), does not seem unreasonable.

Proksch Koppie terrace The Proksch Koppie terrace was dated using the profile dating approach. The terrace deposit is best fit with a burial age of 3.40±0.18 Ma. As discussed in the previous chapter, it is more appropriate to use the range between the maximum and minimum ages as the most realistic age estimate for the terrace deposit, due to the large dating uncertainties associated with this old deposit. Thus the true age of the terrace lies somewhere between 4.05 Ma and 2.90 Ma.

Wedburg terrace Unfortunately an age determination for the Wedburg terrace was not possible due the the old age of the associated alluvial deposits and the shallow depth of burial from which dating samples could be collected. A profile dating approach, such as used for the Proksch Koppie terrace, is needed in order to obtain a burial age for these deposits. The faunal age proposed by others of between 4.5 Ma to 3.5 Ma (Helgren 1977*b*, de Wit *et al.* 2000) is incorrect in light of the determined burial age for the Proksch Koppie terrace. It thus appears that fossils can be reworked from older into younger deposits numerous times, providing misleading age indications.

Rietputs Formation These are the best dated alluvial deposits within the whole sequence. The cosmogenic nuclide burial dating data indicates that the gravel deposits of the lower coarse alluvium were deposited from *ca* 1.8 to 1.35 Ma, with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma. During this interval the Vaal River would have most likely have fluctuated between episodes of aggradation, non-deposition and erosion, with the net result being the aggradation of gravels, followed by aggradation of fines.

The inferred sequence of fluvial events within the catchment is outlined below. It is important to emphasise that these events, identified from fluvial remnants, only represent the net results of the fluvial activity of the Vaal River over relatively long periods of time. No short-term changes are recorded in the remnants, but only the overall long-term results of the formative fluvial processes.

1. The Vaal River aggraded the alluvial deposits of the Holpan terrace. These deposits consist of a lower coarse gravel and sand unit covered by fine alluvium. Other data suggest a Miocene age for these deposits.

2. This was followed by net incision of the Vaal River until the early to middle Pliocene.

3. Sometime in the early to middle Pliocene this incision stopped and was followed by a period of aggradation. At this time the Vaal River aggraded the alluvial deposits of the Proksch Koppie terrace. These deposits also consist of a lower coarse gravel and sand unit covered by fine alluvium.

4. This aggradation event was followed by renewed incision.

5. Sometime between the early/middle Pliocene and the earliest Pleistocene, this incision was halted and the Vaal River aggraded the Wedburg terrace deposits. These deposits also consist of a lower coarse gravel and sand unit covered by fine alluvium.

6. After this aggradation event, incision continued until the start of the aggradation of the Rietputs Formation in the earliest Pleistocene.

7. Aggradation of the lower coarse gravel and sand unit of the Rietputs Formation proceeded until *ca* 1.3 Ma. This was then followed by aggradation of fines until *ca* 1 Ma.

8. The Vaal River since 1 Ma has incised very little. Along vast reaches of the modern Vaal River, Rietputs Formation deposits still line the modern channel (Helgren 1979). Very limited, or no incision, has occurred through bedrock. Some sections of the Rietputs Formation deposits have been eroded, with the fines capping the gravels along the immediate river

banks suffering the most erosion (discussed in the previous chapter).

9. Riverton Formation deposits, which occur as a proposed five-fold cut and fill sequence of sand and silts with a few gravel lenses (Butzer *et al.* 1973), were then aggraded over the Rietputs Formation along the immediate river banks.

At this point it is important to emphasise the length of time represented by aggradation events. The Rietputs Formation deposits, which are the best dated, show that an episode of net aggradation of gravels and fines can occur over nearly a million years. If similar lengths of time are represented by the Proksch Koppie and Wedburg deposits, then these lengthy periods of aggradation have important implications for understanding the time represented by net incision events. This aspect will be discussed further below.

5.3 Neogene climate

5.3.1 Introduction

As a start an outline of the climate during the Neogene of southern Africa is provided. There have been important improvements to the palaeoclimatic record in recent years. It is crucial to outline the revised and much more extensive palaeoclimatic record now available, as climate change has in the past been proposed as one of the key driving mechanisms regarding the fluvial history of the lower Vaal River catchment (Helgren 1979). A direct correlation between climatic changes and the sequence of fluvial events or major features of the deposits is now possible. Focus is only given to the climate of the summer rainfall region of southern Africa, which dominates the central and eastern interior of the subcontinent, as this is where the Vaal River catchment is located.

5.3.2 Miocene climate

The southern African climate of the early and middle Miocene was characterised by generally warm and mesic conditions (Tyson & Partridge 2000, Wigley & Compton 2006). This humid interval is believed to have been brought to an end with the initiation of the cold Benguela upwelling system off the west coast of southern Africa and the establishment of the East Antarctic ice-sheet around 15 Ma (Partridge & Maud 2000, Tyson & Partridge 2000, de Wit *et al.* 2000). Aridity in the late Miocene is thought to have resulted in the development of major duricrusts in the landscape (Partridge & Maud 2000). This period of aridity is believed to have continued until the Pliocene (de Wit *et al.* 2000).

5.3.3 Pliocene climate

In general, the climate from *ca* 5.3 Ma to 3.2 Ma has been interpreted to have been warm and stable, with wet and mesic environments persisting over the sub-continent (deMenocal 2004). Supporting evidence comes from the rejuvenation of drainage systems, such as that of the Carnarvon Leegte system, in the semi-arid western interior (de Wit *et al.* 2000, Tyson & Partridge 2000). In addition, between *ca* 4.6 and 3.2 Ma, warmer sea surface temperatures in the Benguela upwelling system off the west coast of southern Africa are indicated (Marlow *et al.* 2000). This would have led to an amelioration of climate in the interior. Stable isotope evidence from Makapansgat in the eastern interior of South Africa indicates that between *ca* 5.0 and 4.0 Ma the local environment was dominated by C_3 vegetation, with carbon isotopes in organic matter from a flowstone indicating a closed or forested environment (Hopley *et al.* 2007*a*). These isotopic data are consistent with a wetter more mesic environment.

At *ca* 3.2 Ma there was a readjustment in the climate over southern Africa (Hodell & Warnke 1991, Christensen *et al.* 2002, Giraudeau *et al.* 2002). At this time Benguela upwelling increased and was associated with a decrease in sea surface temperatures, which would have accentuated aridity over the interior (Marlow *et al.* 2000, Christensen *et al.* 2002). Stable carbon isotope

data from fossil tooth enamel collected from South African hominid sites in the eastern interior also shows a trend to more open environments since *ca* 3.0 Ma (Lee-Thorp *et al.* 2007).

Between *ca* 2.7 to 2.5 Ma it is generally believed that there was a major readjustment of the African climate (deMenocal 1995, Bobe & Behrensmeyer 2004, deMenocal 2004, Fernández & Vrba 2006). This climatic change has been related to the intensification of northern hemisphere glaciation (Ravelo *et al.* 2004, Maslin & Christensen 2007). There are, however, very limited good climatic records for southern Africa during this readjustment (Maslin & Christensen 2007). East Africa, on the other hand, has an ever growing body of research documenting this change.

During the intensification of northern hemisphere glaciation, East African climate was dominated by periods of extreme climate variability (Maslin & Christensen 2007). These consisted of short, alternating periods of extreme wetness and aridity (Trauth *et al.* 2005, Deino *et al.* 2006, Trauth *et al.* 2007). This extreme climate variability was characterised by the precessionally forced appearance and disappearance of large, deep lakes (Trauth *et al.* 2007). At this time there was also a significant increase in dust blowing into the oceans from the Sahara and Arabia into the adjacent ocean basins (deMenocal 1995, deMenocal 2004).

The limited climatic records for southern Africa are also said to show a major readjustment during this period. It is believed that at this period there was massive uplift of the south eastern and eastern hinterland of the subcontinent (Partridge & Maud 1987, Partridge & Maud 2000). This uplift, which totalled 700 to 900 metres, affected the eastern hinterland and plateau areas inland of the Great Escarpment (Partridge & Maud 2000). This uplift accentuated the east-west precipitation gradient that had been established with the initiation of the cool Benguela upwelling system off the west coast. Uplifted areas would have intercepted moisture advected from the Indian Ocean, and precipitation would have been concentrated on the windward side of the uplifted areas, with the accompaniment of rain shadow effects to the west (Tyson & Partridge

2000). A step-like shift to increasing aridity is thus envisioned at this time. The timing of this uplift is, however, not well constrained and remains debated (Partridge & Maud 2000, Gurnis *et al.* 2000, van der Beek *et al.* 2002), calling into question the significance of this forcing mechanism.

Support for a step-like increase in aridity comes from evidence for major cooling steps of the Benguela upwelling system at 2.8 and 2.5 Ma (Marlow *et al.* 2000), which would have lead to increasing aridity in the west of the country. However, a study using stable carbon isotope data from fossil tooth enamel from the eastern interior of South Africa (Lee-Thorp *et al.* 2007), shows only a general trend to more open environments since *ca* 3.0 Ma, with no abrupt change associated with the intensification of northern hemisphere glaciation, as documented in East Africa (Maslin & Christensen 2007). In addition, a study that considered significant morphometric differences between eastern and southern African fauna (Reynolds 2007), did not find a correlation with this event. It thus appears that, although southern Africa moved towards increasing aridity from *ca* 3.2 Ma, there is no conclusive evidence for a major step-like readjustment of the climate centred on the intensification of northern hemisphere glaciation (Maslin & Christensen 2007), and that a step-like change in the climate only occurred at the beginning of the Pleistocene (discussed below).

5.3.4 Pleistocene climate

An important change in African climates occurred around *ca* 1.9 to 1.7 Ma (deMenocal 1995, deMenocal 2004, Maslin & Christensen 2007, McClymont & Rosell-Melé 2005, Ravelo *et al.* 2004, Trauth *et al.* 2005, Trauth *et al.* 2007). This change has been attributed to the development of the atmospheric Walker Circulation (Maslin & Christensen 2007). The Walker Circulation is a dominant component of the modern day climate. A dominant feature of this system is the strong easterly trade wind belt that maintains and enhances the Pacific Ocean east-west gradients in sea surface temperatures (McClymont & Rosell-Melé 2005, Ravelo *et al.* 2004). In East Africa, this climatic transition is again accompanied by extreme climatic variability and a shift to drier conditions and

the spread of grasslands over large areas (Trauth *et al.* 2007).

In southern African the climatic record for this period (*ca* 1.9 to 1.7 Ma) has benefited from recent research that has provided good isotopic data from fossils and a cave flowstone for the summer rainfall region; these are crucial for an understanding of the palaeo-climate of the region (Hopley *et al.* 2007*a*, Hopley *et al.* 2007*b*, Lee-Thorp *et al.* 2007). Stable carbon isotope data from fossil tooth enamel collected from South African hominid sites in the eastern interior, recording relative proportions of C_3, mixed and C_4 feeding herbivores, indicate that open, grassy environments became a dominant component of the landscape at *ca* 1.7 Ma (Lee-Thorp *et al.* 2007). These authors make the important point that the success of C_4 dominated vegetation in sub-tropical Africa (mid-latitudes), indicates that conditions were highly favourable for C_4 grasses and less favourable for C_3 tree growth (Lee-Thorp *et al.* 2007). These authors point out that C_4 grasses will dominate in environments with high solar radiation and high minimum temperatures in the rainy/growing season, and will be able to withstand dry and/or cold environments in the non-growing season (Lee-Thorp *et al.* 2007). They conclude that the success of C_4 dominated vegetation in southern Africa may be the result of an increase in seasonality which occurred at *ca* 1.7 Ma. Southern Africa, with large seasonal differences in precipitation and temperatures between the summer/rainy and winter/dry seasons, would have provided ideal conditions for C_4 grassland to dominate (Lee-Thorp *et al.* 2007). Supporting evidence for an increase in seasonality, influencing the success of C_4 vegetation, has also been identified by others (Huang *et al.* 2001, Lee-Thorp 1995, Levin *et al.* 2004). A further recent study that has directly identified an increase in seasonality associated with the development of the Walker Circulation is that of Ravelo *et al.* (2004).

A further isotopic study on a cave flowstone from Makapansgat also provides crucial palaeoclimatic evidence for the region (Hopley *et al.* 2007*a*, Hopley *et al.* 2007*b*). The flowstone provides both oxygen and carbon isotope data for the time period from 1.99 to 1.52 Ma (Hopley *et al.* 2007*b*). In this study it has been argued that the oxygen isotope record is a proxy for monsoon

rainfall intensity in the summer rainfall region, while the carbon isotope record documents changes in the surrounding vegetation type (C_3/C_4) (Hopley *et al.* 2007*b*). These authors determined that the isotopic records demonstrate that independent orbital periodicities can dominate co-occurring rainfall and vegetation proxies. The oxygen isotope data are dominated by orbital precession and the carbon isotope data are dominated by orbital obliquity (Hopley *et al.* 2007*b*). It was concluded, however, that the effect of monsoonal rainfall on the vegetation was responsible for the coupling of the two parameters at the precessional frequency, especially when monsoon forcing was at its maximum (Hopley *et al.* 2007*b*).

As the time-span of the flowstone covered the climatic period associated with the development of the Walker Circulation, these authors analysed the isotopic data to see if there was a significant shift to drier conditions. They identified isotopic shifts between 1.8 and 1.7 Ma in both records, with the carbon isotope shift being of greater magnitude than that of oxygen (Hopley *et al.* 2007*b*). These authors interpreted these isotopic shifts as showing a reduction in rainfall and a corresponding increase in C_4 grasses (Hopley *et al.* 2007*b*). They concluded that their data recorded a sudden reduction in rainfall around 1.7 Ma, coincident with the records from East Africa. These authors also suggested that the increase in C_4 grasses and reduction in rainfall were related to the reorganisation of tropical climate, specifically the onset of the Walker Circulation, which resulted in drier conditions over southern Africa (Hopley *et al.* 2007*b*).

The above discussion of the two isotopic studies highlights two important points. The first is that the dominance of C_4 vegetation does not necessarily imply a reduction in annual rainfall, but could rather reflect an increase in seasonality. The oxygen isotope record from the flowstone at Makapansgat indicates only a slight decrease in rainfall at *ca* 1.7, but the carbon isotope record shows a large increase in the contribution of C_4 vegetation (Hopley *et al.* 2007*b*). The data could thus be interpreted as a shift to increased seasonality and not necessarily a large decrease in total precipitation, as proposed by the authors. The Makapansgat flowstone study does, however, emphasise

a second important point. This study highlights the rapidity with which environments in the summer rainfall region oscillated between forest dominated (C_3) and grass dominated (C_4) end-members (Hopley *et al.* 2007*b*). In conclusion, the early Pleistocene climate seems to have oscillated in line with orbital parameters until the next major climatic transition (drying event) at *ca* 1.2 to 1.0 Ma (Marlow *et al.* 2000, Maslin & Christensen 2007).

This next drying event over Africa was related to the onset of the Mid-Pleistocene Revolution (a shift to the lengthening and intensification of glacial-interglacial climatic cycles) recorded at a number of sites around Africa (Schefuβ *et al.* 2003, deMenocal 2004, Maslin & Christensen 2007), as well as in southern Africa (Diekmann & Kuhn 2002, McClymont *et al.* 2005). During the Mid-Pleistocene Revolution there is a switch from orbital obliquity driven climatic cycles to the hundred thousand year eccentricity cycles that characterise our modern climate (Maslin & Christensen 2007). It is important to note that, from this time onwards, the contrast between glacial/interglacial cycles becomes more severe (Diekmann & Kuhn 2002). In addition, these cycles developed their typical asymmetrical pattern, with long periods of cold climates that are terminated by periods of relatively rapid warming (Diekmann & Kuhn 2002).

Marine records provide the best palaeo-climatic evidence for southern Africa for this period. These records indicate strengthening of trade winds and Walker Circulation beginning near 1.2 Ma (McClymont & Rosell-Melé 2005), as well as northward migration of the Polar Front south of Africa (Diekmann & Kuhn 2002, McClymont *et al.* 2005) and cooling of the Benguela upwelling system (Marlow *et al.* 2000), all of which would have led to drying of the interior. Marine records also indicate that there was a step-like shift towards more arid conditions in southern Africa between 900 and 800 thousand years ago (Diekmann & Kuhn 2002). Glacial/interglacial cycles also became most severe after 650 thousand years ago (Diekmann & Kuhn 2002). In conclusion, it is apparent that at *ca* 1.2 Ma there was a change to more arid conditions over southern Africa, with the climate subsequently alternating between long, cold glacial periods followed by shorter, warm interglacials.

5.4 A southern African palaeoclimatic model

It is important to outline briefly how the southern African climate, on shorter time scales than discussed above, would have responded to the climatic shifts and driving mechanisms outlined in the previous section. There is general agreement on the broad outlines of a palaeoclimatic model for southern Africa (Tyson 1999, Partridge *et al.* 2004, Denison *et al.* 2005, Hopley *et al.* 2007*b*, Hopley *et al.* 2007*a*, Kristen *et al.* 2007, Pickering *et al.* 2007). On time scales compatible with major adjustments of the circulation over southern Africa, there is a general association between warmer, wetter and cooler, drier conditions in the continental interior (Tyson 1999). In general warmer, wetter periods involve the expansion poleward of the tropical easterlies, while expansion equatorward of the westerlies and associated frontal disturbances leads to cooler, drier conditions in the summer rainfall region of southern Africa (Tyson 1999).

Some researchers explain this relationship by linking the summer rainfall area to changes in circulation patterns over the Antarctic (Partridge *et al.* 2004). A decrease in the amount of sea ice and the intensity of the thermal gradient across Antarctica is thought to lead to a contraction of the circumpolar vortex and the poleward advance of the tropical atmospheric circulation, leading to warmer, wetter conditions (Partridge *et al.* 2004). Cooler, drier conditions result from an extension of the Antarctic sea ice, increase in the diameter of the circumpolar vortex, and an increase in the latitudinal thermal gradient, which results in the expansion of the westerlies and the subtropical highs leading to a reduction in rainfall (Partridge *et al.* 2004).

Studies indicate that changes in orbital precession are also instrumental in modulating these climatic shifts (Denison *et al.* 2005, Hopley *et al.* 2007*a*, Hopley *et al.* 2007*b*). Southern hemisphere precessional maxima cause the inter-topical convergence zone to migrate southward, leading to enhanced tropical forcing and wetter, warmer conditions over the summer rainfall region (Tyson 1999). During precessional minima the inter-tropical convergence zone moves north toward the equator, leading to enhanced polar forcing and drier, cooler

conditions (Tyson 1999).

There is growing evidence that moisture availability is controlled by orbital precession in southern Africa. An oxygen isotopic study at Makapansgat, recording variations in sub-tropical monsoon rainfall is dominated by a precessional signal (Hopley *et al.* 2007*a*, Hopley *et al.* 2007*b*), as is a carbon isotope study on vegetation in southwest Africa (Denison *et al.* 2005). In addition, studies of proxies for rainfall changes in southern Africa over the last two hundred thousand years, recorded in lake sediments from the Tswaing impact crater, are dominated by a precession signal (Partridge *et al.* 1997, Kristen *et al.* 2007). All these studies strongly support the proposed southern African palaeoclimatic model.

5.5 Correlation between the fluvial history and proposed driving mechanisms

As outlined in Chapter 2, there has been much debate over the years on the factors which led to the formation and preservation of the various fluvial deposits within the lower Vaal River valley, and thus about the geomorphic history of the lower Vaal River catchment. Climatic factors have dominated the interpretations (van Riet Lowe 1952*b*, Helgren 1979), while others have abandoned climatic explanations in favour of other geomorphic processes such as tectonics, river capture, variable lithologies and the cyclic passage of knickpoints (Partridge & Brink 1967). All these studies have suffered from a poor chronological framework, as the timing of the proposed driving mechanisms could not be correlated with any certainty to the results. Direct comparison between climatic changes, tectonic processes, and the sequence of fluvial events or major features of the deposits has, in fact, previously not been possible.

Now that an absolute fluvial chronology is available for the lower Vaal River catchment through the application of cosmogenic nuclide burial dating, it is possible to compare the proposed driving mechanisms with the interpreted sequence of fluvial events. The two key driving mechanisms that can be tested

for correlation with the sequence of fluvial events include climate change and tectonic processes.

Two periods of tectonic uplift in the Neogene are believed to have imparted a slight increase to the gradients of westward flowing rivers, such as the Vaal. The first of these uplift events is believed to have taken place around the beginning of the Miocene (Partridge & Maud 2000). The second, a much larger uplift event, is thought to have begun in the early Pliocene (Partridge & Maud 2000). It is believed that these uplift events, in combination with relatively wet climatic conditions, resulted in two major periods of river rejuvenation/incision (de Wit *et al.* 2000). In addition, a study by Marshall (1990) attributed the incision event prior to aggradation of Rietputs Formation equivalent deposits, along right bank tributaries of the Vaal River, to tectonic uplift.

In considering if there is a correlation between the uplift events and the fluvial chronology, a few cautionary notes are needed. As stated earlier, the timing of the Pliocene uplift event is not well constrained, and continues to be debated (Partridge & Maud 2000, Gurnis *et al.* 2000, van der Beek *et al.* 2002). In addition, no absolute age determination of the Holpan terrace has been obtainable. All that can be concluded is that a Miocene age is not unreasonable. These uplift events are also said to occur, perhaps fortuitously, during intervals of relatively wet climatic conditions (de Wit *et al.* 2000), so that climatic control is not independent of tectonic control. Other authors (Westaway *et al.* 2003, Bridgland & Westaway 2008) have also dismissed Pliocene tectonic uplift of the Vaal River catchment which is situated on an stable Archaean craton.

Although, tectonic uplift may have influenced the fluvial history, it is impossible to correlate the Miocene uplift event with incision due to the poor dating control for old terrace deposits. Debate around the Pliocene uplift event and its timing also does not facilitate correlation. The Vaal River has incised through bedrock several times since the beginning of the Pliocene, with incision ending around the start of the Pleistocene. This incision has occurred as a series of events following periods of aggradation, and is thus probably

not related to tectonic events. As discussed below, the fluvial chronology can best be correlated with elements of climate change throughout the Neogene; thus climate appears to play a far more significant role than does tectonic control. It is important to note that this climatic control is not as straightforward as previous studies have indicated (Helgren 1979), but operates in a complex relationship with other factors and mechanisms.

5.6 Vaal River bedrock incision model

As noted previously, the Rietputs Formation deposits, which are the best dated, show that individual cycles of aggradation of gravels and fines can span almost a million years. If similar lengths of time are represented by the Proksch Koppie and Wedburg deposits then these lengthy periods of aggradation have important implications for understanding the time represented by net incision events. Following aggradation of the Proksch Koppie terrace deposit, the Vaal River incised up to 45 metres into bedrock, with incision ending with the aggradation of the Rietputs Formation deposits. This period of net incision ranges in length of roughly two million years if the maximum age of the Proksch Koppie terrace is used, or roughly one million years if the minimum age is used. In addition, the Wedburg terrace deposit was aggraded during a break in this cycle of bedrock incision.

If the time represented by the Wedburg terrace is comparable to the time represented by the Rietputs Formation (as determined by cosmogenic nuclide burial dating), then the time represented by periods of active bedrock erosion is comparatively short. In support of this, Helgren (1979) identified Wedburg equivalent terraces along the Riet, Harts and Orange Rivers. He concluded that the Vaal River must have remained static at Wedburg levels for a substantial period of time to enable extended plains to be eroded at this level throughout the basin. It is thus proposed that, during the Pliocene incision events occurred relatively rapidly following lengthy periods of net aggradation.

It is clear that a bedrock incision mechanism is needed to explain this rapid

erosion. As outlined in Chapter 2, the Vaal River has been re-excavating valleys within the pre-Karoo surface (Proterozoic to late Carboniferous unconformity). Where river channels are confined to valleys in this pre-Karoo surface terrace deposits are best preserved, as the rivers were not able to move laterally across a floodplain but have rather cut through the soft Karoo rocks that filled the valleys. These easily erodible Karoo rocks, which consist dominantly of shale and tillite, and the older terrace deposits lining the river banks (supplying coarse clasts), provide ideal concentrating and abrading mechanisms allowing for bedrock erosion to occur rapidly within narrow areal limits (discussed below).

A study into sediment and rock strength controls on river incision into bedrock found that bedrock abrasion and erosion occur primarily through impacts by saltating grains (Sklar & Dietrich 2001). The authors of this study found that sediment promotes erosion at low supply rates by providing tools for abrasion, whereas large amounts of sediment inhibit erosion by burying bedrock beneath alluvial deposits, thus providing bedrock shielding (Sklar & Dietrich 2001). These authors also found that fine grained sediments such as sand (less than two millimetres in diameter) provided poor tools for bedrock erosion because they tended to travel in suspension, while larger gravels clasts that move as bed load provide the best tools for erosion. Maximum erosion rates were found to occur at a critical level of coarse sediment supply where the bedrock was only partially exposed. In addition, soft easily erodible bedrocks were eroded up to three times as fast by strong clasts, such as quartzite, in comparison to erosion by clasts of the same lithology as the bedrock (Sklar & Dietrich 2001). Other studies have also found that bed load deposits need to be removed before bedrock incision can take place (Hanson *et al.* 2006), and that increasing bed load provides shielding from further erosion (Jansen 2006).

The findings from the above studies can be applied to the Vaal River in order to gain an understanding of local controls on bedrock incision. The Vaal River valley provides an ideal situation for rapid bedrock erosion to proceed. The Vaal River has largely been confined to pre-Karoo valleys that are filled with soft, easily erodible Karoo rocks. Larger clasts are readily available from erosion

of older terrace deposits lining, and near to, the river banks, as well as from the erosion of the Permo-Carboniferous Dwyka tillite bedrock. These large clasts have a significant content of very resistant lithologies (Helgren 1979). Rapid bedrock erosion and incision would thus take place when formative flow regimes partially exposed bedrock, and coarse sediment supply did not exceed the critical threshold beyond which aggradation of bed load deposits provided shielding. Under these conditions the soft Karoo rocks were rapidly eroded by the saltating resistant clasts. When sediment supply reached the critical level, and could no longer be transported as bed load, gravels aggraded and erosion stopped.

It is important to note that clasts of all size categories were available as erosion tools from the tillite and older gravel deposits. Varying discharge strengths could entrain different clast sizes. Extremely high discharges could mobilise cobbles as bed load, while reduced discharges could mobilise small pebbles only. As long as bedrock was continuously available, varying clast size categories would thus be available at different times as tools for erosion.

It can thus be seen that bedrock incision could have occurred relatively rapidly under ideal conditions. If formative discharges dropped to levels that could not transport particles larger than the sand as bed load, then bedrock incision would be halted or substantially reduced. Formative discharges are defined as discharges that result in the net outcome of either erosion of the channel or aggradation of alluvium over the medium to long term. If large clast sediment supply exceeded the critical transport level then bed load aggradation would proceed and erosion would be halted. Ideal conditions for bedrock erosion probably occur only sporadically under particular climatic conditions, and thus incision must recur periodically over short periods of time.

5.7 Revised fluvial history model

In this section a revised fluvial history for the lower Vaal River catchment is outlined. This history is given in outline only. In the following section the

various aspects of, and supporting evidence for, the model are discussed.

Net bedrock incision As already indicated, incision through bedrock is controlled by climate. After a period of aggradation that resulted in a lower coarse gravel and sand unit being capped by laminated and cross-bedded fine alluvium, climatic conditions shifted towards periodically wetter conditions. These periodically wetter conditions, and the resulting Vaal River flow regime, were characterised by an increase in the number and amplitude of formative discharges. These frequent and large discharges eroded both the upper fine alluvium and lower coarse alluvium, because they were able to mobilise the majority of large clasts, exposing the easily erodible Karoo rocks lining the valley bottom. Incision through bedrock occurred as a result of the repeated impacts and abrasion of saltating hard clasts (e.g. quartzite/Ventersdorp lava) on the soft bedrock.

Net coarse gravel aggradation When coarse sediment supply exceeded a critical level, and large clasts were no longer moved as a saltating bed load, aggradation of coarse gravels and sands ensued. This bed load deposit provided shielding to the underlying bedrock and incision was halted. Either a reduction in formative discharge strength, or an increase in sediment supply to the river channel, or a combination of both, could cause aggradation to commence. Coarse gravels and sands aggraded when discharges were sufficient to mobilise the fines, but not the larger clasts. The resulting deposit was a winnowed channel lag deposit, that continued to form/thicken as coarse clasts were continually supplied to the channel by erosion of older alluvial deposits or tillite lining the river banks. Coarse clasts would continually be available as the Vaal River incised into older terrace deposits. It follows that, net coarse gravel aggradation was climatically controlled.

Net fines aggradation Fines aggradation occurred when formative discharges were unable to transport the bulk of the fines fraction downstream. The erosive power of the river at this point was greatly reduced, with erosion

of older alluvial deposits or tillite lining the river banks probably becoming very limited, or even ceasing. An increase in fine sediment supply from the surrounding landscape would increase aggradation rates. Net fines aggradation marks a clear reduction in formative discharges and erosional capabilities of the Vaal River. Net fines aggradation is, therefore, also climatically controlled.

5.8 Discussion of the fluvial history model

5.8.1 Introduction

The fluvial history model, as outlined above, is based upon the cosmogenic nuclide dated sequence of fluvial events related to the Rietputs Formation deposits. This dated sequence was correlated with the palaeoclimatic record for the summer rainfall region of southern Africa. Correlation between key elements of the geological and climatological records forms the basis of this model, in conjunction with an understanding of the local mechanisms of bedrock incision. Climatic control is proposed as the driving mechanism for key events in the Vaal River's fluvial history. While previous studies have likewise focused on the role of climate changes (Helgren 1979), the relationship is far more complex than was previously proposed. It is important to note that all deposits (i.e. from the Holpan to the Rietputs Formation terraces, as well as those of the Vaal River tributaries) are similar in that they all contain a lower coarse alluvium capped by an upper fine alluvium.

5.8.2 Problems with the previous Rietputs Formation fluvial history model

Historically, the Rietputs Formation has been divided into three individual members (Rietputs A to C) based on topographical, sedimentological and lithological data acquired from limited exposures throughout the Vaal River Basin (Helgren 1979). Post-depositional processes such as calcretisation and

rubification were also used to define and then distinguish the members. Each member, and the intervening non-depositional/erosional event, was then attributed to a particular climatic regime or transition (Helgren 1979). The current study indicates that caution is needed when assigning a specific deposit to a particular stratigraphic unit. Local variability in all of the identifying factors makes it impossible to link deposits visually (and temporally), across the basin, as is required by the member classification system. Similarly, sedimentological, lithological and post-depositional processes vary on scales of a few tens of metres, in relation to localised processes or conditions, and not to large, basin-wide driving mechanisms.

An example of the shortcomings of the member classification system, and thus the conclusions based on the system, is that of Canteen Kopje. As discussed in Chapter 4, two cosmogenic nuclide burial dating samples from two separate pits (40 metres apart) were collected from the site. The first sample has a maximum age of *ca* 1.06±0.19 Ma and a minimum age of *ca* 1.00±0.18 Ma, while the second has a maximum age of *ca* 1.46±0.15 Ma and a minimum age of *ca* 1.37±0.14 Ma. These ages highlight two important points. Firstly, the spread of ages indicates that deposition of the gravels was very complex on a local scale. Adjoining gravel deposits were not necessarily aggraded at the same time and could have very different depositional ages, reflecting separate events as the river migrated laterally within the valley over a long period of time. Secondly, these ages are on the young side of the age model determined for the aggradation of the lower coarse alluvium (*ca* 1.8 to 1.35 Ma). These two points highlight fundamental shortcomings of the member system. Helgren (1979, 224) classified all of the gravels at Canteen Kopje, based on the presence of a rubefied cambic palaeosol in the upper part of the gravels, as member A of the Rietputs Formation (the oldest Rietputs Formation deposit). The burial dating data, however, indicate that this is not the case and that the deposits are, in fact, at the younger end of the sequence. In addition, a deposit cannot necessarily be attributed to one single event of aggradation, as lateral facies of the deposit may date to different times. It can thus be seen that the presence of a rubefied palaeosol in a gravel deposit cannot be used to identify any one

specific temporal event. These problems have crucial implication for Helgren's conclusions as justification for the member classification system falls away.

Helgren's (1979) palaeoclimatic interpretation, based on his member classification system, proposed a variety of varying climates for the Rietputs Formation deposits. He attributed Rietputs Formation member A, as well as the period of bedrock incision that preceded the deposition of the gravels, to an environment more humid than present. He added that a semi-arid environment was established before the deposition of member B, with this member's deposits representing an arid phase of aggradation. Member C was interpreted as representing a long interval of sub-arid to sub-humid environments, with conditions similar to those of the present. The basis for this member classification system does not seem applicable in light of the findings of the current study, thus calling into question this detailed climatic reconstruction. That said, however, some of Helgren's conclusions are supported by the current study, but a much improved palaeoclimatic record and absolute dating has allowed for refinement and modification. Similarly, conclusions by Partridge and Brink (1967) who believed that the Rietputs Formation deposits represented semi-arid accumulations showing the imprint of periodic humid episodes, could also be re-evaluated.

It must be noted that Helgren's (1979) original inference, that the beginning of the Rietputs Formation aggradation could date back to the early Pleistocene, has proved correct. However, his suggestion that most of the deposits were of middle Pleistocene age, has been proved to be incorrect. He also envisioned a period of bedrock incision, spanning about a million years, between the formation of the Wedburg terrace and the aggradation of the Rietputs Formation. The current study indicates that arguments for such a lengthy period of incision is probably not justifiable.

5.8.3 Bedrock incision prior to the aggradation of the Rietputs Formation

Before continuing with a discussion on bedrock incision prior to the aggradation of the Rietputs Formation, the passage of knickpoints and breaching of hard rock barriers, as proposed by other authors as the driving mechanism of bedrock incision, must be examined (Tooth *et al.* 2004, McCarthy & Tooth 2004). A comparative study of three left bank tributaries of the Vaal River, focused on geological controls on alluvial river behaviour, concluded that bedrock incision occurs along separate reaches of a river independently in relation to the breaching of hard rock barriers along the course of the river (e.g. dolerite outcrops) (Tooth *et al.* 2004). Hard rock barriers are said to form the base level for incision for reaches upstream. Upstream of unbreached barriers it was found that lateral erosion dominates, with rivers meandering extensively (Tooth *et al.* 2004, McCarthy & Tooth 2004). When the hard rock barrier is breached, incision occurs upstream. This incision only extends upstream until the next hard rock barrier in encountered. Incision along various reaches of a river are thus seen to occur independently of each other, and independent of climatic forcing, with incision controlled only by the breaching of the hard rock barriers and the resulting passage of a knickpoint upstream (Tooth *et al.* 2004, McCarthy & Tooth 2004).

The above studies highlight two important points. Firstly, that base level fall along the Orange River, the major base level control for the lower Vaal River catchment, will not be transmitted upstream through a hard rock barrier and thus incision events along the Orange River will not greatly control incision along the whole length of the Vaal River. Secondly, these authors conclude that past phases of river incision and aggradation are unlikely to have been synchronous, being controlled by the position in the landscape of hard rock barriers (Tooth *et al.* 2004, McCarthy & Tooth 2004). The findings of the above studies will now be considered in relation the the Vaal River.

Figure 5.1 shows the Vaal River long profile from the infall of the Bamboesspruit to the confluence with the Orange River. Generalised outcroppings of

the Ventersdorp Supergroup and the Karoo Sequence are shown. Outcroppings of the Ventersdorp Supergroup show the locations where the Vaal River is confined to the pre-Karoo valley. It is clear from the long profile that the pre-Karoo geological structure has imparted two prominent knick-zones (or hard rock barriers) along the river's course. The gradients along these knick-zones are substantially steeper than along the rest of the reaches (Table 5.1). These knick-zones are features of the pre-Karoo surface, with the gradients reflecting those of the pre-Karoo valleys.

Table 5.1: Vaal River reach gradients for the study area. Gradients determined from 1:50 000 topographic maps.

Location	**Gradient**	**Bedrock outcroppings**
Bamboesspruit to Christiana/Bloemhof	0.21	Karoo Sequence
Reach near Christiana/Bloemhof	0.77	Ventersdorp Supergroup
Downstream of Christiana/Bloemhof to Warrenton	0.37	Karoo Sequence
Warrenton to Windsorton	2.10	Ventersdorp Supergroup
Windsorton to Barkly West	0.39	Karoo Sequence
Barkly West to Sydney-on-Vaal	1.66	Ventersdorp Supergroup
Downstream of Sydney-on-Vaal	0.51	Karoo Sequence
Reach just downstream of Sydney-on-Vaal	0.46	Ventersdorp Supergroup
To Orange River confluence	0.13	Karoo Sequence

These two knick-zones, along with the Vaal/Orange River confluence, do seem to act as hard rock barriers and anchor/influence the nature of the upstream reaches. In Figure 5.2 it can be seen that meandering is more extensive upstream of these knick-zones. It may, in fact, be concluded that incision upstream of these knick-zones can only occur once incision has taken place along the knick-zones.

The question that then needs to be answered is 'why do these knick-zones, with their steeper pre-Karoo gradients, act as hard rock barriers?'. The pre-Karoo valleys in which they occur are filled with easily erodible soft Karoo rocks that

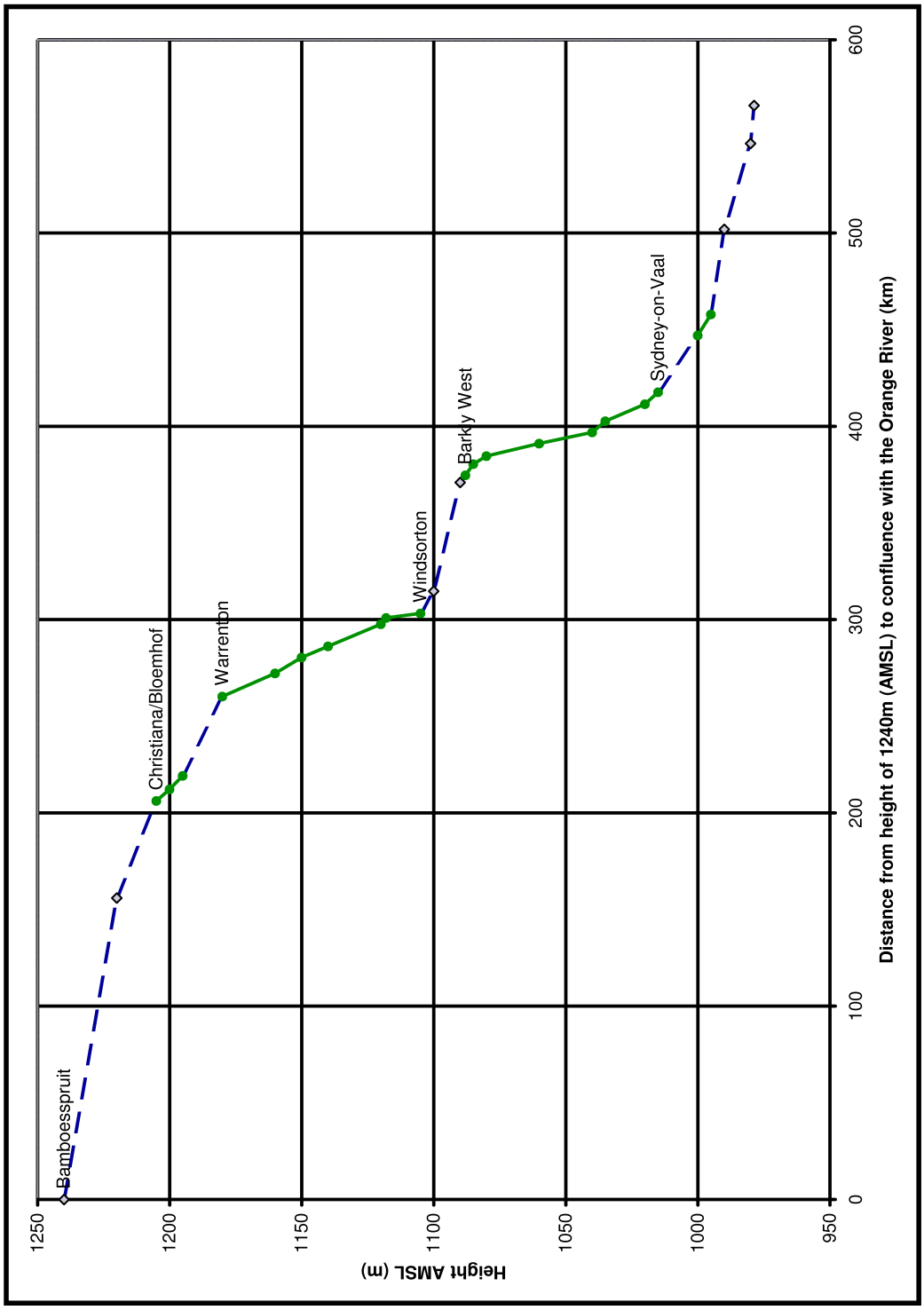


Figure 5.1: Vaal River long profile from the infall of the Bamboesspruit to the confluence with the Orange River. Generalised outcroppings of the Ventersdorp Supergroup (solid line) and the Karoo Sequence (dashed line) are shown. Profile constructed from 1:50 000 topographic maps.

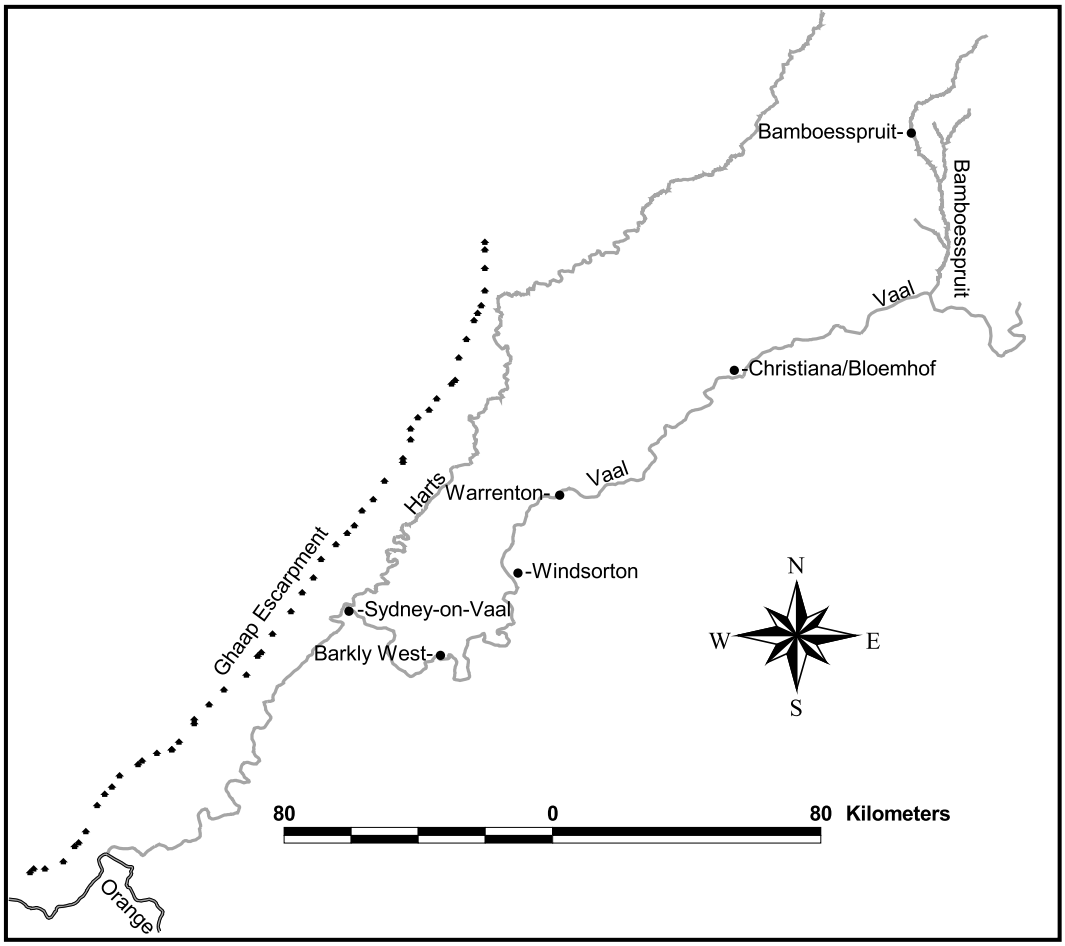


Figure 5.2: Plan view of the study area within the Vaal River catchment. Two prominent knick-zones occur between Warrenton and Windsorton, and between Barkly West and Sydney-on-Vaal. Upstream of these knick-zones, and the Vaal/Orange River confluence, the Vaal River can be seen to meander more extensively.

should be easily incised. The answer to this question is to be found in the armouring of coarse gravels which line the valley bottom along these knick-zone reaches during aggradation events. These gravels provide a very resistant armour that prevents bedrock incision that must be removed before incision can take place. In short, gravel aggradation events along these knick-zones provide the armour which turns these reaches into hard rock barriers. Removal of these gravels and incision into the basal soft Karoo rocks is equivalent to breaching of hard rock barriers described in other studies (Tooth *et al.* 2004, McCarthy & Tooth 2004). The key difference with these knick-zones is however that when incision is halted and coarse gravels are again aggraded, the knick-zones once again act as barriers. Incision events, which include the removal of the coarse gravel armouring, can thus be seen to drive knickpoint migration upstream of these knick-zones, as well as the lowering of these knick-zones within the landscape. It is important to note that these knick-zones would not have migrated upstream during incision but would have only been lowered within the landscape. They are thus essentially static features within the catchment. Once the armouring has been removed incision into the soft bedrock can occur relatively rapidly, as outlined in the bedrock incision model, particularly as gradients along these reaches are steeper, providing higher hydraulic power conditions than along the other reaches. See Figure 5.3 for a schematic model showing how bedrock incision takes place within the lower Vaal River catchment.

Before reverting to the interval of bedrock incision which preceded the aggradation of the Rietputs Formation, a few important points need to be considered. It has been proposed, based on the cosmogenic nuclide burial dated sequence of events, that bedrock incision most likely occurred relatively rapidly. Bedrock incision would have taken place during periodically wetter conditions, characterised by an increase in the number and amplitude of formative discharges. Such large and frequent discharges would be needed to erode through both the upper fine alluvium and lower coarse alluvium lining the Vaal River channel/valley. During these wetter times, well vegetated river banks would have helped focus erosion primarily in the channel. Energy would thus have been available to erode bedrock by the action of saltating clasts, derived from

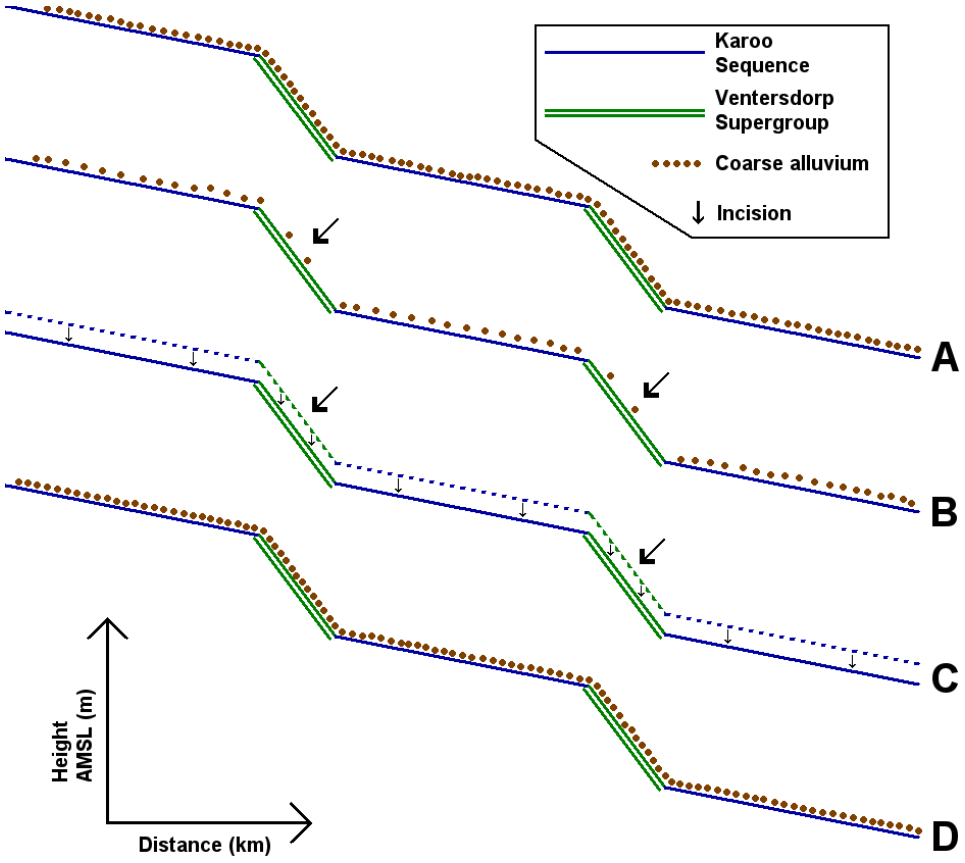


Figure 5.3: Schematic representations of the Vaal River long profile from the infall of the Bamboesspruit to the confluence with the Orange River showing how bedrock incision takes place within the lower catchment. Generalised outcroppings of the Ventersdorp Supergroup and the Karoo Sequence are shown. **A:** Bedrock along the river is protected by a covering of coarse alluvium which prevents incision. **B:** A shift to climatic conditions characterised by an increase in the number and amplitude of formative discharges begins to remove the gravel armouring along the steeper pre-Karoo knick-zone reaches, particularly as these provide higher hydraulic power conditions. **C:** The now exposed, easily erodible Karoo rocks lining the valley bottom along the knick-zone reaches are incised as a result of repeated impacts and abrasion by saltating hard clasts on the soft bedrock. Incision along the knick-zone reaches results in knickpoint migration upstream, resulting in incision of alluvium, as well as bedrock in these flatter regions. **D:** Either a reduction in formative discharge strength, or an increase in coarse sediment supply, or a combination of both, causes the aggradation again of protective gravels which stops bedrock incision.

erosion of the tillite and older terrace deposits. Stabilisation of older terrace deposits by vegetation would have prevented excess clasts from being eroded into the channel and forming an armour, which would have caused incision to stop. It can thus be seen that incision will continue under the appropriate climatic conditions until a reduction in discharge and inability to remove clasts lining the channel, or an increase in clasts eroded into the channel, bring about a stop to this cycle of bedrock erosion.

Net aggradation events will be longer, in terms of time represented, than incision events for several reasons. Once a gravel deposit has been aggraded consistently wetter conditions over a suitable length of time, with an associated increase in the number and amplitude of formative discharges, are needed to remove all of the deposits before bedrock incision can take place. Incision events eroding only partially through lining gravel deposits cannot be separated from net aggradation. Thus, if the armouring is not completely removed, even over numerous climatic cycles, then net aggradation events can apparently span very long periods of time. Also, if there is a rapid increase in clasts eroded into the channel, then the resulting armouring can change an incising river to an aggrading one very quickly. The climatic conditions needed to remove this armour may be infrequent, thus bringing to an end the incision and the start of a long period of aggradation.

It is impossible to say when exactly the bedrock incision event that preceded the aggradation of the Rietputs Formation begun. The palaeoclimatic record for the end of the Pliocene for southern Africa is extremely poor and it is impossible to identify a period with consistently wetter conditions over a suitable length of time, with an associated increase in the number and amplitude of formative discharges, which would have been able to remove the Wedburg gravel deposits lining the base of the Vaal River channel/valley. That such conditions existed can, however, be identified from several lines of evidence.

Evidence for repeated high amplitude discharges was first identified by Helgren at the type-site at Windsorton (Helgren 1979). Helgren identified a pot hole in Ventersdorp lava which extended 18 metres below modern river level. The pot

hole was filled with Rietputs Formation gravels. Helgren proposed that the pot hole in the resistant Ventersdorp lava was in fact a feature of the pre-Karoo surface which had been filled with Karoo sediments. He noted that other such features in the area not only contained gravels but also remnants of Karoo rocks. It was thus apparent that the Karoo rocks had been eroded out by hydraulic action. Helgren (1979, 217) concluded that "*even the excavation of the softer Karoo sediments from the 'pot hole' required extraordinary hydraulic forces*". A similar feature was also identified by the present author at Sydney-on-Vaal (Figure 5.4). It can thus be seen that, at times, suitable hydraulic conditions existed to erode both lining gravels deposits as well as bedrock.



Figure 5.4: Top of a pot hole filled with Rietputs Formation gravels at Sydney-on-Vaal. Gravels were subsequently mined to a depth of approximately 20 to 30 metres below the modern river level.

Further evidence for these extreme wet conditions comes from tufa and associated deposits along the Ghaap Escarpment (Figure 5.2). Although poorly dated the tufa deposits are believed to range in age from early Pliocene to the present (Butzer *et al.* 1978). The Taung Child (*Australopithecus africanus*) was

recovered from these deposits, supporting their antiquity. Irrespectively of specific ages and timing of formation, it has been found that the various tufa members often overlie, or contain, coarse conglomerate lenses (Butzer *et al.* 1978). Although there is much debate around the climatic conditions necessary for tufa formation (Butzer *et al.* 1978, Partridge 1985, Marker 1988), these coarse conglomerates provide information on climatic conditions. It has been argued that the various conglomerate units required surges of hydraulic energy exceeding that of modern day floods (Butzer *et al.* 1978). It was concluded that repeated high intensity rainfalls were needed to produce these deposits (Butzer *et al.* 1978). Although undated and uncorrelated, these clastic conglomerates do provide supporting evidence that suitable hydraulic conditions existed, at least periodically, that were conducive for bedrock incision to take place.

It can thus be seen that suitable conditions for the removal of the gravel armouring and subsequent bedrock incision did recur in the past. It is, however, not possible to say when they commenced or how long they lasted. All that can be concluded is that changing climatic conditions brought these incision events to an end at the beginning of the Pleistocene. That this incision was climatically controlled is evidenced by the fact that incision only reached the pre-Karoo channels in certain reaches. Between Windsorton and Sydney-on-Vaal (Figure 5.2) this incision generally stopped with the exhumation of the pre-Karoo surfaces (Helgren 1979). From Sydney-on-Vaal to the confluence with the Orange River, as well as in the Harts, Riet and Orange River valleys, it was halted before all Karoo sediments had been removed (Helgren 1979). It can thus be seen that soft Karoo rocks were still available to be eroded but, due to external climatic changes, the incision was halted and the Vaal River changed from an incising to an aggrading regime. At the type-site at Windsorton all pits examined in the current study contained shale bedrock, in support of the above point.

Before concluding with this discussion of bedrock incision a few final points need to be considered. The conclusion of previous studies that past phases of river incision and aggradation are unlikely to have been synchronous, due to the position in the landscape of hard rock barriers (Tooth *et al.* 2004, McCarthy

& Tooth 2004), seems not to be applicable to the Vaal River. If the same external driving mechanism was responsible for removing the gravel armouring along the knick-zone reaches, then their incision would have be relatively synchronous.

As the differences in bedrock depth below the Rietputs Formation deposits, in relation to the modern river level, are not greatly dissimilar along the various reaches of the river (Table 4.5), given normal variations in bedrock and measurement uncertainties, and cosmogenic nuclide burial dates are consistent for the subsequent aggradation event, it can be concluded that the preceding gravel armouring removal occurred relatively simultaneously throughout the catchment. In this way it can be seen that incision along various reaches of the river occurred at roughly the same time, and not independent of each other as proposed by other authors (Tooth *et al.* 2004). Incision would obviously not have occurred to exactly the same levels throughout the catchment, but what is clear is that incision was synchronous along the various reaches. Climatically driven removal of the gravel armouring would have occurred at roughly the same time along the knick-zones, resulting in a catchment wide period of incision. Incision along the lowest reaches of the Vaal River would, however, have been controlled by base level fall along the Orange River.

In respect of its tributaries, the Vaal River would have acted as a base level control. Knickpoint migration upstream and incision would, however, not necessarily have been synchronous with those in the Vaal River due to the position of hard rock barriers along different reaches of the tributaries as proposed by other others (Tooth *et al.* 2004). This point is emphasised by the fact that Wedburg and Proksch Koppie equivalent terraces are not preserved along right bank tributaries (Marshall 1990). The Vaal River is a special case in that it has been confined to a pre-Karoo valley, filled with easily erodible rocks, since the Miocene. This pre-Karoo structure has also imparted the two prominent knick-zones which have greatly influenced periods of incision (discussed above). Claims that the period of incision prior to Rietputs Formation aggradation along right bank tributaries was driven by tectonic uplift do not therefore seem very feasible (see Marshall 1990).

5.8.4 Rietputs Formation coarse gravels aggradation

At the beginning of the Pleistocene the Vaal River changed from an incising to an aggrading regime. Cosmogenic nuclide burial dating of the Rietputs Formation has shown that aggradation of the lower coarse gravel and sand unit occurred from *ca* 1.8 to 1.35 Ma. This change was brought about by a change in the climate over the summer rainfall region of southern Africa at the beginning of the Pleistocene. At this time there was an increase in seasonality, with the large seasonal differences in precipitation and temperatures between the summer/rainy and winter/dry seasons becoming a dominant component of the climate. This seasonality change caused a shift away from forest dominated to grass dominated vegetation. There may also be an overall slight drying of the region at this time. The early Pleistocene climate was characterised subsequently by oscillating warm/wet and cool/dry conditions driven by orbital mechanisms. Warm/wet periods were characterised by an increase in forest dominated vegetation, while cool/dry periods were characterised by grass dominated vegetation.

In terms of the proposed fluvial history model, a reduction in formative discharges with no change in sediment input, or an increase in sediment supply and no change in formative discharges, or a combination of both, will result in aggradation of gravels. During the aggradation of coarse gravels, sediment input included coarse clasts from erosion of both tillite and older terrace deposits within the river valley. The most important change in the climate of the Pleistocene seems to have been the increase in seasonality and associated change in vegetation. Total precipitation may have decreased slightly, but it appears that, rather than there being a net reduction, rainfall became more seasonal. The summer/rainy season would thus have been characterised by an increase in rainfall and associated discharges, as rainfall was reduced during the winter/dry season, with net yearly precipitation remaining roughly the same. Vegetation cover would have become reduced as grass dominated vegetation flourished and replaced forest dominated species, in response to the increased seasonality.

These changes in the climate and the environment would have provided the conditions necessary for aggradation to be initiated. It appears that there was probably no reduction in formative discharges, and that, in fact, they may have increased in amplitude as rainfall became more seasonal. It thus appears that there was an increase in the supply of coarse sediment to the river channel at this time. A move away from forest dominated to grass dominated vegetation, and the resulting reduction in vegetation cover, as well as the reduction in vegetation cover during the winter dry season, would have provided suitable conditions for an increase in erosion of older terrace deposits lining the Vaal River channel. An increased input of large clasts from this erosion could well have resulted in a change to aggradation. In addition, if increased large flood surges came in early spring when vegetation cover was still greatly reduced after the dry winter, then very rapid erosion of older terrace deposits lining the river bank could take place. Large inputs of clasts from such events would result in fairly quick armouring of the bedrock channel.

During this period of gravel aggradation the climate would also have oscillated between warm/wet and cool/dry conditions driven by orbital mechanisms. During cool and dry periods there may have been substantial decreases in vegetation cover, associated with increased bank erosion. A few large discharges during such dry times would have resulted in rapid bank erosion and increased sediment supply to the river. During these dry periods formative discharges may have been reduced in both number and amplitude, causing a reduction in the capacity of the river to remove large clasts from the channel. If renewed periods of wetness were unable to remove the large clasts then gravel aggradation would continue.

In conclusion, this episode of gravel aggradation is characterised by an increase in sediment supply to the Vaal River channel. This increase was caused primarily by an increase in seasonality of the climate and oscillations between warm/wet and cool/dry conditions. Wet events, with associated increase in the amplitude and number of formative discharges, were unable to remove all of the sediment introduced into the fluvial system. Coarse sediment supply exceeded the critical transport capacity and gravel deposits were thus aggraded.

A net increase in coarse sediment supply resulted in net aggradation of gravels over the long term, even though climate in the shorter term oscillated between warm/wet and cool/dry conditions over this period.

Supporting evidence for increased erosion of the older terrace deposits lining the Vaal River's banks (due to a reduction in vegetation cover), and resulting coarse gravel aggradation, comes from the cosmogenic nuclide data. Several of the cosmogenic samples that consisted of individual large clasts gave problematic ages. The cosmogenic nuclide data indicate that larger clasts were eroded from older terrace deposits fairly rapidly. These large clasts were not exposed for a sufficient period of time at the surface to obtain suitable concentrations of nuclides. The burial ages obtained either overestimate the age of the deposit or provide an erroneously young age if the clast was obtained from a very old deposit, such as the Proksch Koppie terrace (discussed in Chapter 4). The data thus indicate rapid erosion of older deposits lining the Vaal River channel during Rietputs Formation times.

Supporting evidence for reduced vegetation cover during dry-spells, and associated increased sediment input, comes from the site of Canteen Kopje near Barkly West (Figure 5.2). Canteen Kopje, from where two cosmogenic nuclide burial dating samples were collected, is situated in an exposed pre-Karoo valley of Ventersdorp lava (Helgren 1979). The Vaal River and associated Rietputs Formation deposits here are surrounded by small koppies of Ventersdorp lava. As noted previously, the clasts in the coarse alluvium are much more angular when compared to other Rietputs Formation deposits and are dominated by Ventersdorp lava clasts derived from the surrounding koppies (Figure 4.17). It is thus apparent that reduced vegetation cover at this locality resulted in an increase in Ventersdorp lava clasts being eroded into the river from the surrounding hills. As noted by Helgren (1979), Ventersdorp lava, when exposed as bedrock koppies, weathers into ready made sub-rounded clasts, which characterise the deposits at Canteen Kopje. It can thus be deduced that during dry periods, with reduced vegetation cover, there was an increase in coarse sediment supply to the Vaal River which would have resulted in coarse gravel aggradation.

Supporting evidence for increased rainfall seasonality, rather than a total net reduction in precipitation, comes from several lines of evidence. In addition, these lines of evidence also show that the climate was at least periodically wetter than it has been for the past million years and that there was not necessarily a sudden reduction in rainfall at *ca* 1.7 Ma, as recorded in East Africa (Maslin & Christensen 2007) and proposed for southern Africa (Hopley *et al.* 2007*b*).

The nature of the deposits themselves, i.e. boulder grade gravels, indicates that the formative discharges were much larger than anything that occurred during the last 1 Ma. The Riverton Formation that follows it is comprised only of sands and silts, with a few gravel lenses, indicating a reduction in discharge (Butzer *et al.* 1973). The Rietputs Formation gravels are also well sorted. The deposits fine upwards and elongated clasts are often placed in imbrication (Figure 5.5). This indicates that large clasts were being transported locally, indicating frequent and large formative discharges.

In addition, cosmogenically dated tributaries of the Vaal River, such as the Bamboesspruit (see Figure 5.2) that essentially became defunct at *ca* 1 Ma (discussed below), were able to carry and deposit coarse cobble grade gravels during the earlier Pleistocene (Marshall 1990). As outlined in Chapter 2, Marshall's (1990) study of Rietputs Formation equivalent deposits of the right bank tributaries of the Vaal River, upstream from Windsorton, indicated that the modern drainage basin and pattern of these tributaries has not changed since the early Pleistocene. Palaeo-channel width was about 30 metres, as compared to 10 metres at present. Channel depth was around six to seven metres. Gravels up to 200 metres in width have been found, which probably represent lateral channel migration of the streams. Study of the meander wavelength of the palaeo-channel, compared to the present drainage indicated that there was a higher discharge in these tributaries. It can thus be seen from Marshall's study that there was a higher discharge out of this drainage basin during Rietputs Formation times into the Vaal River, which also supports the occurrence of a periodically wetter climate. It is apparent that the early Pleistocene climate was sufficiently wet to support well developed feeder drainages that are today



Figure 5.5: Mining pit showing upward fining coarse alluvium of the Rietputs Formation.

essentially defunct and have not flowed as vigorously in the last million years.

This wet environment is confirmed by the deposition of tributary limestone tufa deposits, derived from the distant (7 to 15 kilometre) Ghaap carbonate escarpment, that are locally inter-fingered with the Rietputs Formation deposits, indicating substantial groundwater flow (Helgren 1979). Helgren noted that small modern stream at these sites are extremely ephemeral and do not deposit tufas under the current climatic regime, and that a significantly more humid environment would be needed to generate these deposits today.

In conclusion, it must be noted that periods of gravel aggradation would have occurred periodically throughout the span of net aggradation. Climatic shifts, driven by orbital parameters, would most likely have controlled shorter cycles of aggradation, non-deposition and erosion. This net period of gravel aggradation is, however, characterised by an overall increase in sediment supply to the Vaal River channel. This increase in sediment supply was primarily caused by an increase in seasonality of the climate and oscillations between warm/wet and cool/dry conditions, in combination with the resulting vegetation changes. Although the gravel deposits represent a restructuring of the climate (i.e. increase in seasonality) there is good evidence to show that there was not a sudden reduction in net rainfall over the region, and that conditions were wet enough, at least periodically, to support well developed feeder drainage systems.

5.8.5 Rietputs Formation fines aggradation

In contrast to the restructuring of the climate at the beginning of the Pleistocene, when there was not a substantial reduction in total precipitation, the Mid-Pleistocene Revolution (*ca* 1.2 to 1.0 Ma) was characterised by a substantial reduction in rainfall. Various fluvial deposits within the lower Vaal River catchment attest to this drying event.

First and foremost, there is a major change in the nature of the deposits being

aggraded by the Vaal River from coarse gravels and sands to the fine size factions of sands, silts and clays only. This fines aggradation occurred as a result of a reduction in the capacity of formative discharges to transport the majority of the fines downstream. Previously, the fines had been transported by the Vaal River leaving behind the winnowed lag of the gravels. The erosive power of the river would have been greatly reduced, with erosion of older terrace deposits or tillite being very limited or even ceasing. An increase in fine sediment supply from the surrounding landscape, due to reduction in vegetation cover, would also have increased aggradation rates.

The cosmogenic nuclide burial dating data show that this fines aggradation occurred at *ca* 1.35 to 1.15 Ma, coincident with the restructuring and drying of the climate in the summer rainfall region of southern Africa. At this time there was a change to more arid conditions over southern Africa, with the climate subsequently alternating between long, cold glacial periods followed by shorter, warm interglacials.

Helgren (1979) generally attributed the upper fine alluvium, which overlies the Rietputs Formation gravels at the type-site at Windsorton and elsewhere, to the Riverton Formation. He considered these fines to be substantially younger than the gravel deposits. The current study, through the use of cosmogenic nuclide burial dating has, however, determined that they were deposited immediately after the the aggradation of the coarse gravels had ceased. These fines were aggraded across the immediate river valley capping all the gravel deposits. Similarly, fine deposits were also deposited above Rietputs Formation gravel equivalent deposits along tributaries of the Vaal River (Marshall 1990). It is proposed that the change to more arid conditions was the key driving mechanism for the fines aggradation period.

Good evidence for this climatic control comes from the dated right bank tributaries of the Vaal River. As outlined in Chapter 2, it has been argued by Marshall (1990) that there has been extensive desiccation of the climate since gravel deposition times, which resulted in the deposition and calcretisation of the finer-grained sediments on top of the gravel deposits, just as is found along

the Vaal River. The deposits fine upwards, with the gravels overlain by up to seven metres of finer grained alluvial sands and muds. The gravel deposits are found between three to ten metres below the modern drainage, indicating that aggradation has dominated since their deposition (Marshall 1990). In addition, pans now occupy many of these dry channels. As the pans lie within dry channels and there is no evidence for tectonic disruption, it was argued that this is evidence of a drying climate (Marshall 1990). In addition, the present right bank tributaries of the Vaal River consist of small, dry, insignificant streams that flow only during extensive floods, remaining dry for periods of up to 10 years.

Cosmogenic nuclide burial dating of right bank tributaries of the Vaal River thus indicates that at *ca* 1.3 to 1.2 Ma fine sediment was aggraded. These catchments then dried up and essentially became defunct, with no evidence for substantial fluvial activity since *ca* 1.0 Ma. As it has been determined that the modern drainage basin and pattern of these tributaries has not changed since the early Pleistocene, climatic change can be seen to be the only viable control mechanism altering the nature of these catchments. A wetter climate than has persisted in the last million years would have been needed for the right bank drainage systems to be prominent in contributing water to the Vaal River.

Evidence that fluvial activity in the lower Vaal River has been greatly reduced over the last million years is evidenced by the fact that Rietputs Formation deposits still line the modern channel today along vast reaches (Helgren 1979). These gravel deposits have not been breached in the last *ca* 1.3 Ma, indicating that formative discharges have never, in this time, been sufficient to allow for substantial bedrock incision. In addition, Riverton Formation deposits, which occur as a proposed five-fold cut and fill sequence of sand and silts with a few gravel lenses (Butzer *et al.* 1973), were then aggraded over the Rietputs Formation along the immediate river banks. These finer Riverton Formation deposits similarly show a reduction in formative discharge strengths.

In conclusion, it can be seen that fluvial remnants preserved within the lower

Vaal River catchment attest to a major drying of the southern African climate which started *ca* 1.2 Ma. Changes in the nature of the deposits being aggraded (i.e. coarse gravels to fine alluvium) are a direct result of this drying which also caused tributaries of the Vaal River to become defunct. These tributary drainage systems never again formed a substantial component of the lower Vaal River drainage system.

5.8.6 Inherited erosion rates

Before discussing the older terrace deposits and fluvial events and assessing whether the proposed fluvial history model is similarly applicable, attention is first given to the calculated cosmogenic nuclide inherited erosion rates. As discussed, the inherited erosion rate is the erosion experienced by a piece of quartz during its accumulation of ^{26}Al and ^{10}Be before the piece of quartz is buried in the terrace deposit. This erosion rate thus gives a general erosion rate for the Vaal River catchment.

The calculated inherited erosion rates for the Rietputs Formation deposits (both the lower coarse alluvium and upper fine alluvium) are very consistent and indicate that, during the span of their aggradation, the Vaal River catchment was eroding at an approximate rate of 250 cm/Ma (see Table 4.5). No inherited erosion rates were calculated for the Wedburg terrace deposits as no suitable dating samples were available. The calculated inherited erosion rates for each of the Proksch Koppie samples were, however, several fold higher than those for the Rietputs Formation (Table 4.5). Although highly variable, values ranged from 355 to 1851 cm/Ma (average=1038 cm/Ma) indicating significantly increased erosion rates within the catchment during this earlier time period. Finally, the inherited erosion rates from the modern river samples provide a current erosion rate for the catchment. Only one of the two samples from the modern Vaal River provided a good indication of current erosion rates, as older terrace deposits have been combined with the current sediment due to mining operations (discussed in Chapter 4). The best calculated inherited erosion rate of 153 cm/Ma for the modern river reflects the probable current

erosion rate for the catchment.

Erosion rates for the catchment during Proksch Koppie times are substantially higher than during Rietputs Formation times, while current erosion rates even lower. It thus appears that, as southern Africa experienced cooling and drying over the past five million years, there has been a slowing down in landscape denudation. Reduction in rainfall and a trend to more arid conditions appears to have resulted in slowing of landscape erosion.

5.8.7 Holpan fluvial history

As an absolute age determination for the Holpan terrace was not possible, it is difficult to relate episodes of incision or aggradation to changes in climatic conditions which would have provided the necessary controlling mechanisms for these events. As a result, only a general proposition can be formulated.

As discussed, the climate of the early and middle Miocene is generally believed to have be warm and wet, followed in the late Miocene by a period of aridity which saw the development of major duricrusts in the landscape. The calcretisation of the Holpan terrace deposit is seen to be part of this widespread duricrust formation (de Wit *et al.* 2000). As a broad generalisation it is possible that the start of aridification in the late Miocene, associated with a reduction in vegetation cover and decrease in number and amplitude of formative discharges, resulted in an increase of coarse sediments being eroded into the river valley, resulting in aggradation of the coarse gravel deposits. Increasing aridity, and a subsequent reduction in formative discharge strengths to transport fines, resulted in the fine alluvium being deposited above the gravels. Absolute dating of both the terrace deposits and climatic events is needed to substantiate the above proposition.

5.8.8 Proksch Koppie fluvial history

In general the climate of southern Africa from *ca* 5.3 Ma to 3.2 Ma has been interpreted as warm and stable, with wet and mesic environments persisting

over the sub-continent. The age of the Proksch Koppie terrace falls within a rather large time span between 4.05 Ma and 2.90 Ma, with a model best fit age of 3.40±0.18. It is thus clear that the terrace deposits were aggraded either during or near to the end of this warm and wet period. As already discussed, the inherited erosion rates recorded from the Proksch Koppie terrace deposits are relatively high. These high erosion rates are consistent with the warm and wet environment of the early Pliocene. As discussed, with increasing drying of the region erosion rates have decreased. This trend can be seen in the lower erosion rates for the Rietputs Formation and still lower rates for the modern catchment. It can thus be seen that the inherited erosion rates, in conjunction with the cosmogenic nuclide burial dating of the terrace deposits, are consistent with the palaeoclimatic record. At 3.2 Ma there was a readjustment in the climate over southern Africa with a movement towards increasing aridity (Hodell & Warnke 1991, Christensen *et al.* 2002, Giraudeau *et al.* 2002).

It is impossible to say exactly when the period of bedrock incision following the Holpan terrace and preceding Proksch Koppie terrace aggradation occurred. Sometime during the warm and wet early Pliocene conditions would most likely have been suitable for the erosion of Holpan deposits lining the river channel/valley. Wet conditions, with an increase in amplitude and frequency of formative discharges, would have been needed to achieve this erosion. The arid late Miocene does not seem to have been as suitable a period for this incision to have occurred as the wet early Pliocene. It is impossible to say if tectonic uplift contributed in any way to this period of incision.

It is similarly difficult to say when this period of incision ended. This transition could have occurred at any time during the wet early Pliocene, under appropriate conditions, when a gravel armouring was aggraded that could not subsequently be pierced. That this period of aggradation started during the early Pliocene wet period is supported by both the inherited erosion rates and burial dating data. After this gravel aggradation it appears that at, *ca* 3.2 Ma, with a restructuring of the climate towards increased aridity, there was a reduction in formative discharge strengths and the upper fine alluvium was aggraded over the gravel deposits.

5.8.9 Wedburg fluvial history

The climatic record from *ca* 3.2 Ma to the start of the Pleistocene is particularly poor. There is agreement on a shift to increasing aridity from 3.2 Ma; there, however, is no consensus on whether or not there was a step like change in the climate focused on the intensification of northern hemisphere glaciation at *ca* 2.7 Ma to 2.5 Ma. As a result of this dearth of local information it is impossible to relate fluvial deposits/events to any specific climatic changes.

What is clear is that, at least once, conditions must have become relatively wet, with an increase in the number and amplitude of formative discharges. When exactly this happened cannot be determined in light of the poor palaeoclimatic data. It should, however, be mentioned that during the intensification of northern hemisphere glaciation in East Africa, climate was dominated by periods of extreme climate variability, consisting of alternating periods of extreme wetness and aridity. If similar conditions occurred in southern Africa, then one of these extreme wet cycles may have provided the conditions necessary for rapid erosion of Proksch Koppie deposits lining the Vaal River channel/valley and subsequent bedrock incision. Unfortunately it is impossible to offer any firm correlation. Similarly, it is impossible to say when Wedburg gravel aggradation started or when the drying occurred that resulted in fines being aggraded over the gravels. A substantially improved palaeoclimatic record is needed for a better understanding the fluvial history during this period.

5.9 Revised macro-scale fluvial evolution of the lower Vaal River catchment

As outlined in Chapter 2 the macro-scale fluvial evolution of the Vaal River catchment since the Cretaceous is said to include two major periods of river rejuvenation (Partridge & Maud 2000, de Wit *et al.* 2000). It is believed that tectonic uplift events, in combination with relatively wet climatic conditions, resulted in these two major periods of river rejuvenation/incision (de Wit

et al. 2000). The first, in the Miocene, resulted in major changes in the drainage net, producing a network roughly the same as the present (de Wit *et al.* 2000). After this period of rejuvenation it is believed that the Holpan terrace was aggraded (de Wit *et al.* 2000). Following a period of aridity in the Miocene, late Pliocene rivers are again said to have incised their valleys and gravel sequences were deposited (de Wit *et al.* 2000). This period was again inferred to have been associated with wetter conditions and tectonic uplift. Subsequently it is believed that oscillating climates during the Pleistocene constrained the development of the gravels and overbank deposits of the Rietputs Formation, as well as the finer fluvial sediments of the Riverton Formation (de Wit *et al.* 2000).

The current study indicates that this macro-scale fluvial evolution model is in need of re-evaluation. It has been argued that incision events occur sporadically when suitable climatic conditions develop that allow for the complete erosion of alluvial deposits lining the Vaal River channel/valley. Once these deposits have been removed then bedrock incision occurs fairly rapidly. These periods of bedrock incision are thus independent of controls such as tectonic uplift. It can thus be seen that there is no need to invoke debated uplift events with poor age constraints, to explain periods of river incision or rejuvenation.

Similarly, the current study highlights the fact that although climate controls the fluvial evolution of the Vaal River, this control is more complex than previously considered. Climate controls fluvial events (i.e. periods of aggradation or incision) by determining the Vaal River's net transporting ability. Various combinations of changes in transport and erosion, of both the river and surrounding landscape, will result in varying fluvial outcomes. An example is the aggradation of the Rietputs Formations coarse gravels and sands. During this period it has been argued that there was no substantial decrease in formative discharge strengths from the preceding period of bedrock incision. In other words the transport potential remained unchanged. It has, however, been argued that a periodic reduction in vegetation cover, due to the restructuring of the climate (i.e. an increase in seasonality), promoted increased bank erosion of older gravel deposits lining the river, which resulted in an increase of coarse

sediment supply and a change to aggradation. In conclusion, it has been highlighted that the fluvial evolution of the Vaal River catchment is unique for a number of reasons. The structure of the pre-Karoo surface and the readily availability of resistant clasts from older terrace deposits and tillite have proved crucial in shaping the Vaal River's fluvial history.

Chapter 6

The Acheulean Industrial Tradition and the hominid environment

Development of Acheulean technology marks an important milestone in hominid cultural evolution often linked to the appearance of *Homo ergaster* (*H. erectus*) in Africa (Klein 2000). The Acheulean Industrial Tradition spread widely across Africa and Eurasia, but the rapidity with which the new technology expanded is based on only a few dates, with no firm chronology existing for southern Africa (Klein 2000). Until now, the earliest part of the Acheulean has been dated only in the East African Rift valley. The earliest dates for an assemblage assigned to the Acheulean are *ca* 1.7 at Konso Gardula in Ethiopia (Asfaw *et al.* 1992, Beyene *et al.* 2006) and at 1.65 Ma at West Lake Turkana, Kenya (Roche & Kibunjia 1996). Other early Acheulean sites in the Rift valley are generally dated to 1.5 to 1.4 Ma. These include East Lake Turkana in Kenya (Isaac 1997) and Olduvai Gorge, middle and upper Bed II (Leakey 1976, Hay 1976). Equivalent artefacts first appear outside Africa at *ca* 1.4 Ma at Ubeidiya in Israel (Bar-Yosef & Goren-Inbar 1993, Ronen 2006). By 0.83 Ma, hominids with an Acheulean-like technology appear further east, with the well dated sites of southern China (Hou *et al.* 2000).

In southern Africa early Acheulean artefacts have been described from cave deposits and undated river gravels (Klipplaatdrif) in north eastern South Africa

(Mason 1962, Kuman 1994, Kuman 1998, Kuman 2007, Field 1999), but it has been previously considered that a drier climate towards the west of southern Africa prevented expansion of handaxe-using hominids westwards until much later (Klein 2000). While Acheulean technology has been described in southern Africa at a range of sites (Kuman 2007), there has been little absolute chronology with which to compare its appearance to that at East African sites. This is generally due to a dearth of datable volcanic deposits. Recently, palaeomagnetic and cosmogenic analyses of cave deposits has shown that hominids are most likely represented at Wonderwerk Cave during early Acheulean times (see Figure 6.1) (Ron *et al.* 2005, Chazan *et al.* 2008).

Due to the artefactual richness of the lower Vaal River catchment, archaeologists were highly active from the 1920s through the 1950s (van Riet Lowe 1927, van Riet Lowe 1937, van Riet Lowe 1945, van Riet Lowe 1952*a*, van Riet Lowe 1952*b*, Goodwin 1928, Goodwin 1933, Goodwin 1953, Goodwin & Van Riet Lowe 1929, Malan 1947). However, many of the sweeping cultural stratigraphic interpretations attempted by this early generation of archaeological researchers were later challenged, and the next few decades saw greater emphasis on site-specific studies (Mason 1967, Fock 1968, Beaumont & Morris 1990, Beaumont & McNabb 2000, McNabb 2001, Kuman 2001, Beaumont & Vogel 2006, Chazan *et al.* 2008). Although the archaeological record of the Vaal River basin is known to be one of the richest in southern Africa, the lack of absolute dates has meant that the true time-depth represented by these deposits was not known.

As a side project to the primary fluvial history investigation, an attempt was made to provide a better understanding of the Acheulean artefacts preserved within the Rietputs Formation deposits. As cosmogenic nuclide burial dating provided the first absolute ages for these deposits, it became apparent that a provenanced collection of artefacts was needed for comparison with artefacts from elsewhere. Due to the great depth of the Vaal River alluvial sediments concerned, it was necessary to work with active diamond mining operations to retrieve a suitable sample of artefacts. 465 stone tools from one pit in the lower coarse alluvium, at the type site at Windsorton, were obtained by collecting

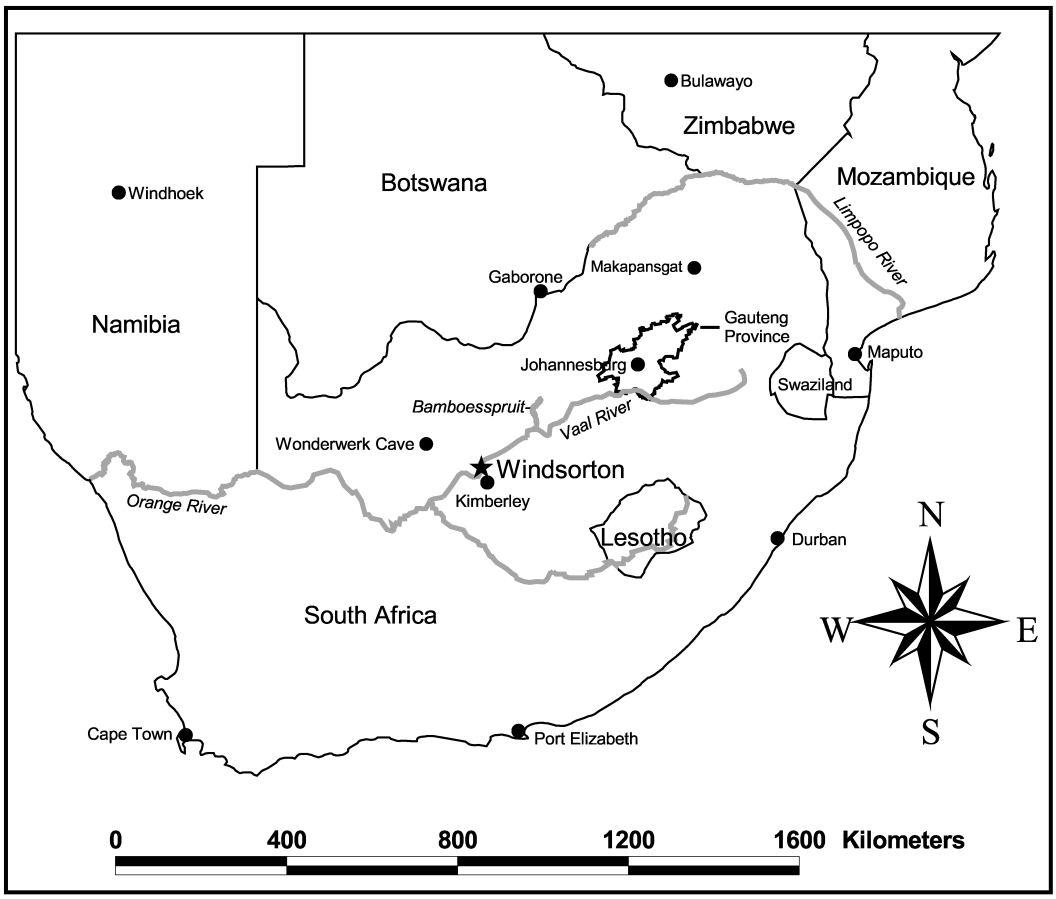


Figure 6.1: Map of South Africa and neighbouring countries showing locations of sites referred to in the text.

artefacts from a mine conveyor belt, with size sorting carried out before the material reached the belt (see Figure 4.4 for pit location). The sample is relatively small, as collecting took place during 10 hours over two days on one conveyor, while mining continues 24 hours a day with several conveyors running simultaneously. However, the sample is from a single pit in the lower unit, which I was able to verify on site as free from admixed material from overlying strata. The upper strata were sterile and were dumped at some distance from the active pit. The sample is thus representative of tools preserved within these early deposits. Similar artefacts were also examined in waste dumps at intervals over several months. Size sorting limited the collection to a range of 32 to 150 mm. It must also be noted that all pits sampled for burial dating contained similar Acheulean biface technology recovered from the lower coarse gravel unit.

The sample of 465 stone tools from the pit in the lower coarse alluvium is consistent with early Acheulean technology (Figure 6.2) (Kuman & Gibbon in press). It must be recognized that the burial dates provide a minimum age only for the stone tool technology preserved within the deposits, and each assemblage represents a time averaged collection. The cosmogenic nuclide data provide absolute ages for the Acheulean in southern Africa and the first datable evidence for artefacts assigned to its early phase outside of the caves of the Gauteng Province to the north-east (Figure 6.1). The age of the Rietputs Formation is nearly twice as old as previously thought and is contemporaneous with deposits in East Africa. It is thus apparent that handaxe-using hominids inhabited southern Africa as early as their counterparts in East Africa. The more or less simultaneous appearance of the Acheulean in different parts of the continent implies relatively rapid technology development and the widespread use of large cutting tools in the African continent by *ca* 1.6 Ma. The age of the deposits also revises the currently accepted view that Acheulean hominids were restricted to the northern and eastern parts of southern Africa before one million years ago, and that they colonised the central and western (drier) regions only later (Klein 2000).

In addition to the current study providing an age determination for the stone

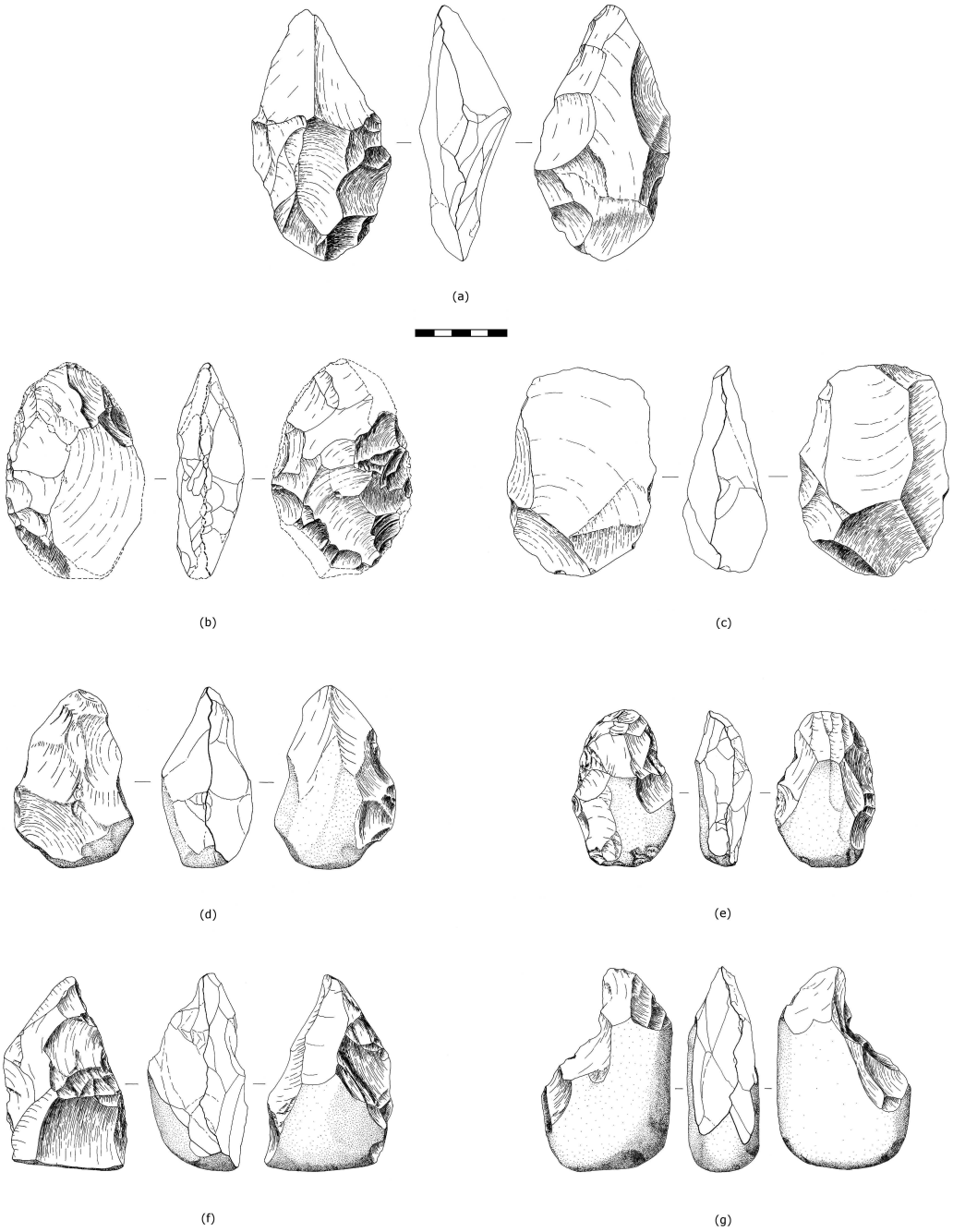


Figure 6.2: Early Acheulean tools from the lower coarse alluvium, Rietputs Formation: handaxes (a,b) and a cleaver (c) on flakes; handaxes (d,e) and picks (f,g) on cobbles. See Figure 4.4 for site location. Scale bar in cm.

artefacts, the revised fluvial history model and climatic evidence from the lower Vaal River catchment provide an improved understanding of the environment in which the hominids were living at the time. It has been argued that the increase in sediment supply during the Rietputs Formation coarse gravel aggradation was caused primarily by an increase in climatic seasonality, and oscillations between warm/wet and cool/dry conditions driven by orbital forcing mechanisms. Although the gravel deposits reflect a restructuring of the climate (i.e. increase in seasonality) there is good evidence to show that there was not a sudden reduction in net rainfall over the region, and that conditions were wet enough, at least periodically, to support well developed feeder drainage systems. The upper fine alluvium overlying the gravels attests, however, to a major drying of the southern African climate which started *ca* 1.2 Ma. Changes in the nature of the deposits being aggraded (i.e. coarse gravels to fine alluvium) are a direct result of this drying. In addition, this drying caused tributaries of the Vaal River to become defunct. These tributary drainage systems never again form a substantial component of the lower Vaal River drainage system.

It is therefore proposed that hominids were occupying a region that, during the coarse gravel aggradation, was at times wetter than today. They would not have been confined to the Vaal River valley only during these wet periods, and would have been able to move out along the tributaries to colonise the larger drainage basin. Similar Acheulean artefacts are preserved within the gravel deposits of these Vaal River tributaries such as the Bamboesspruit (Figure 6.1). As the climate became more seasonal, hominids may have had to migrate to the Vaal River during the dry winter months as tributaries dried up, but would have been able to expand their range during the wet summer periods. Similarly, during cool/dry intervals driven by orbital forcing, the Vaal River would most likely have provided a refuge for the hominids by providing a constant water source that was not available everywhere in the region. In conclusion, although the climate shifted between warm/wet and cool/dry conditions during this period, the fluvial evidence indicates an environment that in general was suitably wet to support a widespread hominid population

across the summer rainfall region of southern Africa. This period ended at *ca* 1.0 Ma with the marked drying that ushered in the deposition of the Riverton Formation.

It is interesting to note that both the appearance of *Homo ergaster* and Acheulean technology in southern Africa is associated with a climatic shift associated with an increase in seasonality and a shift to warm/wet and cool/dry climatic cycles. It can be speculated that dry periods, both on a repeated seasonal and longer orbital basis, may have exerted evolutionary pressure. It is likely that, during these periods, the Vaal River would have acted as a refuge, increasing competition for resources as hominid populations were forced together. Hominid populations better able to thrive during these dry periods may have been able to out-compete other groups and come to dominance. Speculation aside, although the Vaal early Acheulean material is associated with alluvial habitats, it nevertheless expands the range of *Homo ergaster* occupations beyond the Gauteng Province to one of the richest Acheulean regions in the interior of South Africa.

Chapter 7

Conclusion

7.1 Introduction

In this chapter the key findings of the current study are summarised. The isotopically dated sequence of fluvial events forms the basis of the study. The application of the cosmogenic nuclide burial radiometric dating technique to determine the age of ancient alluvial terrace deposits in the lower Vaal River catchment has for the first time provided an accurate fluvial chronology. A poor chronological framework has been the primary shortcoming of previous studies, as there was no accurate way to evaluate or correlate the proposed driving mechanisms with the fluvial events themselves. The fluvial chronology provided by the current study was compared to those available for likely forcing mechanisms, particularly climate change and tectonic events. It is apparent that climate change has played the most important role in controlling the fluvial evolution of the Vaal River. However, this climatic control is more complex than was previously proposed. It was also determined that the lower Vaal River catchment is unique in a number of respects; and it is these aspects that have played a crucial role, in conjunction with climate change, in shaping the fluvial history of the catchment.

7.2 Cosmogenic nuclide burial dating

The burial ages of the various alluvial deposits within the lower Vaal River catchment, from oldest to youngest, are outlined. An absolute age determination for the Holpan terrace was not possible. The cosmogenic nuclide data are, however, consistent with a very old deposit. A Miocene age, as proposed by others (de Wit *et al.* 2000), does not seem unreasonable. The Proksch Koppie terrace was dated using the profile dating approach. This terrace is best fit with a burial age of 3.40±0.18 Ma; however, due to model uncertainties its true age lies somewhere between 4.05 Ma and 2.90 Ma. Unfortunately an age determination for the Wedburg terrace was not possible due the antiquity of the associated alluvial deposits and the shallow depth of burial from which dating samples could be collected. The Rietputs Formation alluvial deposits are the best dated within the entire sequence. The cosmogenic nuclide burial dates indicate that the gravel deposits of the lower coarse alluvium were deposited from *ca* 1.8 to 1.35 Ma, with the capping fine alluvium being deposited *ca* 1.35 to 1.15 Ma.

7.3 Bedrock incision

The cosmogenically dated sequence of events highlighted the importance of periods of bedrock incision, which have occurred relatively rapidly over short periods of time, following lengthy periods of net aggradation during the Pliocene. A mechanism to account for rapid bedrock incision was thus needed to explain these events. It was determined that the lower Vaal River catchment provided the ideal situation for rapid bedrock erosion to proceed sporadically. The Vaal River in its lower reaches is largely confined to pre-Karoo valleys that are filled with soft, easily erodible Karoo rocks (tillite and shale). When these soft Karoo rocks are at least partially exposed along the river channel/valley, rapid bedrock erosion and incision occurs through the action of salting resistant clasts abrading the channel floor during frequent, high magnitude formative discharges. There is a constant supply of resistant clasts of all sizes to the

channel from erosion of both older alluvial terrace deposits and the tillite. That cycles of rapid bedrock incision could occur along the lower Vaal River valley is due to its two unique characteristics: confinement to a pre-Karoo valley, filled with easily erodible rocks, and the ready availability of resistant clasts. It must be emphasised that the timing of this rapid incision was controlled by climatic conditions that have occurred only sporadically through the Pliocene.

7.4 Revised fluvial history model

The new model, outlined hereafter in its simplest form, is based upon the dated sequence of fluvial events revealed by the Rietputs Formation deposits. This sequence was matched to the palaeoclimatic record for the summer rainfall region in southern Africa. Correlation between key aspects of the geological and climatological records form the basis of the model, when they are viewed in conjunction with the foregoing explanation for recurrent episodes of bedrock incision. In the following section the model is discussed in relation to the Rietputs Formation. The model's applicability to the older fluvial deposits/events is then considered.

Net bedrock incision Intervals of river incision through bedrock are controlled by climate. After a period of aggradation that produced a lower coarse gravel and sand unit capped by laminated and cross-bedded fine alluvium, there is a shift towards periodically wetter conditions. These periodically wetter events, and the resulting Vaal River flow regime, were characterised by an increase in the number and amplitude of formative discharges. These frequent and large discharges eroded both the upper fine alluvium and lower coarse alluvium because they were able to mobilise the majority of large clasts, exposing the easily erodible Karoo rocks lining the valley bottom. Incision through bedrock occurred as saltating hard clasts (e.g. quartzite/Ventersdorp lava) abraded and eroded the soft floor rocks of the channel.

Net coarse gravel aggradation When coarse sediment supply exceeded a

critical level and large clasts were no longer moved as a saltating bed load, aggradation of coarse gravels and sands ensued. Aggradation of this bed load deposit provided shielding to the underlying bedrock and incision was halted. Either a reduction in formative discharge strength, or an increase in sediment supply to the river channel, or a combination of both, could initiate such aggradation. Coarse gravels and sands would aggrade when discharges were sufficient to mobilise the fines but not the larger clasts. The resulting deposit would be a winnowed channel lag deposit, that would continue to form/thicken as coarse clasts were continually eroded into the channel from erosion of older alluvial deposits or tillite lining the river banks. Coarse clasts would continually be available as the Vaal River migrated laterally within the valley, eroding older terrace deposits.

Net fines aggradation Fines aggradation occurred when formative discharges lacked the energy and turbulence to transport the majority of the fine fraction downstream. At this time the erosive power of the river was greatly reduced, with erosion of older alluvial deposits or tillite lining the river banks probably being very limited or even ceasing. An increase in fine sediment supply from the surrounding landscape would also tend to increase aggradation rates. Net fines aggradation signals a clear reduction in formative discharges and the erosional capability of the Vaal River.

7.5 Bedrock incision prior to the aggradation of the Rietputs Formation

The long profile of the lower Vaal River demonstrates that the pre-Karoo geological structure had imparted two prominent knick-zones (or hard rock barriers) along the river's course in reaches where the river is confined to pre-Karoo valleys. The gradients along these knick-zones are substantially steeper than along the rest of reaches. These two knick-zones, together with the Vaal/Orange

River confluence, acted as hard rock barriers and anchored/influenced the nature of the upstream reaches. These two knick-zones act as hard rock barriers when alluvial gravels were aggraded along them. The gravels provided a resistant armour that prevented bedrock incision and must be removed before renewed incision can take place. Their removal and the ensuing incision into the underlying soft Karoo rocks is equivalent to the breaching of hard rock barriers described in other studies (Tooth *et al.* 2004, McCarthy & Tooth 2004). The key difference with these knick-zones is, however, that when incision is halted and coarse gravels are again aggraded, the knick-zones once again act as hard rock barriers. Incision events, which included the removal of the coarse gravel armouring, can thus be seen to drive knickpoint migration upstream of these knick-zones, as well as the lowering of these knick-zones within the landscape. It is important to note that these knick-zones would not have migrated upstream but would rather have been lowered in relation to the surrounding landscape. They are thus essentially static features within the catchment. Once the gravel armouring has been removed incision into the soft bedrock can occur relatively rapidly, as outlined in the bedrock incision model, particularly as gradients along these reaches are steeper, providing higher hydraulic energy than along the other reaches.

It is impossible to say exactly when the bedrock incision event that preceded the aggradation of the Rietputs Formation begun. The palaeoclimatic record for the end of the Pliocene in southern Africa is poorly documented and dated and it is impossible to isolate a period with consistently wetter conditions over a suitable length of time and an associated increase in the number and amplitude of formative discharges, which would have been able to remove Wedburg gravel deposits lining the base of the Vaal River channel/valley. That such conditions existed can, however, be inferred from several lines of evidence. These include the excavation of Karoo rocks from pre-Karoo geological structures (i.e. potholes) which would have required substantial hydraulic forces (Helgren 1979), as well as from clastic conglomerate lenses associated with tufa deposits along the Ghaap escarpment. It has been argued that deposition

of the various conglomerate units required surges of hydraulic energy exceeding that of modern day floods, and that repeated high intensity rainfall events would have been needed to produce these deposits (Butzer *et al.* 1978).

Changing climatic conditions brought this incision event to an end at the beginning of the Pleistocene. That this period of incision was climatically controlled is further evidenced by the fact that incision only reached the pre-Karoo channels in certain reaches, and that soft Karoo rocks remained available to be eroded along vast sections of the river. It has also been argued that incision events were fairly synchronous throughout the catchment. This accords with the notion that external climatic forcing removed the gravel armouring along the knick-zone reaches more-or-less simultaneously.

7.6 Rietputs Formation coarse gravels aggradation

At the beginning of the Pleistocene the Vaal River changed from an incising to an aggrading regime. Cosmogenic dating of the Rietputs Formation has shown that aggradation of the lower coarse gravel and sand unit occurred from *ca* 1.8 to 1.35 Ma. This change was brought about by a change in the climate of the summer rainfall region of southern Africa. This interval of gravel aggradation was characterised by an increase in sediment supply to the Vaal River channel, driven primarily by an increase in seasonality of climate and frequent oscillations between warm/wet and cool/dry conditions. A move away from forest dominated to grass dominated vegetation, and the resulting reduction in vegetation cover, as well as the reduction in vegetation cover during the winter dry season, would have provided suitable conditions for an increase in erosion of older terrace deposits lining the Vaal River channel. An increased input of large clasts from this erosion would result in a change to aggradation. In addition, if increased large flood surges came in early spring, when vegetation cover was still greatly reduced after the dry winter months, then very rapid erosion of older terrace deposits lining the river bank could take place.

During this period of gravel aggradation the climate also oscillated between warm/wet and cool/dry conditions driven by orbital cycles. During cool/dry periods there may have been substantial decreases in vegetation cover, associated with increased bank erosion. A few large discharges during such dry times would result in very rapid erosion and increase in sediment supply to the river. During these dry periods formative discharges may also have been reduced both in number and amplitude, thus causing a reduction in the capabilities of the river to remove large clasts from the channel. It can thus been seen that during this period coarse sediment supply exceeded the critical transport level and gravel deposits were aggraded.

Supporting evidence for increased erosion of the older terrace deposits lining the Vaal River's banks (due to a reduction in vegetation cover), and resulting coarse gravel aggradation, comes from the cosmogenic nuclide data themselves. These indicate that large clasts were eroded from older terrace deposits fairly rapidly. These large clasts had not been exposed for a sufficient period of time at the surface to obtain suitable concentrations of nuclides for burial dating. In addition, evidence for reduced vegetation cover during dry-spells, and associated increased sediment input, comes from the site of Canteen Kopje near Barkly West. The Rietputs Formation gravels at this location consist predominantly of angular Ventersdorp lava clasts. Reduced vegetation cover at this hilly locality resulted in an increase in local clasts being eroded into the river from the surrounding hills. It is thus confirmed that during dry periods, with reduced vegetation cover, there was an increase in coarse sediment supply to the Vaal River, which would have resulted in coarse gravel aggradation.

In terms of palaeoclimate, supporting evidence for an increase in rainfall seasonality, rather than a total net reduction in precipitation, comes from several lines of evidence. These also show that the climate was at least periodically wetter than it has been for the past million years, and that there was not necessarily a sudden reduction in rainfall at *ca* 1.7 Ma, as recorded in East Africa (Maslin & Christensen 2007) and proposed for southern Africa (Hopley *et al.* 2007*b*). The nature of the deposits themselves, i.e. boulder grade gravels

which are well sorted, indicates that the formative discharges were more frequent and much larger than anything that occurred during the last 1 Ma. The subsequent Riverton Formation deposits comprise only sands and silts with a few gravel lenses, indicating a marked reduction in discharge (Butzer *et al.* 1973). In addition, tributaries of the Vaal River such as the Bamboesspruit, that essentially became defunct at *ca* 1 Ma (determined by the cosmogenic dating), were able to carry and deposit coarse cobble grade gravels during the earlier Pleistocene (Marshall 1990). Marshall's (1990) study of the right bank tributaries of the Vaal River upstream from Windsorton, indicated that there was a higher discharge out of this drainage basin during Rietputs Formation times into the Vaal River, which supports the existence of a periodically wetter climate in those times. The present right bank tributaries of the Vaal River consist of small, dry, insignificant streams that only flow during extensive flooding, remaining dry for periods of up to 10 years (Marshall 1990). It is thus apparent that the climate of the early Pleistocene was sufficiently wet to support well developed feeder drainages that are today essentially defunct and have not flowed as vigorously over the last million years. This wetter environment is supported also by the deposition of tributary limestone tufa deposits that are locally inter-fingered with the Rietputs Formation deposits, derived from the distant (7 to 15 kilometre) Ghaap carbonate escarpment, indicating substantial groundwater flow (Helgren 1979).

7.7 Rietputs Formation fines aggradation

In contrast to the restructuring of the climate at the beginning of the Pleistocene, where there was no substantial reduction in total precipitation, the Mid-Pleistocene Revolution (*ca* 1.2 to 1.0 Ma) was characterised by a substantial reduction in rainfall over southern Africa. Various alluvial deposits within the lower Vaal River catchment attest to this drying event. First and foremost, there is a major change in the nature of the deposits being aggraded by the Vaal River. The Vaal river changes from a system aggrading coarse gravels and sand to one depositing only the fine size factions of sand, silt and

clay. This fines aggradation occurred as a result of a reduction in the capacity of formative discharges to transport the majority of the fine fraction further downstream. The cosmogenic data show that this fines aggradation occurred at *ca* 1.35 to 1.15 Ma, at the same time as the restructuring and drying of the climate in the summer rainfall region of southern Africa. At this time there was a shift to more arid conditions over southern Africa, with the climate subsequently alternating between long, cold glacial periods followed by shorter, warm interglacials.

Good evidence for this climatic control comes from the dated deposits of the right bank tributaries of the Vaal River. It has been argued by Marshall (1990) that there has been extensive desiccation of the climate since gravel was deposited in them, which resulted in the deposition and calcretisation of the finer-grained sediments on top of the gravel deposits, just as occurred along the Vaal River. In addition, pans now occupy many of these dry channels. As the pans lie within dry channels and there is no evidence for tectonic disruption, it was argued that this is good evidence for a drying climate (Marshall 1990). There is, furthermore, no evidence for substantial fluvial activity taking place within these catchments since *ca* 1.0 Ma. A wetter climate than has persisted during the last million years, would have been needed for the right bank drainage systems to be readily prominent in contributing water to the Vaal River.

In conclusion, it can be seen that fluvial remnants preserved within the lower Vaal River catchment attest to the major drying of the southern African climate which started *ca* 1.2 Ma. Changes in the nature of the deposits being aggraded (i.e. coarse gravels to fine alluvium) are a direct result of this drying. In addition, this drying caused major tributaries of the Vaal River to become defunct. These tributary drainage systems never again formed a substantial component of the lower Vaal River drainage system.

7.8 Holpan fluvial history

The revised fluvial history model can be applied to the Holpan sequence of fluvial events in only a very general way due to dating uncertainties in respect of both climatic and fluvial events. In very general terms it can be inferred that the start of aridification in the late Miocene, associated with a reduction in vegetation cover and a decrease in number and amplitude of formative discharges, resulted in an increased supply of coarse sediments into the river valley and the aggradation of coarse gravel deposits. Continued or increasing aridity and a subsequent reduction in formative discharge strengths resulted in fine alluvium being deposited above the gravels. Absolute dating of both the terrace deposits and climatic events is needed to substantiate this tentative proposition.

7.9 Proksch Koppie fluvial history

It is impossible to say exactly when the period of bedrock incision, following deposition of the Holpan terrace and preceding the Proksch Koppie terrace aggradation, took place. Sometime during the warm and wet early Pliocene conditions would most likely have favoured the erosion of Holpan deposits lining the river channel/valley. Wet conditions, with an increase in the amplitude and frequency of formative discharges would have been needed to achieve this. The arid late Miocene does not seem to have been as suitable a period for this incision to have occurred as the wet early Pliocene. It is impossible to say whether tectonic uplift contributed in any way to this incision.

It is similarly difficult to infer when this period of incision stopped. This transition could have occurred at any time during the wet early Pliocene when a gravel armouring accumulated. That this period of aggradation started during the early Pliocene wet period is supported by both the inherited erosion rates and burial dating data. The cosmogenic nuclide inherited erosion rates recorded from the Proksch Koppie terrace gravel deposits are relatively high. These high erosion rates are consistent with the warm and wet environment

of the early Pliocene. As discussed previously, with increasing drying of the region erosion rates have decreased. This trend can be seen in the lower erosion rates for the Rietputs Formation and still lower denudation indications for the modern catchment. Following this gravel aggradation it appears that at *ca* 3.2 Ma, with a restructuring of the climate towards increased aridity, there was a reduction in formative discharge strengths and the upper fine alluvium was aggraded over the gravel deposits.

7.10 Wedburg fluvial history

The climatic record from *ca* 3.2 Ma to the start of the Pleistocene is particularly poor. There is agreement on a shift to increasing aridity from 3.2 Ma; however, there is no consensus on whether or not there was a step like change in the climate during the intensification of northern hemisphere glaciation at *ca* 2.7 Ma to 2.5 Ma. As a result of this poor climatic record it is impossible to relate Wedburg fluvial deposits/events to any specific climatic changes.

7.11 Revised macro-scale fluvial evolution of the lower Vaal River catchment

The macro-scale fluvial evolution of the Vaal River catchment since the Cretaceous has been said to include two major periods of river rejuvenation (Partridge & Maud 2000, de Wit *et al.* 2000). It is believed that tectonic uplift events, in combination with relatively wet climatic conditions, resulted in these two major periods of river rejuvenation/incision (de Wit *et al.* 2000). The current study indicates, however, that this macro-scale model of fluvial evolution is in need of re-evaluation. It has been argued that incision events occur sporadically when climatic conditions develop that are suitable for the complete erosion of alluvial deposits lining the Vaal River channel/valley. Once these deposits have been removed then bedrock incision occurs fairly rapidly. These periods of bedrock incision are thus independent of controls such as tectonic uplift events

or more general climatic shifts. It can thus be seen that there is no need to invoke controversial uplift events, with poor age constraints, to explain periods of river incision or rejuvenation.

Similarly, the current study highlights the fact that, although climate controls the fluvial evolution of the Vaal River, this control is more complex than previously thought. Climate controls fluvial events (i.e. periods of aggradation or incision) by determining the Vaal River's net transporting ability. Various combinations of changes in transport and erosion potentials, of both within the river and surrounding the landscape, will result in varying fluvial outcomes. In conclusion, it has been highlighted that the fluvial evolution of the Vaal River catchment is unique for a number of reasons. The structure of the pre-Karoo surface and the readily available resistant clasts from older terrace deposits and tillite have proved crucial in shaping the Vaal River's fluvial history.

7.12 The Acheulean Industrial Tradition and the hominid environment

The findings of the current study also have the potential to contribute to our understanding of the areas occupied by our early ancestors and the environment in which they lived. Along the lower Vaal River catchment Rietputs Formation deposits have preserved Acheulean stone artefacts. Cosmogenic nuclide burial dating provides the first absolute ages for these deposits and thus a minimum age for the tools preserved within them. The stone tools in the lower coarse alluvium are consistent with early Acheulean technology, and burial dating provides the first good evidence for artefacts assigned to this early phase outside of the caves of the Gauteng Province to the north-east. It is now apparent that handaxe-using hominids inhabited southern Africa as early as their counterparts in East Africa. The more or less simultaneous appearance of the Acheulean in different parts of the continent implies relatively rapid technology development and the widespread use of large cutting tools in the

African continent by *ca* 1.6 Ma. The age of the deposits also revises the currently accepted view that Acheulean hominids were restricted to the northern and eastern parts of southern Africa before one million years ago, and that they colonised the central and western (drier) regions only later (Klein 2000).

In addition to the current study providing an age determination for the stone artefacts, the revised fluvial history model and climatic evidence from the lower Vaal River catchment provide an improved understanding of the environment in which the hominids were living during the early Pleistocene. It has been proposed that hominids were occupying a region that, during the Rietputs Formation coarse gravel aggradation, was at times wetter than today. They would not have been confined only to the Vaal River valley during these wet periods, and would have been able to move out along the tributaries to colonise the larger drainage basin. As the climate became more seasonal, hominids may have had to migrate to the Vaal River during the dry winter months as tributaries dried up, but would have been able to expand their range during the wet summer periods. Similarly, during cool/dry intervals indicated by orbital forcing, the Vaal River most likely would also have provided a refuge for the hominids by providing a constant water source that was not available elsewhere in the region. In conclusion, although the climate shifted between warm/wet and cool/dry conditions during this period, the fluvial evidence supports the existence of an environment that, in general, was suitably wet to support a widespread hominid population across the summer rainfall region of southern Africa. It is only at *ca* 1.0 Ma that dramatic drying of the region is recorded in the fluvial history.

7.13 Future work

As the middle Orange River contains a similar sequence of alluvial terrace deposits as the Vaal River it would be important to develop an accurate fluvial chronology for that catchment. An initial survey of these deposits demonstrates that they are equally suitable for the application of cosmogenic nuclide

burial dating. A comparison between chronologies for the two catchment's would provide an ideal opportunity to evaluate the role of climatic forcing over a wider region. Periods of aggradation along the Orange River would most likely correlate with those in the lower Vaal River catchment; periods of incision could, however, be unrelated due to the different local geological setting. Questions such as these could be clarified only with the aid of an absolute fluvial history from that area.

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