

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.



# **SOURCES OF SUSPENDED LOAD IN THE UPPER ORANGE RIVER, SOUTH AFRICA**

**Livhuwani Maake**

*B.Sc. (Hons.) (University of Cape Town)*

Submitted in fulfilment of the requirements for the degree

**Master of Science**

in the

Department of Geological Sciences

Faculty of Science

University of Cape Town

Supervisor: Prof: J.S. Compton

May 2012

# ABSTRACT

A lot of work has been done on the upper Orange River but little attention has been given to the source of its suspended sediment load. The source of the suspended load is important because it can provide insight into soil erosion, a major problem in South Africa and globally. In this study the composition of the suspended sediment load of upper Orange River tributaries is related to bed rock geology, topography, soils and land use. Orange River catchment bed rock includes sedimentary rocks of the Karoo Supergroup and flood basalts of the Drakensberg Group each with distinct geochemical signatures. It was established through geochemistry of river suspended sediments, top soils and weathered bedrock that suspended sediments are primarily derived from Karoo sedimentary rocks. Chemical composition was determined by X-ray fluorescence and mineralogy was determined from petrography of bedrock samples and X-ray diffraction analysis of soil and suspended river sediment. Basalt soils contain plagioclase feldspar, pyroxene, rock fragments and smectite clay minerals. Karoo sedimentary rock soils contain quartz, K-feldspar and illite as well as smectite clay minerals. Rivers flowing on the upper Karoo Supergroup sedimentary formations were found to carry more suspended sediment than those rivers flowing on the basalt. There is a relationship between slope, relief and soil cover and the sediment load of the rivers. Rivers flowing from high relief, steep slopes and poor soil cover have higher sediment loads relative to rivers draining flat, well-bounded soil. Karoo sedimentary soil is more susceptible to erosion than basalt soil because Karoo soils have higher sand and silt content which is less resistant to erosion when compared to the more clayey basalt soils. The basalt soils are densely rooted by grassland vegetation which limit the amount of basalt soil and bedrock erosion. Chemical analyses and field evidence indicate that the suspended load of the upper Orange River is derived from both bedrock and soil erosion. Bedrock (gully) erosion is most active along the Drakensberg Escarpment whereas topsoil erosion is related to agricultural areas and the loss of vegetation or the replacement of grass by shrubs.

# ACKNOWLEDGEMENT

I should like to express my gratitude to and acknowledge the following people and institutions

- Assoc. Prof. John Compton for his endless patience, guidance, and support. There was never a dull moment with him
- Goldfields for giving me the time and support to turn my dream to reality
- Dr. Ian Newton in the Department of Archeology for assisting in stable isotope analysis
- Prof. Dave Reid for assisting with XRF analysis
- To my friends, Mbilu, Carla, Bronwyn, Cath and Takalani for all your support, proof reading of the numerous drafts and your words of encouragement, you made the journey easier
- And finally to my family, without whose love, support and encouragement this thesis could not have been realized. Ndo livhuwa

Aa!

‘IF I HAVE SEEN FURTHER IT’S BECAUSE I AM STANDING ON THE SHOULDERS OF GIANTS’.

Isaac Newton

# TABLE OF CONTENTS

<b>ABSTRACT</b> .....	<b>i</b>
<b>ACKNOWLEDGEMENT</b> .....	<b>ii</b>
<b>LIST OF TABLES</b> .....	<b>v</b>
<b>LIST OF FIGURES</b> .....	<b>vi</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Study Rationale.....	1
1.2 Study Objectives .....	4
1.3 General introduction to the Orange River system.....	5
1.4 Geological Setting.....	9
1.4.1 Beaufort Group.....	9
1.4.2 Stormberg Group .....	13
1.4.3 Drakensberg Group.....	14
1.5 Soil.....	15
1.6 Vegetation cover .....	17
1.7 Land Use .....	20
<b>2 Methodology</b> .....	<b>22</b>
2.1 Sampling.....	22
2.1.1 Bedrock and Soil samples.....	25
2.1.2 River suspended load, Riverbank and Paleoflood deposits .....	29
2.1.3 Catchment area of the Orange River.....	32
2.2 Sample analyses.....	34
2.2.1 Grain size analysis .....	37
2.2.2 Petrography .....	37
2.2.3 X-ray diffraction (XRD) analysis .....	38
2.2.4 X-ray fluorescence (XRF) elemental analysis.....	38
2.2.5 Organic carbon content and carbon isotope analysis .....	39
<b>3 Results</b> .....	<b>42</b>
3.1 Bed Rock Description.....	42
3.1.1 Adelaide Subgroup (Lower Beaufort) .....	42
3.1.2 Upper Beaufort Group (Tarkastad Subgroup).....	42
3.1.3 Molteno Formation .....	43
3.1.4 Elliot Formation .....	44
3.1.5 Clarens Formation.....	44
3.1.6 Drakensberg Group Basalt.....	45
3.2 Grain size distribution.....	46
3.3 Mineralogy .....	49
3.3.1 Petrography .....	49
3.3.2 Mineralogy (XRD).....	52

3.4	Geochemistry.....	53
3.4.1	XRF elemental composition.....	53
3.4.2	Percent carbonate, and organic carbon content and isotope composition ( $\delta^{13}C$ ) ..	60
<b>4</b>	<b>Discussion.....</b>	<b>63</b>
4.1	Bedrock and soils in the catchment area.....	63
4.2	Source of the river suspended load, riverbank deposits and paleoflood deposits .....	68
4.2.1	River suspended sediments .....	68
4.2.2	Suspended sediments vs. bedrock.....	73
4.2.3	Mineralogy and Geochemistry.....	74
4.3	Organic Carbon analysis.....	78
4.4	Soil erosion variation in the catchment areas .....	82
<b>5</b>	<b>Conclusions .....</b>	<b>89</b>
<b>6</b>	<b>References.....</b>	<b>92</b>

**Appendix A: Compton and Maake, 2007**

**Appendix B: XRD scans**

**Appendix C: Sample GPS co-ordinates**

University of Cape Town

# LIST OF TABLES

Table 2.1: Sample name, numbers, type and location of soil and bedrock samples. ....	27
Table 2.2: Source river, sample name and sample number of suspended, river bank and paleoflood deposits.....	31
Table 2.3: Relative percentage of geological catchment bedrock formations in the upper Orange River and its tributaries. ....	33
Table 3.1: Grain size distribution of soils (wt%). Samples with letters a-c correspond to increasing soil profile depth. River bank deposit samples are designated by the letter d.....	47
Table 3.2: Grain size distribution of river suspended sediments, river bank (RB) and paleoflood (P) deposits.....	48
Table 3.3: Suspended sediment load of river samples in dried grams/ litre.....	49
Table 3.4: Major (wt%) and trace (ppm) element composition of soil samples taken from the surface and from soil profiles. ....	56
Table 3.5: Major (wt%) and trace (ppm) element composition of river suspended load, river bank (RB) and paleoflood (P) deposits (nm = not measured). ....	59
Table 3.6: Calcium carbonate and organic carbon content (wt%) and carbon isotope composition of organic matter from soils and weathered bedrock (D=duplicate OC and $\delta^{13}\text{C}$ sample)61	
Table 3.7: Calcium carbonate and organic carbon content (wt%) and carbon isotope composition of organic matter of river suspended sediments, river bank and paleoflood deposits(D=duplicate OC and $\delta^{13}\text{C}$ sample).....	62
Table 4.1: Suspended sediment load of the rivers sampled in grams/litre. ....	71

# LIST OF FIGURES

Figure 1.1: Orange River catchment showing major rivers, dams and towns from Bremner et al. (1990). Dashed lines indicate ephemeral rivers. ....	6
Figure 1.2: The average annual precipitation of the Orange River Catchment (Source: Department of Water Affairs and Forestry, 1997, <a href="http://www.dwaf.gov.za/orange/climate.htm">http://www.dwaf.gov.za/orange/climate.htm</a> ) .....	8
Figure 1.3: Average annual sediment production in the Orange River catchment (Bremner, 1990). 9	
Figure 1.4(a): Simplified geological map of the Orange River and surrounding areas showing the major lithologies, insert (zoomed in on Figure 1.4b) showing the study area which is described further in Methods and Discussion chapters (map extracted from the Geological Map of South Africa, Council for Geoscience). ....	11
Figure 1.4(b): Geological map of the upper Orange River, the study area showing the geology of the area and sample locations (black circles are bedrock and soil samples (Table 2.1) and red circles are river suspended samples (Table 2.2)). Adapted from Compton et al. (2010) and Council for Geoscience 1:1000000 scale map. ....	12
Figure 1.5: Map showing the soils of the study area, sourced from <a href="http://www.agis.agric.za">www.agis.agric.za</a> and interpretation from Fey (2010). Cumulic soils are mixed with the above shown soil types. No soil data are available for Lesotho (shown in grey). ....	17
Figure 1.6: Distribution of grassland biomes in the study area data source: South African National Biodiversity Institute and Mucina and Rutherford (2006). ....	19
Figure 1.7: Land use distribution in the upper Orange River catchment map from River Health Programme (2003). ....	21
Figure 2.1: Geological map of upper Orange River catchment area showing the distribution of different geological formations drained by the Orange River and its tributaries (black circles are bedrock and soil samples (Table 2.1) and red circles are river suspended samples (Table 2.2)). Adapted from Compton et al. (2010) and Council for Geoscience 1:1000000 scale map and the Aliwal North 1:250000 scale map. ....	24
Figure 2.2: Map showing the sample locations and the towns near where the samples were collected. Names with light blue backdrop are small and large dams (adapted from the map provided courtesy of the Department of Water Affairs). ....	26
Figure 2.3: Profile showing location of samples relative to the river. A shows a soil profile from top soils to weathered bedrock (sample 1a to 1d); B shows a palaeoflood deposits (P); C shows a modern river bank deposit (RB) and D shows sediment suspended in the flowing river. ....	30
Figure 2.4: Map showing the location of river suspended load, river bank and paleodeposit sample points. The coloured areas indicate the individual river catchment (River Health Programme 2003). The Bundi sample was collected at Vooilsdrift 150 km from the Orange River mouth (Fig. 1.1). ....	32
Figure 2.5: Elevation map of the upper Orange River and Vaal River catchment areas (River Health Programme, 2003). ....	34
Figure 2.6: Flow chart for sample preparation and analyses. ....	36

Figure 2.7: Comparison of SiO <sub>2</sub> analyses of duplicate samples determined by XRF.....	39
Figure 2.8: Plot of organic carbon content (wt% OC) of samples run in duplicate (%OC R).....	41
Figure 3.1: Photomicrographs of petrographic thin sections from the Tarkastad, Elliot, Clarens and Drakensberg Basalt bedrock in the study area. Cross polarised light.....	51
Figure 3.2: XRD scans of the Elliot Formation bulk powdered rock and soil samples .....	52
Figure 3.3: XRD scans for the clay fraction of soils overlying basaltic rock from the Drakensberg Formation. ....	53
Figure 3.4: XRD scans of the suspended load samples.....	53
Figure 4.1: Ratio of major elements (Mg+Na)/K determined by XRF for bulk soil samples collected in August 2009.....	67
Figure 4.2: Ratio of major elements (Mg+Na)/K and trace elements (Rb + Ba)/ (Ni + Cr + V) determined by XRF for bulk soil samples collected in February 2006. ....	68
Figure 4.3: Grain size distribution of river suspended load (three samples on the far right), river bank (RB) and paleoflood (P) deposits. ....	70
Figure 4.4: Ratio of major elements (Mg + Na)/K and of trace elements (Rb + Ba)/ (Ni + Cr + V) determined by XRF for river bank deposits, paleoflood deposits and river suspended sediment load. ....	76
Figure 4.5: Photo showing both top soil erosion (reddish brown) and gullies showing previous bedrock erosion (light grey) near the town of Smithfield on the southern side of the study area (Compton and Maake, 2007).....	81
Figure 4.6: Photo showing farming on gentle slopes near the town of Lady Brand on northern side of the study area.....	82
Figure 4.7: Soil erosion rates from magisterial districts of South Africa (Compton et al., 2010). Soil erosion is most intense in areas of high rainfall and erodible soils of the Karoo sedimentary rocks (Figure 4.3 and 4.7) and heavily cultivated land (Le Roux, 1990)...	83
Figure 4.8: Map showing the vegetation cover of the upper Orange River catchment. The study area (rectangle) is located on Highveld grassland (from <a href="http://www.orangesenqurak.com/river/hydrology/cycle/groundwater.aspx">http://www.orangesenqurak.com/river/hydrology/cycle/groundwater.aspx</a> ) .....	85
Figure 4.9: Map showing the distribution of land use in the upper Orange catchment area. Brown lines indicate catchment boundaries ( <a href="http://www.orangesenqurak.com/river/hydrology/cycle/groundwater.aspx">http://www.orangesenqurak.com/river/hydrology/cycle/groundwater.aspx</a> ).....	87
Figure 4.10: Photo showing gully erosion in the Elliot Formation near the town of Lady Brand.	87

# 1 Introduction

## 1.1 Study Rationale

Large rivers are the major pathways for the transport of erosion products from the continents to the oceans. They are studied by geochemists to estimate the fluxes of continental material supplied to the oceans (Dingle and Hendey, 1984; Martin, 1987; Compton et al., 2010), to investigate the erosion processes on a global scale (Walling and Fang, 2003) and to calculate chemical and physical denudation rates and types of geology prone to erosion (Kounov et al., 2007). The transportation of sediments by rivers is a significant component of global erosion and a significant proportion of sediments transported by rivers represent soil eroded from the catchment areas (Walling and Fang, 2003). Soil chemistry, particle size distribution and structure play a significant role in determining the susceptibility of soil to erosion (Garland et al., 1999). Soils with high silt and sand contents tend to be more erodible than those with high clay content (Rooseboom and Harmse, 1979). This study uses the mineralogy, texture and geochemistry of the suspended load in the Orange River to infer whether the erosion of sediments carried by the Orange River is derived from the erosion of the Drakensberg basalts or the erosion of the upper Karoo sedimentary rocks.

Soil erosion is a major problem in South Africa (Le Roux et al., 2007). Land degradation caused by soil erosion not only involves the loss of fertile topsoil but also leads to sediment infilling of reservoirs and increased suspended sediment concentrations in streams with consequent effects on ecosystem health (Garland et al., 1999). Given the increasing threat to environmental sustainability, there is a need to improve the knowledge of factors affecting soil erosion in order to prevent and manage soil erosion effectively (Le Roux et al., 2007). The average sediment yields from sub-basins in the Orange River system vary from less than 10 to more than 1000 tons km<sup>-2</sup> year<sup>-1</sup> (Rooseboom, 1975). A large part of the upper

Orange River catchment has been affected by soil erosion and this is believed to be due to variable factors.

Foster et al. (2007) found that sediments in Orange River sub-basins of the Karoo uplands are predominantly derived from top soil and from hill slope top soil, and that bedrock erosion through gully incisement is not a major source of sediment. Keay-Bright and Boardman (2004) show that there has been little change in the extent of gully systems since 1945 implying that most gully systems are currently inactive. Foster et al. (2007) stress the importance of land use in controlling sediment availability for transport. Despite the increase in high intensity rainfalls events in the post-1970 period, Foster et al. (2007) found that sediment accumulation rates in the Karoo uplands decreased suggesting that sediment delivery is supply limited rather than energy limited.

Boardman et al. (2003) argued that there is significant evidence for active gully development in the period 1937 to the 1960s and that it seems likely that it is related to high stock numbers and disturbance of the vegetation in the first half of the 20th century. There is some evidence in the Karoo as a whole that very high stock numbers (sheep largely) are the cause of vegetation change and soil erosion leading to the formation of badlands and gully systems (Boardman et al., 2003). Major source of sediments in the upper and middle Orange River catchment is derived from the aggraded valleys and regional slopes where soils have hard B horizons when dry and have low permeability when wet (Rooseboom and Harmse, 1979). As erosion progresses the available soil for erosion decreases resulting in a progressive deterioration of the soil moisture regime and a loss of topsoil which in turn affects the quality of the soil. Rooseboom and Harmse (1979) conclude that most of the sediments reaching the upper and middle Orange River originate from the erosion of silt, mudstones and siltstones exposed on the steep slopes of the Drakensberg Escarpment. High

intensity summer rainfall, steep slopes and easily eroded soils and bedrock as well as the type of farming practiced in the catchment influence erosion (Compton et al., 2010). This study is focused on the above mentioned high rainfall, steep slopes and easily eroded soils of the Drakensberg Escarpment as a potential source of the high sediment load in the upper Orange River catchment.

Previous studies done on the upper Orange River catchment have shown that much of the erosion occurs on the Karoo sedimentary soils and bedrock as opposed to the Drakensberg basaltic soils (Compton and Maake, 2007; see Appendix A and Compton et al., 2010). The Elliot Formation was found to be more susceptible to erosion compared to the other rock formations of the upper Karoo Supergroup formations in the study area (Compton and Maake, 2007; Compton et al., 2010). In order to achieve soil sustainability, better management and mitigation measures are needed. This can only be achieved when there is a good understanding of the factors affecting erosion. According to Le Roux et al. (2008), previous studies conducted in South Africa on a regional scale disregarded important erosion factors such as soil erodibility in regards to parent material and degree of soil weathering. Studies done on soil erosion in South Africa have mainly concentrated on identifying places where erosion occurs and identified land use as one of the primary factors impacting erosion (Barker, 1985; Marker and Evers, 1976; Kelbe et al., 1992). Calculations by Garland (1987) show that natural rates for erosion are between 0.02 and 0.75 t ha<sup>-1</sup> yr<sup>-1</sup> and that variation in erosion rates can mainly be accounted for by slope, rainfall and soil type (Garland et al., 1999). Other authors state that geology is probably the dominant factor controlling the inherent erodibility of South African soils (Weaver, 1991; Le Roux et al., 2008). This project will look at the relation of the geology of the study area to the suspended load of the rivers draining that geology, and will attempt to determine the relative importance of erosion in the low lying Karoo sedimentary rocks compared to the highly

elevated Drakensberg basalts as well the relative contribution of topsoil erosion compared to bedrock erosion.

## 1.2 Study Objectives

This project concerns the possible origin of the suspended sediments of the upper Orange River system. A significant amount of research has been carried out on the sediments offshore in the Orange Basin (Compton *et al.*, 2002; Meadows *et al.*, 2001; Compton *et al.*, 2010) as well as the Namaqualand mud belt on the continental shelf (Meadows *et al.*, 2001; Herbert and Compton, 2007) and it is important to understand the source area for these sediments from the continental interior in order to determine areas with high erosion susceptibility. Information on the source of river suspended sediment can be used in understanding the processes of erosion, in order to establish the relative importance of gully and topsoil erosion and for the development of land use policy aimed at reducing soil loss.

The aim of this project is to identify the sources of the suspended sediment transported by the Orange River. The mineralogy and geochemistry will indicate whether the suspended load in the Orange River is derived from the erosion of the Drakensberg basalts or the erosion of the upper Karoo sedimentary rocks or the soils derived there from. Land degradation is a serious problem in the study area and the results of this study will show the relative contributions of erosion of bedrock and valuable top soil.

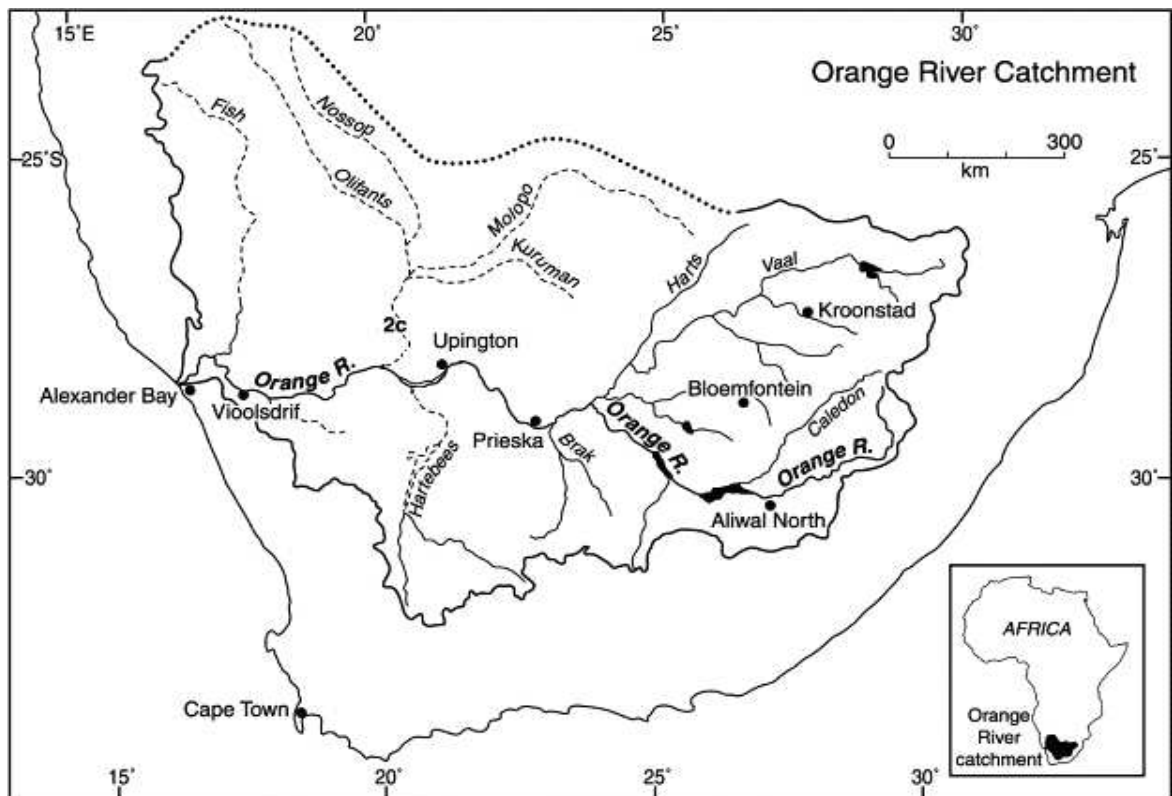
The objectives of the study are:

- Determine the mineralogy and chemistry of the soils in the study area impacted by erosion
- Analyse the mineralogy and chemistry of the suspended sediment river load and river bank sediments draining the study area
- Compare the mineralogy and chemistry of the soils to that of the suspended sediments in the rivers

- Examine paleodeposits in the rivers and streams to establish the history of soil erosion
- Compare the extent and nature of soil erosion in a north-south transect along the western Drakensberg Escarpment.

### **1.3 General introduction to the Orange River system**

Rising in the east, the Orange River flows westward for 2300 km across an interior plateau (Figure 1.1). In advancing from the steep mountains through the pastures of Lesotho; the region flattens, progressively assuming the nature of a desert, which near the Atlantic Ocean receives less than 100 mm/yr rainfall. The total catchment of the Orange River drainage Basin amounts to 891 780 km<sup>2</sup> (Bremner *et al.*, 1990). Wellington (1958) described the features of the Orange River basin and divided the river into the upper Orange above the confluence with the Vaal, the middle Orange between this confluence and Augrabies Falls, situated downstream of Upington and the lower Orange from the Augrabies Falls to the river mouth at Alexander Bay on the Atlantic Ocean. This project focuses on the upper Orange. The Caledon River, which forms a border between South Africa and Lesotho, is the main tributary of the Orange River in the study area.



**Figure 1.1: Orange River catchment showing major rivers, dams and towns from Bremner et al. (1990). Dashed lines indicate ephemeral rivers.**

The Orange River has been discharging large amount of sediments onto the western continental margin of South Africa for about 125 million years. Noble and Hemens (1978) found that the Orange River drains 45% of South Africa's land surface and delivers approximately 22% of its mean annual runoff to the Atlantic Ocean. Most of the runoff is derived from high-rainfall areas of the upper Orange catchment and only 1.8% is derived from below the Orange /Vaal confluence (Kriel, 1972; Benade, 1988). Although the Orange River is small in comparison with most of the World's major rivers, it ranks as the most turbid in Africa and the fourth most turbid in the World, and due to the building of dams the modal size of suspended sediments has changed from silt to clay (Bremner, 1990).

The climate conditions vary greatly from the source to the mouth of the river. The climate at the source is cool and temperate but becomes more arid as the river moves towards the west (Tooth and McCarthy, 2004). Although the catchment experiences summer rainfall,

physiographic diversity of the region results in the rainfall being greatly varied (Department of Water Affairs and Forestry, 1997) (Figure 1.2). The average annual precipitation in the Lesotho Highlands is 1800 mm and the average annual potential evaporation is 1100 mm (Nel and Sumner, 2008). At Alexander Bay the average annual precipitation decreases to 50 mm and the average annual evaporation increases to 3000 mm.

The average daily temperature varies from 12°C in the Lesotho Highlands to 22°C near the mouth. Extreme temperatures of -10°C in the Lesotho Highlands can be experienced and some areas experience more than 200 days of frost a year. The temperatures along the banks of the lower Orange River can reach up to 50°C and higher (Department of Water Affairs and Forestry, 1997). A clear decrease in average annual precipitation can be seen from the source of the Orange River towards the mouth of the river at Alexander Bay (Figure 1.2). Higher rainfall in the eastern catchment could be explained by orographic rainfall resulting from high elevation in the region. The high rainfall area also corresponds to high sediment production (Figure 1.3). Rainfall has been declared by far to be the most important factor of erosion and weathering of soil (Seuffert *et al.*, 1999; Compton *et al.*, 2010). Therefore, high sediment production is predicted in high rainfall areas and the total erosion map corresponds with areas with high rainfall (Bremner *et al.*, 1990).

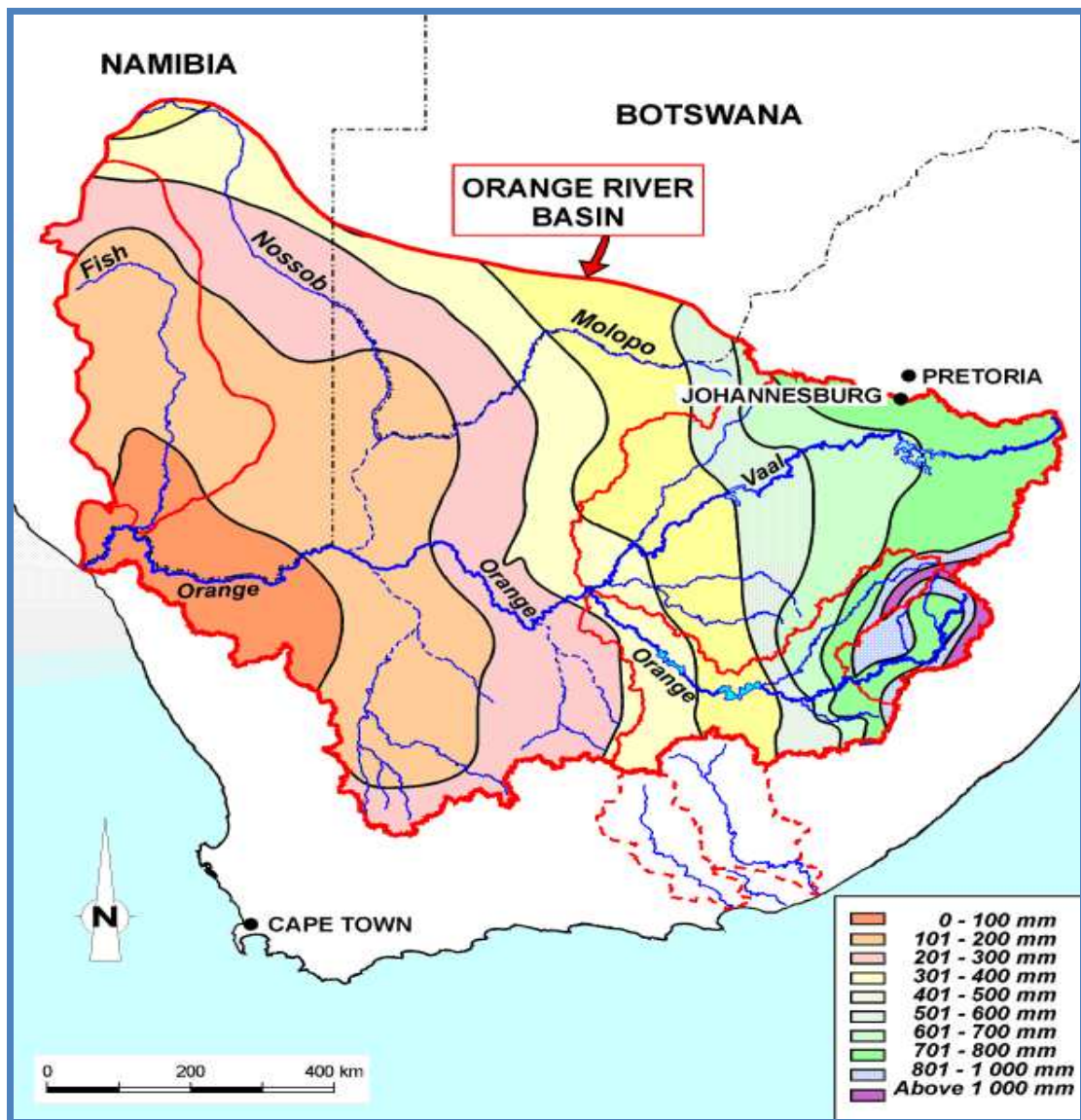
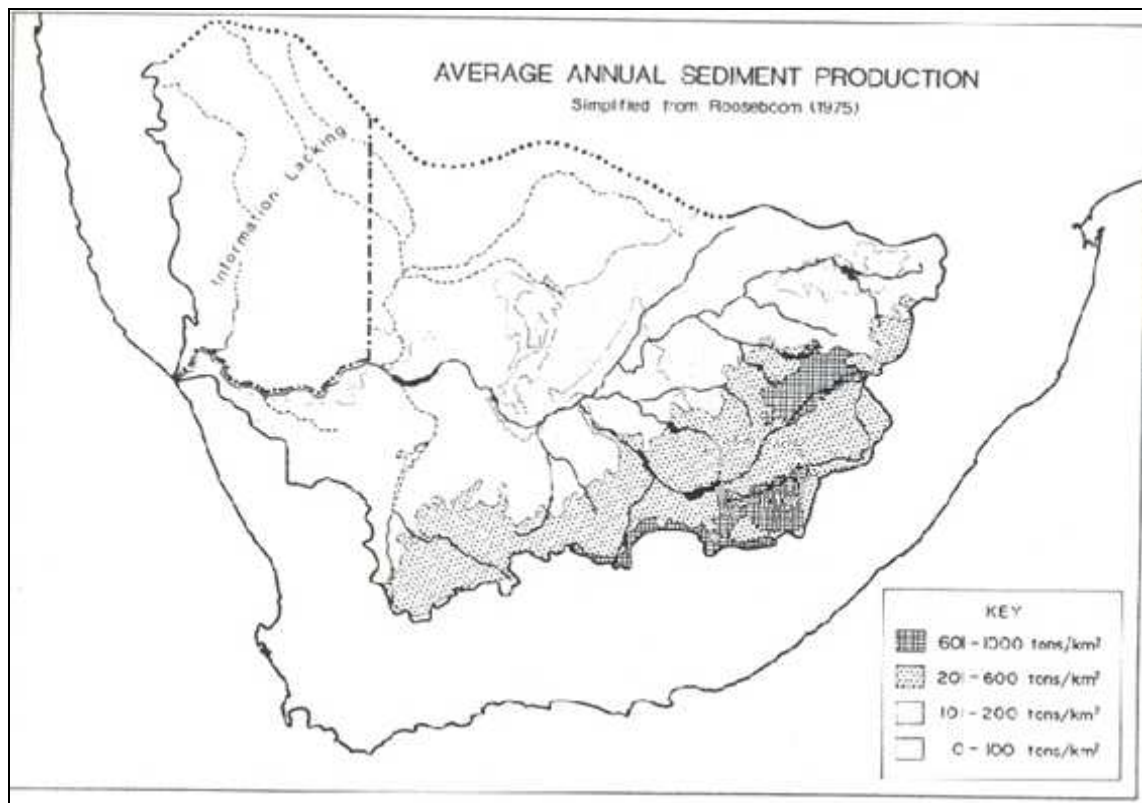


Figure 1.2: The average annual precipitation of the Orange River Catchment (Source: Department of Water Affairs and Forestry, 1997, <http://www.dwaf.gov.za/orange/climate.htm>)



**Figure 1.3: Average annual sediment production in the Orange River catchment (Bremner, 1990).**

## 1.4 Geological Setting

The Orange River system drains a catchment area with rocks ranging from Archean granites to Cenozoic volcanics (Figure 1.4a). For this study samples were collected from the upper catchment area and include the Adelaide Subgroup and Tarkastad Subgroup of the Beaufort Group, Molteno, Elliot, Clarens formations of the Stormberg Group and the Drakensberg Group (Figure 1.4b). These groups and formations are described in detail in the Results chapter.

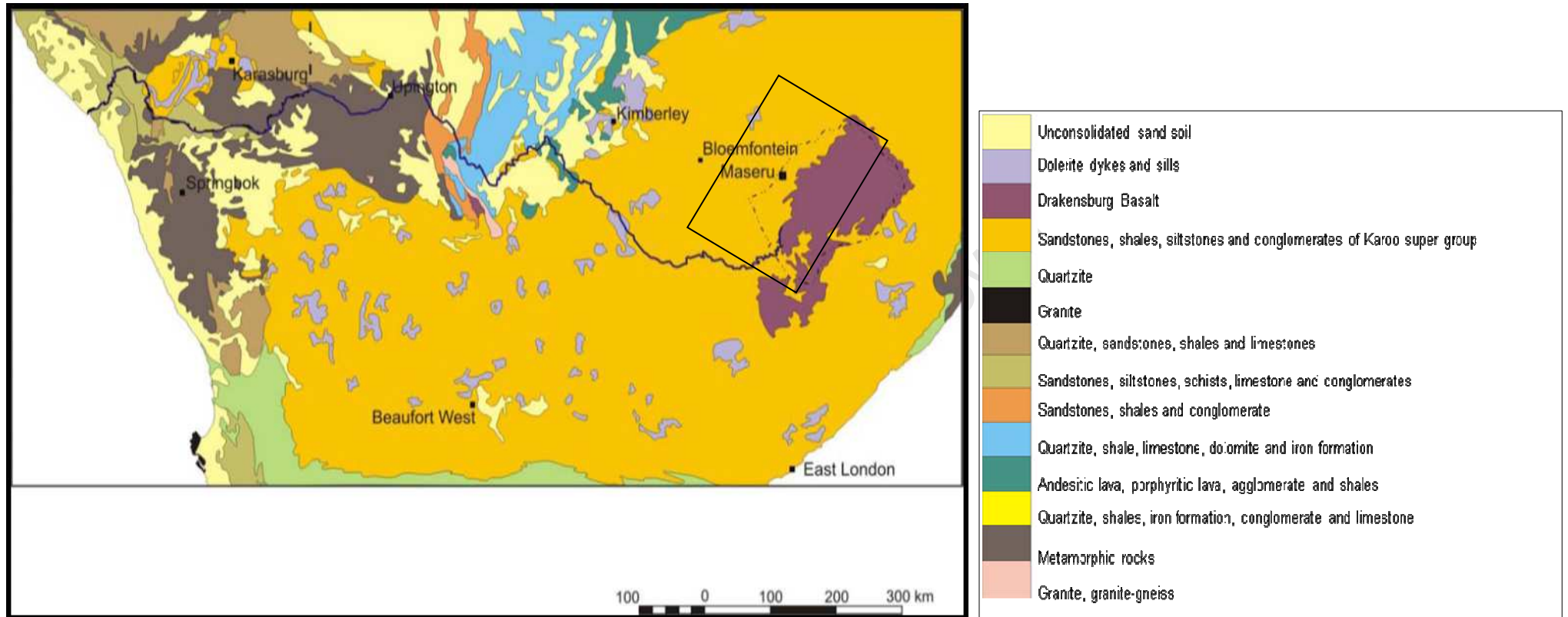
### 1.4.1 Beaufort Group

The Beaufort Group is made up of a lower Adelaide Subgroup and an upper Tarkastad Subgroup.

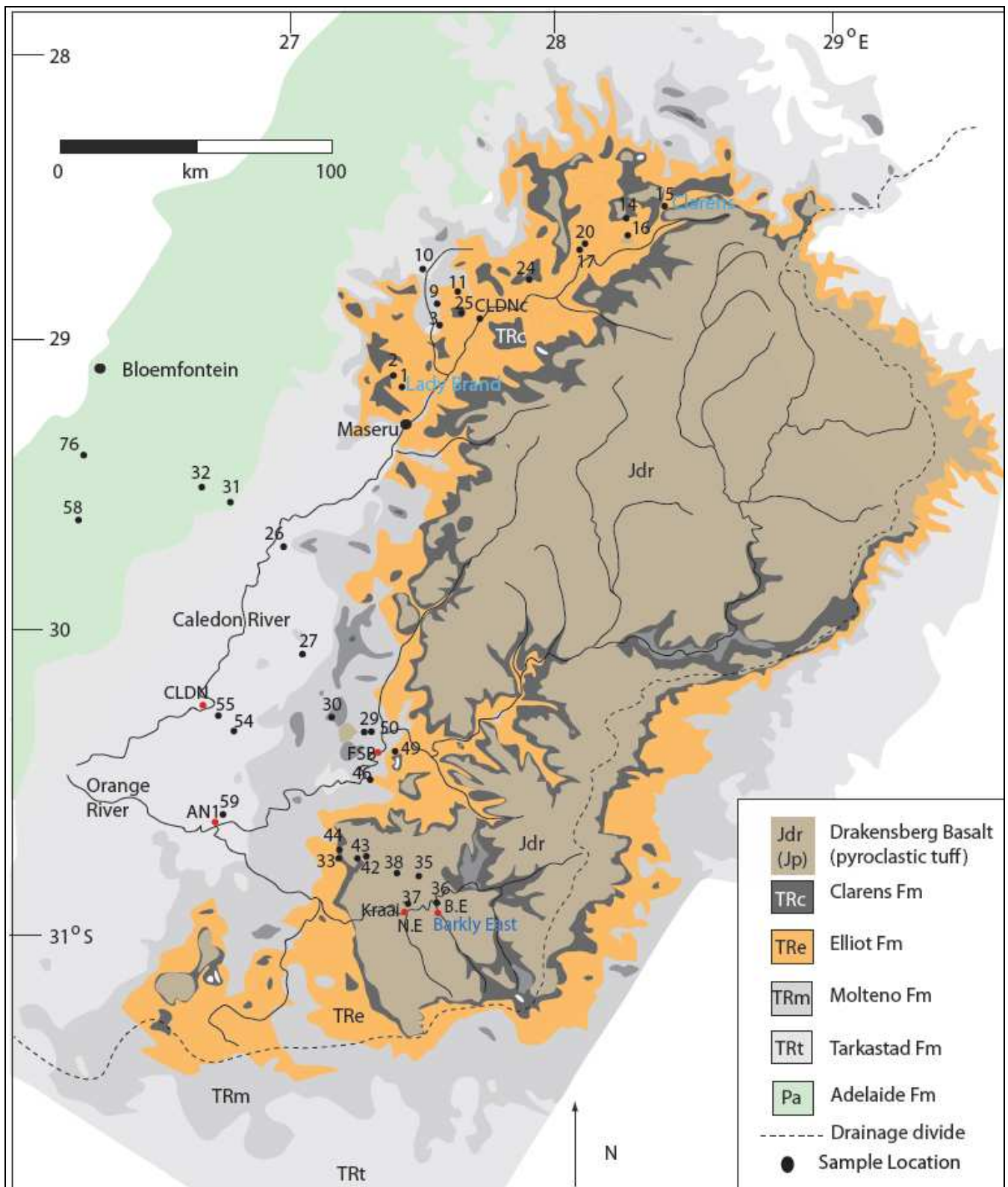
#### **1.4.1.1 Adelaide Subgroup**

The oldest rocks in the study area belong to the lower Beaufort Group; Adelaide Subgroup. The Adelaide Subgroup originated in the Triassic in response to tectonic uplift of a source area which allowed the accumulation of 2700 m of fining upward succession of sandstones and reddish brown mudstones with numerous thin chert bands (Truswell, 1970). The subgroup has lenses of red mudstone which are likely to have been deposited in a sub-aerial fluvial environment. The climate was semi-arid, and it supported a lush flora and fauna that thrived along meandering rivers (Truswell, 1970). The sandstone dominated deposits are believed to have been deposited by overbank flooding from meandering and low sinuosity river systems while the thick mudstone dominated deposits consist of lacustrine facies at the base, overlain by vertically stacked fining upward sequences (Johnson et al., 2006).

University of Cape Town



**Figure 1.4(a):** Simplified geological map of the Orange River and surrounding areas showing the major lithologies, insert (zoomed in on Figure 1.4b) showing the study area which is described further in Methods and Discussion chapters (map extracted from the Geological Map of South Africa, Council for Geoscience).



**Figure 1.4(b):** Geological map of the upper Orange River, the study area showing the geology of the area and sample locations (black circles are bedrock and soil samples (Table 2.1) and red circles are river suspended samples (Table 2.2)). Adapted from Compton et al. (2010) and Council for Geoscience 1:1000000 scale map.

#### 1.4.1.2 Tarkastad Subgroup

The Tarkastad Subgroup of the upper Beaufort Group sediments was deposited in the Late Triassic in an intracratonic basin, with the sediments derived from a volcanically active source located to the south and west (Turner, 1978). The sediments primarily consist of sandstones, siltstones and mudstones as well as a few lenticular limestone and abundant calcareous concretions. The sandy fluvial facies of this group are believed to have aggraded rapidly in a tectonically down-warped foreland basin related to activity in the Cape Fold Belt and its eastward extension beyond the existing continental margin (Tankard et al., 1982). The more proximal facies of this fluvial system were displaced by the subsequent breakup of Gondwana. The Tarkastad Subgroup is characterized by a greater abundance of both sandstone and red mudstones compared to the Adelaide Subgroup (Johnson et al., 2006)

#### **1.4.2 Stormberg Group**

The Stormberg Group is made up of Molteno Formation, Elliot Formation and Clarens Formation.

##### **1.4.2.1 Molteno Formation**

The Molteno Formation was deposited during the Late Triassic. The sediments of this formation are an intracratonic, bed load- dominated fluvial wedge derived from a tectonically active source to the south and south east (Rust, 1962; Turner, 1970) and they are somewhat coarser grained when compared to the Tarkastad Subgroup. This orogenic source may represent renewed uplift of the eastern extension of the Cape Fold Belt (Tankard et al., 1982). The formation consists of alternating medium to coarse grained sandstones and grey mudstones, with secondary quartz over growth giving the sandstone a glittering appearance. Sandstones of the Molteno Formation are coarse grained and they are usually overlain by red shales showing an upward fining sequence (Johnson et al., 2006).

##### **1.4.2.2 Elliot Formation**

The Elliot Formation was deposited in the Late Triassic in a fluvio-lacustrine environment within a long-established internal drainage basin, remote from any marine shoreline (Johnson et al., 2006). Fine-grained red beds and the lenticular yellow sandstone make up the Elliot Formation, which follows conformably on the Molteno and represents a reduction in fluvial energy and proportion of bed load (Tankard et al., 1982). The hematitic coloration characterizes the finest grain size sediments. There are also some green lamellae enclosed within the red mudstone, green mud clasts with iron oxide rims, which have been interpreted by Tankard et al. (1982) as showing that oxidation may have been a product of early diagenesis. Soils derived from the Elliot Formation are commonly friable and easily eroded (Rooseboom and Harmse, 1979).

#### **1.4.2.3 Clarens Formation**

Progressive Late Triassic desiccation reached a maximum during the deposition of the Clarens Formation. Beukes (1970) has divided the Clarens Formation into three units. The central unit represents true desert conditions in the north, grading southwards into intercalated water-laid sediments. The lower and upper units reflect a less severe climate, with numerous shallow lake deposits. The Clarens Formation is made up of eolian sands, corresponding in general with the preceding fluvial depository of the Molteno and Elliot formations. Major channel-fill sandstones are commonly present towards the base of the Clarens Formation. The Clarens Formation sandstone sediments are green in colour and they weather to different colours as they leach different elements. The sandstones of the Clarens Formation have well-developed cross-bedding and are extremely friable in places.

#### **1.4.3 Drakensberg Group**

The Drakensberg Group is made up of the Drakensburg flood basalts and the subsequent Karoo dolerite suite.

#### **1.4.3.1 Drakensberg flood basalts**

Drakensberg volcanism terminated Karoo sedimentation. Basaltic outpourings produced vast lava fields, of which the 140 000 km<sup>2</sup> Drakensberg plateau is an erosional remnant (Tankard et al., 1982). Volcanism was a manifestation of Gondwana break up 180 million years ago but was initiated earlier than that as evidence has been found from zircon dating (Courtillot et al., 1999), and also there are volcanics present in the Permian-Triassic Ecca and Beaufort groups (Tankard et al., 1982). In the study area the Drakensberg conformably follows the Clarens Formation although the relationship between the two is complex (Marsh and Eales, 1984). The majority of the Drakensberg basalts are amygdaloidal, with the cavities filled by zeolites (Marsh and Eales, 1984). The flood basalts outcrop as erosional remnants and areas between them are intruded by dolerite dykes (Duncan and Marsh, 2006).

#### **1.4.3.2 Dolerite dykes and sills**

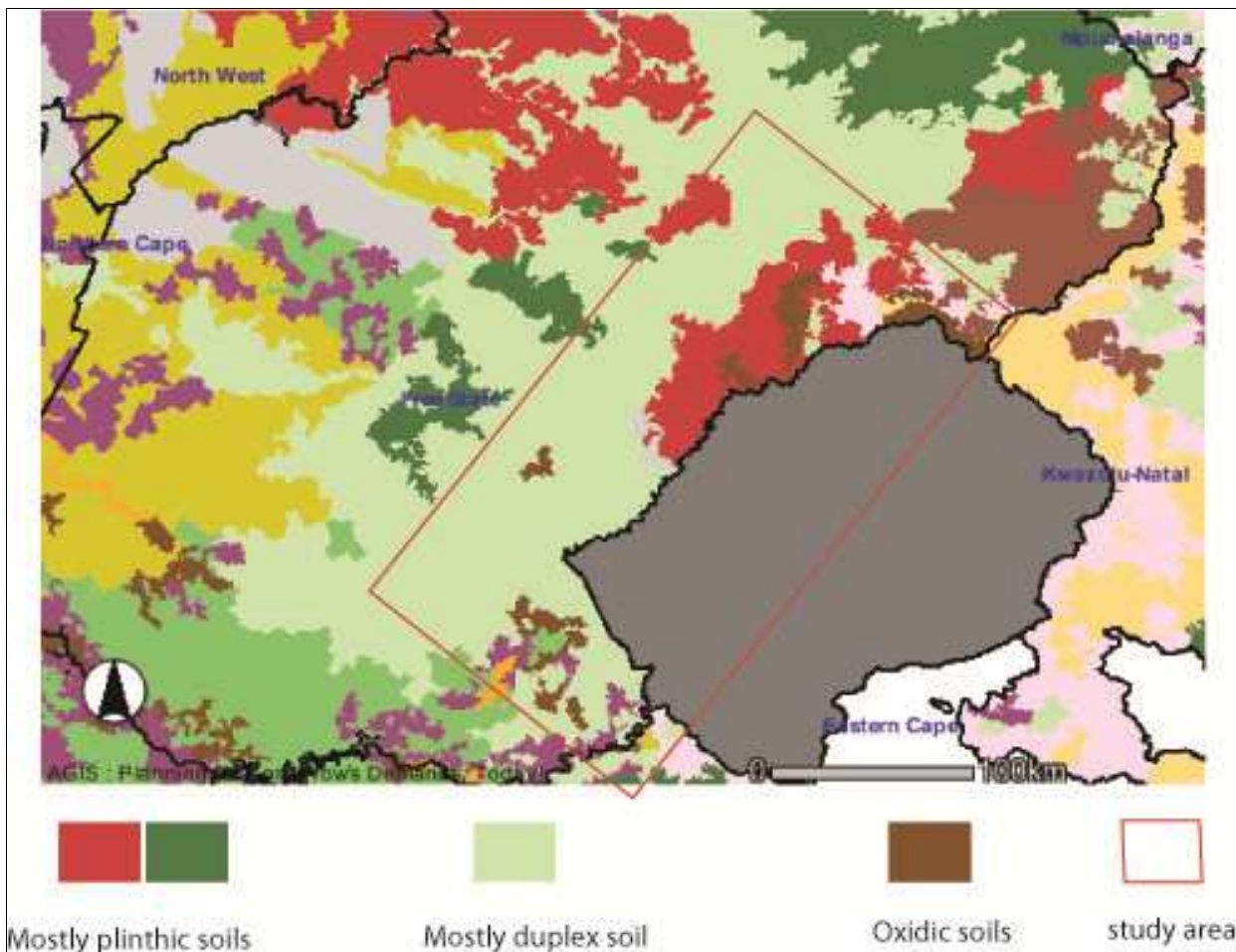
One of the prominent features in the Karoo landscape today is the large number of ring shaped dyke structures present in the study area. The dolerite dykes have been associated with the widespread volcanism that accompanied the outpour of the Drakensburg lavas.

The dolerite dykes and sills are more developed and evident on the Karoo sedimentary rocks and occur as a network of dykes, sills and saucer shaped sheets (Chevallier and Woodford, 1999). The dykes and sills range from a few meters to 200 m or more in thickness and typically form resistant caps of hills comprising of softer Karoo sedimentary sequence.

### **1.5 Soil**

The soil within the catchment area ranges from sandy to clayey with alluvium and bank deposits tending to be mainly sandy. The soil in the catchment area was formed from the weathering of sandstone, mudstone and basalt bedrock in the study area. The field observation has shown that soil of basalt bed rock are dark in colour and contain a relatively high organic matter content and are bound by thick grass roots in comparison to soils

derived from sedimentary bedrock. Moving further from the Lesotho Mountains, including the ridges from the Clarens Formation, the soils of the valley bottoms consist of grey, brown quartzose sand. Further west away from the escarpment are sandy horizons over clayey loam derived from bed rock of the Elliot and to a lesser extent Molteno formations. The soils in the Caledon and upper Orange River catchment area are categorised into four soil types, the clay enriched by illuviation duplex soils, an iron oxide enriched in middle to lower slope in warm, sub-humid climate with a distinct dry season, cumulic soils having recently formed in unconsolidated sediments such as colluviums, alluvium and aeolian sands and, lastly, youthful plinthic soils resulting from either limited rock weathering or rejuvenation through natural erosion on steeper, convex slopes (Fey, 2010) (Figure 1.5). While Rooseboom and Harmse (1979) have classified the soils into 2 categories, the neutral yellow grey and red sand and loams from the weathering of aeolian sands, sandy loess and colluvium. The second category is solodized solonetz in the northern side of the study area and solonetz lithols in the southern side of the study area. The solodized solonetz soils resulted from the weathering of Karoo Supergroup mudstone and siltstones and are highly susceptible to erosion.



**Figure 1.5: Map showing the soils of the study area, sourced from [www.agis.agric.za](http://www.agis.agric.za) and interpretation from Fey (2010). Cumulic soils are mixed with the above shown soil types. No soil data are available for Lesotho (shown in grey).**

## 1.6 Vegetation cover

The Grassland Biome dominates in the upper catchment area where the topography is mainly flat and undulating and includes the escarpment (Figures 1.6). Grassland biome in the study area has been categorized as Drakensberg grassland, Mesic Highveld and dry Highveld grassland (Mucina and Rutherford, 2006) (Figure 1.6). The Drakensberg grassland biomes occur in high altitude and high rainfall areas. These grasslands have occasional shrubs in disturbed areas (Mucina and Rutherford, 2006). The grasses are almost entirely underlain by basaltic rocks with some of the shallow soils covering the Clarens Formation. The amount of cover depends on rainfall and the degree of grazing. Trees are absent, except along the rivers and are scattered. Frosts, fire and grazing maintain the grass dominance and

prevent the establishment of trees (Rutherford and Westfall, 1986). The dry Highveld grassland is found in undulating hills and valleys of rivers such as the Orange River and the Vaal River catchment (Mucina and Rutherford, 2006), and prevails in areas where annual rainfall is less than 600 mm. There are two categories of grass plants in the study area. Sweet grasses have low fibre content, maintain their nutrients in the leaves in winter and are palatable to stock. Sour grasses have high fibre content and tend to withdraw their nutrients from the leaves during winter so that they are unpalatable to stock (Rutherford and Westfall, 1986). Dry Highveld grasses fall under the sweet grass category. At higher rainfall and on more acidic soils, sour grasses prevail, with 625 mm per year taken as the level at which unpalatable grasses predominate (Mucina and Rutherford, 2006). C4 grasses dominate throughout the catchment area, except at the highest altitudes where C3 grasses become prominent.

University of Cape Town

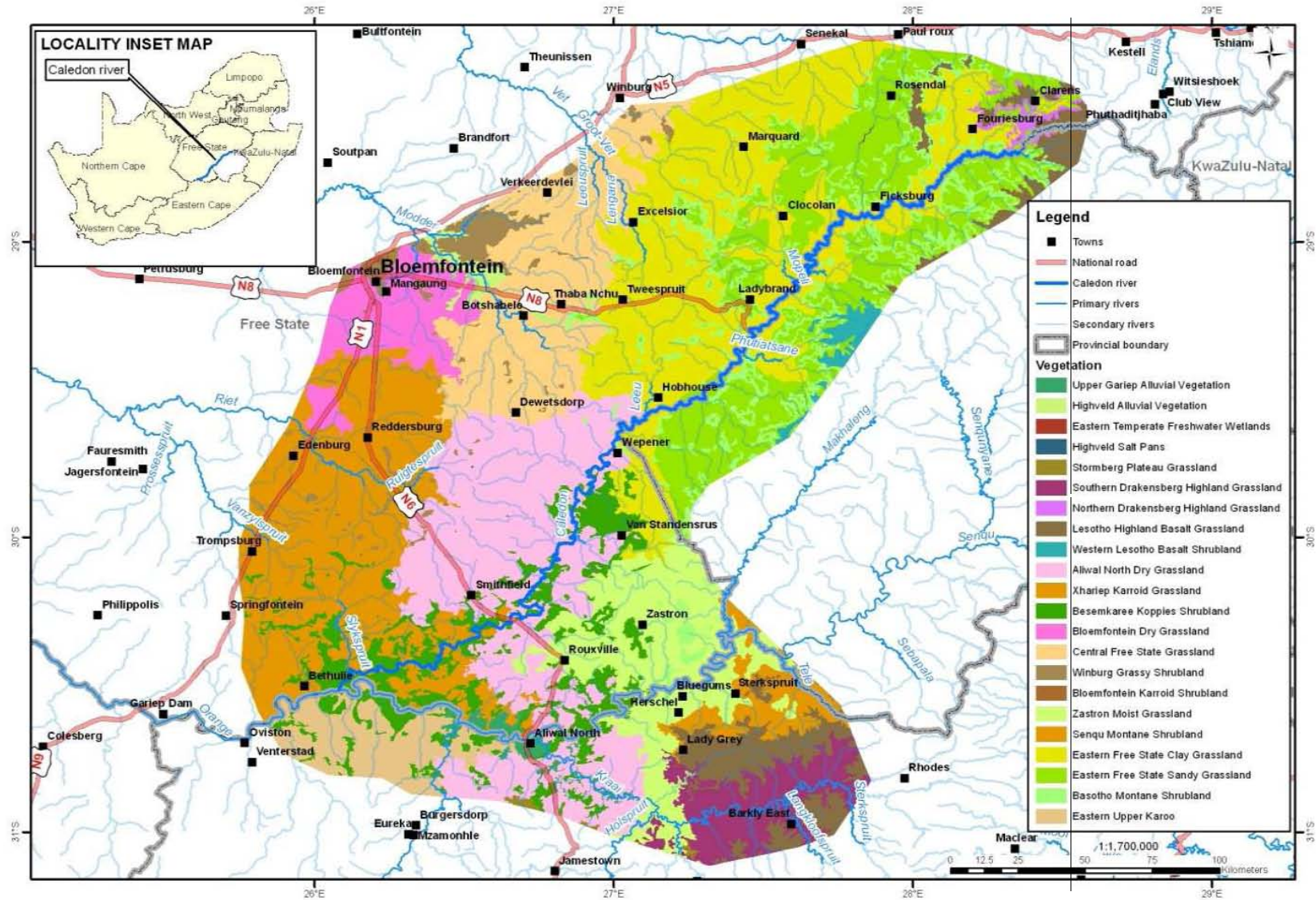


Figure 1.6: Distribution of grassland biomes in the study area data source: South African National Biodiversity Institute and Mucina and Rutherford (2006).

Grass plants tolerate grazing, fire and are able to produce new stems readily, using a wide variety of strategies. Mesic Highveld grassland are mainly in the Zaaron area and are considered to be the sour grasses, shrubs are found within Mesic Highveld grassland (Mucina and Rutherford, 2006). Shrubland occurs within the above mentioned grassland in areas restricted to rocky slopes and shallow soils. The Grassland Biome is the cornerstone of the maize crop, and many grassland types have been converted to this crop. Sorghum, wheat and sunflowers are also farmed on a smaller scale (Rutherford and Westfall, 1986). Grasslands have deep soils that are very nutrient rich because of the large amount of plant tissue ('biomass') that dies off and is added to the soil through decomposition every year. This is why grassland is often converted into farmland. Often grassland soil contains a large proportion of clay, which retains moisture better than sandy soils so that plants growing there can put on a great deal of growth in the spring when there is more rain. Grasses have very deep and extensive root systems that can reach down to get water and they lose less water through their leaves than many other plant types (Rutherford and Westfall, 1986).

## **1.7 Land Use**

The present land use in the catchment area is mostly under natural vegetation with flock farming (sheep, cattle and some game) as the main economic activity (Figure 1.7). Extensive dry land cultivation, mostly for the production of grains, is found in the north-eastern parts of the study area. Ficksburg is famous for the cherry orchards in the region, large areas under irrigation for the growing of grains and fodder crops have been developed along the main rivers, mostly downstream of irrigation dams. The Orange River is highly regulated with dams having been built for irrigation, electricity generation, flood control, and water transfer (Tooth and McCarthy, 2004). There are two storage reservoirs on the Orange River in South Africa, the Gariep Dam (shown on the map) and the Vanderkloof Dam, and one in Lesotho, where the Orange River is called Senqu River, the Katse Dam. The Gariep Dam is the largest reservoir in South Africa and the Vanderkloof Dam is the second largest. The

Vanderkloof Dam controls the flow of water between the dam and Alexander Bay for 1400 km. The Gariep Dam and the Vanderkloof Dam are used to regulate river flow for irrigation and produce hydro-electricity during peak demand periods (DWAf, 1997). Except for the Vaal River, which is the largest and most important tributary of the Orange River, not much of the water from the Orange River is used for domestic or industrial purposes. The use of water by the irrigation sector for agriculture is one of the highest in the upper catchment areas. Grazing is important, but overgrazing converts this grassland to a Karoo shrub land type. The clay rich soils associated with grasslands are excellent for agronomy, and extensive areas are cultivated for maize and other crops. The remnant patches of natural vegetation are intensively grazed and are consequently often degraded.

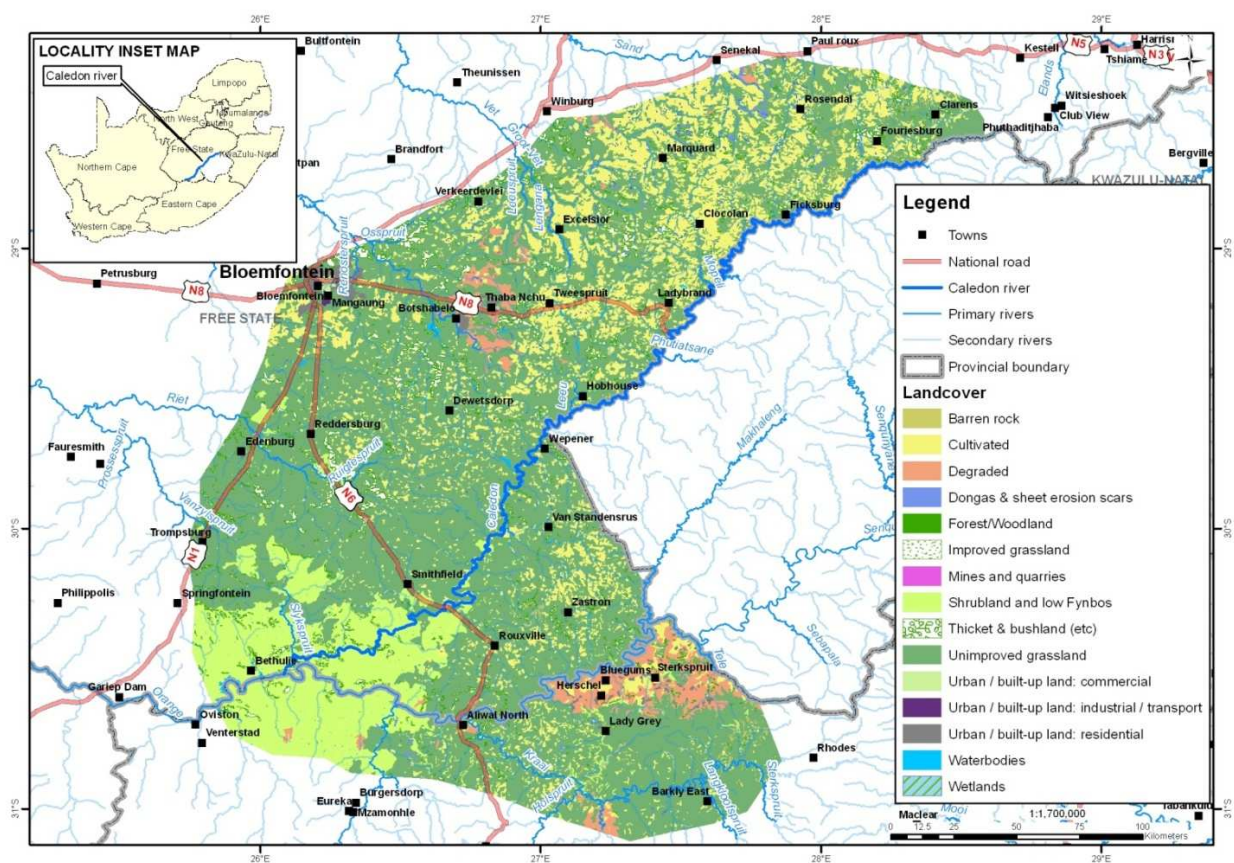


Figure 1.7: Land use distribution in the upper Orange River catchment map from River Health Programme (2003)

## **2 Methodology**

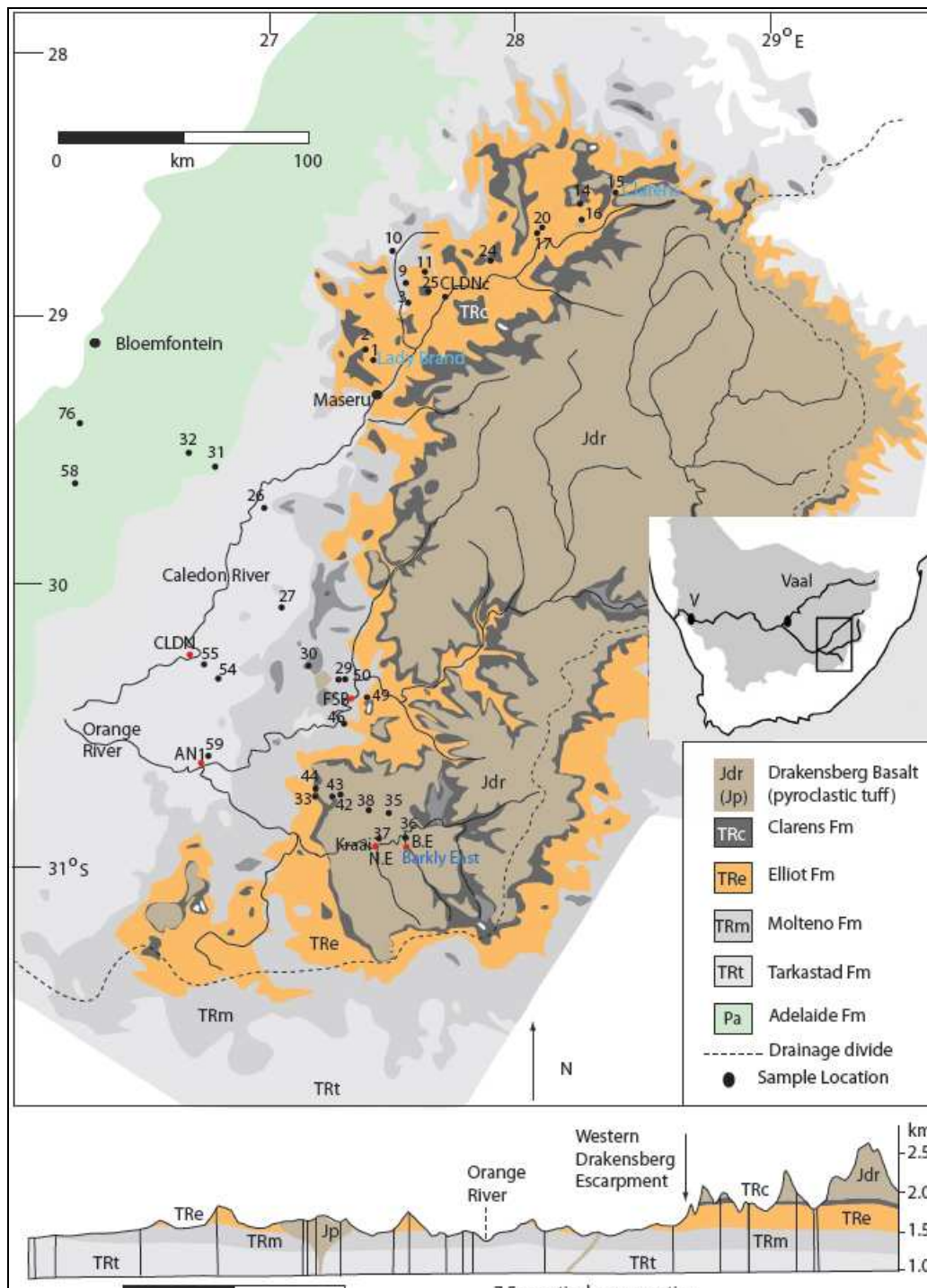
### **2.1 Sampling**

The study area is located in the Free State Province and the far northern part of the Eastern Cape Province with the focus on the upper catchment area of the Orange River at the upper reaches where it is called Senqu, the Caledon river catchment area and to a smaller extent the Vaal river catchment (Figure 2.1 and Figure 2.2). The project covers an area from Barkly East to the town of Clarens near Highland national park. A few samples were collected from the Vaal catchment area and the lower Orange River catchment for comparison. Suspended sediment load was collected from the Caledon River, Orange River at Aliwal North, and Free State Border (upper catchment area) and Vioolsdrift (lower Orange River catchment), and Vaal River 20 km upstream from the town of Douglas and the Kraai River at Barkly East and New England (Figure 2.1).

Three major sampling trips were made to the upper Orange River catchment between February 2006 and August 2009. The sampling trips included the collection of soil samples from the upper catchment of the Orange River and the suspended sediment loads of the upper Orange River, its tributaries and the Caledon River. Modern river bank deposit sand raised river bank (paleoflood) deposits of the Orange River, the Caledon River and their tributaries were also collected during the second and the third sampling trips. The first sampling trip (Feb 2006) extended from the town of Aliwal North towards the town of Bloemfontein to the west and to the south east towards the town of Barkly East (Figure 2.2). The first trip mainly focused on the collection of river suspended sediment and soil profile samples. The second trip (Jan 2007) started at Aliwal North and extended north to the town of Douglas where the Vaal River was also sampled. The second trip focused on the collection of suspended river samples, soil samples, paleoflood and modern river bank deposits. The third trip (August 2009) covered the region from Lady Brand to Clarens

(Figure 2.1). Figure 2.1 shows the different samples that were collected from different geological formations for the purpose of the study from the three different trips that were undertaken. The third trip focused on the collection of soil samples and soil profiling in areas affected by erosion. The first two trips concentrated on the southern part of the study area where erosional features are observed as generally not as extensive as in the northern part of the study area where erosional features are common, such as deeply incised gullies. The general geology, vegetation cover, land use and the extent of erosion were observed and documented at the time of sample collection.

University of Cape Town



**Figure 2.1: Geological map of upper Orange River catchment area showing the distribution of different geological formations drained by the Orange River and its tributaries (black circles are bedrock and soil samples (Table 2.1) and red circles are river suspended samples (Table 2.2)). Adapted from Compton et al. (2010) and Council for Geoscience 1:1000000 scale map and the Aliwal North 1:250000 scale map.**

### **2.1.1 Bedrock and Soil samples**

Samples were named in the field and were later allocated sample numbers (Table 2.1). Bedrock samples consist of sandstone, mudstone and basaltic rocks collected from outcrops or road cuts using a geological hammer. Soil and weathered bedrock samples were collected from the different geological rock formations drained by the Orange River and its tributaries (Figure 2.1). Soil and the weathered bedrock samples consist of unconsolidated sediment at various levels between the underlying bedrock and the ground surface (Table 2.1). The soil samples are the topmost unconsolidated sediments on the surface and include soils collected from farms. Soil samples were collected by scooping 1.5-2.5 kg with a plastic trowel from the surface and to about 15 cm below surface. In some locations surface or top soil samples were collected from the dark, organic-rich 'A Horizon' and subsoil samples were collected from 20-40 cm below the surface. The weathered bedrock samples were collected from the semi hard weathered rock more than 50 cm below surface. The names of bedrock and soil samples were derived as follows, the first character is the first letter of the geological formation sampled followed by one of two letters of the name of the nearest town and then followed by the number of the sample. Where vertical soil profiles were sampled letters a-d (Table 2.1) were added to indicate the relative depth of the samples.

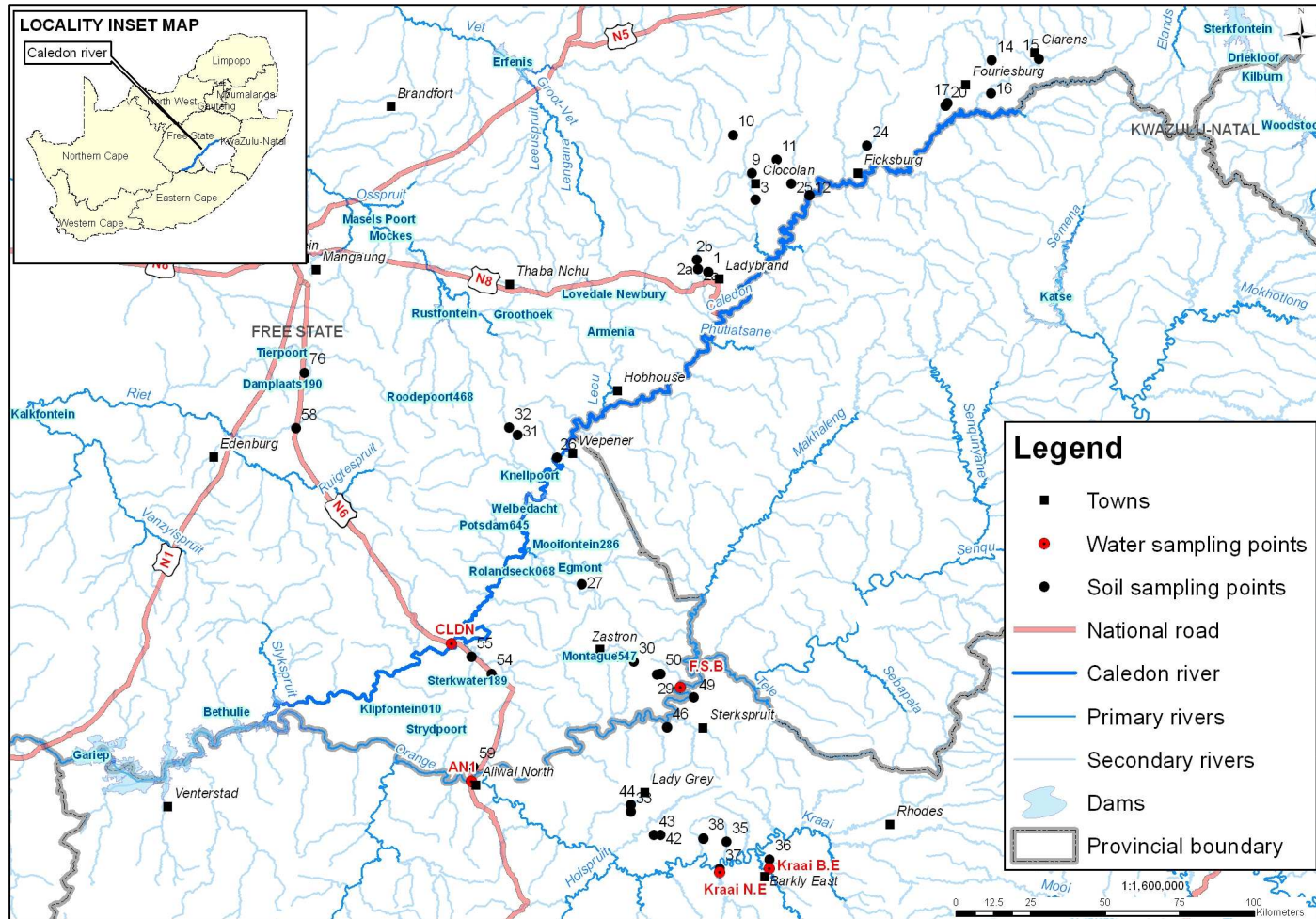


Figure 2.2: Map showing the sample locations and the towns near where the samples were collected. Names with light blue backdrop are small and large dams (adapted from map provided courtesy of the Department of Water Affairs).

**Table 2.1: Sample name, numbers, type and location of soil and bedrock samples.**

Sample name	Sample no	Nearby town	Sample type	Geology	Catchment	Elevation m
Elb12a	1a	Lady Brand	Top soil	Elliot	Caledon River	1516
Elb12b	1b	Lady Brand	Sub soil	Elliot	Caledon River	1516
Elb12c	1c	Lady Brand	Chunky bedrock	Elliot	Caledon River	1516
Elb12d	1d	Lady Brand	River bank deposit of stream nearby	Elliot	Caledon River	1515
Clb13a	2a	Mondderkop	Rock sample	Clarens	Caledon River	1763
Clb13b	2b	Mondderkop	Farm soil	Clarens	Caledon River	1701
Tcl14a	3a	Clocodan	Alluvium deposit	Tarkastad	Caledon River	1540
Tcl14b	3b	Clocodan	River bank deposit	Tarkastad	Caledon River	1540
Mcl15	9	Clocodan	Farm soil	Molteno	Caledon River	1592
Tmar15	10	Marquad	Top soil	Tarkastad	Caledon River	1612
Ecl17	11	Marquad	Farm soil	Elliot	Caledon River	1647
Efr18	14	Fouriesburg	bed rock	Elliot	Caledon River	1784
Cfr18	15	Fouriesburg	bed rock	Clarens	Caledon River	1784
E&Cfr19	16	Fouriesburg	River bank deposit	Elliot/Clarens	Caledon River	1643
M22a	17a	Ficksburg	Top soil	Molteno	Caledon River	1633
M22b	17b	Ficksburg	Sub soil	Molteno	Caledon River	1633
M22c	17c	Ficksburg	Weathered bedrock	Molteno	Caledon River	1633
T24a	20a	Ficksburg	top soil	Tarkastad	Caledon River	1590
T24b	20b	Ficksburg	subsoil with clay	Tarkastad	Caledon River	1590
T24c	20c	Ficksburg	Chunky bed rock	Tarkastad	Caledon River	1590
T24d	20d	Ficksburg	river bank deposit	Tarkastad	Caledon River	1590
M23	24	Ficksburg	Top soil	Molteno	Caledon River	1597
B&C23	25	Ficksburg	River bank deposit	Basalt/clarens	Caledon River	1627
Twep24	26	Wepner	Bed rock sample	Tarkastad	Caledon River	1440
Teg25a	27a	Egmont	alluvium deposit	Tarkastad	Caledon River	1502
Teg25b	27b	Egmont	Top soil	Tarkastad	Caledon River	1502
Pa28	31	Wepner	Top soil	Adelaide	Caledon River	1505
Pa29	32	Wepner	Alluvium deposit	Adelaide	Caledon River	1493
16soil hori	54	Rouxville	Topsoil	Molteno	Caledon River	1417
17A	55a	Kleinspirit	Topsoil	Tarkastad	Caledon River	1374
17B	55b	Kleinspirit	Sub soil	Tarkastad	Caledon River	1374
17C	55c	Kleinspirit	Bed rock	Tarkastad	Caledon River	1374
RB 19	58	Reddersburg	Topsoil	Tarkastad	Caledon River	1407
20	76	Reddersburg	Top soil	Tarkastad	Caledon River	1490
LG1 2	33a	Lady Grey	Top soil	Clarens	Orange River	1679
LG2 2	33b	Lady Grey	Bed rock	Clarens	Orange River	1679
N.E 3	35	New England	Top soil	Basalt	Orange River	1754
B.E 4	36	Barkly East	Bedrock	Basalt	Orange River	1790
KPS 7	37	Barkly East	Bedrock	Basalt	Orange River	1606
8A	38a	Barkly East	Topsoil	Basalt	Orange River	1892

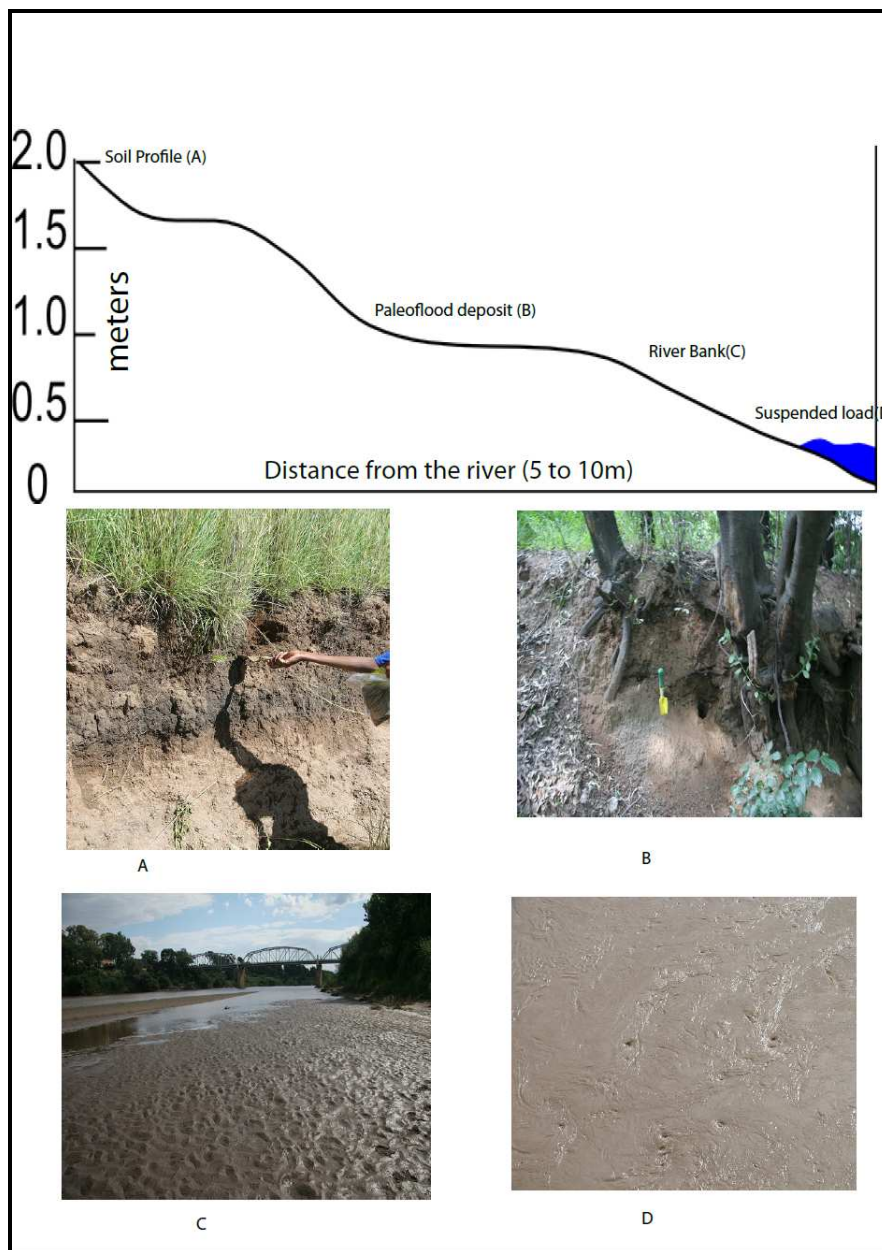
Sample name	Sample no	Nearby town	Sample type	Geology	Catchment	Elevation m
8B	38b	Barkly East	Sub soil	Basalt	Orange River	1892
8C	38c	Barkly East	Sub soil	Basalt	Orange River	1892
8D	38d	Barkly East	Weathered Bed rock	Basalt	Orange River	1892
9 basalt	42	Dordrecht	Top soil	Basalt	Orange River	1916
10 mud	43	Dordrecht	Bed rock	Elliot	Orange River	1660
11A	44a	Dordrecht	Topsoil	Elliot	Orange River	1697
11B	44b	Dordrecht	Bed rock	Elliot	Orange River	1697
12A	46a	Blue Gum	Topsoil	Elliot	Orange River	1488
12B	46b	Blue Gum	Sub soil	Elliot	Orange River	1488
12C	46c	Blue Gum	Weathered Bed rock	Elliot	Orange River	1488
13SP	49	Sterkspruit	Topsoil	Molteno	Orange River	1378
15A O.F.S.B	50a	Zastron	Topsoil	Elliot	Orange River	1515
15B O.F.S.B	50b	Zastron	Sub soil	Elliot	Orange River	1515
15C O.F.S.B	50c	Zastron	Sub soil	Elliot	Orange River	1515
15D O.F.S.B	50d	Zastron	Weathered Bed Rock	Elliot	Orange River	1515
LM-07	59	Aliwal North	Top soil	Tarkastad	Orange River	1329
Ezas26	29	Zastron	Alluvium deposit	Tarkastad	Orange River	1497
Mzas27	30	Zastron	Alluvium deposit	Molteno	Orange River	1561

### **2.1.2 River suspended load, Riverbank and Paleoflood deposits**

Suspended sediment samples were collected from river waters with a plastic bucket at the shoreline of the river (Figure 2.3). River water suspended sediment samples were collected from the edge of the riverbank by submerging, in one rapid and continuous motion, 5-10 litre plastic buckets to a depth of approximately 30 cm below the surface of the river, and were transferred into 2.5 litre bottles and 2 litre jugs. River suspended sediments were collected by settling overnight. The finest suspended sediment, which did not settle out overnight, was collected in plastic jars for settling or centrifuging in the laboratory. At the same time of sample collection, the flow velocity of the surface river water was recorded.

The velocity was measured by throwing a stick in the water and measuring the time it takes to travel through a set distance. Using the predetermined distance and the time measured the velocity was calculated. River water suspended sediment samples were collected from the Orange River upstream of the bridge at Aliwal North (AN1) and upstream of the bridge at the Free State Border (FSB) in February 2006 (Figure 2.4 and Table 2.2). The Caledon River was sampled upstream of the N6 Bridge (CLDN) in February 2006 between the towns of Rouxville and Smithfield and between the towns of Clocolan and Ficksburg (CLDNc) in August 2009 (Figure 2.1, 2.4 and Table 2.2). The Kraai River was sampled downstream of the R58 bridge north of Barkly East (Kraai) and a tributary to the Kraai River was sampled at the town of Barkly East (BE). The second set of river water suspended sediment samples was collected in January 2007 from the Aliwal North site and Caledon River site and included the Vaal River (Vaal) site 25 km upstream from the town of Douglas (Figure 2.1). A suspended sediment sample was also collected from the far western end of the Orange River catchment at Vioolsdrif (Bundi) 150 km from the river mouth at Alexander Bay on the Atlantic coast bordering with Namibia. The first and second sampling was done during the austral summer when most summer rainfall is received in the catchment area and the

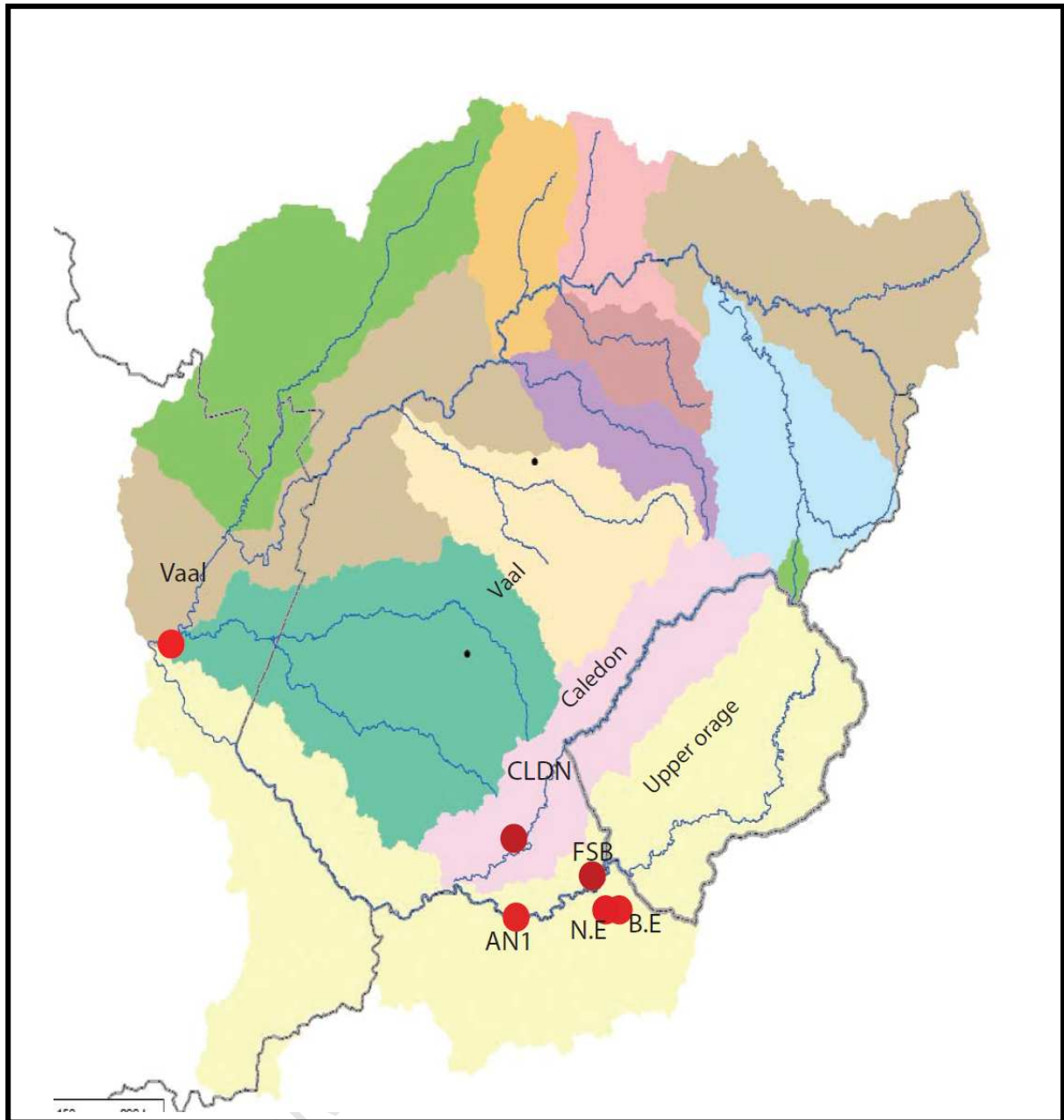
maximum amount of suspended sediment is transported by the Orange River. Paleoflood deposit samples consist of sediment deposited during previous flooding events at various elevations above the river (Figure 2.3.) River bank and paleoflood deposits are indicated by the letter RB and P, respectively added to the source river name (Table 2.2).



**Figure 2.3: Profile showing location of samples relative to the river. A shows a soil profile from top soils to weathered bedrock (sample 1a to 1d); B shows a palaeoflood deposits (P); C shows a modern river bank deposit (RB) and D shows sediment suspended in the flowing river.**

**Table 2.2: Source river, sample name and sample number of suspended, river bank and paleoflood deposits.**

Source River	Sample name	Sample no	Nearby town	Suspended load (g/l) 2006	g/l 2007	Catchment	Elevation m
<b>Orange River</b>	Bundi	Bundi	Vioolsdrift		0.058 g/l	Orange River	150
	AN1	AN1	Aliwal North	2.6 g/l	0.46 g/l	Orange River	1306
	FSB	FSB	Free State border bridge	3.4 g/l		Orange River	1368
<b>Caledon River</b>	Caledon	CLDN	N6 Bridge	3.0 g/l	0.52 g/l	Caledon River	1329
<b>Vaal River</b>		Vaal	Douglas		0.022 g/l	Vaal River	
<b>Kraai River</b>		Kraai B.E	Barkly East	0.05 g/l		Orange River	1754
		Kraai N.E	New England	0.22 g/l		Orange River	1754
<b>RIVER BANK DEPOSITS 2007</b>							
<b>Caledon River</b>							
	CR16a	CLDNc RBa	Clocolan	top soil		Caledon River	1521
	CR16b	CLDNc RBb	Clocolan	river bank deposit		Caledon River	1521
	Caledon River Bank	CLDN RB	N6 Bridge	almost all sand deposit		Caledon River	1329
	Caledon 2 <sup>nd</sup> samples.	CLDN RB Clay	N6 Bridge	clay rich river bank sample		Caledon River	1329
<b>Vaal River</b>	Vaal Windsorton	Vaal RB	Windsorton	sandy river bank deposit		Orange River	
<b>Orange River</b>	AL North clay River Bank 4 <sup>th</sup> Jan	AN1 RB silt	Aliwal north	clay layer on river bank		Orange River	1306
	AL North Clay River Bank	AN1 RB Mud	Aliwal north	fine clay and mud layer		Orange River	1306
	AL North Surface mud	AN1 RB Clay	Aliwal north	clay layer on sandy beds		Orange River	1306
<b>Paleoflood deposits</b>							
<b>Caledon River</b>	Caledon Paleoflood N6	CLDN P	N6 Bridge	very sandy homogenous sed		Caledon River	1329
<b>Vaal River</b>	Vaal Paleoflood(Douglas)	Vaal P	Douglas	sub surface deposit in dry river bed		Vaal River	
<b>Orange River</b>	AL North Paleoflood	AN1 P	Aliwal north	fine silt sampled inbetween tree roots		Orange River	1306



**Figure 2.4:** Map showing the location of river suspended load, river bank and paleodeposit sample points. The coloured areas indicate the individual river catchment (River Health Programme 2003). The Bundi sample was collected at Vooilsdrift 150 km from the Orange River mouth (Fig. 1.1).

### 2.1.3 Catchment area of the Orange River

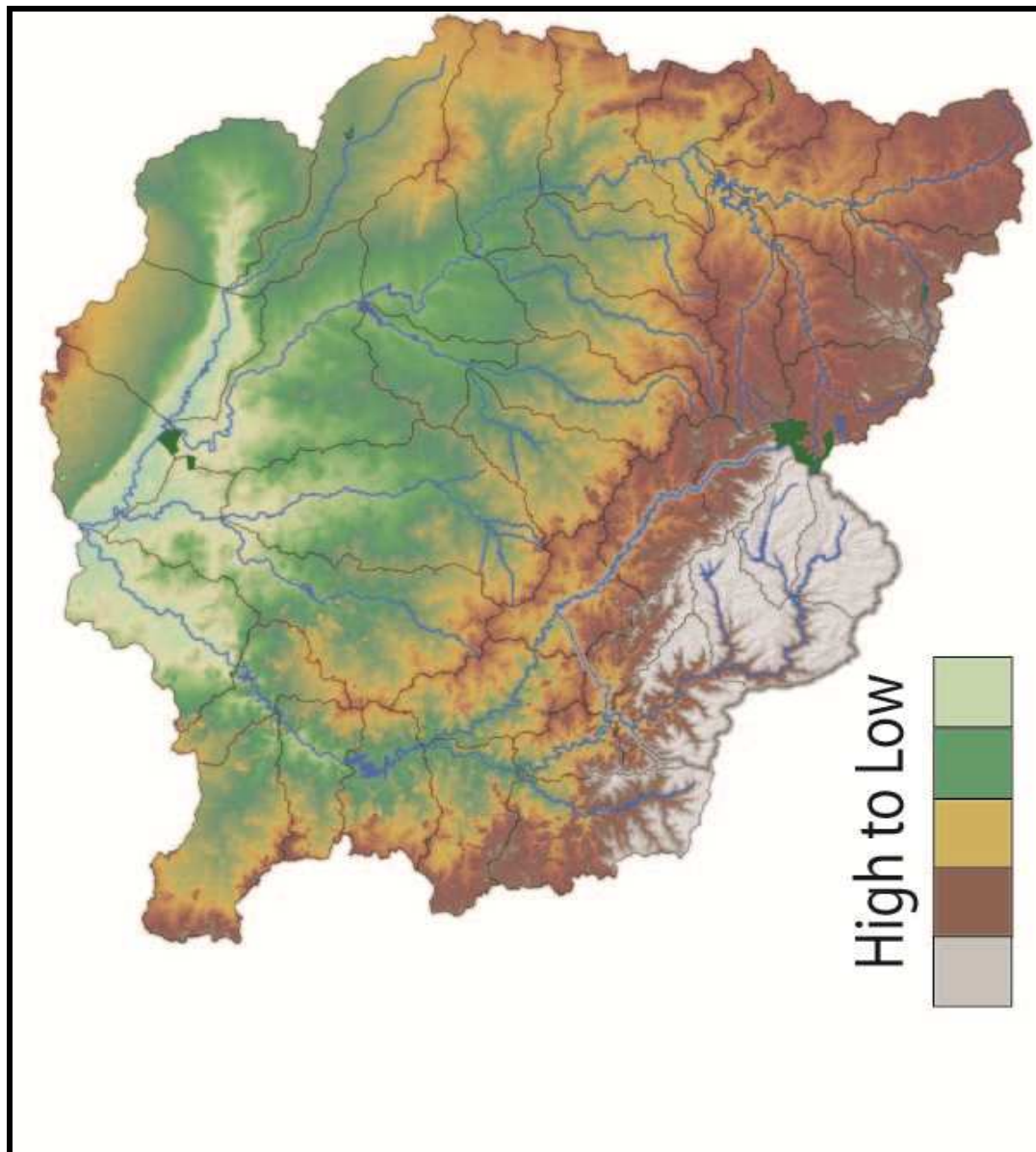
The geological map of the catchment (Figure 2.1) was used together with the catchment area map as defined by the Department of Water Affairs (DWA) (Figure 2.4) to estimate the relative extent of geological formations in the river catchment area (Table 2.3). The catchment area map was superimposed onto the geological map of similar scale and the area of each major rock formation was outlined in the catchment followed by an area calculation.

**Table 2.3: Relative percentage of geological catchment bedrock formations in the upper Orange River and its tributaries.**

<b>Orange River catchment bed rock geology composition</b>						
	<b>Bedrock Formation</b>					
<b>Sample site</b>	<b>Pa</b>	<b>TRt</b>	<b>TRm</b>	<b>TRe</b>	<b>TRc</b>	<b>Jdr</b>
<b>AN1</b>		20	30	20	5	25
<b>FSB</b>		5	20	25	10	35
<b>Kraai</b>					15	85
<b>Caledon River catchment bed rock geology composition</b>						
	<b>Pa</b>	<b>TRt</b>	<b>TRm</b>	<b>TRe</b>	<b>TRc</b>	<b>Jdr</b>
<b>CLDN</b>	5	35	7	30	13	10
<b>CLDNc</b>	0	15	10	50	15	10

The upper Orange River catchment of this study has been defined as the upper catchment area excluding land area in the Caledon River catchment as defined by the Department of Water Affairs (DWAF) (Figure 4.4). The Orange River suspended load and river catchment include samples taken from Aliwal North (AN1), the Free State border (FSB) and the Kraai River at Barkly East and New England (Kraai B.E and Kraai N.E) (Figures 2.1 - 2.4). These samples were further separated relative to their mud and sand content at the time of sampling. The mud and clay river bank samples are fine grained mud settled on top of the sand bars, while silty river bank deposits had more silt or sand than clay. The paleoflood deposits were collected some 5 to 10 m away and upslope from the modern river bank deposits and contain both sand and mud (Figure 2.3).

Highest rainfall and relief (Figure 1.2 and 2.5) in the Orange River catchment occur in the Drakensberg and Maloti Mountains. The upper Triassic and lower Cretaceous Drakensberg flood basalt and the underlying Clarens Formation sandstone form a resistant cap rock to weathering and erosion of the escarpment (Sumner et al., 2009) ( Figure 2.5).



**Figure 2.5: Elevation map of the upper Orange River and Vaal River catchment areas (River Health Programme, 2003).**

## **2.2 Sample analyses**

All soil, water (river suspended) and rock samples were analysed in the University of Cape Town Geological Sciences Laboratory. Each of the soils samples and river suspended sediments was subdivided into 3 batches. The first batch was put in a freeze drier to remove excess moisture and then crushed for chemical analysis by x-ray fluorescence (XRF). The second batch was sent to the Archaeology Laboratory for total organic carbon analysis and stable isotope analysis of organic carbon and the third batch was wet sieved for grain size

analysis detailed in the section below. The clay fraction of the wet sieved soils and suspended sediments were analysed for mineralogy using x-ray diffraction (XRD). Rocks samples were cut into thin sections for binocular microscope mineral identification, while parts of the rock samples were crushed for chemical analysis by XRF. A complete flow chart for sample preparation and analysis is shown in Figure 2.6.

University of Cape Town

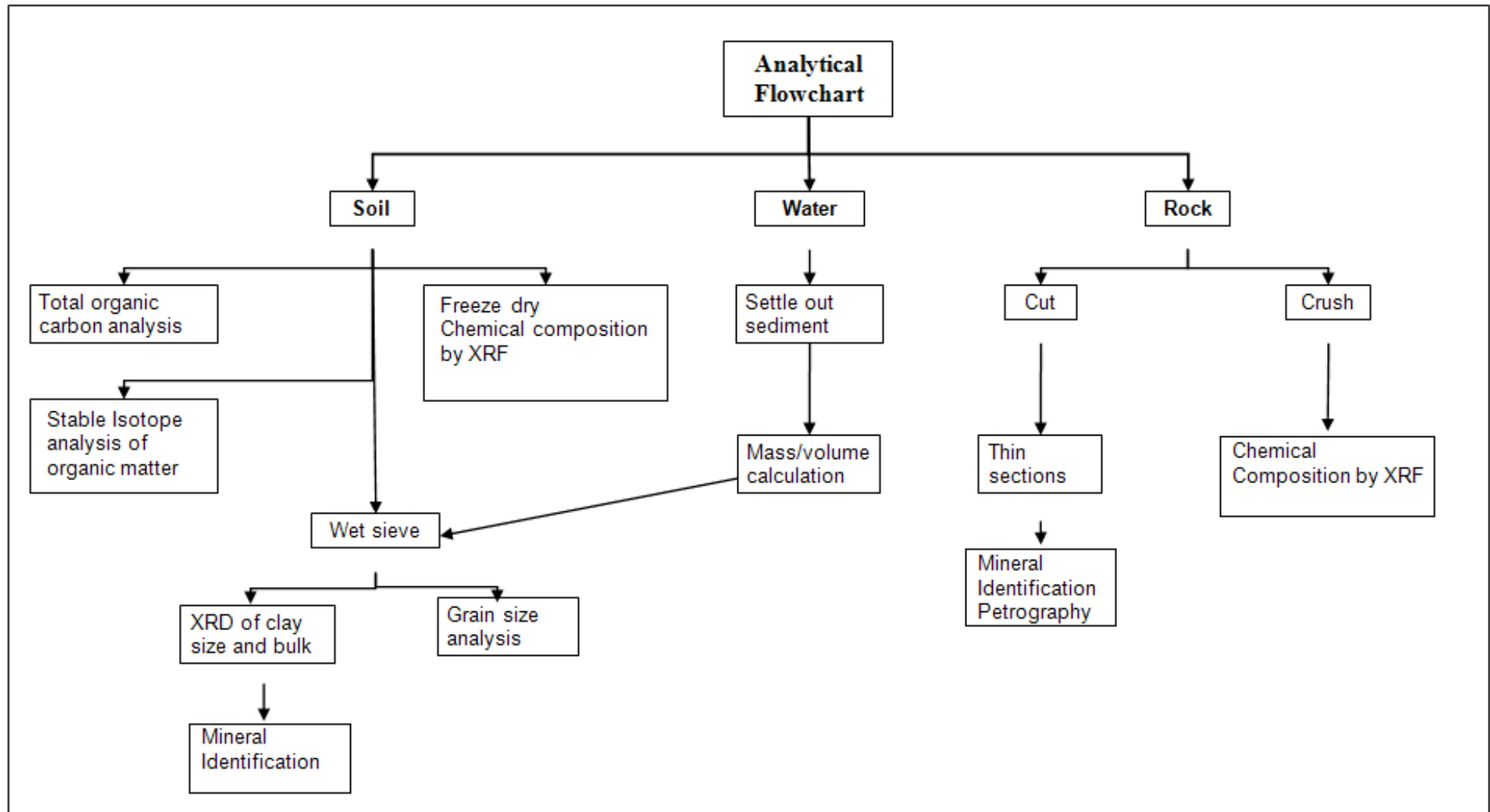


Figure 2.6: Flow chart for sample preparation and analyses.

### 2.2.1 Grain size analysis

The bulk soil and suspended river water samples underwent grain size analysis using a 63 micrometers ( $\mu\text{m}$ ) and 38  $\mu\text{m}$  mesh sieves, separating the sand ( $> 63\mu\text{m}$ ) and coarse silt (38-63 $\mu\text{m}$ ) fractions, respectively. The remaining  $<38 \mu\text{m}$  mud was decanted into 600 and 800 ml beakers and re-dispersed by stirring. After settling for 20 minutes, according to Stoke's Law which assumes perfect spheres, particles left in suspension were operationally defined as clay ( $<2\mu\text{m}$ ) and were decanted from the settled very fine to medium silt fraction (2-38 $\mu\text{m}$ ). A small representative sample of the clay fraction was mounted onto glass slides as slurry for mineralogical analysis by X-ray diffraction (XRD). The rest of the wet sieved sediments were then placed in an 80°C oven to dry and weighed for grain size analysis.

The suspended sediment samples were left to settle for a further 2 to 5 days in the lab. Not all sediment settled in this time period with some sediment still suspended. A measured volume of this residual suspended sediment was filtered through a 0.45  $\mu\text{m}$  pre-weighed filter. The weight of the suspended sediment after 2 to 5 days of settling was added to the total settled weight and the filtered suspended sediment was mounted on glass slides for mineralogical analysis by XRD. The settled suspended sediment and bulk soil samples were freeze dried to remove excess moisture and powdered for chemical analysis by XRF and total carbon analyses. The soil was freeze dried using a Virtis Benchtop SIC 2, 4 and 6k machine. The drying process removes 99% of the moisture from the sample without compromising the sample. The sediments must be frozen before freeze-drying to below -40°C to minimise freeze-drying time. The machine uses a vacuum for removal of air and other non-condensable vapour and condenser for removal of moisture from the soil.

### 2.2.2 Petrography

Petrography of rock thin sections was carried out using a Nikon Libophot transmitted light microscope. The mineralogy and texture were described to document changes in

composition and texture between the samples. The petrography of sand and coarse silt size fractions of the suspended river load and soil samples were described using an Olympus binocular microscope. XRD was used to complement the thin section in identifying the mineralogy of very fine-grained rocks.

### **2.2.3 X-ray diffraction (XRD) analysis**

XRD analysis was carried out on the clay size fraction of the wet sieved suspended river water sediment and soil samples and on the bulk soil samples to determine mineralogy of the samples. The bulk soil samples were crushed and finely ground into a powder using an agate mortar and pestle. The powder was mixed with a small amount of distilled water to make a slurry, which was then transferred by pipette onto a glass slide. A small amount of the clay fraction was mounted as wet slurry on a glass slide for XRD analysis. The sample was allowed to air dry and then was loaded into the XRD for analysis. The instrument used was a Philips PW1390 Powder X-Ray Diffractometer at the Department of Geological Sciences at UCT, which uses a Copper K- $\alpha$  X-ray tube with wavelength of 1.542 Å. D-spacing, the distance between atomic layers in mineral crystals are measured using Bragg's Law:

$$n\lambda = 2d\sin\Theta$$

Where  $n$  is an integer,  $\lambda$  is the wavelength of the beam,  $\Theta$  is the incident angle, and  $d$  is the d-spacing of the crystal in Angstroms. Bragg  $2\Theta$  angles between 2.5 and 50° were used for the analysis. Peaks in the XRD patterns corresponding with d-spacing of minerals were used to identify the minerals present in the sample.

### **2.2.4 X-ray fluorescence (XRF) elemental analysis**

Major oxide and trace element analysis was done by XRF analysis. Weathered and fresh bedrock samples and freeze dried suspended sediment and bulk soil samples were crushed and powdered in an agate mortar and pestle for XRF analysis. For major oxides, XRF fusion disks were prepared using 0.7 g of powdered sample and 6 g of flux. For trace element analysis briquettes were prepared using 6 g of sample with one drop per gram of mowiol

(used as a binder to hold the sample together) pressed at 10 tons. All samples were run at the University of Cape Town with the exception of three suspended river sediment samples which were run at the University of Stellenbosch (US) using the following methods: pressed pellets were prepared using 6g of sample pressed at 7 tons, and glass beads were made using 0.5 g of sample and 1.5 g of additive (Li-B La-free flux) melted at 1000°C. Diameter of beads and pellets must be more than 25 mm. Duplicate samples were run for major oxides and the values were reproducible to within 7% (Figure. 2.7).

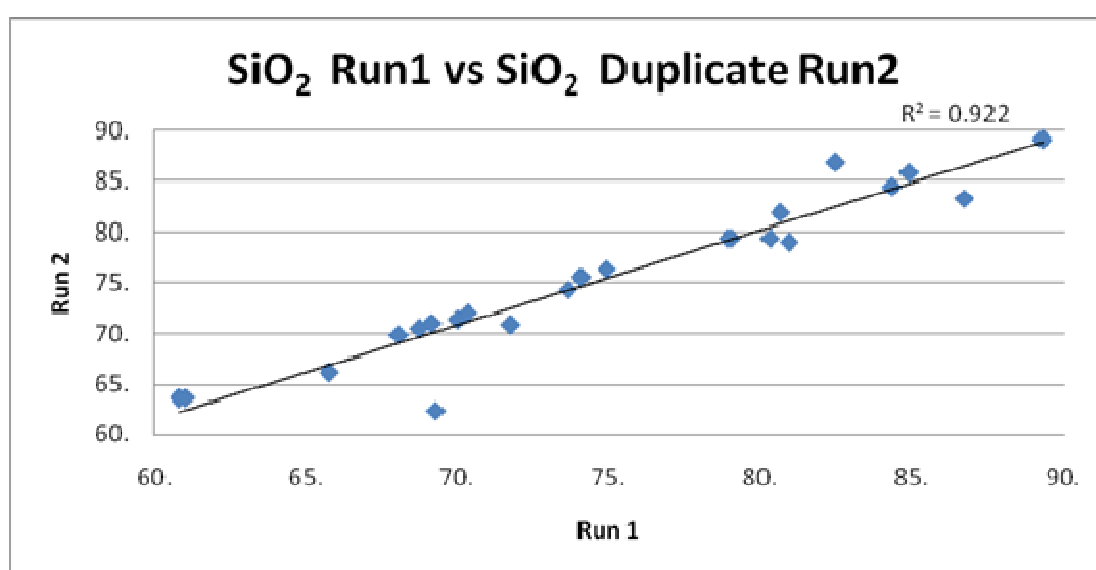


Figure 2.7: Comparison of SiO<sub>2</sub> analyses of duplicate samples determined by XRF.

### 2.2.5 Organic carbon content and carbon isotope analysis

The organic carbon content and the isotope composition of the organic carbon were determined on the suspended sediment and soil samples. Carbonate carbon (mostly present as CaCO<sub>3</sub>) was first removed by placing freeze-dried samples for a minimum of 5 hours in a buffered (pH 5) acetic acid-sodium acetate solution consisting of 0.5 M acetic acid buffered using 82g/L sodium acetate to prevent any damage to clay minerals. Leached samples were then washed repeatedly with ultraclean distilled water, until the litmus test indicated a pH of 7. The non-carbonate (acid-insoluble residue) was separated from the supernatant by

centrifugation for 25-30 minutes at a minimum of 5000 rpm (revolutions per minute). Sediment that remained in suspension after centrifugation was allowed to settle overnight. The acid insoluble residue was dried at 60-70°C, weighed and CaCO<sub>3</sub> percent was calculated by mass difference. The acid insoluble residue of digested samples were ground with acetone in an agate mortar and pestle and approximately 1 mg was weighed with a microbalance into tin cups, which were then squashed to enclose the sample. The samples were run on a Thermo Finnigan Delta Plus XP stable light isotope mass spectrometer coupled via a ConFlo III device to a Thermo 1112 Flash elemental analyzer in the Archaeology Laboratory at UCT. The flow rate of gas, released by burning samples in a mass spectrometer run, was measured in volts per second and was converted to carbon content using the known content of the in-house reference materials, namely Merck gel, chocolate powder, plant Nasturtium and sucrose. These standards have been calibrated against international Atomic Agency standards, and the results are expressed relative to those standards. Isotope results are reported in per mil (‰) according to the VPDB (Vienna Pee-Dee Belemnite) standard equation:

$$\delta^{13}\text{C}_{\text{org}} (\text{‰}) = \left[ \left( \frac{^{13}\text{C}/^{12}\text{C}}{^{13}\text{C}/^{12}\text{C}} \right)_{\text{sample}} / \left( \frac{^{13}\text{C}/^{12}\text{C}}{^{13}\text{C}/^{12}\text{C}} \right)_{\text{standard}} - 1 \right]$$

All organic carbon percentages were corrected for the pre- analysis digestion of calcium carbonate. Instrument precision is better than 0.1‰. The standard deviation of standards was 0.0129 for chocolate, 0.076 for Merck gel, 0.138 for Nasturtium and 0.052 for sucrose.

The second batch of samples was run twice for carbon analysis to check for precision of the sample preparation. Repeat analyses of samples can vary up to more than 100% (Figure 2.8 sample 20a) showing probable sample identity error , and duplicates can vary up to 20% and reflect inhomogeneity of the small (2 mg) sample size, as well as analytical error

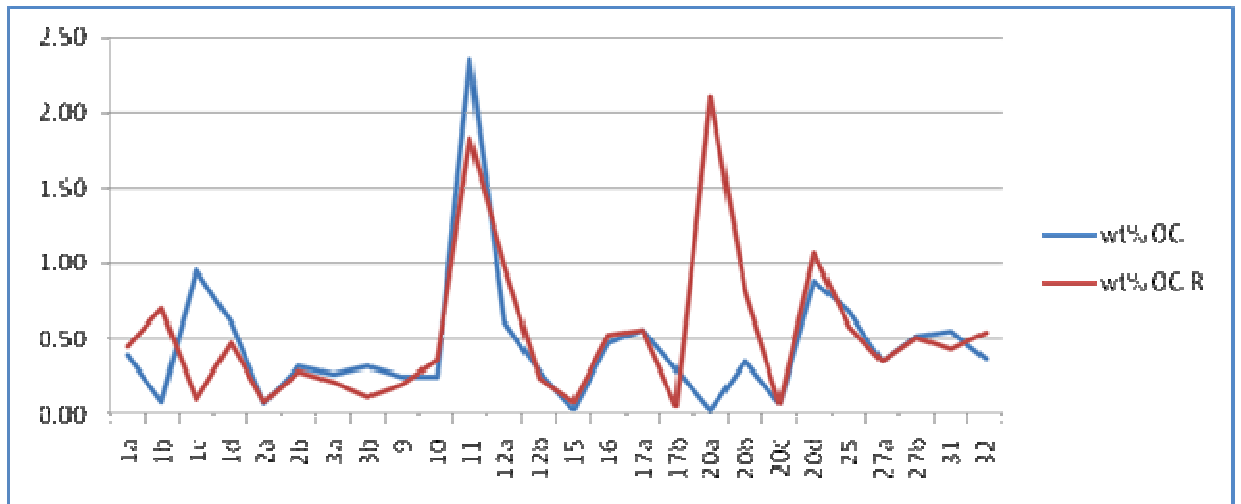


Figure 2.8: Plot of organic carbon content (wt% OC) of samples run in duplicate (%OC R).

University of Cape Town

## **3 Results**

### **3.1 Bed Rock Description**

#### **3.1.1 Adelaide Subgroup (Lower Beaufort)**

The oldest rocks in the study area are those of the Adelaide Subgroup, which stretches from the town of Bloemfontein on the far west to the town of Klipfontein on the eastern side and forming a broad 100 to 150 km wide belt in the Free State interior (Figure 2.1). The Adelaide Subgroup is located west of the Caledon River catchment area between the Tarkastad Subgroup and shales and sandstones of Ecca Group. The Adelaide is described as comprising of grey and reddish –brown mudstones, yellow and grey fine grained sandstones (Johnson *et al.*, 2006) and is locally intruded by extensive Karoo dolerite dykes. The sandstones and mudstones of the Adelaide subgroup consist of equigranular sub to well-rounded quartz grains and minor amounts of feldspar. The mudstone has higher clay mineral content than the sandstone and the predominant clay minerals are smectite and illite. The area where the Adelaide Subgroup is exposed comprises undulating to strongly undulating lowlands and hills covered by grass and to lesser extent shrubs. Low slopes are found on much of the land drained by the Vaal River. Due to low relief the outcrops exposures were poor and no bedrock was sampled. Soil sampling was mainly done on alluvium and river bank deposits of rivers draining only the Adelaide, as indicated from geological maps. The soils of the Adelaide Subgroup are greenish to blue grey sandy soils.

#### **3.1.2 Upper Beaufort Group (Tarkastad Subgroup)**

The Tarkastad Subgroup occurs in a belt from Klipfontein in the west to Wepner in the east widening to the south towards the town of Aliwal North (Figure 2.1). The Tarkastad Subgroup is located in the foothills below the Drakensberg escarpment and lies between the Adelaide Subgroup in the west and bounded by the Molteno Formation towards the

escarpment. Like the Adelaide, the subgroup is intensively intruded by extensive dolerite sheets.

The Tarkastad Subgroup has a greater portion of sandstone and red mudstone when compared to the Adelaide Subgroup (Johnson et al., 2006). The Tarkastad Subgroup is described as comprising fine to medium grained yellow and grey sandstones and maroon (red) to green blue mudstone (Johnson *et al.*, 2006). Like the Adelaide subgroup the Tarkastad Subgroup forms part of the undulating foot hills of the Drakensberg escarpment, however west of Zastron the proportion of the landscape with slopes less than 5% increases significantly and lowlands and hills of moderate relief are found. Alluvium, road cut outcrops and farm soils of the Tarkastad Subgroup were sampled. The Tarkastad Subgroup mainly drains to the Vaal River with a lesser amount draining to the Caledon River. Bedrock consists of quartz feldspar and some rock fragments, the clay minerals are illite and smectite. There are some patches of red soil in the study area, but, although red clay soil forms the integral part the soil pattern of this subgroup, they are probably derived from dolerite dykes and differ from sandier soils developed from sandstone and mudstone of the Tarkastad Subgroup.

### **3.1.3 Molteno Formation**

The Molteno Formation forms a narrow belt between the Tarkastad Subgroup on the west and the Elliot Formation to the east (Figure 2.1). The Molteno Formation decreases in thickness from the south side of the study area to the north. The formation comprises alternating medium to coarse grained sandstones and grey mudstones (Johnson et al., 2006). Sandstones of this formation are now mostly exposed as cliffs in the Drakensberg escarpment and can be easily recognised by their sparkling appearance caused by tiny quartz crystals that bind the sand grains together (Johnson et al., 2006). Intrusive dolerite is common. Sandstone tends to produce a series of terraces in the landscape. Drainage of

Molten Formation is to the Caledon River, but below Aliwal North it drains to the Orange River. The Molteno Formation has good outcrop exposures and was sampled at road cuts. Molteno Formation sandstone are coarser grained compared to Tarkastad Subgroup and has an increased feldspar content (Truswell, 1970). The clay content is relatively low and consists of smectite and illite.

#### **3.1.4 Elliot Formation**

The Elliot Formation comprises an alternating sequence of grey green mudstone and fine to medium grained yellowish grey to pale red sandstone (Johnson et al., 2006). Sampling was carried out on river bank, road cuts and streams mostly draining the Elliot Formation. Areas where the Elliot was sampled (e.g., near the town of Lady Brand) show evidence of intensive erosion. Elliot Formation drainage goes to the Caledon River, mainly on the northern side of the study area. The vegetation is typical grassland. The minor streams draining this formation were found to be reddish in colour and to have a high sediment load.

#### **3.1.5 Clarens Formation**

The Clarens Formation forms a narrow belt between the Elliot Formation and Drakensburg flood basalts and forms part of the Drakensberg Escarpment (Figure 2.1). The Clarens Formation forms prominent hills and ridges. It is composed almost entirely of massive, well sorted, fine grained sandstones consisting of well rounded quartz grains (Truswell, 1970). The sandstones are mostly cream coloured, with occasional pink colours. Rock outcrops have thin soils of high sand content. The thin soils on the Clarens bedrock were mostly collected together with basalt soils in river bank or alluvium of streams draining both of these rock formations, as a result some Clarens samples show a strong basalt influence. The feldspar content is relatively high in the Clarens Formation compared to the Molteno and Elliot formations. The Clarens Formation drains on the northern side of the study area to the Caledon River and on the southern side of the study area to the Orange River.

### 3.1.6 Drakensberg Group Basalt

The Drakensberg Group is the upper most rock unit of the Karoo sequence and comprises a series of stacked basalt lava flows (flood basalt) (Figure 2.1). Within the Free State the Drakensberg occupies a relatively small and steep area on the southern side of the escarpment with elevations approaching 2000 m. Beginning in the north from about the province boundary with Free State and with Lesotho border in the west it runs south east towards Giants Castle where it attains its maximum width. South of the southern Lesotho border the basalt occupies relatively extensive areas of the Barkly East district. The basalt also occupies extensive area of the Lesotho Mountains (Figure 2.1). The area occupied by the Drakensberg basalt is described as comprising high mountains (Kruger, 1983) with high relief and limited areas with slopes less the 5%. The Drakensberg basalt has well exposed outcrops from which bedrock and soil samples were collected. The bedrock composition had plagioclase feldspar and pyroxene while the soils had less feldspar and the clay mineral smectite. Stream density is described as medium to high (Kruger, 1983) with drainage via the head waters of streams and rivers feeding the Caledon River and Orange River.

### 3.2 Grain size distribution

The grain size distribution of soil samples, including farm soils, are similar and contain 40 to 80% sand, 4.9 to 21.9% coarse silt, 6.2 to 42.2% fine silt and 3.8 to 38.8% clay (Table 3.1 ). On average, soils have a high sand content of 53.7%, followed by fine silt (17%), clay (15.9%) and coarse silt (11.4%). The greatest amount of clay is associated with the Elliot Formation soil samples (38%; Table 3.1 sample 1b) and Tarkastad Formation soils (37.5 %; Table 3.1 sample 29). Where soil profile sampling was done the amount of clay is greatest in the middle, subsoil samples (Table 3.1, sample 50b and sample 1b). The river bank deposits and paleoflood deposits are less sandy on average and have more fine silt than the soils, with 48.4% sand, 19.8% coarse silt and 23.8% fine silt and 8.2% clay (Table 3.2). The suspended river sediment samples are predominantly made up of 57% fine silt, 15.3% sand, 18.2% coarse silt and 9.2% clay (Table 3.2). Both soil and suspended river sediments contain less than 30% coarse silt while the paleoflood and the river bank deposits have as high as 42% coarse silt (Tables 3.2).

**Table 3.1: Grain size distribution of soils (wt%). Samples with letters a-c correspond to increasing soil profile depth. River bank deposit samples are designated by the letter d.**

Sample no	Sample description	Sand >63µm	Coarse Silt 38-63µm	Fine Silt 2-38µm	Clay<2µm
35	Basalt (Jdr) top soil	70.7	8.8	12.1	8.4
38a	Jdr top soil	66.6	9.2	16.57	7.56
38b	Jdr chunky bedrock	53.2	9.3	21.09	16.4
42	Jdr top soil	49.2	14.81	24.97	11.04
25	Jdr/ TRc alluvium	33.4	13.6	28.5	24.5
33a	Clarens (TRc) topsoil	63.2	8.51	18.9	9.4
16	TRc/TRe alluvium	39.3	12.8	30.1	17.9
1a	Elliot (TRe) top soil	49.1	17.8	20.2	12.9
1b	TRe sub soil	28.1	10.5	22.6	38.8
1c	TRe chunky bedrock	35.1	18.4	25.4	21.1
1d	TRe river deposit	51.4	23.7	18.9	6
11	TRe Farm soil	75.4	12.1	8.8	3.8
46a	TRe top soil	45.2	5.8	25	24
50a	TRe top soil	62.2	13.3	19.6	4.8
50b	TRe sub soil	45	6	13.8	35.1
50c	TRe chunky bedrock	64.2	4.95	14.4	16.3
44a	TRe top soil	64	13.27	15.27	7.41
49	Molteno (TRm) top soil	75.7	8.3	7.9	8.1
54	TRm top soil	59.4	10	16.3	14.7
9	TRm farm soil	77.5	8.6	8.5	5.4
17a	TRm top soil	58.4	10.9	14.9	15.7
3b	Tarkastad (TRt) alluvium	59	8.6	14.3	18.1
10	TRt top soil	59.1	10.8	14.4	15.7
20a	TRt top soil	51.9	12.3	24.9	10.9
20b	TRt sub soil	42.7	5.7	19.7	31.9
20c	TRt chunky bedrock	24.4	12.2	32.7	30.7
20d	TRt river deposit	60.5	7.7	6.2	25.6
26	TRt chunky bedrock	60.5	11.8	17	10.8
27a	TRt alluvium	52.8	6.3	17.2	23.8
29	TRt alluvium	31.2	8.5	22.5	37.8
59	TRt top soil	70	5.7	13.3	11
55a	TRt top soil	63.4	11	15	10.5
76	Adelaide (Pa) top soil	72.9	10.9	9.9	6.2
58	Pa top soil	63.9	9	14.7	12.4
31	Pa top soil	52.8	18	20.5	8.7
32	Pa alluvium	30.7	21.9	33.9	13.6

**Table 3.2: Grain size distribution of river suspended sediments, river bank (RB) and paleoflood (P) deposits**

Sample no	Source River	Sand >63µm	Coarse Silt 38-63µm	Fine silt-38µm	Clay <2µm
AN1	River sus	13	19	59.9	9
CLDN	River sus	28	23	44	4.6
FSB	River sus	4.9	12.8	67	14.5
Bundi RB	Orange	24.7	42	28.2	5.1
AN1 RB silt	Orange	84.6	10.4	3.8	1.2
AN1 RB mud	Orange	62.4	26.6	9.7	1.3
AN1 RB Clay	Orange	39.4	2.6	48	10.1
Vaal RB	Vaal	37.6	16.7	28.9	16.8
CLDN RB	Caledon	62.4	26.6	9.7	1.3
CLDN RB clay	Caledon	42.9	16.1	22.9	18
CLDNc RBa	Caledon	41	27.7	25	6.3
CLDNc RBb	Caledon	56.8	20.1	16	7
CLDN P	Caledon paleo	20.1	13.4	49.2	17.2
Vaal P	Vaal paleo	49.3	12.1	26.7	11.9
AN1 P	Orange Paleo	59.6	23.3	14.4	2.7

Suspended sediment load calculations were carried out for all the rivers sampled in 2006 and 2007 (Table 3.3). The Orange River had 2.6 g sediment per litre at Aliwal North (AN1), with the river flowing at a speed of 0.5 m/s on the outer banks where sampled. Suspended river sample taken from the river bank at the Free State Border Bridge (FSB) had 3.4 g/l, where the river was flowing at 1 m/s in the middle of the river. Caledon River (CLDN) had 3.0 g/l with the river flowing at 2.6 m/s. Kraai River had 0.22 g/l, while its tributary at Barkly East had 0.05 g/l, but the flow velocity was not measured at this location. Regional rainfall was significantly less in 2007 (179.7 mm) compared to 2006 (548.8 mm) and sediment load measured in 2007 for the Orange River was 0.46 g/l at Aliwal North and 0.52 g/l at the Caledon River N6 overpass and 0.058 g/l at Vioolsdrift 150 km from the Orange River mouth. Vaal River near the town of Douglas sampled in 2007 had a suspended load of 0.02 g/l composed mostly of green algae as opposed to sediment.

**Table 3.3: Suspended sediment load of river samples in dried grams/ litre.**

Suspended Loads		Sample No	Location	2006	2007
Orange River					
	Bundi	Bundi	Vioolsdrift		0.058 g/l
	AN1	AN1	Aliwal North	2.6 g/l	0.46 g/l
	FSB	FSB	Free State border bridge	3.4 g/l	
Caledon River					
	Caledon	CLDN	N6 bridge	3.0 g/l	0.52 g/l
Vaal River					
		Vaal	Douglas		0.02 g/l
Kraai River					
		Kraai B.E	Barkly East	0.05 g/l	
		Kraai N.E	New England	0.22 g/l	

### 3.3 Mineralogy

#### 3.3.1 Petrography

The sandstones of the Beaufort Group are quartz wackes, they are made up of medium grained sub rounded to well rounded equigranular grains (Figure 3.1: Tarkastad). Quartz is the dominant mineral and feldspar minerals are predominantly plagioclase, minor amounts of mica can be seen in the muddy matrix. Some minerals show an indication of weathering and iron oxide- staining is common. Stormberg Subgroup shows a decrease of quartz content and an increase in feldspar and interstitial minerals from the basal Molteno Formation to the Clarens Formation which is in agreement with the findings of Sumner *et al.* (2009). Rock fragments are uncommon and comprise combinations of quartz, feldspar, and mica. Elliot Formation mudstones are intensively red stained with quartz, feldspar and iron oxide as major minerals, they consist of medium to fine grained, sub rounded to well rounded grains (Figure 3.1: Elliot). Clarens Formation sandstone is composed of quartz, feldspar and rock fragments, the grains are angular to sub rounded and are poorly sorted, lithic fragments make up the major component of the rock and quartz is the dominant mineral (Figure 3.1: Clarens). Clarens Formation includes clay and mica minerals as well as calcite cement. The basalt bedrock consists of plagioclase, olivine, orthopyroxene and clinopyroxene. Figure 3.1: Basalt shows only plagioclase and orthopyroxene. Plagioclase is

the major mineral present within the basalts and clinopyroxene is the second most dominant mineral. The crystals exhibit an extensive range of sizes from 0.05 to 4 mm in length (Figure 3.1: Basalt). The majority of the clinopyroxenes appear to be unaltered or only slightly altered. Partial alteration to brown-green clay and/or chlorite along crystal boundaries and within cracks has occurred; there are also some dark minerals which might be opaque or glass in the basalt rock. There is some evidence of weathering and red staining by iron oxide.

University of Cape Town



Figure 3.1: Photomicrographs of petrographic thin sections from the Tarkastad, Elliot, Clarens and Drakensberg Basalt bedrock in the study area. Cross polarised light.

### 3.3.2 Mineralogy (XRD)

XRD analyses performed on the bulk soil samples show that the Karoo sedimentary rocks (Figure 3.2) are predominantly made up of quartz with feldspar as the next most abundant non-clay mineral present in most of the samples, but in minor amounts. Calcite is present in trace amounts in some soils. The bulk sedimentary soils include a poorly developed smectite and illite peak and sometimes an amorphous matter peak (most likely organic matter or iron oxides) on bulk samples (Appendix B). The clay fraction XRD analyses show illite and smectite are prominent peaks while chlorite is not well developed in the Karoo sedimentary rocks (Appendix B). The Drakensberg Group shows well-developed smectite and feldspar peaks but no illite peak (Figure 3.3). Smectite is the dominant mineral in the bulk composition of the basalt rocks, but the peaks for quartz are less developed when compared to the sedimentary rocks. The feldspar peak is in basaltic soils better developed when compared to the sedimentary rocks. The clay size fraction shows more distinctive and better developed smectite peaks and illite peaks are absent (Figure 3.3). Suspended river sediments of the Caledon River (Figure 3. 4) are dominated by quartz and feldspar in bulk samples and smectite dominates over illite in the clay size fraction.

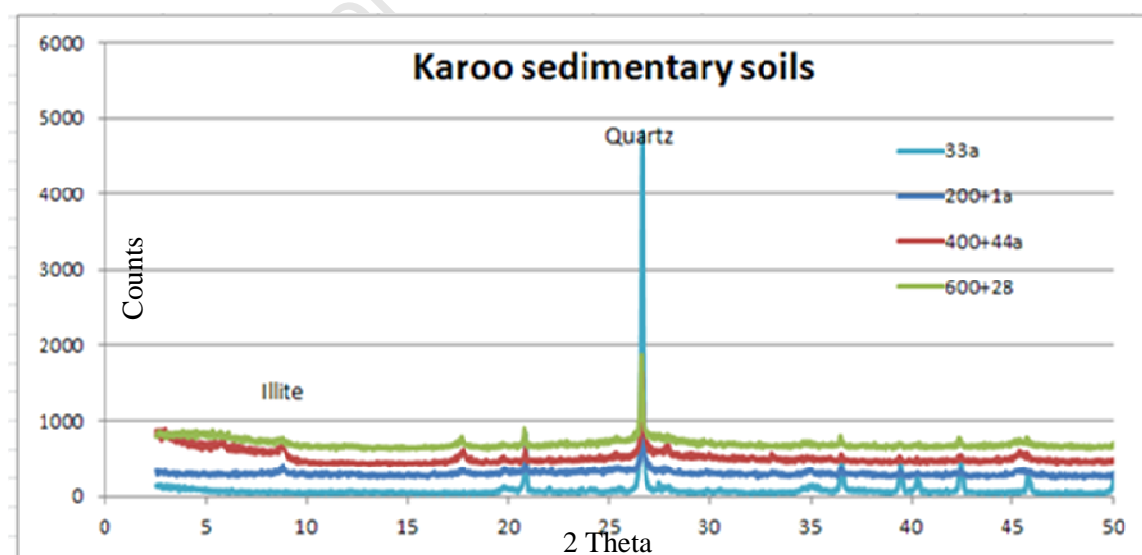


Figure 3.2: XRD scans of the Elliot Formation bulk powdered rock and soil samples

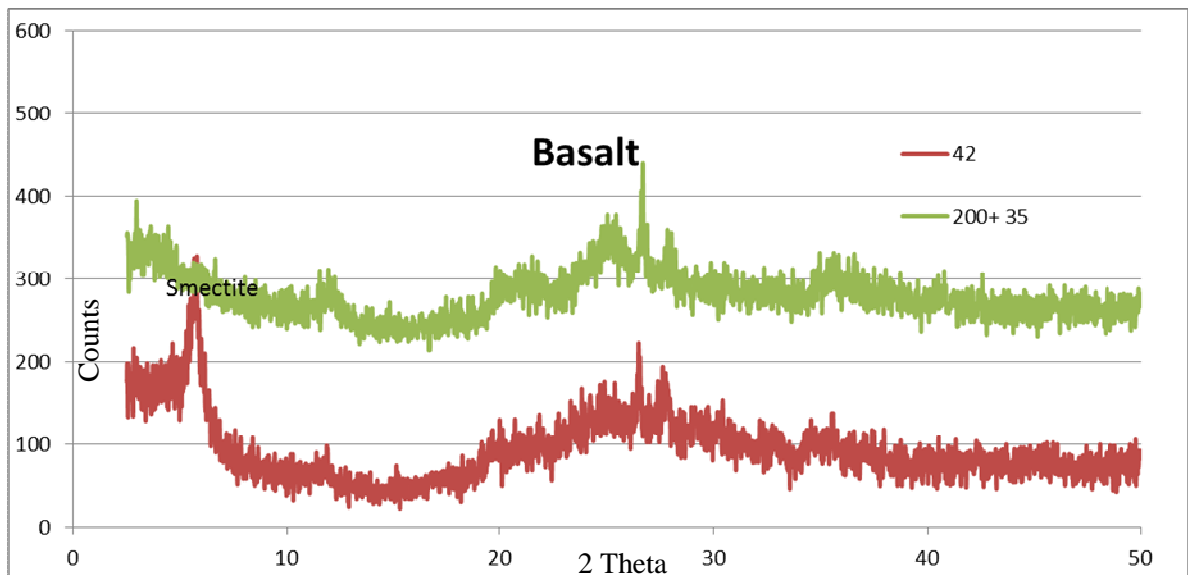


Figure 3.3: XRD scans for the clay fraction of soils overlying basaltic rock from the Drakensberg Formation.

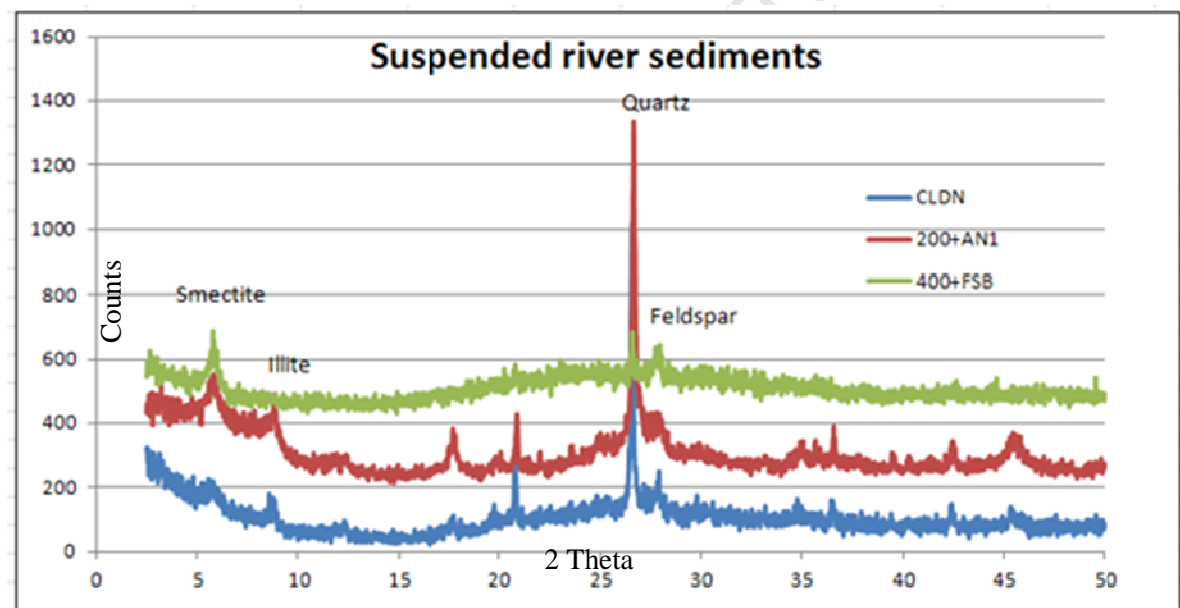


Figure 3.4: XRD scans of the suspended load samples

### 3.4 Geochemistry

#### 3.4.1 XRF elemental composition

Paleoflood deposits and soil samples have high  $\text{SiO}_2$  contents of 55-80% (Table 3.4 and 3.5).

The paleoflood deposits have a similar concentration of major elements  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  to that of sedimentary soil samples. The basaltic soils and river suspended sediments have

lower silica content (45 to 52 wt% SiO<sub>2</sub>; Tables 3.4 and 3.5) than the sedimentary rock soils (58 to 88 wt% SiO<sub>2</sub>). The silica content increases with depth in sedimentary rock soil profile samples (Samples 50, 1 and 20). The silica content of the river suspended sediment samples is slightly higher than in the basaltic soils. Aluminium concentration is higher than in both the river suspended sediments and the basaltic soils, with samples 63 and 27b having the highest values. The total iron content of the river suspended sediment samples is similar to the sedimentary rock soils, and lower than the basaltic rock soils. The river bank deposits and paleoflood deposits show similar amount of iron content to the river suspended sediments (Table 3.5). Caledon River bank deposits show a relatively higher iron content when compared to the other rivers in the study area (Table 3.5).

The concentration of manganese and phosphorus is relatively low and does not change much in basaltic, sedimentary and river suspended sediment samples. Titanium and sodium values are high in basaltic rocks and moderately high in the river suspended sediments while low in sedimentary rocks. Potassium is higher in sedimentary rocks and the Caledon River suspended sediment load while relatively low in the Orange River suspended sediment load and in basaltic soils. Magnesium and calcium oxides are higher in basaltic soils and are relatively high in the river suspended sediment load and they decrease down the soil profile (Table 3.4). The calcium and magnesium oxide contents of the sedimentary soils are low.

The trace element analysis shows that the abundance of Zn, Cu, Ni and, to a lesser extent, Cr and V is greater in basaltic soils than in the sedimentary rock soils (Table 3.4). There is more Zr and Ba in the sedimentary soils compared to the basaltic soils. The river suspended sediments fall in-between the sedimentary and the basaltic soils, but are more similar to the sedimentary than basaltic soils. The basalts are Rb deficient (Table 3.4) in relation to the

sedimentary rocks, with the Caledon River having higher values when compared to Orange River suspended sediment.

**Table 3.4: Major (wt%) and trace (ppm) element composition of soil samples taken from the surface and from soil profiles.**

Bed rock Sample	Clarens 25	Clarens 15	Clarens 2a	Clarens 2b	Elliot Clarens 16	Elliot 11	Elliot 1b	Elliot 1c	Elliot 1d
SiO2	62.4	79.3	79.4	84.5	76.3	85.8	63.6	72.1	79.0
TiO2	1.0	0.5	0.4	0.6	0.7	0.5	0.7	0.6	0.5
Al2O3	14.6	9.3	9.9	6.5	11.0	3.2	15.9	11.0	7.8
Fe2O3	8.1	1.7	1.8	1.9	3.0	1.7	5.6	4.4	1.7
MnO	0.0	0.0	0.0	0.1	0.1	0.0	0.1	2.7	0.1
MgO	0.9	0.8	0.7	0.5	0.7	0.3	1.4	0.8	0.6
CaO	1.1	0.6	0.4	0.4	0.5	0.5	1.1	0.6	1.4
Na2O	0.4	1.9	2.0	0.7	0.9	0.1	0.8	1.3	1.4
K2O	1.2	2.5	2.6	1.6	2.2	0.9	2.9	2.5	2.1
P2O5	0.1	0.1	0.0	0.1	0.0	0.3	0.0	0.2	0.1
SO3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Cr2O3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O-	1.9	1.7	0.6	0.1	0.3	0.2	0.9	0.2	0.2
LOI	7.8	1.7	1.5	2.9	4.3	6.5	6.9	3.6	4.8
Total	99.6	100.2	99.3	99.8	100.1	100.0	100.1	99.9	99.5
Bed rock sample no	Clarens 25	Clarens 15	Clarens 2a	Clarens 2b	Elliot Clarens 16	Elliot 11	Elliot 1b	Elliot 1c	Elliot 1d
Mo	<1	<1	<1	<1	<1	<1	<1	17	<1
Nb	41	31	25	27	36	29	39	34	28
Zr	597	1314	676	1026	938	1116	494	614	962
Y	69	78	43	48	72	49	79	65	47
Sr	188	350	387	153	269	139	293	393	315
U	<4	<4	<4	<4	<4	<4	<4	<4	<4
Th	16	19	8	20	26	25	34	21	15
Rb	139	230	221	162	290	149	404	281	202
Pb	36	61	44	37	55	45	50	48	48
Zn	101	28	37	34	53	66	131	54	32
Cu	66	10	8	11	15	18	29	16	11
Ni	50	4	7	5	12	6	19	22	7
Co	23	<2	<2	6	9	4	15	46	5
Mn	208	108	264	367	457	312	753	321	430
Cr	274	22	27	44	52	61	80	43	37
V	269	28	30	41	61	44	80	65	36
S	73	284	730	200	149	1118	59	187	366

**Table 3.4: Continued**

Bedrock Sample	Molteno 17a	Molteno 17b	Molteno 17c	Molteno 9	Tarkastad 20a	Tarkastad 20b	Tarkastad 20c	Tarkastad 20d	Tarkastad 3a	Tarkastad 27a	Tarkastad 27b	Adelaide 31	Adelaide 32
SiO2	79.3	69.7	70.8	89.1	69.8	83.4	70.5	74.4	86.8	81.8	63.7	75.6	71.0
TiO2	0.6	0.8	0.8	0.5	0.7	0.5	0.7	0.7	0.5	0.6	0.6	0.8	0.7
Al2O3	8.7	12.9	13.4	3.3	10.1	7.5	12.4	10.5	5.8	7.3	17.7	9.5	12.2
Fe2O3	3.4	4.2	2.5	2.3	4.4	2.6	4.9	3.9	1.2	2.9	6.6	4.0	4.4
MnO	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
MgO	0.8	0.9	0.9	0.4	1.4	0.5	1.8	0.8	0.3	0.6	0.8	0.9	1.0
CaO	0.5	0.3	0.3	0.3	1.5	0.3	2.0	0.6	0.2	0.5	0.3	1.1	1.4
Na2O	0.6	1.1	0.9	0.4	0.8	0.1	0.7	0.6	0.3	0.5	0.2	0.9	1.4
K2O	1.9	2.6	2.7	0.9	1.6	1.3	1.8	1.8	1.2	1.1	2.2	1.5	1.9
P2O5	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1
SO3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cr2O3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O-	0.1	4.7	4.6	0.1	0.2	0.8	0.9	1.0	0.8	0.7	0.2	1.0	0.7
LOI	3.3	2.9	3.1	2.1	8.9	2.7	4.5	5.6	2.7	3.6	7.7	4.5	4.6
Total	99.4	100.1	100.2	99.4	99.6	99.7	100.2	100.0	99.9	99.8	100.1	99.9	99.5
Bedrock sampe no	Molteno 17a	Molteno 17b	Molteno 17c	Molteno 9	Tarkastad 20a	Tarkastad 20b	Tarkastad 20c	Tarkastad 20d	Tarkastad 3a	Tarkastad 27a	Tarkastad 27b	Adelaide 31	Adelaide 32
Mo	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Nb	31	47	48	27	44	35	35	39	26	31	33	35	37
Zr	1361	871	1004	1579	579	939	723	959	1380	966	695	1016	820
Y	58	105	133	33	93	64	75	75	34	58	65	61	72
Sr	187	223	223	86	414	245	251	236	119	159	144	243	345
U	<4	<4	4	<4	<4	<4	<4	9	<4	<4	<4	<4	<4
Th	24	43	42	12	45	23	27	30	10	20	34	23	21
Rb	210	416	457	94	286	187	246	250	96	157	363	184	239
Pb	66	69	56	45	77	54	52	59	35	45	53	50	44
Zn	52	83	87	28	134	77	82	66	29	50	87	66	78
Cu	18	14	16	10	10	39	34	21	9	17	21	27	30
Ni	18	13	14	6	13	32	29	18	8	13	28	21	21
Co	15	12	11	3	12	15	17	13	<2	9	20	11	14
Mn	608	311	324	181	358	821	563	624	137	376	560	654	533
Cr	77	45	52	61	51	108	106	74	34	75	98	108	87
V	76	65	70	53	81	85	96	78	32	66	123	92	82
S	90	35	23	174	8	538	90	279	69	171	139	152	97

**Table 3.4: Continued**

<b>Bedrock Sample</b>	<b>Basalt 38a</b>	<b>Basalt 38b</b>	<b>Basalt 36</b>	<b>Basalt 42</b>	<b>Elliot 33</b>	<b>Elliot 44a</b>	<b>Elliot 46a</b>	<b>Elliot 50a</b>	<b>Elliot 50b</b>	<b>Elliot 50c</b>	<b>Malteno 54</b>	<b>Malteno 49</b>	<b>Malteno 58</b>	<b>Tarkastad 55a</b>	<b>Tarkastad 76</b>
SiO2	45.4	50.9	51.6	49.6	77.7	75.9	59.9	55.9	73.5	79.3	76.5	78.9	72.7	74.1	78.9
TiO2	1.1	1.4	1.8	1.1	0.5	0.5	0.4	1.0	0.6	0.5	0.6	0.6	0.6	0.7	0.7
Al2O3	14.0	13.5	13.9	13.5	9.9	8.0	16.8	13.4	10.0	7.6	8.6	8.0	8.9	9.6	7.9
Fe2O3	10.9	10.2	12.6	10.7	3.6	2.2	5.8	9.4	4.3	3.2	3.7	3.4	3.2	4.2	2.5
MnO	0.2	0.2	0.2	0.2	0.0	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MgO	6.1	3.4	4.7	6.2	0.8	0.9	2.0	4.3	1.1	0.7	1.1	1.5	1.3	1.2	0.9
CaO	7.0	3.8	5.6	7.5	0.3	2.9	1.1	5.5	1.9	0.9	1.2	1.9	2.5	1.0	1.5
Na2O	2.0	1.8	2.3	2.1	0.7	1.7	0.5	2.3	0.8	0.8	1.3	1.7	1.9	1.6	1.9
K2O	0.9	1.2	0.9	0.8	1.6	2.0	1.5	1.1	1.6	1.4	1.3	1.5	2.2	1.5	1.9
P2O5	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
SO3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Cr2O3	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O-	3.2	4.1	1.7	2.6	2.3	1.0	3.0	2.6	1.9	1.3	1.8	1.0	1.4	1.8	0.9
LOI	9.5	9.9	4.7	6.4	2.6	4.6	8.6	4.7	4.8	3.6	2.8	2.3	5.8	4.2	2.7
Total	100.6	100.4	100.1	100.8	100.1	99.8	99.8	100.4	100.6	99.4	99.1	100.9	100.8	100.2	100.0

<b>Bedrock Sample</b>	<b>Basalt 38a</b>	<b>Basalt 38b</b>	<b>Basalt 36</b>	<b>Basalt 42</b>	<b>Elliot 33</b>	<b>Elliot 44a</b>	<b>Elliot 46a</b>	<b>Elliot 50a</b>	<b>Elliot 50b</b>	<b>Elliot 50c</b>	<b>Malteno 54</b>	<b>Malteno 49</b>	<b>Malteno 58</b>	<b>Tarkastad 55a</b>	<b>Tarkastad 76</b>
Nb	9	12	12	7	8	9	14	9	9	9	8	9	9	11	8
Zr	86	164	186	114	333	376	138	163	282	362	289	321	248	330	300
Y	17	17	17	16	19	22	37	18	22	23	20	17	19	22	16
Sr	121	101	107	130	33	80	42	127	60	39	77	74	162	70	136
Rb	12	21	16	14	46	50	56	23	53	45	39	36	53	43	45
Pb	<5	<5	<5	<5	6	7	21	<5	<5	7	5	<5	9	5	<5
Zn	153	92	81	96	35	30	73	86	48	30	42	28	39	44	20
Cu	106	87	84	86	32	25	34	83	40	34	38	34	32	39	27
Ni	123	130	97	116	57	48	51	109	59	59	58	62	54	64	51
Co	40	41	44	45	9	7	10	38	11	15	14	12	10	14	8
Mn	1235	1220	1603	1258	196	1199	559	1205	329	631	648	456	447	665	347
Cr	299	365	330	379	99	66	76	265	110	99	118	134	103	118	99
V	224	246	364	273	74	44	57	203	82	65	81	80	72	87	54
Ba	234	323	281	236	358	440	624	336	330	399	367	346	525	417	481
Sc	33	34	42	38	10	7	11	37	13	9	11	10	9	12	8
S	554	452	350	298	454	233	164	73	103	142	177	115	718	282	645

**Table 3.5: Major (wt%) and trace (ppm) element composition of river suspended load, river bank (RB) and paleoflood (P) deposits (nm = not measured).**

Sample name	Orange	Orange	Orange	Orange	Orange	Caledon	Caledon	Caledon	Caledon	Caledon	Vaal	Vaal	Susp Sed	Susp Sed	Susp Sed
	AN1 P	AN1RB clay	AN1 RB silt	AN1 RB mud	Bundi	CLDN RB	CLDN RB clay	CLDN P	CLDNc RBa	CLDNc RBb	Vaal P	Vaal RB	FSB	AN1	CLDN
SiO2	70.0	75.2	62.0	66.4	62.5	59.4	56.9	67.9	71.3	66.1	72.3	78.7	62.47	65.64	62.47
TiO2	0.8	0.7	0.6	0.7	0.8	0.8	1.1	0.7	0.7	0.8	0.7	0.5	0.78	0.80	0.97
Al2O3	11.3	9.8	10.5	14.5	13.5	13.2	11.1	12.1	11.1	11.8	9.6	8.3	13.58	13.10	16.32
Fe2O3	4.4	3.3	5.2	5.1	5.6	7.5	9.6	4.8	4.7	6.5	4.5	2.4	6.14	5.51	5.80
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.12	0.11	0.12
MgO	1.2	1.0	2.4	1.3	1.9	4.1	5.3	2.1	1.6	2.3	2.5	1.2	3.03	2.45	1.60
CaO	1.0	0.9	3.7	0.5	1.9	5.1	5.1	2.8	1.8	3.4	3.0	1.5	3.68	2.78	0.99
Na2O	1.0	1.2	1.1	0.9	1.2	1.8	1.1	1.7	1.0	1.3	1.4	1.5	1.35	1.25	0.51
K2O	2.2	2.1	1.9	3.5	2.2	1.2	1.0	1.9	1.7	1.3	1.4	2.2	1.11	1.34	2.21
P2O5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.10	0.09	0.09
SO3	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	nm	nm	nm
Cr2O3	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.05	0.04	0.05
H2O-	2.5	1.8	3.5	1.1	2.8	2.2	2.3	1.7	0.8	0.9	1.0	0.9	nm	nm	nm
LOI	5.3	4.2	8.8	5.3	7.4	4.6	6.1	3.8	5.2	4.3	3.2	2.1	10.51	7.02	8.96
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.01	0.01
Total	100.1	100.3	100.4	99.5	99.8	100.3	99.9	99.7	100.2	99.2	99.8	99.6	99.98	100.13	100.09

Sample name	AN1 P	AN1RB clay	AN1 RB silt	AN1 RB mud	Bundi	CLDN RB	CLDN RB clay	CLDN P	CLDNc RBa	CLDNc RBb	Vaal P	Vaal RB	FSB	AN1C	CLDN
Mo	6	2	<1.1	2	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	2	2			
Nb	15	13	11	15	15	10	11	12	30.0	26.9	11	10	1.0	3.0	8.0
Zr	1082	570	225	333	225	198	136	269	916.4	787.4	418	400	183.0	232.0	203.0
Y	63	40	22	23	30	24	27	28	58.6	48.0	30	27	28.0	28.0	33.0
Sr	87	86	127	80	108	170	107	155	297.5	362.3	117	104	133.0	120.0	88.0
U	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	<3.6	31.0	38.0	80.0
Th	19	12	8	17	13	5	5	8	13.1	8.2	9	7	nm	nm	nm
Rb	92	72	71	149	89	36	35	68	170.5	114.2	42	58	nm	nm	nm
Pb	16	15	12	26	15	7	9	11	42.5	27.5	9	9	4.0	57.0	20.0
Ba	468	433	377	750	414	291	330	403	nm	nm	316	407	279.0	268.0	473.0
Sc	16	13	17	15	19	27	33	16	nm	nm	17	10	NM	NM	NM
Co	12	11	19	12	17	29	37	17	18.2	26.6	47	8	32.0	28.0	28.0
Mn	420	450	907	758	835	1068	1471	563	634.6	762.9	685	304	NM	NM	NM
Cr	145	113	137	74	124	228	278	140	141.8	231.9	388	123	125.0	114.0	101.0
V	89	70	94	82	105	177	215	90	104.4	152.4	88	51	106.0	90.0	84.0
Zn	76	63	88	100	89	83	103	76	63.74	74.83	58	39	57.0	58.0	71.0
Cu	30	27	43	18	51	54	76	36	40.16	37.52	34	18	11.0	10.0	11.0
Ni	64	62	82	53	74	87	101	69	31.20	45.05	71	56	77.0	67.0	64.0
S	135	143	1257	130	192	146	225	127	256.2	124.1	118	56	S	NM	NM

### 3.4.2 Percent carbonate, and organic carbon content and isotope composition ( $\delta^{13}\text{C}$ )

The calcium carbonate content of the soils ranges from 0.1 to 13.9 wt% and the organic carbon content ranges from 0.08 to 2.6 wt% (Table 3.6). The percentage of organic carbon is relatively high in basaltic soils (1.2-2.6 wt %) compared to the Beaufort and Stormberg groups sedimentary rock soils (0.2-2.1 wt %), with the Tarkastad Formation having the highest organic carbon content of 2.1 wt%. The average total organic carbon content decreases with soil depth (Sample 20a-c). The river suspended sediments total organic carbon content is similar to the sedimentary bedrock soils, ranging from 0.9-1.3 wt%. Calcium carbonate content and organic carbon content of river bank and paleoflood deposits are similar to that of Karoo sedimentary rocks. There is significant variation in calcium carbonate concentration within the Karoo sedimentary rock soils, basaltic soils and suspended river sediments. The Caledon River has the highest calcium carbonate content of 13.9 wt% followed by basaltic soils which range from 5.5-10.5 wt% while the Clarens Formation has the lowest calcium carbonate content of 0.05 wt%. The paleoflood deposit of the Vaal River (Vaal P) has the highest calcium carbonate content of 11.1 wt% when compared to the other river bank and paleoflood deposits (Table 3.7). The  $\delta^{13}\text{C}$  values of the organic carbon in the soil samples within soils overlying the Tarkastad Formation show a wide variation and range from -26.3 to -10.7‰ PDB. The river bank and paleoflood deposits show relatively less variability in  $\delta^{13}\text{C}$  with values from -14.9 to -23.07‰ PDB. The River suspended sediment  $\delta^{13}\text{C}$  values range from -19.7 to -16.9‰ PDB (Table 3.7).

**Table 3.6: Calcium carbonate and organic carbon content (wt%) and carbon isotope composition of organic matter from soils and weathered bedrock (D=duplicate OC and  $\delta^{13}\text{C}$  sample)**

Sample no	Bedrock	CaCO <sub>3</sub> (wt%)	OC (wt%)	$\delta^{13}\text{C}$ (PBD)
38a	Basalt top soil	10.49	2.39	-18.4
38a (D)	Basalt top soil	10.49	2.63	-18.51
38b	Basalt subsoil?	8.25	2.26	-12.66
36	Basalt top soil	5.5	1.9	-13.31
42	Basalt top soil	9.47	1.22	-16.15
25	Basalt top soil	4.71	0.58	-18.74
2a	Clarens top soil	0.05	0.28	-19.79
2b	Clarens bed rock	0.35	0.08	-25.3
15	Clarens top soil	3.71	0.08	-24.59
33a	Clarens top soil	2.94	0.72	-15.25
33a (D)	Clarens Top soil	2.94	0.71	-14.9
16	Elliot and Clarens top soil	1.85	0.52	-16.22
1a	Elliot top soil	0.60	0.45	-18.61
1b	Elliot subsoil	2.65	0.70	-16.46
1c	Elliot bed rock	0.10	0.10	-23.22
1d	Elliot RB deposit	4.61	0.48	-22.33
11	Elliot farm soil	1.70	1.83	-19.94
44a	Elliot top soil	7.09	0.59	-21.45
44a (D)	Elliot top soil	7.09	0.61	-21.41
46a	Elliot top soil	4.72	0.87	-12.98
50a	Elliot top soil	7.5	0.26	-16.17
50b	Elliot sub soil	6.07	0.23	-17.81
50c	Elliot bed rock	3.92	0.41	-15.1

**Table 3.6: Continued**

Sample no	Bedrock	CaCO <sub>3</sub> (wt%)	OC (wt%)	δ <sup>13</sup> C(PBD)
58	Molteno top soil	6.16	1.48	-17.53
49	Molteno top soil	3.49	0.32	-18.38
54	Molteno top soil	3.82	0.49	-15.04
9	Molteno farm soil	0.35	0.20	-19.6
17a	Molteno top soil	2.64	0.56	-19.72
17c	Molteno bedrock	8.30	0.06	-25.4
3a	Tarkastad top soil	3.05	0.21	-18.72
3b	Tarkastad RB deposit	3.45	0.12	-18.86
20a	Tarkastad top soil	6.31	2.11	-21.28
20b	Tarkastad sub soil	3.80	0.82	-16.3
20c	Tarkastad bed rock	1.30	0.07	-26.03
20d	Tarkastad RB deposit	2.15	1.07	-19.69
10	Tarkastad top soil	2.00	0.35	-15.75
27a	Tarkastad alluvium	3.64	0.35	-16.3
27b	Tarkastad top soil	1.65	0.51	-14.22
71	Tarkastad top soil	0.55	0.86	-10.64
55a	Tarkastad top soil	4.74	0.82	-14.26
55a (D)	Tarkastad top soil	4.74	0.86	-14.63
76	Adelaide top soil	3.23	0.42	-19.89
76	Adelaide top soil	3.23	0.37	-19.8
31	Adelaide top soil	2.60	0.43	-14.12
32	Adelaide top soil	3.70	0.54	-14.87

**Table 3.7: Calcium carbonate and organic carbon content (wt%) and carbon isotope composition of organic matter of river suspended sediments, river bank and paleoflood deposits(D=duplicate OC and δ<sup>13</sup>C sample).**

Sample no	Source River	CaCO <sub>3</sub> (wt%)	OC (wt%)	δ <sup>13</sup> C (PBD)
CLDN P	Caledon N6	1.35	0.15	-18.88
CLDN RB	Caledon N6	1.40	0.50	-19.88
CLDN RB Clay	Caledon N6	1.85	0.64	-22.94
CLDNc RBa	Caledon Clocolan	1.20	0.98	-18.59
CLDNc RBb	Caledon Clocolan	3.45	0.24	-14.97
AN1 P	Orange Aliwal north	1.30	0.37	-17.03
AN1 RB Clay	Orange Aliwal north	2.90	1.14	-23.07
AN1 RB Silt	Orange Aliwal north	1.50	0.36	-21.69
AN1 RB Mud	Orange Aliwal north	2.95	0.76	-18.42
Vaal P	Vaal	11.11	0.46	-20.96
AN1	Orange Aliwal north	7.82	1.19	-19.47
AN1 (D)	Orange Aliwal north	7.82	1.01	-19.74
CLDN	Caledon N6	13.91	0.86	-16.88
CLDN (D)	Caledon N6	13.91	1.04	-17.05
FSB	Orange Border	7.55	1.25	-18.57
FSB (D)	Orange Border	7.55	1.15	-19.15

## 4 Discussion

### 4.1 Bedrock and soils in the catchment area

The suspended load of rivers in the study area may be derived from the erosion of soil sediments or from the erosion of bedrock in the catchment area. One of the objectives of this study is to try and distinguish the relative importance of these two sediment load sources. Chemical weathering of bedrock commonly results in changes in mineralogy and elemental composition of overlying soils and it is these differences which are outlined here. It is then argued what these differences imply in terms of the source of sediment to the river suspended load. Soils in the catchment area vary in composition due to physical and chemical weathering of the different types of bedrock in the catchment. The chemistry of the soils is expected to be closely related to that of the bedrock from which the soils are derived and can be used to trace the source of sediment carried by rivers.

There is a relative decrease in quartz content from the Beaufort Group to the Clarens Formation accompanied by an increase in feldspar. The Elliot Formation shows a relatively higher clay content in its mudstone composition compared to the other Karoo sedimentary formations. The texture varies from angular, poorly sorted and coarse-grained sandstone of the Clarens Formation to a well rounded and well-sorted mudstone of the Adelaide and Elliot formations. The textural variation assists in understanding the evolution of the rock formations; the Adelaide and Elliot formations are texturally mature and distal in origin while the Clarens Formation is immature and proximal in origin (Turner, 1985). According to Sumner *et al.* (2009) the Clarens Formation is harder and more resistant to weathering and subsequent erosion than the siltstone and mudstone of the Elliot Formation; this difference was also evident during field sampling.

The minerals of the Karoo sedimentary rocks consist of quartz, feldspar, minor calcite and variable amounts of mica and organic matter, which corresponds to the petrographic work done by Beukes (1970) and Eriksson (1981) stating that sandstones consist of 35-90% quartz, 20% feldspar and 10-60% matrix. The matrix normally consists of silica and calcite cement. Feldspars and mica in the Karoo sedimentary rocks are altered to clay minerals illite and smectite during chemical weathering. The mudstones have a similar mineralogy to the sandstones but tend to have more clay minerals.

The XRD analysis shows that the clay size (<2  $\mu\text{m}$ ) fraction of Karoo Supergroup sedimentary bedrock soils is made up of quartz, feldspar, illite and some smectite, but in areas where profile sampling has been conducted, smectite is absent in deeper soils. This may reflect the in place weathering of illite to smectite as well as allochthonous smectite eroded from basaltic soils and deposited on Karoo sedimentary soils. The presence of illite throughout the profile indicates that illite is derived from the weathering of the bedrock

The basalt bed rock samples are dominated by plagioclase, orthopyroxene, olivine and clinopyroxene and these minerals are largely altered to clay minerals such as smectite during chemical weathering (Best and Christiansen, 2001). From the work cited by Sumner *et al.* (2009) it was found that the main cause of basalt deterioration is the expansion of swelling clays and the volume changes in the clay minerals that occurs as soon as they are exposed to moisture changes. Smectite was the only mineral identified in the clay fraction XRD analysis of basaltic soils while illite peaks were absent. Smectite (montmorillonite) clay minerals are derived from the alteration of olivine and plagioclase and they are present as interstitial secondary minerals in all the basalt samples examined (Sumner *et al.*, 2009).

Soils derived from basalt bedrock have low  $\text{SiO}_2$  contents with bulk samples having an averaging of 45 wt%  $\text{SiO}_2$  reflecting the low  $\text{SiO}_2$  content of minerals making up basalt bedrock. Soils derived from Karoo sedimentary rocks have a high  $\text{SiO}_2$  content (65 wt%) compared to basalt. The average  $\text{Al}_2\text{O}_3$  content of Karoo sedimentary rocks of 9.7wt% (ranging from 3.2 and 15.9 wt%) is lower than basaltic soils which have an average  $\text{Al}_2\text{O}_3$  content of 13 wt%. The high concentration of aluminium and iron in basaltic soils is due to the presence of minerals with high iron content such as pyroxenes and olivine and high aluminium minerals like plagioclase feldspar. High concentrations of CaO and MgO in basalt soils are derived from plagioclase and clinopyroxene while low concentrations of these elements in sedimentary soils are due to low concentration of these Ca and Mg bearing minerals. Soil samples collected from the farms located on Karoo sedimentary bedrock are sandy and consist of >85% quartz ( $\text{SiO}_2$ ) sand. The concentration of quartz sand may have resulted from the preferential erosion of finer material by wind and runoff during irrigation and rainfall events. The  $\text{Al}_2\text{O}_3$  content of the farm soils is low and likely reflects the loss of fine grained Al-rich clay minerals from the soil.

$\text{Na}_2\text{O}$  and  $\text{TiO}_2$  concentrations are relatively high in basaltic soils compared to Karoo sedimentary soils due to the presence of plagioclase. Clarens Formation soils have a relatively high  $\text{Na}_2\text{O}$  content compared to the other Karoo sedimentary soils which reflects the increase in feldspar in the sandstone composition and maybe to a lesser extent the mixture of sandstone and basalt derived soils in stream alluvium.  $\text{K}_2\text{O}$  and Rb are high in Karoo sedimentary soils from the presence of illite, mica and K-feldspar minerals. There is a high concentration of Zr, Ba, and Rb in Karoo sedimentary rocks from mica and K-feldspar minerals, which are compatible to host those trace elements. High Zn, Cu, Ni, Cr, and V concentrations in basalt bed rock samples reflect the compatibility of basalt minerals for these elements (Best and Christiansen, 2001). Ba shows dilution caused by input from

basaltic soils since basalt does not have any minerals compatible to host Ba (samples from the second trip were not analyzed for Ba). Both the basalt and the sedimentary soils do not have minerals compatible to host V. Therefore, V could be from accessory minerals found in both the soils, for example, vanadium-bearing magnetite.

To further differentiate the basalt sourced soils from Karoo sedimentary sourced soils element ratios can be used because the suspended load generally provides an integrated, homogeneous sampling of the eroded catchment bedrock and soil. The major oxide ratio  $(Mg+Na)/K$  is high (mean value of 7.9) for the basalt soil end member whereas the Karoo sedimentary rock soil end member has a low mean value of 1.4 (Figures 4.1 and 4.2). The trace element ratio  $(Rb+Ba)/(Ni + Cr + V)$  also discriminates between basalt (mean of 0.4) and Karoo sedimentary rock soils (mean of 2.0) (Figure 4.2). The major oxide ratio shows more variability in basalt than in Karoo sedimentary rock soils and vice versa in the case of the trace element ratio (Figure 4.2). Major oxide ratio of the Karoo sedimentary rocks is below 2.5, except sample 50a. Both major and trace element ratios show that sample 50a has a more basalt signature compared to the other Karoo sedimentary rock soils. Sample 50a was collected close to a dolerite dyke and the topsoil composition might have been influenced by the dolerite dyke.

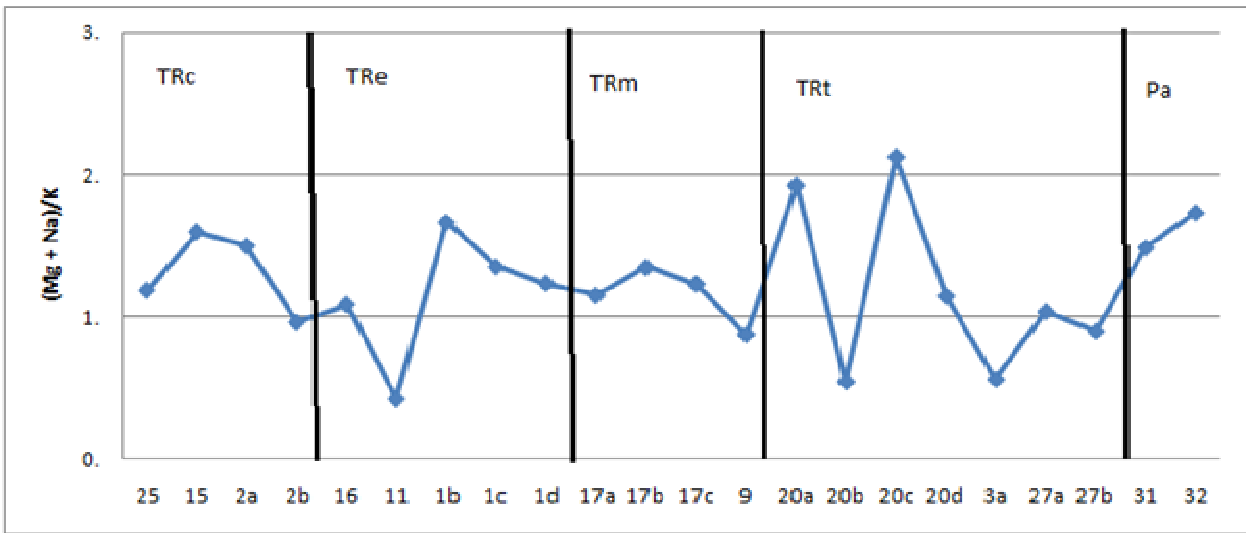


Figure 4.1: Ratio of major elements (Mg+Na)/K determined by XRF for bulk soil samples collected in August 2009.

University of Cape Town

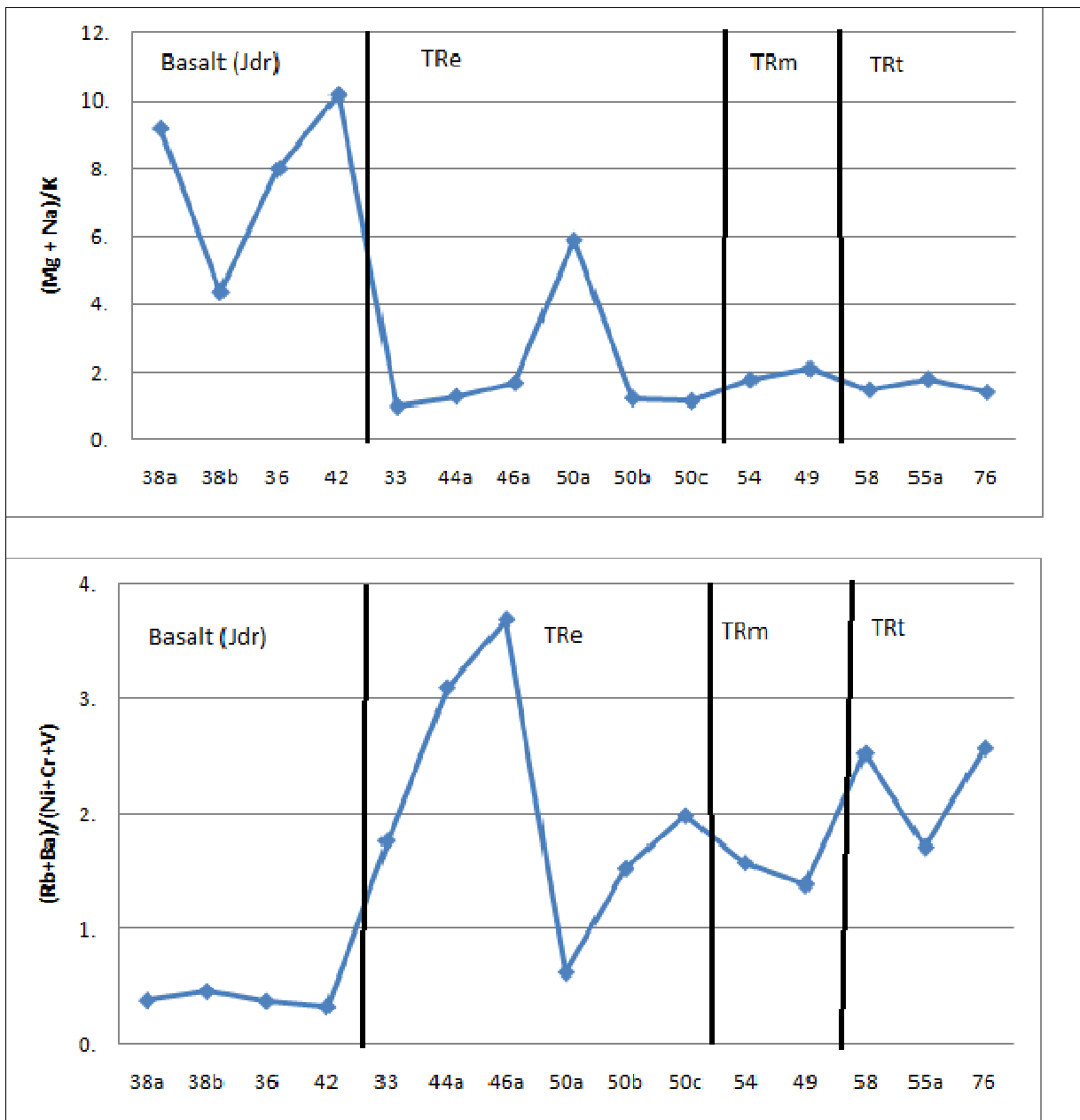


Figure 4.2: Ratio of major elements  $(Mg+Na)/K$  and trace elements  $(Rb + Ba)/(Ni + Cr + V)$  determined by XRF for bulk soil samples collected in February 2006.

## 4.2 Source of the river suspended load, riverbank deposits and paleoflood deposits

### 4.2.1 River suspended sediments

In addition to suspended sediment samples collected from rivers, the modern river bank and older, more elevated paleoflood river bank deposits were sampled. Riverbank and paleoflood deposits provide an abundant source of previous suspended sediment loads, especially for rivers such as the Vaal that currently have low suspended sediment loads. The

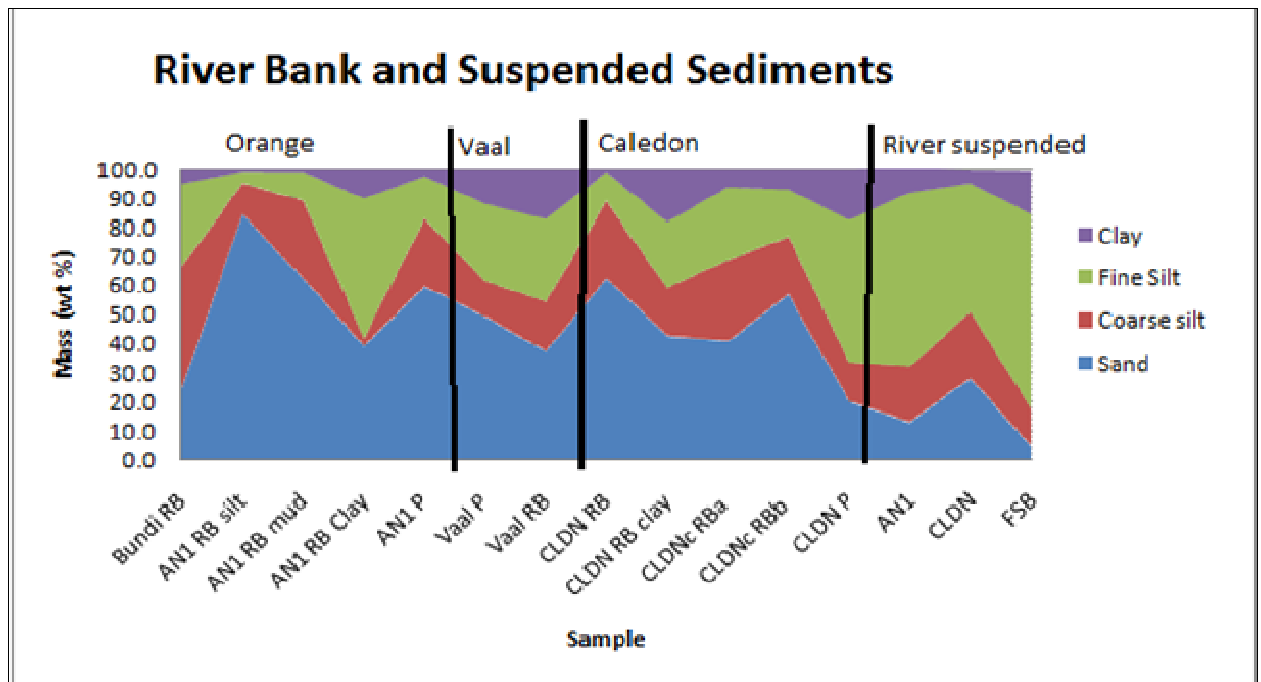
comparison of suspended sediment, riverbank and paleoflood deposits provide data on how the sediment load composition and geochemistry has varied over time.

The sediment suspended loads of rivers vary in composition due to source-rock diversity in the catchment areas, physical and chemical weathering properties of these source rocks and the transport pathways within the fluvial system (Johnson et al., 1996). Geology, mineralogy and chemical composition of the source rocks and their soils as discussed above in comparison to the composition of the suspended sediments in the rivers should be able to give some clues as to source of suspended sediments of the upper Orange River. In this section, the mineralogy and chemical composition of the sediment suspended load, river bank and paleoflood deposits is compared to bedrock and soil sources to determine possible sources within the catchment.

#### **4.2.1.1 Orange River**

The suspended sediment load of the Orange River and its small tributaries varies depending on the sample site and the period the samples were taken. The river bank deposit samples are brown to dark brown sediments deposited out during higher river water levels, and were collected from Aliwal north (AN1) and at Vioolsdrift (Bundi).

The sediments from the mud and clay river bank deposits contained fine silt and small fraction of clay (Figure 4.3). When comparing the river suspended sediments and soils in the upper Orange River catchment, sample site was found to be of importance depending on its geology and relief. Temporal and spatial distribution of rain events is important due to the amount of rain and the subsequent runoff of that period (Figure 1.3). The Orange River at the Free State border does not drain a large part of the Karoo sedimentary rocks when compared to the Orange River at Aliwal North (Figure 2.1 and Table 2.1). The relief, and associated runoff, at the Free State border site is higher than at the Aliwal North site.



**Figure 4.3: Grain size distribution of river suspended load (three samples on the far right), river bank (RB) and paleoflood (P) deposits.**

River suspended load has higher fine silt content compared to the soils, paleoflood and river bank deposits. Paleoflood and river bank deposits have relatively high coarse silt content. Low sand and coarse silt content in suspended load indicates the preferential erosion of the finer grained materials from soils and the sampling of the surface flow of the river with much of the sand carried near or on the river bed. The suspended load at Aliwal North and the Free State Bridge was high and the river water was brown to dark brown. In contrast, the suspended load of the Kraai River was very low and the river water was clear.

The Kraai River where sampled mainly drains Drakensburg basalts (Figure 2.1 and Table 2.1). The banks of these basalt bedrock tributaries (Kraai B.E and Kraai N.E) had dark clayey soils tightly bound by abundant plant roots. It therefore appears that the dense vegetation cover (mostly grasses and shrubs) and hard basalt bedrock limit suspended sediment production, despite steep slopes and rapid flow rates.

The greatest amount of sand and highest total suspended load occurs at the Free State Bridge (FSB), where the gradient is steepest (Figure 2.1 and 2.6). The amount of suspended

sediment load is mostly related to the amount of runoff as seen in the much greater load during the higher rainfall period of 2006 compared to 2007 (Table 4.1). The sediment load of the Orange River has been greatly reduced by sediment trapping in dams as reflected in the low sediment load at the border crossing at Vioolsdrif (Bundi on the South African map insert in the geological map). Mean sediment discharge has dropped from 60 million t/year between 1929 and 1969 to 17 million t/year after the building of major dams since 1970 (Bremner *et al.*, 1990). The reduction in total sediment load of 72% is similar to the mean sand and coarse silt content of 70.5% of soils from this study and suggests that most of the sand and coarse silt grains of eroded catchment soils are trapped by dams (Compton and Maake, 2007).

**Table 4.1: Suspended sediment load of the rivers sampled in grams/litre.**

Sample Number	Location	Site description		Latitude	Longitude	Elevation (m)
		2006	2007			
Bundi	Vioolsdrif		0.058 g/l	28°41'08.6"	17°33'48.5"	150
AN1	Aliwal North	2.6 g/l	0.46 g/l	30°41'10.5"	26°42'20.7"	1306
FSB	Free State border bridge	3.4 g/l		30°24'19.6"	27°20'14.1"	1368
CLDN	N6 Bridge	3.0 g/l	0.52 g/l	30°16'44.0"	26°39'16.7"	1329
Vaal	Douglas		0.022 g/l	29°04'17.9"	23°44' 17.9"	999
Kraai BE	Barkly East	0.05 g/l		30°57'08.6"	27°36' 24.3"	1754
Kraai NE	New England	0.22 g/l		30°52' 09.0"	27°28' 40.5"	17 54

#### 4.2.1.2 Caledon River

The Caledon River suspended load was sampled at the N6 Bridge near Smithfield (CLDN). River bank deposits of the Caledon River were sampled at the N6 Bridge near Smithfield (CLDN RB) and upstream of Clocolan town (CLDNc RB) where it forms the border between South Africa and Lesotho. River suspended sediment load was not collected at the Clocolan site as the suspended load was significantly lower than during the 2007 sampling trip (Table 4.1). River bank deposits at the N6 Bridge were sampled from an overall sandy river bank, but samples were selected for their high mud content (CLDN RB). The second

sample of the river bank deposit (CLDN RB clay) was sampled at the same location 2 days later, from a mud rich layer on the river bank after the water level had dropped by 50 cm compared to when the first sample was taken. The river bank sediments upstream of Clocolan (CLDNc RBa and b) were sandier compared to those sampled at the N6 Bridge. The Caledon River upstream of Clocolan drains areas with relatively high amounts of basalt bedrock (Table 2.1). Large parts of the tributaries of the Caledon River at the Clocolan site have their headwaters in the high relief Drakensberg Mountains (Figure 2.1). The Caledon River at the N6 bridge drains more Karoo sedimentary bedrock compared to the Clocolan site (CLDNc) further upstream (Figure 2.1 and Table 2.3). The Caledon River catchment drains relatively low lying areas (Figure 2.4).

The suspended sediment load of the Caledon River has the least amount of sand because it is mainly draining relatively low-lying areas. Generally the Caledon River has a higher sediment load than the Orange River although the samples taken in 2006 show higher sediment load for the Orange River (FSB) (Table 4.1). The high sediment load is due to the Caledon River mainly draining the more erodible soils of the Karoo sedimentary rocks (Figure 2.1 and Table 2.1). Previous studies have shown that most sediment is transported during Orange River floods and that the Caledon River carries the largest proportion of fine mud (Harmse, 1974; Rooseboom and Harmse, 1979). The paleoflood and river bank deposits of Caledon River have relatively high clay contents (excluding the silty river bank deposits) compared to the Orange River which is consistent with the high clay content of the Caledon River in general. In the field, thin clay layers were observed on top of sand-rich layers on the river banks indicating the gravitational settling out of a fining upward river bank deposit (Figure 5.8).

#### **4.2.1.3 Vaal River**

The low suspended load of the lower Vaal River (most of which was living green algae and not sediment) is related to the low topographic gradient of the Vaal catchment and the large dams upstream making the Vaal more of a lake than a river. The generally rocky, sediment-starved river bed and banks, and small paleoflood deposits indicate a low sediment load of the Vaal River. Prior to the building of dams, the Vaal River contributed 22% of the mean total water discharge, but carried less than 5% of the total sediment load of the Orange River based on Department of Water Affairs data collected between 1928 and 1943 (Rogers, 1977). The paleoflood and river deposits of the Vaal River have relatively high clay and low sand contents compared to the Orange and Caledon rivers (Figure 4.3). The low sand to clay ratio of the Vaal River indicates that little sand is transported and deposited on its relatively small river bank and flood plains.

#### **4.2.2 Suspended sediments vs. bedrock**

When comparing the river suspended load to the bedrock they are draining it was observed in the field that clear running streams drain the Drakensberg basalt and Clarens Formation sandstone with low sediment loads of 0.05 g/l measured at Barkly East (B.E) and 0.22 g/l at New England (N.E). These low sediment loads indicate low levels of soil erosion from areas underlain by basalt bedrock. The highest suspended load appears to correlate with the site that drains the largest land area covered by the Elliot Formation (Table 2.1). The sediment load of the upper Orange River tributaries, and more especially the Caledon, only increases after the river has incised the relatively easily eroded mudstone of the underlying Elliot Formation and to a lesser extent mudstone beds of the Molteno Formation (Compton and Maake, 2007). The Elliot Formation consists mainly of mudstone while the more resistant Molteno Formation has resistant sandstone layers inter bedded with mudstone. Incision below the Elliot Formation is limited by underlying resistant Molteno Formation sandstone layers. Therefore, the Elliot Formation represents the cutting edge of the Drakensberg

escarpment, constituting only 1.1% of the catchment area but providing a significant amount of the total Orange River mud flux (Compton *et al.*, 2010).

### 4.2.3 Mineralogy and Geochemistry

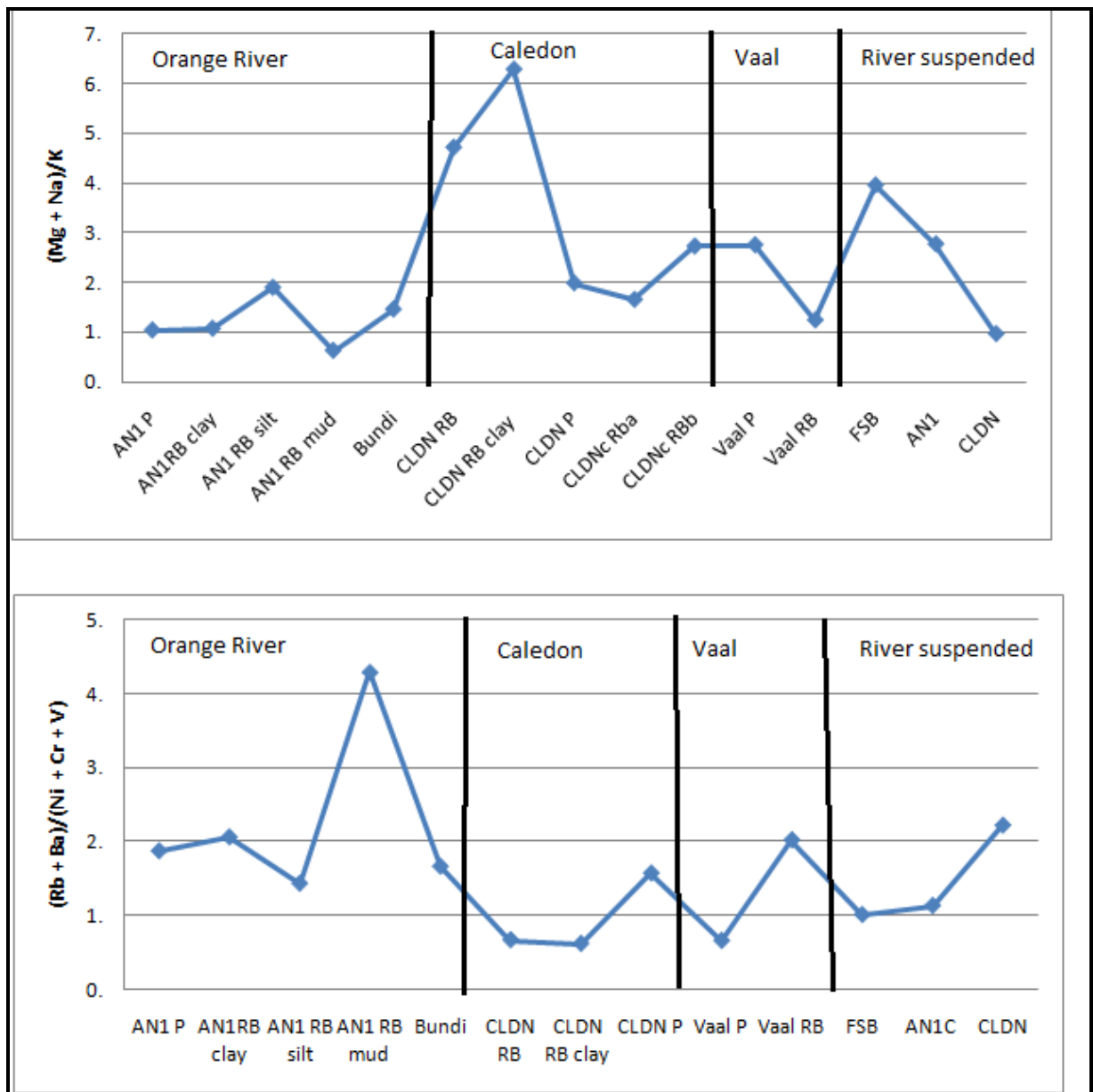
The catchment area bedrock can be divided into two geochemical end members. Some have argued that the properties of sediments in water bodies generally differ from those of their sources as a result of differential transport and chemical transformations during transport (Rooseboom and Harmse, 1979), but the geochemistry of the suspended load in this study can be related to the two geochemical end members in the catchment. Due to the low sediment load in the Vaal River geochemical analyses were not done on the Vaal River suspended sediments. Sediment load derived from Karoo sedimentary rock soils can be differentiated from basalt soils due to the high concentration of quartz, K-feldspar and illite. X-ray diffraction profiles provide a qualitative estimate of these mineralogical differences but variations in the amount of clay minerals is difficult to quantify by XRD alone. Differences in mineralogy lead to differences in major and trace element geochemistry that are more easily quantified by XRF.

There is a large difference in the chemistry and sediment loads of the Caledon River and the Orange River. In addition, there is some difference in the chemistry of the sediment load of the Orange River sampled at Free State Border, and that sampled at Aliwal North. There is also variation between the Caledon River sediments sampled near Clocolan town (CLDNc RB) compared to those sampled at the N6 Bridge (CLDN RB). The geology and relief drained by these rivers can be used to explain these differences.

Difference between the upper Orange River sampled at FSB and Aliwal North (AN1) can be attributed to the fact that less upper Karoo sediments have been traversed by the river at FSB (Table 2.1). Difference in the sediment load of the tributaries sampled can be explained by

relief, geology and the nature of the vegetation. The Caledon River mainly drains relatively low-lying areas in comparison to the Orange River at both Aliwal North (AN1) and FSB. Tributaries draining the basalt bedrock have a very low sediment load, which suggests that the basalt bedrock and overlying soils are not easily eroded. Evidence from the field showed that the basaltic soils were tightly bound by the dense root mass of the grass vegetation, while most of the soils of the Karoo sedimentary rocks are not as densely vegetated. Binding of the soil by plant roots reduces the susceptibility of the soils to erosion. In general the Caledon River has a higher sediment load compared to the Orange River at Aliwal North (AN1) taking into consideration the velocity of the rivers. FSB has a higher sediment load compared to the Caledon (CLDN) and Aliwal North (AN1) because it drains a large area of high relief and consequently has high run off during periods of heavy rainfall.

The bulk sediment suspended load sampled from the Caledon River has higher concentrations of  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ , Zr and Rb in comparison to suspended sediment from the upper Orange River. The Caledon River suspended sediment has low concentrations of  $\text{Na}_2\text{O}$ , CaO and MgO when compared to the upper Orange River. This is the manifestation of the Caledon not eroding the basaltic bedrock except at its uppermost reaches with basaltic soil input from erosion and runoff from the mountains during the high rainfall summer season. The high concentration of elements mentioned above in the Caledon River is a result of the Caledon draining mostly sedimentary rocks, which have illite and mica. Mica and illite minerals can host the elements mentioned above, as well as Rb and Zr. These elements are low in the upper Orange River suspended sediment load because the upper Orange River primarily drains basalt bedrock and only briefly crosses the upper Karoo sedimentary rocks upstream of where it was sampled at Aliwal North.



**Figure 4.4: Ratio of major elements (Mg + Na)/K and of trace elements (Rb + Ba)/(Ni + Cr + V) determined by XRF for river bank deposits, paleoflood deposits and river suspended sediment load.**

Element ratios can be used to differentiate between the basalt and sedimentary bedrock sources because the suspended load generally provides an integrated, homogeneous sampling of the eroded catchment bedrock and soil. The major element ratio is high (mean value of 7.9) for the basalt soil end member whereas the Karoo sedimentary rock soils end member has a low mean value of 1.4 (Figures 4.1 and 4.2). The trace element ratio

$(\text{Rb}+\text{Ba})/(\text{Ni} + \text{Cr} + \text{V})$  also discriminates between basalt (mean of 0.4) and Karoo sedimentary rock soils (mean of 2.0). The major oxide ratio shows more variability in basalt than in Karoo sedimentary rock soils and vice versa in the case of the trace element ratio (Figures 4.1 and 4.2). The major oxide ratio  $(\text{Mg} + \text{Na})/\text{K}$  of the Caledon river suspended load is low (0.9) (Figure 4.9) and similar to that of soils on Karoo sedimentary rocks which have a mean major oxide ratio of 2.0. The Orange River suspended load at the Free State Border (FSB) with a major oxide ratio of 3.95 shows a relatively high basalt signature when compared to the suspended load at Aliwal North (AN1) with a major oxide ratio of 3.0 and the suspended load of the Caledon River with a major oxide ratio of 0.9 (Figure 4.4). The river bank deposits of the Caledon River at the N6 Bridge (CLDN RB) show a more basalt signature with a major oxide ratio mean value of 3.55 compared to the Caledon River paleoflood (CLDN P) and river suspended load (CLDN) at the same site and the river bank deposits upstream at Clocolan (CLDNc RB) (Figure 4.4). The reason for this one Caledon River bank sample to have a more basaltic major oxide value is unclear, but it may relate to the sample being derived from the upper reaches of the catchment area dominated by basalt bedrock. This sample demonstrates that, even in a river drainage dominated by Karoo sedimentary rocks, it is possible to have suspended loads with a large headwaters basalt signature.

Difference in the element ratios between the river sampled at the Free State Border (FSB) and Aliwal North (AN1) is small but indicates an increasing Karoo sedimentary rock soil contribution. The difference in the element ratios is most pronounced in Caledon River sample (CLDN) which shows a predominantly Karoo sedimentary rock soil ratio. The geochemical trend among the river suspended sediment samples is consistent with the percentage of basalt and Karoo sedimentary rocks within their catchment areas (Table 2.1). A relatively small percentage of Caledon River tributaries above the N6 Bridge drain basalt

terrains in comparison to tributaries upstream from Aliwal North. The Caledon River drains mostly Karoo sedimentary rocks, which make up approximately 89% of its catchment area (Figure 2.1 and Table 2.1), and contain abundant illite and K-feldspar rich in the elements K, Rb and Ba. The upper Orange River catchment above the Free State Border primarily drains basalt bedrock with only 28% of the catchment having upper Karoo sedimentary bedrock. The slightly greater Karoo sedimentary rock soil signal at Aliwal North reflects an increased proportion of Karoo sedimentary rocks (35%) in the catchment above Aliwal North (Figure 2.1). Therefore, the Caledon River contributes a significant amount of the suspended fine mud carried by the Orange River sourced from the erosion of Karoo sedimentary rocks. The elemental ratio of river bank sediments and paleoflood deposits of the Vaal and Orange River indicates an increasing Karoo sedimentary rock contribution.

### **4.3 Organic Carbon analysis**

River export of organic matter from the continent to oceans forms an important component in the global carbon cycle. Organic carbon in rivers can be derived from primary productivity in the river or from the erosion of old carbon from bedrock and soil. Primary production was observed in the Vaal River but in the upper Orange and Caledon the majority of the organic matter in the suspended river load appears to be recycled from bedrock and soil sources. Organic carbon analysis shows that the soils of upper Karoo sedimentary rocks have a total organic carbon content of less than 1 wt% with an average value of 0.63 wt% including the spikes from the Tarkastad alluvium at 2.11 wt% and Molteno at 1.48 wt%. The Karoo sedimentary bed rock have a total carbon content <0.5 wt % and averaging at 0.18 wt% .The paleoflood and river bank deposits have organic carbon contents which are similar to the Karoo top soils and range from 0.15 wt% in Caledon River paleoflood deposits to 1.14 wt % in Orange River clayey river bank deposits at Aliwal North.

Basaltic soils have relatively high total organic carbon contents ranging from 1-2.6 wt% and averaging 2.03 wt%. The top soils overlying basalt bedrock are tightly bound by grasses and have dark brown to black colour from the presence of abundant organic matter. The suspended sediment samples have a high (>1.2 wt%) total organic carbon content when compared to the upper Karoo sedimentary rocks at 0.63 wt% which could reflect a greater contribution from top soil erosion as opposed to bedrock erosion. Field evidence shows relatively high top soil erosion when compared to bedrock erosion (Figure 4.5). The field evidence of topsoil erosion was mostly on the northern parts of the study area along the floodplain of the Caledon River where cultivated fields are abundant (Figure 4.6). Field evidence of bedrock erosion was mostly on the southern part of the study area, where grazing lands dominate over cultivated farm lands (Figure 4.5). More donga and gully activities were observed near the town of Sterkspruit (Figure 4.5). Overall the field evidence has shown that topsoil erosion is significant when compared with bedrock erosion in the study area

Stable carbon isotope ratios ( $^{13}\text{C}/^{12}\text{C}$ ) are potentially useful as tracers of carbon pathways in a variety of systems. In terrestrial systems, soil organic matter is derived from the prevailing vegetation cover. Plants following the Calvin–Benson ( $\text{C}_3$ ) photosynthetic pathway are markedly more depleted in  $^{13}\text{C}$  ( $\delta^{13}\text{C}$  mean of -26) than are grasses following the Hatch-Slack ( $\text{C}_4$ ) pathway ( $\delta^{13}\text{C}$  mean of -12) in much of southern African interior, especially those areas drained by the Orange River.  $\text{C}_4$  grasses dominate the vegetation and the  $\text{C}_3$  component is restricted to trees and shrubs (Meadows *et al.*, 2001).

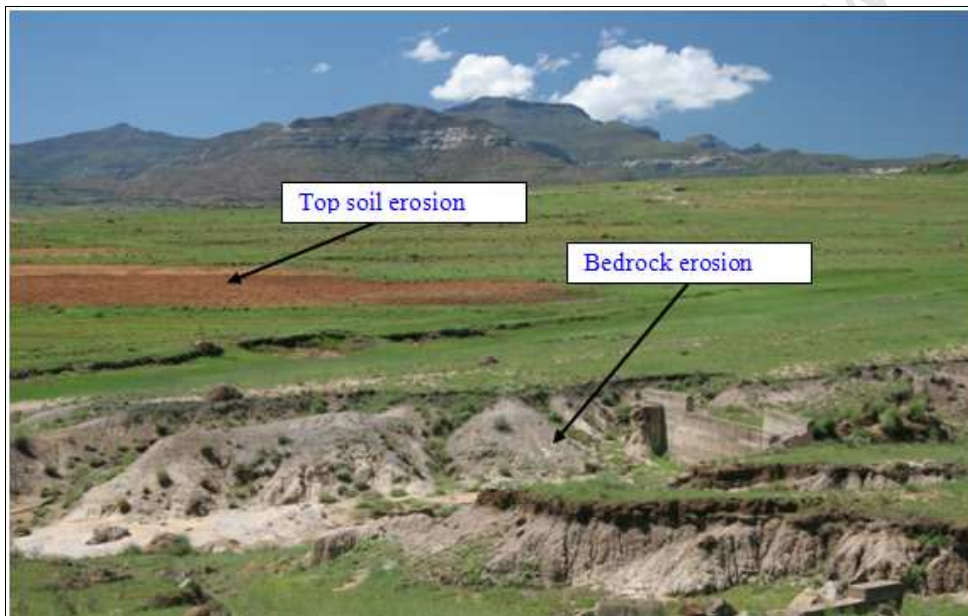
Vogel (1978) showed that the  $^{13}\text{C}/^{12}\text{C}$  isotope ratio indicates whether  $\text{C}_3$  or  $\text{C}_4$  grasses grew in an area.  $\text{C}_3$  grasses presently occupy regions where mean daily maxima are below 25°C during their growth (rainy) period.  $\text{C}_4$  grasses presently occupy the eastern areas of southern Africa,

where summer daily maximum temperatures are above 25°C. C<sub>3</sub> grasses are most common in the Western Cape and at high altitudes in the Drakensberg where the effects of altitude moderate temperature (Lewis, 2005). Lewis (2005) showed that although there are problems in relating the isotopic evidence to vegetation (since, for example, where C<sub>3</sub> plants are indicated they could have been derived from aquatics, semi-aquatics, Karoo bushes, shrubs or other herbs and not necessarily from C<sub>3</sub>grasses), the isotopic evidence remains valuable. All bedrock derived organic matter will be at δ<sup>13</sup>C of -26 as C<sub>4</sub> plants had not yet evolved and organic content of bedrock is relatively more depleted in <sup>13</sup>C compared to soils which host most organic carbon from plants.

The present-day Orange River delivers terrestrial organic matter of mixed C<sub>3</sub>/C<sub>4</sub> origin, which is sourced predominantly from the erosion of upper Orange River catchment soils. The soil organic matter in this study has δ<sup>13</sup>C values that range from -10.66 to -26.03‰ showing contribution from both C<sub>3</sub>/C<sub>4</sub>grasses and the contribution of both bedrock and topsoil erosion. Orange River suspended load δ<sup>13</sup>C values (-16.9 to -19.7) are similar to the river bank and paleoflood deposits (-17.03 to -20.96‰), varying in response to local vegetation cover rather than terrestrial degradation (Holtvoeth *et al.*, 2004). Mean δ<sup>13</sup>C of C<sub>4</sub> plants is -12‰, but δ<sup>13</sup>C values range from -9 to -14‰ (Ehleringer and Rundel, 1989). On land southern African woody plants have a mean δ<sup>13</sup>C value of -26‰ (-20 to -35‰) (Ehleringer and Rundel, 1989) and undergo Calvin–Benson (C<sub>3</sub>) photosynthesis utilizing the Ribulose-1.5-biphosphate carboxylase (RuBisCO) enzyme (Koch, 1998). The greater resistance of woody C<sub>3</sub> plant material to degradation and the binding of soil by grasses can be used to explain the more negative river suspended load and river bank deposits δ<sup>13</sup>C values than source soil organic matter.

The Orange River suspended load clay fraction δ<sup>13</sup>C becomes more negative downstream from the upper Orange River (sample 62, -18.57‰; sample 61, -19.74‰) to the lower

Orange River (bulk and clay fraction  $\delta^{13}\text{C}_{\text{org}}$  of -19 and -20.2‰, respectively), suggesting an increase in the  $\text{C}_3$  (shrub) component downstream (Herbert, 2009). The Caledon River introduces clay fraction organic matter of a mixed, but mainly  $\text{C}_4$  source ( $\delta^{13}\text{C}_{\text{of}}$  -16.5‰), whereas the Vaal River is mostly an algal source having a  $\delta^{13}\text{C}_{\text{org}}$  value of -19.5‰. Poor land-use practices along the Orange and Caledon river banks has led to soil erosion, which may affect modern river  $\delta^{13}\text{C}$  values. Paleoflood clay fraction  $\delta^{13}\text{C}_{\text{org}}$  values record pre-anthropogenic, Holocene Orange River organic matter loads that varied from mixed  $\text{C}_3/\text{C}_4$  (-16.2‰ to -20.0‰) and are similar to modern Orange River organic matter (Herbert, 2009).



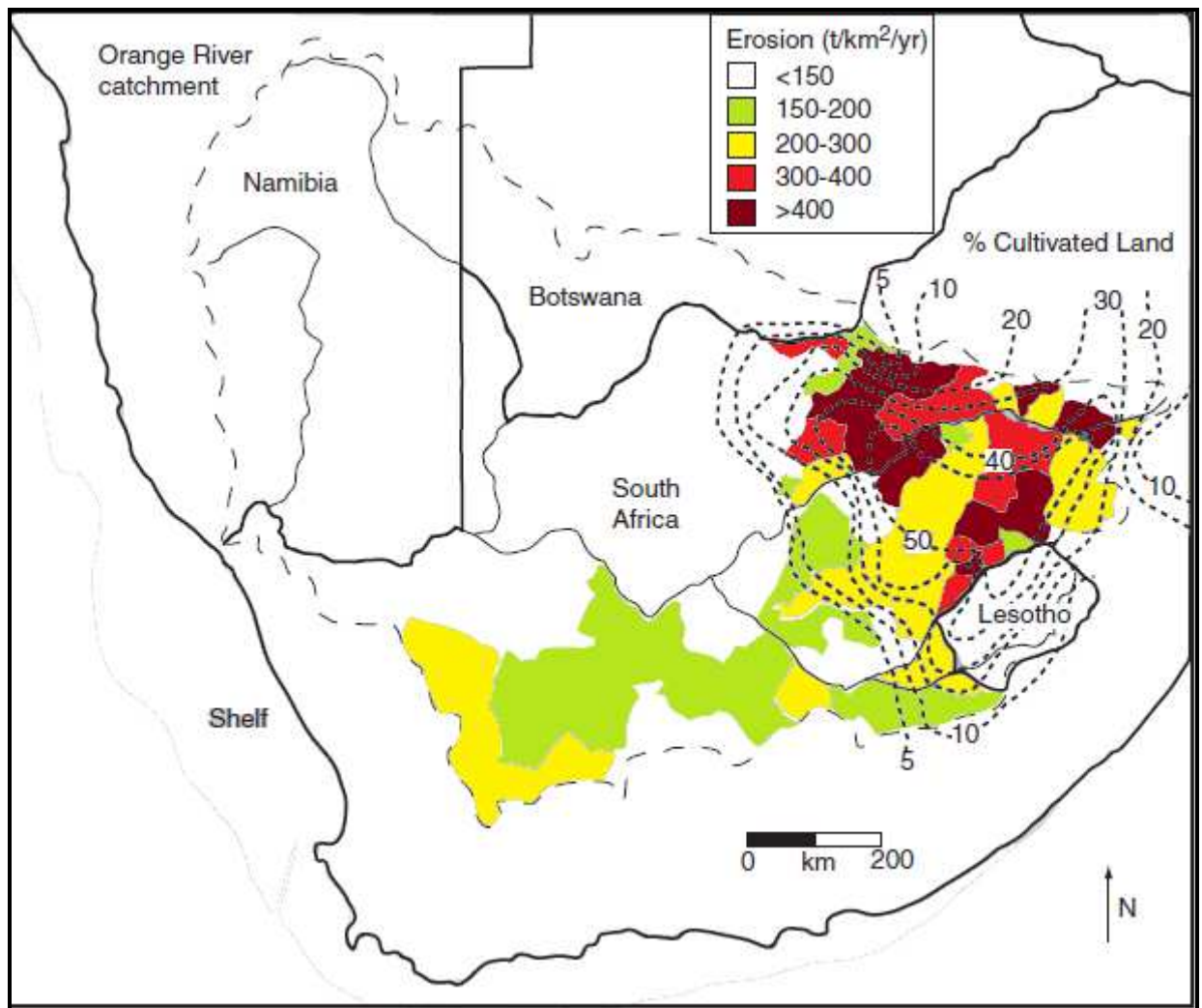
**Figure 4.5: Photo showing both top soil erosion (reddish brown) and gullies showing previous bedrock erosion (light grey) near the town of Smithfield on the southern side of the study area (Compton and Maake, 2007).**



**Figure 4.6: Photo showing farming on gentle slopes near the town of Lady Brand on northern side of the study area.**

#### **4.4 Soil erosion variation in the catchment areas**

The upper Orange River catchment is especially susceptible to accelerated erosion due to a combination of factors including steep slopes, erodible soils, and intensive rainfall patterns. Large areas of the Free State and Gauteng provinces are undergoing intensive erosion (Figure 4.7). Compton *et al.* (2010) have shown that erosion has shifted from the areas of high relief and rainfall of the Drakensberg escarpment during the Holocene to easily erodible soils and intensely cultivated lands of low relief with moderate to high rainfall in the eastern catchment of the Orange River catchment area (Figure 4.7).

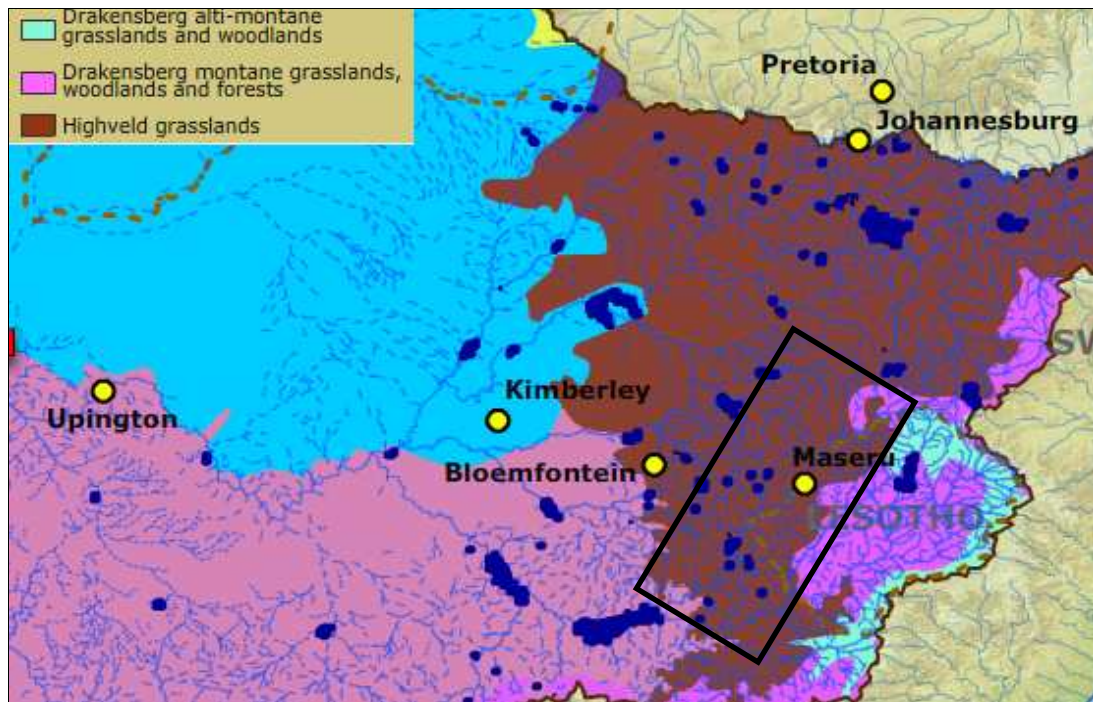


**Figure 4.7: Soil erosion rates from magisterial districts of South Africa (Compton et al., 2010). Soil erosion is most intense in areas of high rainfall and erodible soils of the Karoo sedimentary rocks (Figure 4.3 and 4.7) and heavily cultivated land (Le Roux, 1990).**

The bedrock geology and its overlying soils have a strong influence on soil erosion (Weaver, 1991) and many soil properties are inherited from parent rocks (Rooseboom and Harmse, 1979). Therefore, mineralogy of river sediments should be able to indicate where a significant amount of erosion is taking place. The soils of the study area have been derived from two bedrock end members as shown above. There are silty and sandy soils derived from the Karoo sedimentary rocks and the more clay rich black soils derived from the basalts and dolerites. (Rooseboom and Harmse, 1979) have shown that soils tend to be more erodible as the texture ranges from sand to silt and less erodible as clay content and clay mineral content increases. The Karoo sedimentary rocks have been classified as silty sand or

sandy therefore making them relatively more susceptible to erosion. The soils derived from basaltic alluvium are usually black and have higher clay content making them more stable and more resistant to erosion. The chemistry in the rivers suggests that there is some erosion of basaltic bedrock and topsoil; in the field the basalt bedrock seemed very hard and much less susceptible to erosion and the soils were tightly bounded by grasses. Although in general terms it has been observed that most of the suspended load is derived from the Karoo sedimentary rock, the sandstones of the Clarens Formation and to a lesser extent those of the Molteno Formation seem to form resistant ridges and show more resistance to erosion. Streams draining the Clarens Formation and the Drakensberg Formation were found to be clear compared to those draining the Beaufort Group and the Elliot Formation.

Vegetation cover plays a major role in erosion (Garland *et al.*, 1999). The vegetation cover in the study area is Highveld grassland (Figure 4.8); these grasses bind together the basaltic soils of the Drakensberg Formation which limit erosion. Fanning (1999) found that loss of vegetation cover can lead to an increased surface runoff and an increased run off can lead to channel erosion on valley floor while Boardman *et al.* (2003) have argued that bare areas will remain the source of erodible material. During low rainfall periods shrubs were observed in the study area, shrub vegetation does not protect the soil from erosion as well as grass, and an increase in shrubs can result in an increase in erosion (Cowling and Richardson, 2003). Several authors have emphasised the necessity for major disturbance of grassland/shrub vegetation in semiarid areas in order to initiate major erosion.



**Figure 4.8:** Map showing the vegetation cover of the upper Orange River catchment. The study area (rectangle) is located on Highveld grassland (from <http://www.orangesenqurak.com/river/hydrology/cycle/groundwater.aspx>)

Garland *et al.* (1999) assessed different land-use types at a national scale in terms of the main types of soil degradation affecting them. Rill, and gully erosion were found to be the most important types of land degradation on the communal grazing lands of the eastern parts of the country. Current observations indicate that erosion sites occur commonly in subsistence farming areas on soils with high erodibility values. The results of Rooseboom *et al.* (1992) support the concept that areas with erodible soils tend to yield the most suspended sediment.

South Africa has a high soil-loss rate due to extensive cultivation and over grazing (Figure 4.7-4.9). A total of 62% of the country is currently under commercial and subsistence farming, including areas that have slopes of 10% or more (National Land Cover, 2000). The areas predicted to be greatly affected by soil loss when compared to the National Land Cover appear to be the degraded unimproved grasslands. Unimproved grasslands are associated with subsistence agriculture where overgrazing of livestock has been excessive

(Figures 4.6 and 4.10). It is well known that clearance of natural vegetation to provide land for cultivation will commonly cause increased rates of soil erosion. Morgan (1986), for example, compares soil erosion rates under natural vegetation with those on cultivated land in several areas of the world and shows that the latter may be up to several orders of magnitude greater. The importance of vegetation cover for soil-erosion control and the dangers inherent in changes in land use practice has been emphasized by work done by Lewis et al. (2005). They have found that over 26 million hectares (m. ha) (at least 30% of national land) would be subject to high erosion risk without maintenance of the current vegetation cover and land use. Importantly, around 4.7 m. ha (37%) of cultivated land surface in South Africa falls in the high to extremely high potential erosion class (Lewis *et al.*, 2005). Agricultural intensification could change the land cover, leading to poorer vegetation cover which is the major pressure indicator for soil erosion. The upper Orange River catchment has been used extensively for grazing by commercial farmers; flood plains are cultivated to produce fodder for livestock (Dollar and Rowntree, 1995). Montgomery (2009) showed that erosion rates from conventionally ploughed agricultural fields average 1-2 orders of magnitude greater than rates of soil production, erosion under native vegetation and long term geological erosion. Keay-Bright and Boardman (2004) have supported the fact that land use plays a major role in erosion but further argued that erosion associated with cultivated lands was more dominant in the early 20<sup>th</sup> century, but currently limited to local scales where ploughing of soils was followed by big rainfall. The vegetation cover in the study area is mostly grass and to a lesser extent shrubs which are more obvious in low rainfall periods. The resistance to scour provided by grassland limits erosion as seen on basaltic bedrock in the field. Therefore, vegetation cover where grass dominates might limit the extent of soil erosion in the study area.

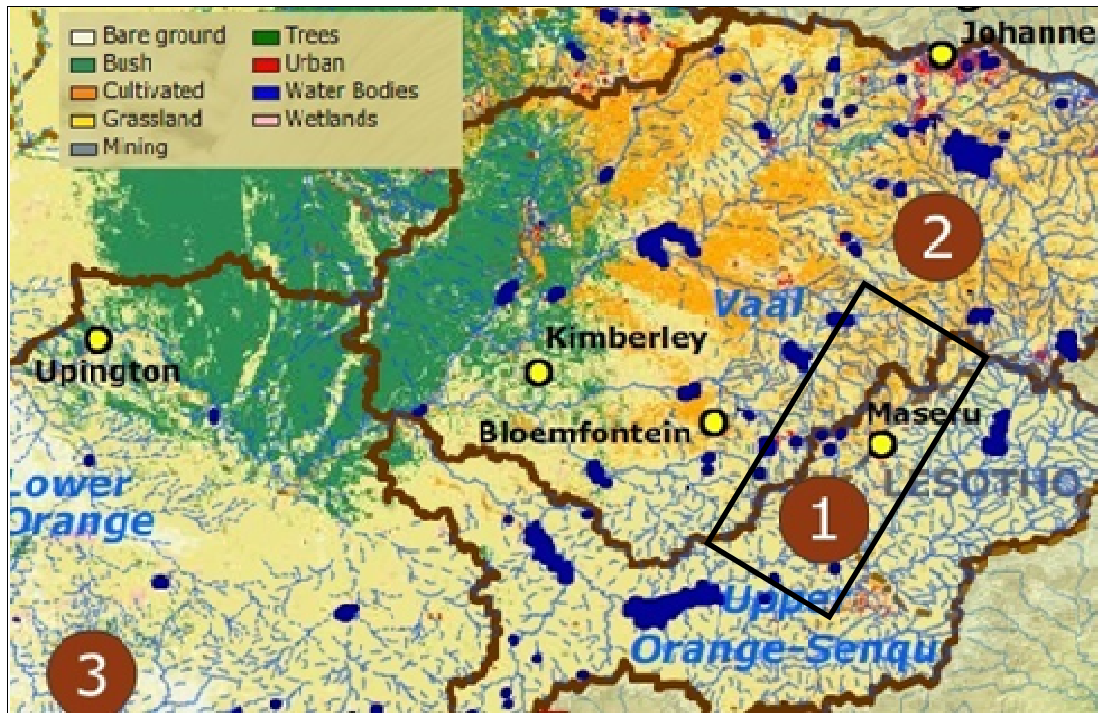


Figure 4.9: Map showing the distribution of land use in the upper Orange catchment area. Brown lines indicate catchment boundaries (<http://www.orangesenquak.com/river/hydrology/cycle/groundwater.aspx>)

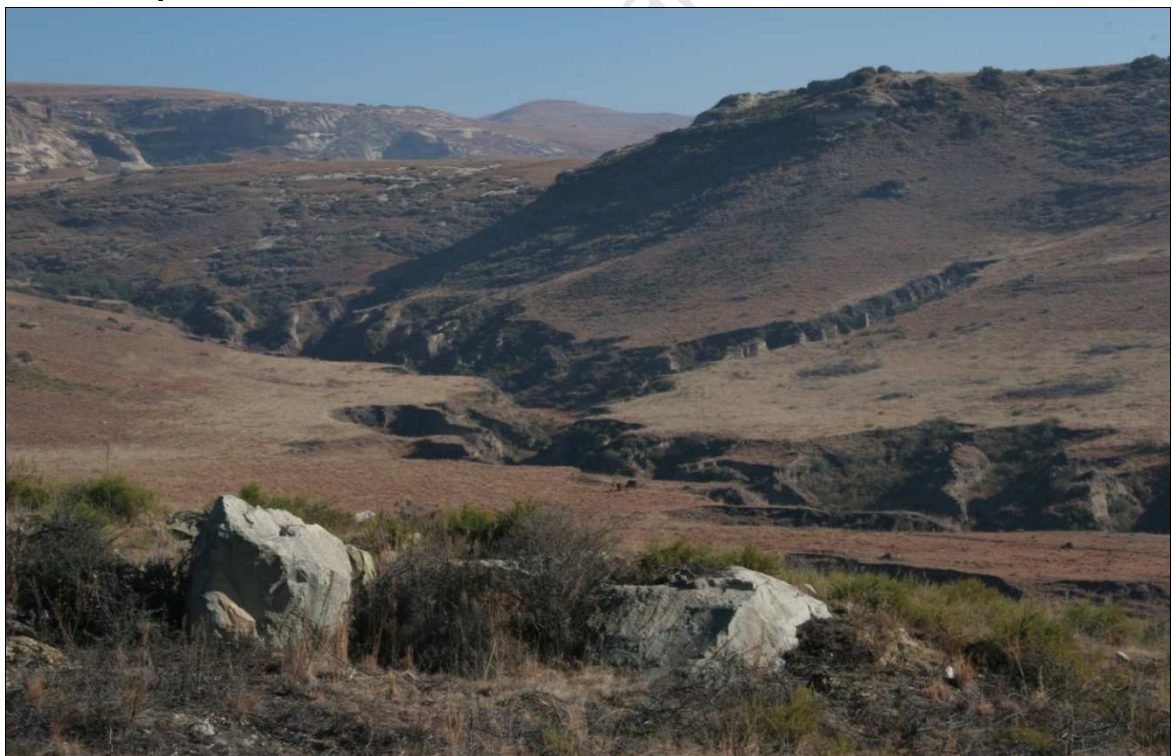


Figure 4.10: Photo showing gully erosion in the Elliot Formation near the town of Lady Brand.

The relationship between wet and dry cycle rainfall, together with the magnitude and frequency of storm events, plays an important role in the hydrological response of the

catchment in terms of both the run off response and the precipitation/ vegetation- erosion interaction. This was evident in the field as the major active gully was observed in 2006 (Figure 4.10) when the rainfall was higher than in 2007 and 2009. Climate is also a factor as shown by Keay-Bright and Boardman (2004), with periods of drought affecting vegetation, and vegetation disturbance such as loss of grass species or replacement of grass by shrubs is most likely to result in increased soil erosion.

In some areas, there is strong field evidence that significant bedrock is being eroded by rivers, and might dominate over top soil erosion (Figure 4.10). There is also evidence of valuable topsoil loss through erosion of tilled soils (the orange surface in Figure 4.5). The high suspended sediment load in the Caledon River also indicates that topsoil erosion is taking place as the river is flowing through relatively flat terrain. Therefore sheet flow could be more dominant than channel flow. In the case of deeply scoured out bedrock (dongas and gullies), the volume of bedrock eroded is far greater than that of topsoil (Figure 4.10) (Lewis *et al.*, 2004). But in the study area, few dongas of the dimensions shown in Figure 4.5 were observed. Therefore, topsoil erosion may be less obvious but more widespread than bedrock erosion.

Wallbrink and Murray (1996) did profile work looking at river bank erosion vs topsoil erosion and their findings suggested that the cultivated farm reservoirs are filled with sediment predominantly derived from burned top soils and from other hill slope top soils which do not appear to have changed significantly over the course of their sedimentary histories. In particular, there was little evidence to suggest that the gully systems are, in themselves, a major source of sediment over the lives of the reservoirs.

## 5 Conclusions

Many researchers have worked on the Orange River system (Rooseboom and Harmse, 1979; Foster *et al.*, 2007; Compton and Maake 2007; Compton *et al.*, 2010), which is not surprising considering that the Orange River is the largest river in South Africa. Although a lot of research has been done on the river, little attention has been given to the source of the large amount of sediment that it discharges offshore on the west coast. Erosion is a major issue in South Africa, but little has been done to establish where the sediments in the rivers are being derived. It is uncertain whether they are from the erosion of the bedrock or erosion of valuable topsoil or, perhaps, from the erosion of both bedrock and topsoil.

The results of this project have established that the chemical composition of the suspended load carried by the upper Orange River and its tributaries can be related to the geology of the area they are draining. Two bedrock types were identified in the catchment area: basalt and Karoo sedimentary rocks. In addition, the study has looked at the effects that geology, relief, and erosion have on sediment production. The project has presented and quantified the variation in composition of the suspended river sediments, topsoils and weathered bedrock in the upper Orange River catchment. Basalt soils contain plagioclase feldspar, pyroxene, rock fragments and smectite clay minerals. Karoo sedimentary rock soils contain quartz, K-feldspar and illite as well as smectite clay minerals. The results from the chemical analyses indicate that the suspended sediments in the upper Orange River are derived from both basaltic soils and the Karoo sedimentary soils, with the Karoo soils dominating.  $K_2O$  and Rb are high in sedimentary soils and in suspended river sediments indicating the contribution of sedimentary rocks in the chemistry of the suspended river sediments, while  $SiO_2$  and  $Al_2O_3$  concentration in suspended river sediments is similar to their concentration in basaltic soils indicating the input of basaltic soils. The major oxide ratio  $(Mg + Na)/K$  and trace element ratio  $(Rb + Ba)/(Ni + Cr + V)$  were used to quantify the mineralogical differences observed.

These ratios clearly differentiate basalt and Karoo sedimentary rock and their soils and indicate that most of the Orange River suspended sediment load is derived from erosion of the Karoo sedimentary bedrock and soils.

There is a relationship among slope, relief and soil cover and the sediment load of the rivers. Rivers flowing from high relief, steep slope and poor soil cover have higher sediment loads relative to rivers draining flat, well-bounded soil. The Caledon River has higher concentrations of  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ , Zr and Rb and lower concentration of  $\text{Na}_2\text{O}$ , CaO and MgO when compared to the upper Orange River; this was attributed to the fact that the Caledon River only drains basalt bedrock at its uppermost reaches. The upper Orange River primarily drains basalt bedrock and only briefly crosses the upper Karoo sedimentary rocks upstream of where it was sampled. The concentration of the above-mentioned elements are even less in the Orange River sampled at Aliwal North compared to at the Free State Border because less upper Karoo sediments have been traversed by the Orange River at the Free State Border. It was also found that the Caledon River bank deposits during periods of lower rainfall show a significant influence from the basaltic rocks compared to the Caledon suspended sediments sampled the previous year with higher rainfall. The Caledon River was found to deliver most of the fine mud suspended load of the Orange River.

The study has established indirectly that the Karoo sedimentary topsoil is more susceptible to erosion than the basaltic topsoil. The hard bedrock underlying the clayey basalt soils densely rooted by grassland vegetation limit the amount of basalt soil and bedrock erosion. River sediment load calculations and field evidence show that rivers flowing on Karoo sedimentary soils have higher sediment load than those draining basaltic soils. Chemical analyses and field evidence indicates that there is both bedrock erosion and topsoil erosion. The sampled area shows more evidence of bedrock erosion than topsoil erosion suggesting

that bedrock erosion is more dominant than the topsoil erosion in the Karoo sedimentary soils while the organic carbon content and carbon isotope composition suggest that much of the suspended load is derived from erosion of top soils rather than erosion of bedrock. Therefore, it is likely that both bedrock and soil erosion are important but vary regionally.

The study has shown that the Karoo sedimentary rocks are more susceptible to erosion because of their higher sand and silt content which is less resistant to erosion when compared to the more clayey basaltic soils. Vegetation was found to be less influential in erosion because it is dominated by grass and grass roots tend to bind the soil closely together. However, the loss of vegetation or the replacement of grass by shrubs may lead to an increase in soil erosion. Land use contribution to soil erosion was largely limited to local cultivated lands which are subjected to high and intense rainfall events just after they were ploughed. The sediment load of the upper Orange River has shown that erosion is currently active in catchment areas having Karoo sedimentary erodible soils despite improvements in land management.

## 6 References

Barker, J. 1985: The effect of catchment land use on the sediment input to Swartvlei, Unpublished MSc dissertation. *University of Cape Town*.

Benade, C. 1988: Episodic flood events in the Orange River system – an ecological perspective. Proceedings of Conference: Floods in perspective, Pretoria, Paper 3.6, 1-16.

Best, M. G. and Christiansen, E. H. 2001: *Igneous Petrology*. Oxford: Blackwell Science.

Boardman, J., Parsons, A.J., Holland, R., Holmes, P.J., Washington R. 2003: Development of badlands and gullies in the Sneeuberg, great Karoo, South Africa. *Catena*, 50, 165-184.

Bremner, J. M. 1990: The Orange River and its 1988 flood in perspective. In: R.R. Maud (Guest Editor) *Palaeoecology of Africa and the surrounding islands*. A.A. Balkema Press, Rotterdam, Vol. 21, 89-97.

Bremner, J.M., Rogers, J. and Willis, J.P. 1990: Sedimentological aspects of the 1988 Orange River floods. *Transactions of the Royal Society of South Africa*, **47**, 247-294.

Beukes, N.J. 1970: Stratigraphy and sedimentology of the Cave Sandstone Stage, Karroo System. In: S.H. Haughton (Editor). *Proceedings 2nd IUGS Symposium on Gondwana Stratigraphy and Palaeontology*, CSIR, Pretoria, South Africa, 321–341.

Chevallier, L. and Woodford, A. 1999: Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo, South Africa. *South African Journal of Geology*, 102, 43–54.

Compton, J.S. and Maake, L. 2007: Source of suspended load of the upper Orange River, South Africa. *South African Journal of Geology*, 110(2/3), 339-348.

Compton, J.S., Herbert, C.T., Hoffman, M.T., Schneider, R.R. and Stuut, J. B. 2010: A tenfold increase in soil erosion estimated from the Holocene Orange River terrigenous mud flux. *The Holocene*, 20, 155-122.

Compton, J.S., Mulabisana, J. and McMillan, I.K. 2002: Origin and age of phosphorite from the Last Glacial Maximum to Holocene transgressive succession off the Orange River, South Africa. *Marine Geology*, 186, 243-261.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. and Besse, J. 1999: On causal links between flood basalts and continental break-up. *Earth and Planetary Science Letters*, 166, 177-195.

Cowling, R.M. and Richardson, D.M. 1995: *Fynbos: South Africa's Unique Floral Kingdom*. Fernwood Press, Cape Town.

Department of Water Affairs and Forestry, 1997: Introduction to the Orange River Basin.

<http://www.dwaf.gov.za/orange/default.htm>

Dingle, R.V. and Hendey, Q.B. 1984: Late Mesozoic and Tertiary sediment supply to the Eastern Cape Basin (SE Atlantic) and palaeo-drainage systems in southwestern Africa. *Annals of the South African Museum*, 56, 13-26.

Dollar, E.S.J. and Rowntree, K.M. 1995: Hydroclimatic trends, sediment sources and geomorphic response in the Bell River catchment, Eastern Cape Drakensberg. South Africa. *South African Geographical Journal*, 77, 21-32.

Duncan, A.R. and Marsh J.S. 2006: The Karoo Igneous Province. In: Johnson, M.R., Anhaeusser, C.R. and Thomas R.J., (Editors), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, 501-520.

Ehleringer, J.R. and Rundel, P.W. 1989: Stable isotopes: History, units and instrumentation. In: Rundel, P.W., Ehleringer, J.R. and Nagy, K.A. (Editors), *Stable Isotopes in Ecological Research*. Ecological Studies, Springer-Verlag, 86, 1-15.

Eriksson, P.G. 1981: A palaeoenvironmental analysis of the Clarens Formation in the Natal Drakensberg. *Transactions of the Geological Society of South Africa*, 84, 7-17.

Fanning, P.C. 1999: Recent landscape history in arid western New South Wales, Australia: A model for regional change. *Geomorphology*, 29, 191–209.

Fey, M. 2010: *Soils of South Africa*. Cambridge University Press.

Foster, D.L., Boardman, J. and Keay-Bright, J. 2007: Sediment tracing and environmental history for two small catchments, Karoo Uplands, South Africa. *Geomorphology*, 90, 126-143.

Garland, G.G. 1987: Rates of soil loss from mountain footpaths: an experimental study in the Drakensburg Mountains, South Africa. *Applied Geography*, 7, 41-54

Garland G.G., Hoffman T. and Todd S. 1999: Soil degradation. In *A national review of land degradation in South Africa*, unpublished report, (Editors) T. Hoffman, S. Todd, Z. Ntshona, and S. Turner, pp. 69–107. South African National Biodiversity Institute, Pretoria. Available online: <http://www.nbi.ac.za/landdeg>

Harmse, H.J von M.1974: An evaluation of the possible influence of rock and soil on erosion in the catchment area of the Hendrik Verwoerd Dam. In: E. M. Van Zinderen Bakker, Sr. (Editor), The Orange River: Progress Report. *Proceedings of the 2<sup>nd</sup> Limnology Conference on Orange River System*. Institute of Environmental Science. University Orange Free State, Bloemfontein, 31-40.

Herbert, C.T. 2009: Holocene sediment dynamics of the western margin of South Africa. Unpublished PhD dissertation. *University of Cape Town*.

Herbert, C.T. and Compton, J.S. 2007: Geochronology of Holocene sediments on the western margin of South Africa. *South African Journal of Geology* 110, 327-338.

Holtvoeth, J., Kolonic, S. and Wagner, T. 2004: Soil organic matter as an important contributor to late Quaternary sediments of the tropical West African continental margin. *Geochimica et Cosmochimica Acta*, 69(8), 2031-2041.

Johnson, M.R and Van Vuuren, C.J., Visser, J.N.J, Cole, D.I, Wickens, H.V., Christie, A.D.M., Roberts, D.L. and Brandl, G. 2006: Sedimentary rocks of the Karoo Supergroup. In Johnson, M.R., Anhaeusser, C.R., and Thomas, R.J. (Editors). *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/ Council for Geosciences, Pretoria, 461-499.

Keay-Bright, J. and Boardman, J. 2004: Changes in the distribution of degraded land over time in the central Karoo, South Africa. *Catena*, 67, 1-14.

Kelbe, B., Mulder, G. Bodenstein, B. and Hattingh, D. 1992: An investigation of the hydrological response to third world settlement in peri-urban areas of KwaZulu Natal. *Water Research Commission Report*, 203.

Koch, P.L. 1998: Isotopic reconstruction of past continental environments. *Annual Reviews of Earth and Planetary Science*, 26, 573-613.

Kounov, A., Niedermann, S., de Wit, M.J., Viola, G., Andreoli, M. and Erzinger, J. 2007: Present denudation rates at selected sections of the South African escarpment and the elevated continental interior based on cosmogenic  $^3\text{He}$  and  $^{21}\text{Ne}$ . *South African Journal of Geology*, 110(2/3), 235-248.

Kriel, J. P. 1972: The role of the Hendrik Verwoerd dam in the Orange River project. *Civil Engnr. S. Africa*, 14, 51-61.

Kruger, G.P.1983: Terrain morphology map of southern Africa. Soil and Irrigation Research Institute, Dept of Agriculture, Pretoria.

Le Roux, J.S.1990: Spatial variations in the rate of fluvial erosion (sediment production) over South Africa. *Water SA*, 16, 185–94.

Le Roux, J.J., Morgenthal, T.L., Malherbe, J., Pretorius, D.J. and Sumner, P.D. 2008: Water erosion predictions at a national scale for South Africa. *Water SA*, 34, 305-314.

Le Roux, J.J., Newby, T.S. and Sumner, P.D. 2007: Monitoring soil erosion in South Africa at a Regional scale: review and recommendations. *South African Journal of Science*, 103, 329-335.

Lewis, C.A. 2005: Late Glacial and Holocene palaeoclimatology of the Drakensberg of the Eastern Cape, South Africa. *Quaternary International*, 129, 33-48.

Marker, M.E. and Evers, T.M. 1976: Iron Age settlement and soil erosion in the eastern Transvaal, South Africa. *South African Archaeological Bulletin*, 123, 153-165.

Marsh, J.S and Eales, H.V. 1984: The chemistry and petrogenesis of igneous rocks of the Karoo central area, Southern Africa. In A.J. Erlank (Ed.) *The petrogenesis of the volcanic rocks of the Karoo Province*. The Geological Society of South Africa, Special Publication 13, 27-68.

Martin, A.K. 1987: Comparison of sedimentation rates in the Natal Valley, south-west Indian Ocean, with modern sediment yields in East Coast Rivers of Southern Africa. *South African Journal of Science*, 83, 716–24.

Meadows, M.E., Rogers, J., Lee-Thorp, J.A., Bateman, M.D. and Dingle, R.V. 2001: Holocene geochronology of a continental shelf mud belt off southwestern Africa. *The Holocene*, 12, 59–67.

Montgomery, D.R. 2009: Soil erosion and agricultural sustainability. *The Proceedings of the National Academy of Sciences*, 104, 13267-13272.

Morgan, R. P. C. 1986: *Soil Erosion and Conservation*. Harlow, Longman, 298 p.

Mucina, L. and Rutherford, M.C. 2006: The vegetation of South Africa, Lesotho and Swaziland. *Strelitzia 19*, South African National Biodiversity Institute, Pretoria.

Nel, W. and Sumner, P.D. 2008: Rainfall and temperature attributes on the Lesotho-Drakensberg escarpment edge, southern Africa. *Geografiska Annaler*, 90, 97-108.

Noble, R.G. and Hemens, J. 1978: Inland water ecosystems in South Africa- a review of research needs. National Scientific Programmes Unit: CSIR, SANSP Report 34, Nov 1978, pp 160.

River Health Programme, 2003: State of Rivers Report: Free State Region River Systems, Department of Water Affairs and Forestry Pretoria.

Rogers, J. 1977: Sedimentation on the Continental Margin off the Orange River and the Namib Desert. *Bulletin of the Joint Geological Survey/University of Cape Town Marine Geoscience Unit*, **7**, 212.

Rooseboom, A. 1975: Sedimentproduksiekaart vir Suid-Afrika. Technical Report, Department of Water Affairs, South Africa, 61, 1-13.

Rooseboom, A. and Harmse, H.J.van 1979: Changes in the sediment load of the Orange River during the period 1929-1969 in the hydrology of areas of low precipitation. Proceedings of the Canberra Symposium "The Hydrology of areas of low precipitation". *Scientific Publication of the International Association of Hydrological Sciences (IAHS-AISH)*, 128, 459-479.

Rooseboom, A., Lotriet, H.H., Verster, E. and Zietsman, H.L. 1992: The development of a new sediment yield map for southern Africa. Water Research Commission. Pretoria.

Rust, I.C. 1962: On the sedimentation of the Molteno sandstones in the vicinity of Molteno, C.P. *University of Stellenbosch (Ann)*, 37, 165-234.

Rutherford, M.C. and Westfall, R.H. 1986: The Biomes of Southern Africa - an objective categorization. *Memoirs of the Botanical Survey of South Africa*, 54, 1-98.

Seuffert, O., Herrig, K., Ollesch G. and Busche D. 1999: REI an integrated rainfall erosivity index for assessing and correlating rainfall structure, runoff and erosion. *Geokodynamic*, 20, 1-52.

Sumner, P.D., Hall, K.J., van Roy, J.L. and Meiklejohn, K.I. 2009: Rock weathering on the eastern mountains of southern Africa. Review and insights from case studies. *Journal of African Earth Sciences*, 55,236-244.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter W.E.L. 1982: *The crustal evolution of southern African 3.8 Billion years of earth history*. Springer-Verlag, 523 p.

Tooth, S. and McCarthy, T.S. 2004: Anabranching in mixed bedrock-alluvial rivers: the example of the Orange River above Augrabies Falls, Northern Cape, South Africa. *Geomorphology*, 57(2/3), 235-262.

Truswell, J.F. 1970: *An introduction to the historical geology of South Africa*. Purnell & Sons.

Turner, B.R. 1986: Tectonics and climatic controls on the continental depositional facies in the Karoo basin of northern natal South Africa. *Sedimentary Geology*, 46, 231-257

Turner, B.R. 1978: Sedimentary patterns of uranium mineralization in the Beaufort Group of the Southern Karoo (Gondwana) Basin, South Africa. In Miall, A.D. (Editor), *Fluvial Sedimentology*. Memoir Canadian Society of Petroleum Geology, 5, 831-848.

Turner, B.R. 1970: Facies analysis of the Molteno sedimentary cycle. In: S.H. Haughton (Editor). Proceedings 2nd IUGS Symposium on Gondwana Stratigraphy and Palaeontology, CSIR, Pretoria, South Africa, 321–341.

Vogel, J.C. 1978: Isotopic assessment of the dietary habits of ungulates. *South African Journal of Science*, 74, 298-301.

Wallbrink, P. J. and Murray, A. S. 1996: Distribution and variability of  $^7\text{Be}$  in Soils under different surface cover conditions and its potential for prescribing soil redistribution processes. *Water Resources Research*, 32(2), 467.

Walling, D.E. and Fang, D. 2003: Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change*, 39, 111-126.

Walling, D.E., Owens P.N. and Leeks, J.L. 1999: Finger printing sediments sources in the catchment of the river Ouse, Yorkshire, UK. *Hydrological processes*, 13, 955-975.

Weaver, A. 1991: The distribution of soil erosion as a function of slope aspect and parent material in Ciskei, Southern Africa. *Geojournal*, 23, 29-34.

Wellington, J.H. 1958: The evolution of the Orange River basin: some outstanding problems. *South African Geographical Journal*, 40, 3-30.

**Appendix A: Compton and Maake, 2007**

University of Cape Town

## Source of the suspended load of the upper Orange River, South Africa

John S. Compton and Livhuwani Maake  
 Department of Geological Sciences  
 University of Cape Town, Rondebosch 7700, South Africa  
 e-mail: john.compton@uct.ac.za; livhuwani.maake@goldfields.co.za

© 2007 September Geological Society of South Africa

### ABSTRACT

The Orange River is one of the World's most turbid; delivering 60 million tons of sediment each year to the western margin of South Africa. Much of this sediment is believed to be from soil erosion, an increasing environmental threat to sustainability in southern Africa. This study focuses on the upper reaches of the Orange River above the Caledon River confluence, because it is here that high rainfall and topographic relief of the Drakensberg Mountains produce most of the Orange River's suspended load. Comparison of grain size, mineralogy and geochemistry of the suspended sediment load with catchment bedrock soils provides an estimate of the source of the suspended sediment. Major and trace element ratios indicate that the suspended sediment load is primarily derived from Karoo (upper Beaufort and Stormberg groups) sedimentary rocks rather than Drakensberg basalt. The Caledon River carries the largest fine-mud suspended load primarily from the erosion of Karoo sedimentary rock soils. The organic carbon content of the suspended load ranges from 1.0 to 1.3 weight % with  $\delta^{13}\text{C}$  values that range from  $-19.7$  to  $-16.9$ ‰ PDB. The  $\delta^{13}\text{C}$  values of the organic fraction of soils is highly variable ( $-21.5$  to  $-12.7$ ‰ PDB) and reflect the mix of C3 and C4 vegetation in the catchment area.

### Introduction

Since the break up of Gondwana, the Orange River has delivered large amounts of sediment to the western continental margin of South Africa. The vast majority of the Orange River's terrigenous sediment was delivered during the warm and humid climates of the middle and late Cretaceous (Dingle and Hendey, 1984; de Wit, 1999). Terrigenous sedimentation on the margin has tapered off during the increasingly arid climates of the late Cenozoic so that now most runoff from the 0.9 million km<sup>2</sup> Orange River catchment area is derived from the high-rainfall areas of the Upper Orange River with only 1.8% derived from below the Orange/Vaal confluence (Kriel, 1972; Benade, 1988). Although the mean annual runoff of 11 km<sup>3</sup>/year is small in comparison with most other major rivers, the Orange River carries a relatively large suspended sediment load and ranks as the most turbid river in Africa and the fourth most turbid in the World (Bremner *et al.*, 1990).

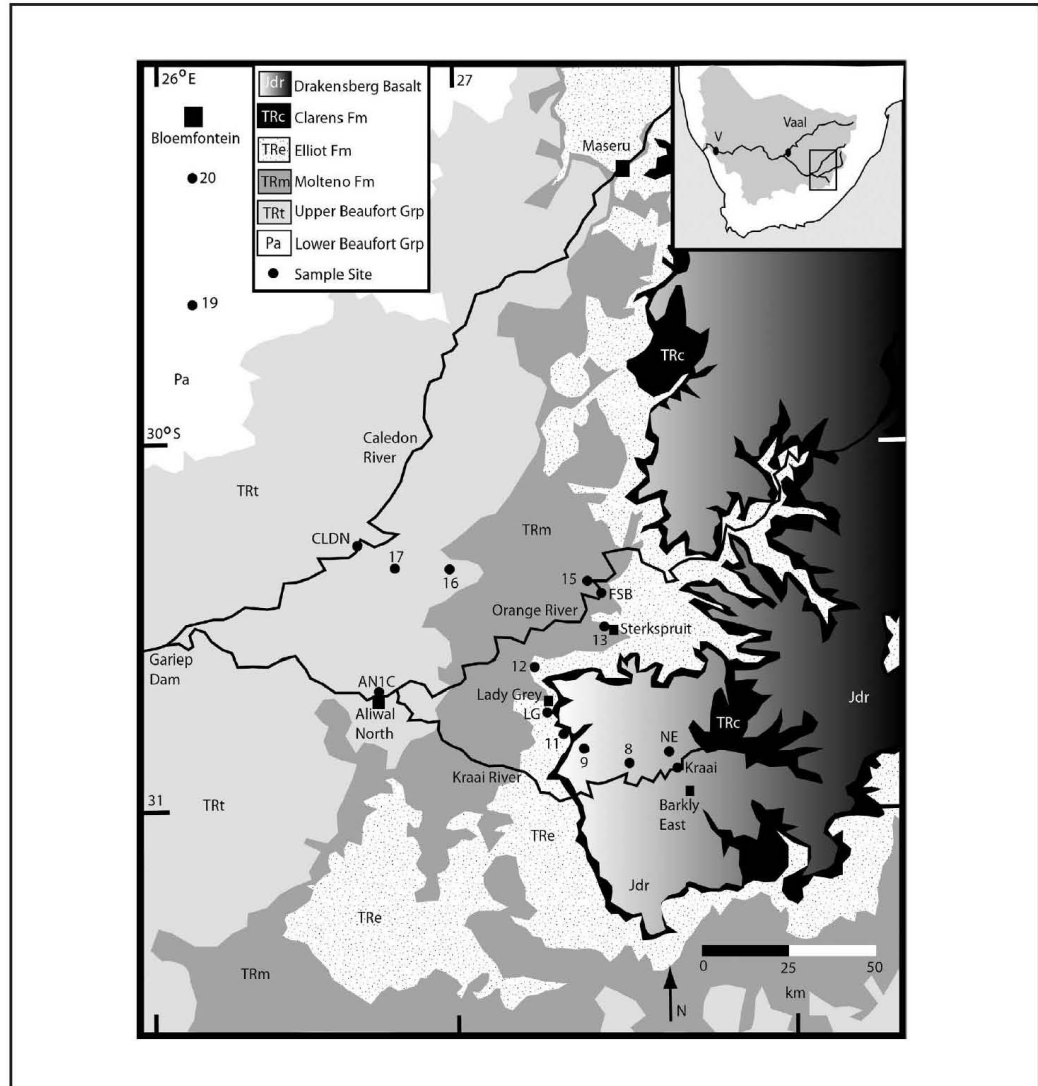
The Orange River originates in the Drakensberg Mountains of Lesotho and flows west for 2300 km across an increasingly arid interior plateau (Figure 1). Most of the sediment delivered by the Orange River to the Atlantic Ocean ends up widely dispersed across the western continental margin. The sand fraction of the Orange River sediment load is transported north to the Namib Desert by longshore drift driven by high-energy waves and strong southerly winds (Rogers, 1977; Rogers and Bremner, 1991; Rogers and Rau, 2006), while the mud fraction is transported offshore and south by a poleward undercurrent to form the mudbelt (Mabote *et al.*, 1997). The depositional history of deposits such as the mudbelt on the western margin is related, in part, to the input of Orange River sediment (Herbert and Compton, 2007). The Orange River suspended load is

therefore important in understanding the source of offshore deposits and linkages between the terrestrial and marine realms.

Land degradation, in the loss of valuable topsoil and deep erosional gullies (dongas) which scour sediment-filled valleys and bedrock, is an increasingly large threat to sustainable development in southern Africa (Garland *et al.*, 1999). This study includes regions documented to have experienced high erosional activity in the recent past (Rooseboom, 1975; Seuffert *et al.*, 1999). Determining the source of the suspended sediment load can help in land management and the development of effective land use policies (Conley and van Niekerk, 2000). For example, variations in the clay mineralogy of the suspended load have been used to infer the source area of specific Orange River flood events (Bremner *et al.*, 1990). In this paper the texture, mineralogy and geochemistry of the suspended river sediment and the soils of the major bedrock types of the catchment area are compared to determine the source of the suspended load of the upper Orange River above the confluence with the Caledon River.

### Geological setting

The Orange River catchment receives primarily summer rainfall, which varies from 700 to 800 mm/year in the far eastern catchment to less than 100 mm/year in the far western catchment. Higher rainfall in the eastern catchment is explained by orographic rainfall resulting from the high elevation of the region. The high rainfall area also corresponds to areas of high sediment production (Rooseboom, 1975; Seuffert *et al.*, 1999) which occur primarily in the Upper Orange River above the confluence with the Vaal (Wellington, 1958). The focus of this paper is on the uppermost reaches of

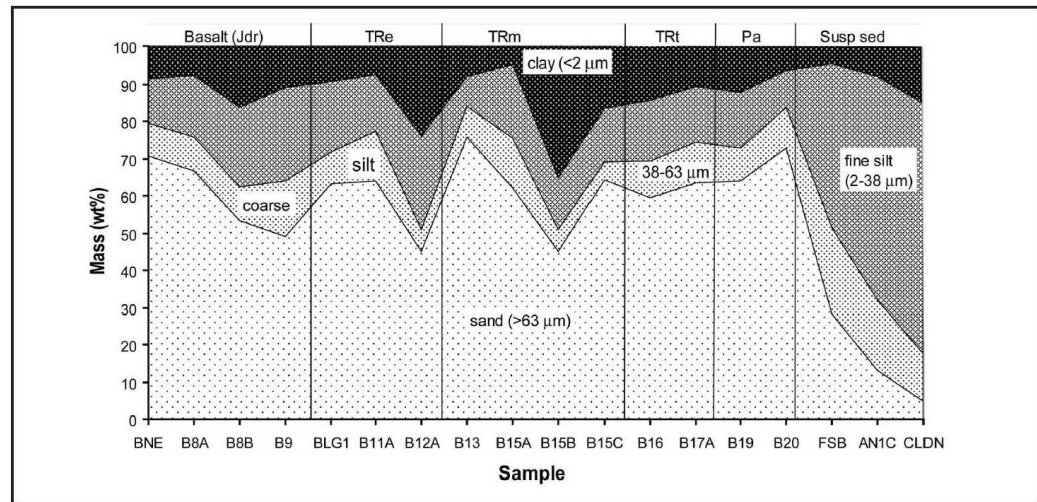


**Figure 1.** Geological map of the study area (modified after the Council for Geosciences 1:1 000 000 map) showing location of sample sites and major river courses. Inset of southern Africa shows catchment area of the Orange River shaded in grey and sample sites on the lower Vaal River and Orange River at Violsdrif (V).

the Orange River above the confluence with the Caledon River (Gariep Dam; Figure 1) because most Orange River suspended sediment is produced upstream of the Caledon-Orange river confluence (Bremner *et al.*, 1990). In addition, no major dams occur above the Caledon confluence with the exception of the Katse Dam in the Lesotho Highlands, completed in 1997.

The Orange River catchment above the Caledon confluence includes continental sedimentary rocks of the Beaufort Group, as well as the Molteno, Elliot and Clarens formations of the Stromberg Group. These sedimentary rocks are capped by the Drakensberg

Group succession of flood basalts (Figure 1). Together, these rocks constitute the upper portion of the Karoo Supergroup. Beaufort Group sediments were deposited in the Late Triassic in an intracratonic basin, with the sediments derived from a volcanically active source located to the south and west (Turner, 1978; 1990). The Beaufort Group primarily consists of sandstones, siltstones and mudstones as well as some lenticular limestone and abundant calcareous concretions (Tankard *et al.*, 1982). The sediments of the Molteno Formation are an intracratonic, bedload-dominated fluvial wedge derived from a tectonically active source



**Figure 2.** Grain size distribution of soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

to the south and south east (Rust, 1962; Turner, 1970) and are somewhat coarser grained compared to those of the upper Beaufort Group. The Elliot Formation was deposited in a fluvio-lacustrine environment within a long-established internal drainage basin, remote from any marine shoreline. Fine-grained red beds and lenticular yellow sandstones make up the Elliot Formation, and represent a reduction in fluvial energy and bed load in comparison to the underlying Molteno Formation (Tankard *et al.*, 1982). The Clarens Formation is made up of quartzose aeolian sands, derived in general from the preceding fluvial deposits of the Molteno and Elliot formations. Drakensberg volcanism terminated Karoo sedimentation approximately 182 million years ago and heralded the break up of Gondwana. Flood basalts produced vast lava fields, of which the 140 000 km<sup>2</sup> Drakensberg plateau is an erosional remnant (Tankard *et al.*, 1982). In addition to flood basalts, the region is cut by numerous dolerite dykes and sills (not shown in Figure 1).

#### Methods

River water samples were collected from the Orange River upstream of the bridge at Aliwal North (AN1C) and upstream of the bridge at the Free State Border (FSB) in February 2006 (Figure 1). The Caledon River (CLDN) was sampled upstream of the N6 bridge between the towns of Rouxville and Smithfield. The Kraai River was sampled downstream of the R58 bridge north of Barkly East (Kraai) and a tributary to the Kraai River was sampled at the town of Barkly East (BE). River water samples were collected from the edge of the riverbank by submerging, in one rapid and continuous motion, 5-10 litre plastic buckets to a depth of approximately 30 cm below the surface of the river. River water suspended sediment was collected by settling in the

field and filtration through a 0.45 micrometre ( $\mu\text{m}$ ) filter in the laboratory. Collected suspended sediment was dried under vacuum (<100 mtorr) in a VirTis freeze drier at  $-85^{\circ}\text{C}$  at the University of Cape Town (UCT). Soil samples were collected from road cut or riverbed exposures of the major rock types in the catchment area. The suspended sediment load (but no other data) was determined for a second set of river water samples collected in January 2007 from the Aliwal North site and Caledon River site as well as from the Vaal River 25 km upstream of the town of Douglas and at Vioolsdrif near the mouth of the Orange River (Figure 1; Table 1).

**Table 1.** Suspended sediment load of river samples in milligrams/litre.

Location	mg/l	Date	mg/l	Date
Barkly East	50	Feb 2006		
Kraai	220	Feb 2006		
FSB	3400	Feb 2006		
AN1C	2600	Feb 2006	460	Jan 2007
CLDN	3000	Feb 2006	520	Jan 2007
Vaal			<20	Jan 2007
Vioolsdrif			60	Jan 2007

The settled suspended river samples and bulk soil samples were wet sieved into sand (>63  $\mu\text{m}$ ) and coarse silt (38 to 63  $\mu\text{m}$ ) size fractions. The mud was separated into fine silt (2 to 38  $\mu\text{m}$ ) and clay (<2  $\mu\text{m}$ ) size fractions by allowing the suspended mud fraction to settle for 20 minutes and assuming that the fine silt particles follow Stoke's law (spherical grains with a density of quartz). Mineralogy was determined by petrography of thin sections of bedrock, sand and silt size fractions

**Table 2.** Major oxide composition of soil and river suspended sediment (Susp sed) samples by XRF.

Sample Type	BNE	B8A	B8B	B9	BLG1	B11A	B12A	B13	B15A	B15B	B15C	B16	B17A	B19	B20	FSB	AN1C	CLDN
	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	River bank	River bank	Susp sed	Susp sed	Susp sed
Bedrock	Jdr	Jdr	Jdr	Jdr	TRc	TRc	TRc	TRm	TRm	TRm	TRm	TRt	TRt	Pa	Pa	Water	Water	Water
SiO <sub>2</sub>	51.61	45.41	50.85	49.55	77.71	75.92	59.91	78.88	55.88	73.45	79.30	76.51	74.14	72.69	78.94	62.47	65.64	62.47
TiO <sub>2</sub>	1.83	1.05	1.43	1.11	0.53	0.53	0.41	0.60	0.95	0.63	0.53	0.61	0.65	0.64	0.66	0.78	0.80	0.97
Al <sub>2</sub> O <sub>3</sub>	13.91	13.97	13.51	13.51	9.85	8.00	16.81	8.01	13.38	9.95	7.57	8.56	9.63	8.92	7.94	13.58	13.10	16.32
Fe <sub>2</sub> O <sub>3</sub>	12.63	10.93	10.22	10.65	3.60	2.17	5.82	3.40	9.38	4.29	3.20	3.71	4.24	3.21	2.50	6.14	5.51	5.80
MnO	0.21	0.16	0.15	0.16	0.04	0.15	0.08	0.07	0.16	0.05	0.09	0.09	0.09	0.07	0.06	0.12	0.11	0.12
MgO	4.68	6.12	3.37	6.22	0.83	0.86	2.04	1.48	4.25	1.13	0.73	1.08	1.16	1.29	0.87	3.03	2.45	1.60
CaO	5.55	7.00	3.76	7.47	0.30	2.90	1.08	1.85	5.49	1.90	0.90	1.22	0.99	2.49	1.50	3.68	2.78	0.99
Na <sub>2</sub> O	2.28	2.03	1.75	2.11	0.71	1.69	0.51	1.68	2.25	0.81	0.83	1.27	1.61	1.93	1.86	1.35	1.25	0.51
K <sub>2</sub> O	0.87	0.89	1.17	0.82	1.55	1.97	1.51	1.51	1.10	1.57	1.36	1.32	1.54	2.17	1.94	1.11	1.34	2.21
P <sub>2</sub> O <sub>5</sub>	0.08	0.20	0.12	0.13	0.05	0.05	0.04	0.05	0.10	0.05	0.04	0.08	0.07	0.12	0.07	0.10	0.09	0.09
SO <sub>3</sub>	0.02	0.01	0.01	0.03	0.00	0.03	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.05	0.03	NM	NM	NM
Cr <sub>2</sub> O <sub>3</sub>	0.06	0.05	0.06	0.07	0.02	0.01	0.02	0.03	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.04	0.05
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01
H <sub>2</sub> O-	1.67	3.24	4.13	2.59	2.27	0.95	3.03	0.98	2.62	1.87	1.28	1.82	1.84	1.44	0.88	NM	NM	NM
LOI	4.65	9.53	9.87	6.41	2.59	4.55	8.55	2.29	4.72	4.82	3.56	2.78	4.22	5.79	2.72	10.51	7.02	8.96
Total	100.06	100.60	100.40	100.83	100.05	99.79	99.82	100.85	100.35	100.56	99.42	99.08	100.23	100.82	99.99	99.98	100.13	100.09
Mg+Na/K	8.02	9.20	4.38	10.17	0.99	1.29	1.69	2.10	5.91	1.24	1.15	1.78	1.80	1.48	1.41	3.95	2.76	0.95

NM=not measured

**Table 3.** Trace element composition of soil and river suspended sediment (Susp sed) samples by XRF.

Sample Type	BNE	B8A	B8B	B9	BLG1	B11A	B12A	B13	B15A	B15B	B15C	B16	B17A	B19	B20	FSB	AN1C	CLDN
	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	River bank	River bank	Susp sed	Susp sed	Susp sed
Bedrock	Jdr	Jdr	Jdr	Jdr	TRc	TRc	TRc	TRm	TRm	TRm	TRm	TRt	TRt	Pa	Pa	Water	Water	Water
Nb	11.6	8.5	11.5	6.6	8.1	9.3	14	9.7	8.7	9	9	8.1	10.9	8.7	7.6	1	3	8
Zr	186	86	164	114	333	375	138	321	163	282	362	289	330	248	299	183	232	203
Y	16	17	17	16	19	22	37	17	18	22	23	20	22	19	16	28	28	33
Sr	107	121	101	130	33	80	42	74	127	60	39	77	70	162	136	133	120	88
Rb	16	12	21	13	46	50	56	36	23	53	45	39	43	53	45	31	38	80
Pb	<4.7	<4.7	<4.7	<4.7	5.9	7.1	21.4	<4.7	<4.7	<4.7	6.8	4.8	5.3	9	<4.7	4	57	20
Zn	81	153	92	96	35	30	73	28	86	48	30	42	44	39	20	57	58	71
Cu	83	106	87	86	32	25	34	34	83	40	34	38	39	32	27	11	10	11
Ni	97	122	130	116	57	48	51	62	109	59	59	58	63	54	51	77	67	64
Co	44	40	41	45	8	7	10	12	38	11	15	14	14	10	8	32	28	28
Mn	1603	1235	1220	1258	196	1199	559	456	1205	329	631	648	665	447	347	NM	NM	NM
Cr	330	299	365	379	99	66	76	134	265	110	99	118	118	103	99	125	114	101
V	364	224	246	273	74	44	57	80	203	82	65	81	87	72	54	106	90	84
Ba	281	234	323	236	358	440	624	346	336	330	398	367	417	525	480	279	268	473
Sc	41.8	32.7	34.2	37.8	9.9	7.4	10.6	10.3	37.4	13.2	9	10.5	11.5	9.2	7.6	NM	NM	NM
S	350	554	452	298	454	233	164	115	73	103	142	177	281	718	645	NM	NM	NM
(Rb+Ba)/ (Ni+Cr+V)	0.38	0.38	0.46	0.32	1.76	3.10	3.70	1.38	0.62	1.53	1.99	1.58	1.72	2.52	2.57	1.01	1.13	2.22

NM=not measured

and X-ray diffraction (XRD) analysis of the fine silt and clay size fractions mounted as wet slurries on glass slides. Bulk soil and settled river water samples were freeze dried and powdered for elemental analysis by X-ray fluorescence (XRF) and organic carbon analyses at UCT. The three suspended river sediment samples were analysed by XRF at the University of Stellenbosch. The results are assumed to be representative of the long-term erosion of the catchments sampled because of the high discharge and sediment load of the three river waters sampled in February 2006. This assumption will be tested by the future sampling and analysis of the suspended sediment load at the three sites.

Carbonate carbon (mostly present as  $\text{CaCO}_3$ ) in freeze-dried samples was removed by reaction with a buffered 0.5M acetic acid-sodium acetate solution with a pH of five for a minimum of five hours. Samples were rinsed three to four times with distilled water, until the pH was neutral. The carbonate-free samples were run on a Thermo Finnigan Delta Plus XP stable light isotope mass spectrometer at UCT to determine the organic carbon content and isotope composition. Uncertainty in the carbon isotope measurements is  $\pm 0.1\text{‰}$  and  $\delta^{13}\text{C}$  values are reported corrected to in-house reference materials calibrated against the PDB (Pee Dee Belemnite) international standard.

### Results

The Karoo sedimentary rocks consist mainly of quartz, feldspar, mica, calcite and rock fragments. Quartz and feldspar are dominant (70 to 80%), whereas mica, calcite and rock fragments occur in subordinate to minor quantities. The basalt bedrock consists of plagioclase, orthopyroxene, olivine, and clinopyroxene, and zeolite-filled amygdals are common. Soil samples of Karoo sedimentary rocks are predominantly made up of quartz and feldspar, with lesser amounts of mica and calcite. The clay-size fraction of Karoo sedimentary rock soils is dominated by illite and smectite and by smectite in the basalt soils.

The grain size distributions of most soils sampled are similar and are dominated by 50 to 70% sand (Figure 2). The suspended sediment load in February 2006 was 3.4 grams/litre (g/l) at the Free State Border (FSB), 2.6 g/l at Aliwal North (AN1C) and 3.0 g/l for the Caledon River (CLDN) at the N6 bridge (Table 1). The suspended load of the Kraai River was 0.22 g/l and 0.05 g/l for a tributary of the Kraai River sampled at the town of Barkly East. Rainfall and suspended sediment loads were significantly less in January 2007 (Table 1). The suspended river sediments are dominated by 40 to 60 weight % fine silt with sand, coarse silt and clay each varying between 10 and 20% (Figure 2). Suspended river sediments contain quartz, feldspar and clay minerals. Smectite dominates over illite in the clay-size fraction.

The major oxide and trace element composition of Karoo sedimentary rock soils is distinct from basalt soils. River suspended sediment elemental compositions tend to be intermediate between the two. Basalt soils have

similar or higher major oxide contents than Karoo sedimentary rock soils, except for silica and potassium (Table 2) and basalt soils have similar or higher trace element contents than Karoo sedimentary rock soils, except for Ti, Rb, Zr, Pb and Ba (Table 3). The major oxide ratio of  $(\text{Mg} + \text{Na})/\text{K}$  has a mean value of 7.9 for basalt soils and 1.4 for Karoo sedimentary rock soils (excluding sample B15A) (Figure 3) and the trace element ratio  $(\text{Rb} + \text{Ba})/(\text{Ni} + \text{Cr} + \text{V})$  has a mean value of 0.4 for basalt soils and 2.0 for Karoo sedimentary rock soils (excluding sample B15A) (Figure 4).

The organic carbon content of the soil samples ranges from 0.2 to 2.9% and for the suspended river sediment from 1.0 to 1.3% (Table 4). The percentage of organic carbon in basaltic soils (1.3 to 2.9 weight %) is higher than in Karoo sedimentary rock soils (0.2 to 1.6 weight %). The organic carbon content is reported on a carbonate-free basis, but the carbonate content of these samples is low, ranging from 0.5 to 5 weight %. The  $\delta^{13}\text{C}$  values of the organic carbon in the soil samples range from  $-21.5$  to  $-12.7\text{‰}$  PDB and from  $-19.7$  to  $-16.9\text{‰}$  PDB for the suspended river sediment samples. Duplicate  $\delta^{13}\text{C}$  analyses can vary by up to 20% and reflect inhomogeneity of the small (2 mg) sample size, as well as analytical error.

**Table 4.** Organic carbon (OC) content on a carbonate-free basis and organic matter isotope composition of soil and river suspended sediment (Susp sed) samples.

Sample	Soil bedrock	OC (weight %)	$\delta^{13}\text{C}$ (‰ PDB)
BNE	Basalt (Jdr)	2.00	-13.31
B8A	Basalt (Jdr)	2.65	-18.40
B8A(D)		2.90	-18.51
B8B	Basalt (Jdr)	2.45	-12.66
B9	Basalt (Jdr)	1.34	-16.15
BLG1	Elliot (TRe)	0.74	-15.25
BLG1(D)		0.73	-14.90
B11A	Elliot (TRe)	0.63	-21.45
B11A(D)		0.65	-21.41
B12A	Elliot (TRe)	0.91	-12.98
B13	Molteno (TRm)	0.33	-18.38
B15A	Molteno (TRm)	0.28	-16.17
B15B	Molteno (TRm)	0.24	-17.81
B15C	Molteno (TRm)	0.43	-15.10
B16	Beaufort (TRt)	0.51	-15.04
B17A	Beaufort (TRt)	0.86	-14.26
B17A(D)		0.90	-14.63
B19	Beaufort (Pa)	1.57	-17.53
B20	Beaufort (Pa)	0.43	-19.89
B20(D)		0.38	-19.80
FSB	Susp sed	1.34	-18.57
FSB(D)	Susp sed	1.24	-19.15
AN1C	Susp sed	1.28	-19.47
AN1C(D)	Susp sed	1.09	-19.74
Caledon	Susp sed	0.98	-16.88
Caledon(D)	Susp sed	1.18	-17.05

D = duplicate

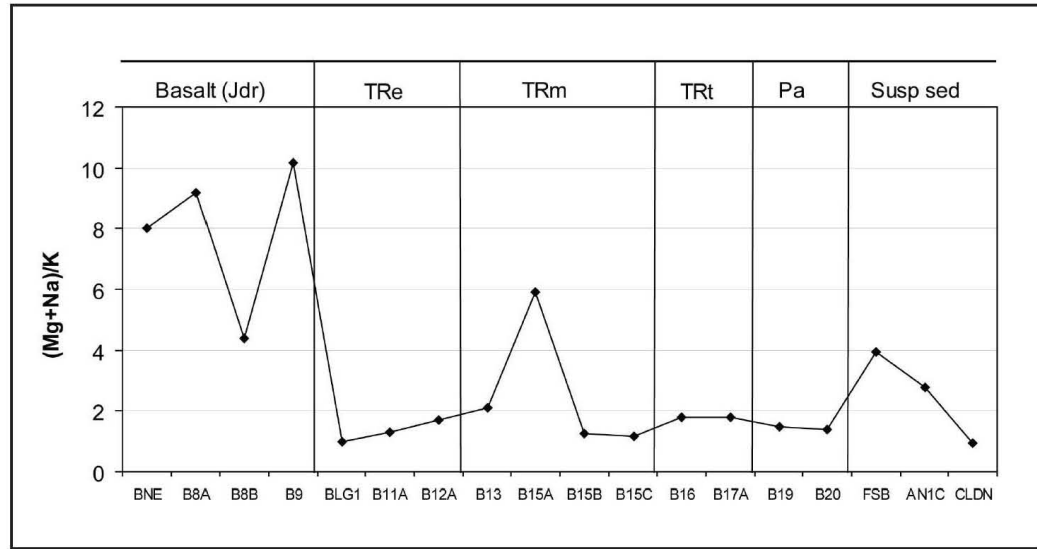


Figure 3. Ratio of major elements (Mg + Na)/K determined by XRF (Table 1) for soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

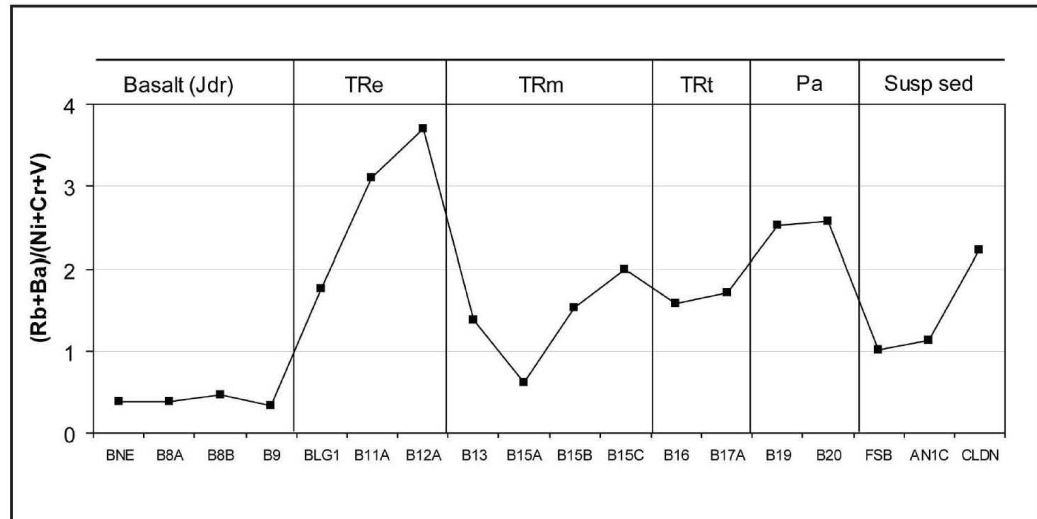


Figure 4. Ratio of trace elements (Rb + Ba)/(Ni + Cr + V) determined by XRF (Table 2) for soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

## Discussion

### Suspended sediment load

The suspended sediment load varies significantly among the rivers sampled in this study (Table 1). Rivers draining the basalt bedrock of the Drakensberg Mountains have a low suspended sediment load compared to those draining Karoo sedimentary rocks. In the field, clear river water was observed flowing over the bare basalt bedrock surfaces of Orange River tributaries. The banks

of these basalt bedrock tributaries had dark clayey soils tightly bound by abundant plant roots. It therefore appears that the dense vegetation cover (mostly grasses) and hard basalt bedrock limit suspended sediment production, despite steep slopes and rapid flow rates. The suspended sediment load increases after the rivers cut into the generally softer and, therefore, more easily eroded underlying Karoo sedimentary rocks (Bremner *et al.*, 1990; and references therein).

The grain size of the river suspended load varies in relation to elevation and bedrock type. The greatest amount of sand and highest total suspended load occurs at the Free State Bridge (FSB), where the gradient is steepest. The least amount of sand occurs at the Caledon River (CLDN), which has a low topographic gradient (Figure 2). The large decrease in grain size between the suspended river sediment and the bulk soil samples reflects the preferential erosion of finer grained material from soils and the sampling of the surface flow of the river with much of the sand carried near or on the river bed. The amount of suspended sediment load is mostly related to the amount of runoff as seen in the much greater load during the high rainfall of 2006 compared to 2007 (Table 1). Previous studies have shown that most sediment is transported during Orange River floods and that the Caledon River carries the largest proportion of fine mud (Bremner *et al.*, 1990; and references therein).

The low suspended load of the lower Vaal River (most of which was living green algae and not sediment) is related to the low topographic gradient of the Vaal catchment and the large dams upstream, so that the modern Vaal River resembles a linear lake more than a flowing river. The generally rocky, sediment-starved river bed and banks, and small palaeoflood deposits indicate a low sediment load of the Vaal River. Prior to the building of dams, the Vaal River contributed 22% of the mean total water discharge, but carried less than 5% of the total sediment load of the Orange River based on Department of Water Affairs data collected between 1928 and 1943 (Rogers, 1977). The sediment load of the Orange River has been greatly reduced by sediment trapping in dams as reflected in the low sediment load at the border crossing at Vioolsdrif. Mean sediment discharge has dropped from 60 million t/year between 1929 and 1969 to 17 million t/year after the building of major dams since 1970 (Bremner *et al.*, 1990). The reduction in total sediment load of 72% is similar to the mean sand and coarse silt content of 70.5% of soils from this study (Figure 2) and suggests that most of the sand and coarse silt grains of eroded catchment soils is trapped by dams.

#### **Geochemistry of the suspended load**

Sediment derived from Karoo sedimentary rock soils can be differentiated from basalt soils from their greater abundance of quartz, K-feldspar and illite. X-ray diffraction profiles provide a qualitative estimate of these mineralogical differences but variations in the amount of clay minerals is difficult to quantify by XRD alone. Differences in mineralogy lead to differences in major and trace element geochemistry that are more easily quantified by XRF. The catchment area bedrock can be divided into two geochemical end members. The Drakensberg Group basalts and dolerite dykes have a mafic igneous rock composition and the Karoo sedimentary rocks have a predominately sialic continental crust composition. Element ratios can be used to differentiate between these two bedrock sources

because the suspended load generally provides an integrated, homogeneous sampling of the eroded catchment bedrock and soil. The major oxide ratio (Mg + Na)/K is high (mean value of 7.9) for the basalt soil end member whereas the Karoo sedimentary rock soil end member has a low mean value of 1.4 (Figure 3). Sample B15A was excluded from calculating the mean for the Karoo sedimentary rocks because it was derived largely from local dolerite dykes rather than from the Molteno Formation. The trace element ratio (Rb + Ba)/(Ni + Cr + V) also discriminates between basalt (mean of 0.4) and Karoo sedimentary rock soils (mean of 2.0, excluding sample B15A) (Figure 4). The major oxide ratio shows more variability in basalt than in Karoo sedimentary rock soils and vice versa in the case of the trace element ratio.

The difference in the element ratios between the river sampled at the Free State Border and Aliwal North is small but indicates an increasing Karoo sedimentary rock soil contribution (Figures 3 and 4). The difference in the element ratios is most pronounced in the Caledon River sample which shows a predominantly Karoo sedimentary rock soil signal. The geochemical trend among the river water samples is consistent with the percentage of basalt and Karoo sedimentary rock within their catchment areas. A relatively small percentage of Caledon River tributaries above the sample site CLDN drain basalt terrains in comparison to tributaries upstream from Aliwal North (Figure 1). The Caledon River drains mostly Karoo sedimentary rocks, which make up approximately 89% of its catchment area, and contain abundant illite and K-feldspar rich in the elements K, Rb and Ba. The Orange River catchment above the Free State Border primarily drains basalt bedrock with only 28% of the catchment having upper Karoo sedimentary bedrock. The slightly greater Karoo sedimentary rock soil signal at Aliwal North reflects an increased proportion of Karoo sedimentary rocks (35%) in the catchment above Aliwal North.

Therefore, the Caledon River contributes a significant amount of the suspended fine mud carried by the Orange River sourced from the erosion of Karoo sedimentary rocks. Previous workers have argued the same (Harmse, 1974; Rooseboom and Harmse, 1979) relating the large increase in the sediment load of the Caledon River to the easily eroded Elliot Formation and, in particular, upper Beaufort Group (TRe and TRt on Figure 1, respectively). The question still remains as to whether the suspended load of the Caledon River is derived primarily from bedrock or topsoil erosion. Erosional features in the landscape clearly indicate that both bedrock and soil erosion are active (Figure 5) and the study area lies within a region, identified from aerial photographs, to have experienced significant erosion (Seuffert *et al.*, 1999). In the case of deeply scoured out bedrock (dongas and gullies), the volume of bedrock eroded is far greater than that of topsoil (Figure 5). But in the study area, few dongas of the dimensions shown in Figure 5 were observed. Therefore, topsoil



**Figure 5.** (A) A major erosional gully (donga) outside the town of Sterkspruit (Figure 1) showing sources of eroded topsoil (ploughed orange fields and uppermost, dark coloured soils on gully banks) and bedrock sediment (light colour rock of the Molteno and Elliot formations exposed below topsoil). The Clarens Formation (light colour rocks) and overlying Drakensberg basalt are exposed in the mountains in the background. Note eroded out vertical cement weir 2 m in height in river channel on the right hand side of photograph. (B) Same erosional gully as in (A) but photographed approximately one kilometre down stream showing slumping of vertically-cut river channel walls. Road in foreground is the R726 north of Sterkspruit.

erosion may be less obvious but more widespread than bedrock erosion. We do not have sufficient geochemical data to use elemental ratios to differentiate between Karoo bedrock and soil sources of the suspended sediment load of the Caledon River, but the relative contributions of bedrock and soil to the suspended load can be addressed to some extent by the organic carbon data (Table 4).

#### **Organic carbon**

The organic carbon data include the amount of organic carbon and its isotope composition (Table 4). The amount of organic carbon in topsoil is expected to be generally higher than that in Karoo sedimentary bedrock. This is because, although thin coal seams and pockets of plant material have been reported from the Karoo sedimentary rocks of the study area (Haughton, 1969; Tankard *et al.*, 1982), most are sandstones and purple and green mudstones of significantly lower organic carbon content than their grassland topsoil. The mean  $\delta^{13}\text{C}$  value of organic matter eroded from Karoo bedrock is expected to be around  $-26\text{‰}$ , the mean  $\delta^{13}\text{C}$  value of plants which follow the Calvin–Benson (C3) photosynthetic pathway. This is because plants, such as grasses, which follow the Hatch–Slack (C4) pathway with mean  $\delta^{13}\text{C}$  values of  $-12\text{‰}$  had not yet evolved at the time of Karoo sediment deposition.

The  $\delta^{13}\text{C}$  value of soil organic matter from the study area shows a wide range of values from those typical of C4 plants ( $-12.7\text{‰}$ ) to values as low as  $-21\text{‰}$  (Table 4). Most of the study area lies within the grassland biome (Mucina *et al.*, 2005) and, from the road, tall grasses appear to dominate the vegetation. However, in walking through the vegetation, significant numbers of small, low-lying woody shrubs were observed in places. Therefore, it appears that the wide spread in  $\delta^{13}\text{C}$  values for soil organic carbon of this study reflects a wide range in the relative proportion of C3 woody shrubs and C4 grasses.

The mean  $\delta^{13}\text{C}$  values of  $-18.9\text{‰}$  and  $-19.6\text{‰}$  for the Free State Border and Aliwal North river sites, respectively, suggests an approximately equal mixture of C3 ( $-26\text{‰}$ ) and C4 ( $-12\text{‰}$ ) plant material in their suspended loads. Yet the catchment area of the Orange River above the Free State Border site is dominated by Senqu Highland Grassland, with less extensive valley fill areas covered by Senqu Montane Shrubland (Mucina *et al.*, 2005). This suggests that a greater proportion of organic matter is derived from the valley-fill areas than from the steep mountain slopes, consistent with the field observation that basalt soils are tightly bound by densely rooted grasses. In addition to greater retention of organic matter by grassland soils, C3 woody plants may have a greater resistance to degradation in the soil and are more likely than C4 plants to end up in the river suspended load.

The organic carbon (OC) content of the suspended load of the Caledon River (1.1 weight %) is significantly

greater than the mean organic carbon content (0.6 weight %) of catchment soils (Table 4). In contrast, Orange River suspended load organic carbon content (1.3 weight % at FSB and 1.2 weight % at AN1C) is less than the mean for the basalt soils (2.1 weight % OC). In addition, the  $\delta^{13}\text{C}$  value of organic matter from the Caledon River ( $-17.0\text{‰}$ ) is less negative than the upper Orange samples from the Free State Border ( $-18.9\text{‰}$ ) and Aliwal North ( $-19.6\text{‰}$ ) sites, which suggests that the Caledon River carries a greater percentage of eroded topsoil with significantly more C4 plant material. Therefore, the higher organic carbon content and its more positive  $\delta^{13}\text{C}$  value suggests that the Caledon River suspended load has a significant eroded topsoil source, whereas the suspended load of the Orange River above Aliwal North has a significant bedrock source.

#### **Conclusions**

The source of the suspended sediment load of the Orange River can be inferred from the mineralogical and geochemical differences of the two major bedrock types of the catchment area: basalt and Karoo sedimentary rocks. Basalt soils contain abundant rock fragments, plagioclase feldspar and smectitic clay minerals, whereas Karoo sedimentary rock soils contain abundant quartz, K-feldspar and illitic as well as smectitic clay minerals. These mineralogical differences are made quantifiable by the major oxide ratio  $(\text{Mg} + \text{Na})/\text{K}$  and the trace element ratio  $(\text{Rb} + \text{Ba})/(\text{Ni} + \text{Cr} + \text{V})$ . These ratios clearly differentiate basalt and Karoo sedimentary rock soils and indicate that most of the Orange River suspended load is derived from erosion of Karoo sedimentary bedrock and soils. In particular, the Caledon River delivers most of the fine mud suspended load of the Orange River. Although it is difficult to determine the relative contributions of Karoo sedimentary bedrock and topsoil erosion to the suspended load, the organic carbon content and isotope composition suggest that much of the suspended load of the Caledon River is derived from the erosion of topsoil. Future, more detailed geochemical analyses will allow for a more complete evaluation of eroded sediment sources to the Orange River.

The Drakensberg Mountains receive the greatest amount of rainfall and have the steepest slopes of the Upper Orange River catchment. However, the hard basalt bedrock combined with densely rooted grassland vegetation limit the amount of erosion. The sediment load is dominated by the more easily eroded underlying Karoo sedimentary rocks where the river down cuts through the Drakensberg Mountains. It is this difference in erosion rate that makes the cliff-faced Drakensberg Mountain basalts such a prominent topographic feature of southern Africa. Therefore, most of the sediment carried to the western margin by the Orange River is derived from Karoo sedimentary rocks rather than from basalt. However, the sediment derived from Karoo sedimentary rocks is dominated by quartz sand, much of which ultimately ends up in the Namib Desert.

The terrigenous mud of the offshore mudbelt is largely derived from weathering of the upper Karoo sedimentary rocks, but will also include mud derived from the weathering of basalt. Eroded sand and silt sized basalt rock fragments can undergo further weathering downstream to produce the clay mineral smectite much of which is deposited in the mudbelt.

#### Acknowledgements

We thank C Herbert for assisting with field and laboratory work and A Villaros for running the XRF analyses at University of Stellenbosch. J Rogers and G Garland provided useful comments and suggestions. This research was funded by the National Research Foundation (partially through funds to the Inkaba ye Africa program) and the University of Cape Town. This is Inkaba yeAfrica contribution number 11.

#### References

- Benade, C. (1988). Episodic flood events in the Orange River system – an ecological perspective. Proceedings of Conference: Floods in perspective, Pretoria, Paper 3.6, 1-16.
- Bremner, J.M., Rogers, J. and Willis, J.P. (1990). Sedimentological aspects of the 1988 Orange River floods. *Transactions of the Royal Society of South Africa*, **47**, 247-294.
- Conley, A.H. and van Niekerk, P.H. (2000). Sustainable management of international waters; The Orange River case. *Water Policy*, **2**, 131-149.
- De Wit, M.C.J. (1999). Post-Gondwana drainage and the development of diamond placers in western South Africa. *Economic Geology*, **94**, 721-740.
- Dingle, R.V. and Hendey, Q.B. (1984). Mesozoic and Tertiary sediment supply to the western Cape Basin and paleodrainage systems in southwestern Africa. *Marine Geology*, **56**, 13-26.
- Garland, G., Hoffman, T. and Todd, S. (1999). Chapter 6: Soil Degradation. In: M. T. Hoffman, S. Todd, Z. Ntshona, and S. Turner (Editors), Land degradation in South Africa, *Department of Environmental Affairs and Tourism, South Africa*, 69-107.
- Harmse, H.J. von M. (1974). An evaluation of the possible influence of rock and soil on erosion in the catchment area of the Hendrik Verwoerd Dam. In: E. M. Van Zinderen Bakker, Sr. (Editor), The Orange River: Progress Report. *Proceedings of the 2nd Limnology Conference on Orange River System. Institute of Environmental Science. University Orange Free State, Bloemfontein, South Africa*, 31-40.
- Haughton, S.H. (1969). *Geological History of Southern Africa*. The Geological Society of South Africa, Cape Town, 535pp.
- Herbert, C. and Compton, J.S. (2007) Geochronology of Holocene sediments on the western margin of South Africa. *South African Journal of Geology*, **110**, 327-338.
- Kriel, J. P. (1972). The role of the Hendrik Verwoerd dam in the Orange River project. *The Civil Engineer in South Africa, February*, 51-61.
- Mabote, M.E., Rogers J. and Meadows M.E. (1997). Sedimentology of terrigenous mud from the Orange River delta and the inner shelf off Namaqualand, South Africa. *South African Geographical Journal (special edition)*, 108-114.
- Mucina, L., Rutherford, M.C. and Powrie L.W. (Editors) (2005). Vegetation Map of South Africa, Lesotho and Swaziland, 1:1 000 000 scale sheet maps. *South African National Biodiversity Institute*.
- Rogers, J. (1977). Sedimentation on the continental margin off the Orange River and the Namib desert. *Unpublished PhD thesis, Department of Geological Sciences, University of Cape Town, South Africa*, 212pp.
- Rogers, J. and Bremner, J.M. (1991). The Benguela ecosystem. Part VII. Marine-geological aspects. *Oceanography and Marine Biology Annual Review*, **29**, 1-85.
- Rogers, J. and Rau, A.J. (2006). Surficial sediments of the wave-dominated Orange River delta and the adjacent continental margin off southwestern Africa. *African Journal of Marine Science*, **28**, 511-524.
- Rooseboom, A. (1975). Sedimentproduksiekaart vir Suid-Afrika. Technical Report, Department of Water Affairs, South Africa, **61**, 1-13.
- Rooseboom, A. and Harmse, H.J. von M. (1979). Changes in the sediment load of the Orange River during the period 1929-1969. *Scientific Publication of the International Association of Hydrology*, **128**, 459-470.
- Rust, I.C. (1962). On the sedimentation of the Molteno sandstones in the vicinity of Molteno, C.P. *University of Stellenbosch (Annals)*, **37**, 165-234.
- Seuffert, O., Herrig, K., Ollesch G., and Busche D. (1999). REI an integrated rainfall erosivity index for assessing and correlating rainfall structure, runoff and erosion. *Geo-öko-dynamik*, **20**, 1-52.
- Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter W.E.L. (1982). *The crustal evolution of southern African 3.8 Billion years of earth history*. Springer-Verlag, New York, 523pp.
- Turner, B.R. (1970). Facies analysis of the Molteno sedimentary cycle. *2nd International Conference on Gondwana Symposium, Proceedings and Papers, Council for Scientific and Industrial Research, Pretoria*, 689pp.
- Turner, B.R. (1978). Sedimentary patterns of uranium mineralization in the Beaufort Group of the southern Karoo (Gondwana) Basin, South Africa. In: A. Miall (Editor), *Fluvial Sedimentology, Memoirs of the Canadian Society of Petroleum Geologists*, **5**, 831-848.
- Turner, B.R. (1990). Continental sediments in South Africa. *Journal of African Earth Sciences*, **19**, 139-149.
- Wellington, J.H. (1958). The evolution of the Orange River basin: some outstanding problems. *South African Geography Journal*, **40**, 3-30.

Editorial handling: M. J. de Wit and Brian Horsfield

## Appendix B: XRD SCANS

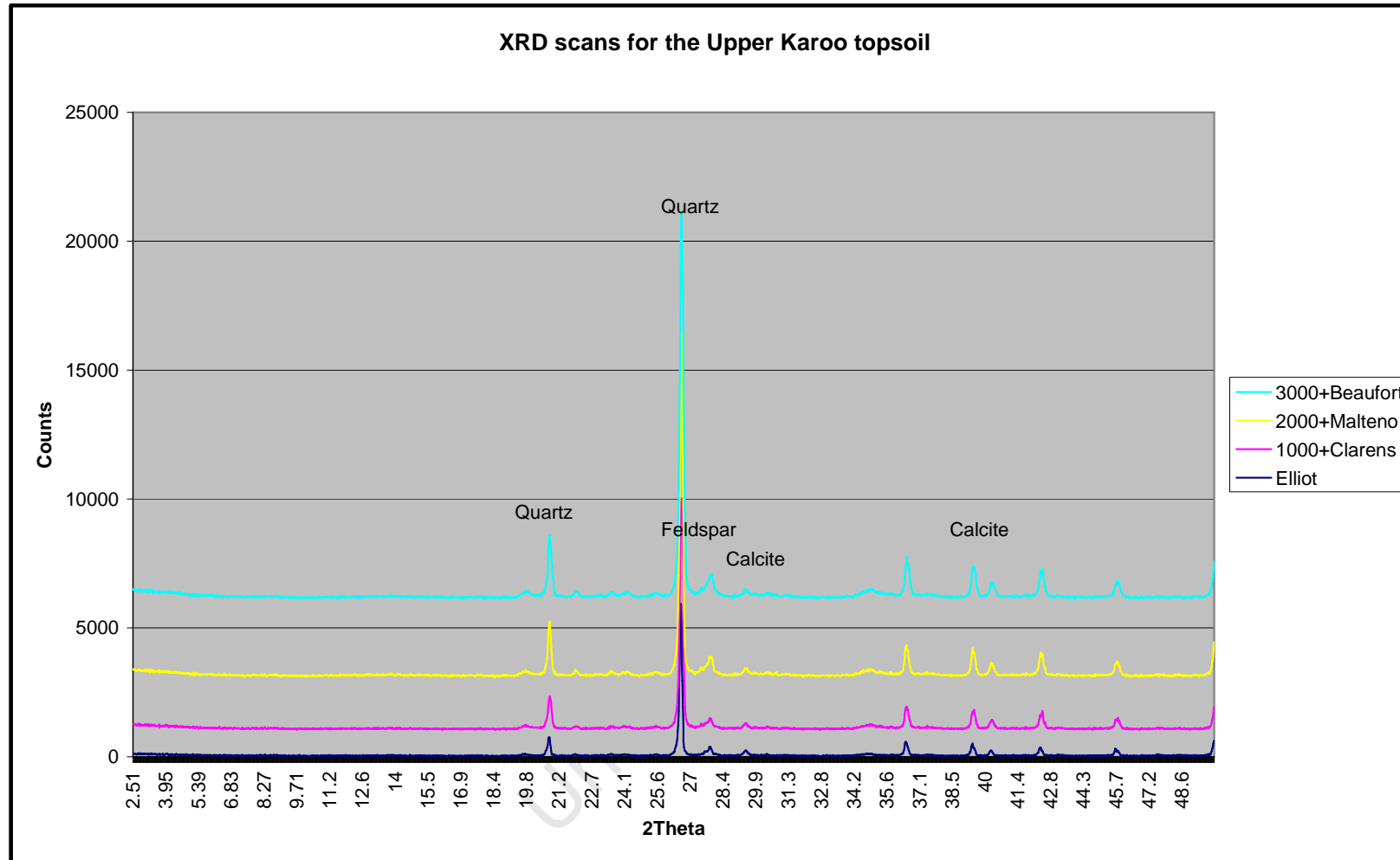


Figure B1. XRD scans for the different Upper Karoo sedimentary formations.

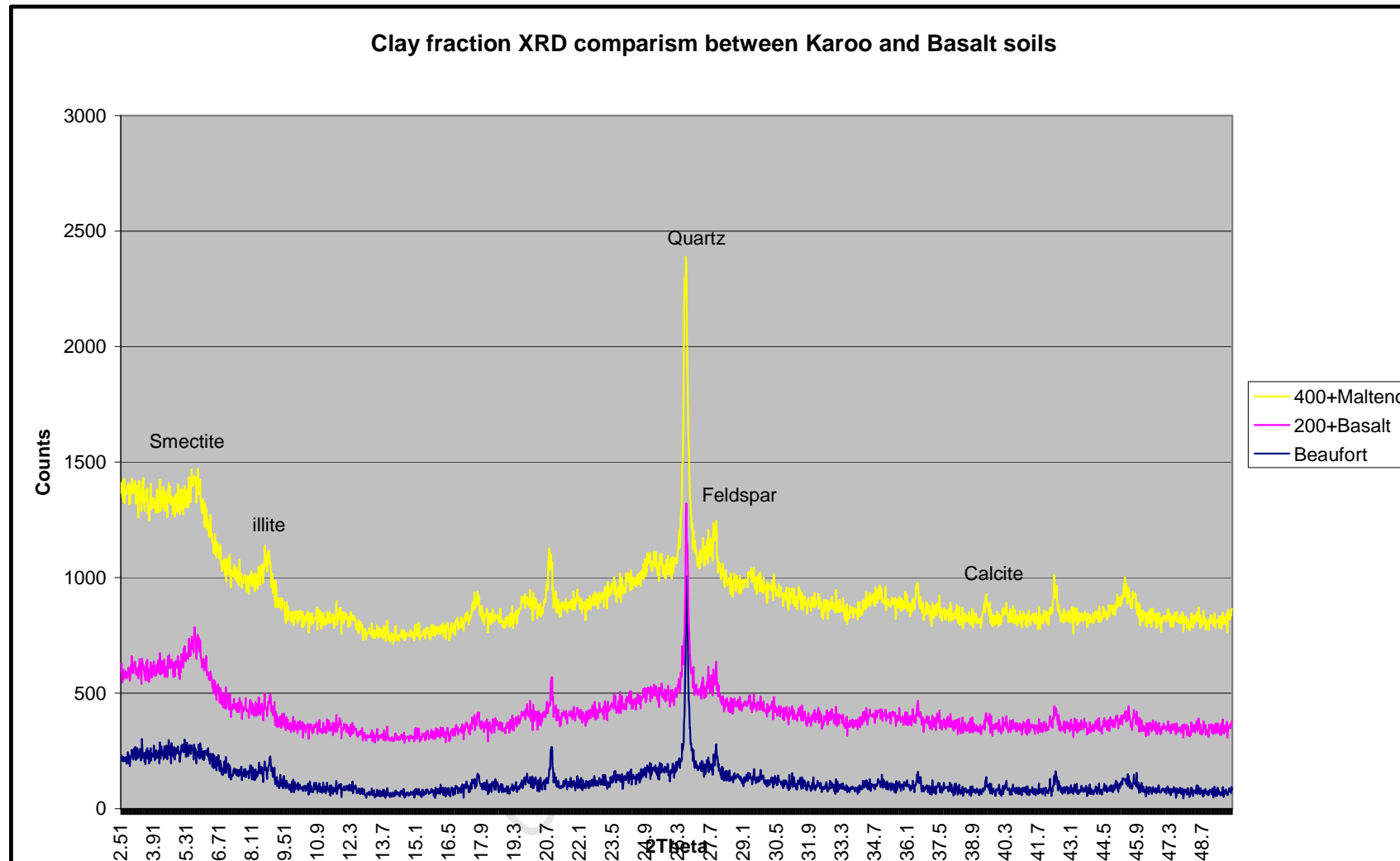


Figure B2: XRD scans showing the mineralogical difference in Karoo sedimentary soils and Basalt soils.

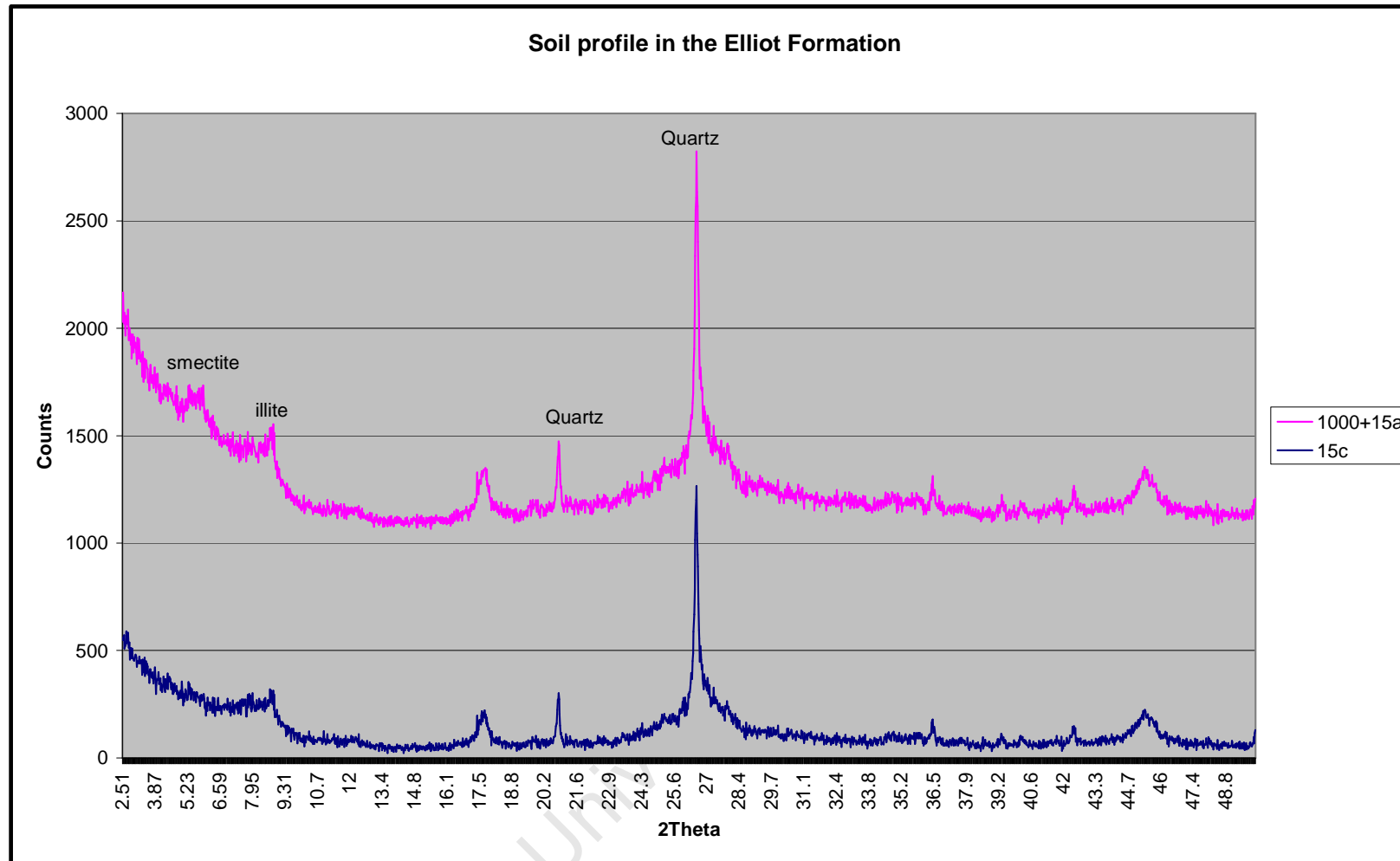


Figure B3 XRD scans showing the difference between the sample 15a and the soil below it, 15b was not plotted because it is the same as 15c.

## Appendix C: Sample location and GPS co-ordinates

Sample name	Sample no	Nearby town	Site description	Latitude	Longitude	Elevation m
Elb12a	1a	Lady Brand	TRe top soil	29° 10' 27,9"	27° 25' 26,3"	1516
Elb12b	1b	Lady Brand	TRe middle unit	29° 10' 27,9"	27° 25' 26,3"	1516
Elb12c	1c	Lady Brand	TRe chunky bedrock	29° 10' 27,9"	27° 25' 26,3"	1516
Elb12d	1d	Lady Brand	TRe river bank deposit of stream	29° 10' 27,9"	27° 25' 25,8"	1515
Clb13a	2a	Mondderkop	TRc rock sample	29° 09' 59,1"	27° 23' 35,1"	1763
Clb13b	2b	Mondderkop	TRc farm soil	29° 08' 20,6"	27° 23' 24,4"	1701
Tcl14a	3a	Clocodan	TRt alluvium deposit	28° 57' 36,6"	27° 33' 58,2"	1540
Tcl14b	3b	Clocodan	TRt river bank deposit	28° 57' 36,6"	27° 33' 58,2"	1540
Mcl15	9	Clocodan	TRm farm soil	28° 52' 52,8"	27° 33' 23,5"	1592
Tmar15	10	Marquad	TRt soil sample	28° 46' 02,5"	27° 29' 58,0"	1612
Ecl17	11	Marquad	TRe farm soil	28° 50' 26,6"	27° 37' 51,8"	1647
Efr18	14	Fouriesburg	TRe bed rock	28° 32' 24,8"	28° 25' 20,6"	1784
Cfr18	15	Fouriesburg	TRc bed rock	28° 32' 24,8"	28° 25' 20,6"	1784
E&Cfr19	16	Fouriesburg	TRe and TRc river bank deposit	28° 38' 37,0"	28° 16' 39,3"	1643
M22a	17a	Ficksburg	TRm top soil	28° 40' 21,1"	28° 08' 44,1"	1633
M22b	17b	Ficksburg	TRm soil sample	28° 40' 21,1"	28° 08' 44,1"	1633
M22c	17c	Ficksburg	TRm soil sample	28° 40' 21,1"	28° 08' 44,1"	1633
T24a	20a	Ficksburg	TRt top soil	28° 40' 48,4"	28° 08' 24,5"	1590
T24b	20b	Ficksburg	TRt subsoil with clay	28° 40' 48,4"	28° 08' 24,5"	1590
T24c	20c	Ficksburg	TRt chunky rock	28° 40' 48,4"	28° 08' 24,5"	1590
T24d	20d	Ficksburg	TRt river bank deposit	28° 40' 48,4"	28° 08' 24,5"	1590
M23	24	Ficksburg	TRm soil sample	28° 47' 55,8"	27° 54' 12,9"	1597
B&C23	25	Ficksburg	Jdr and TRc river bank deposit	28° 54' 45,7"	27° 40' 26,3"	1627
Twep24	26	Wepner	TRt rock sample	29° 43' 39,7"	26° 58' 01,0"	1440
Teg25a	27a	Egmont	TRt alluvium deposit	30° 06' 12,0"	27° 02' 31,9"	1502
Teg25b	27b	Egmont	TRt soil sample	30° 06' 12,0"	27° 02' 31,9"	1502
Ezas26	29	Zastron	TRt alluvium deposit	30° 22' 22,5"	27° 16' 11,1"	1497
Mzas27	30	Zastron	TKm alluvium deposit	30° 19' 06,7"	27° 09' 14,9"	1561
Pa28	31	Wepner	Pa soil sample	29° 39' 33,7"	26° 50' 53,0"	1505
Pa29	32	Wepner	Pa alluvium deposit	29° 35' 28,2"	26° 42' 27,4"	1493

Sample name	Sample no	Nearby town	Site description	Latitude	Longitude	Elevation m
LG1 2	33a	Lady Grey	TRc top soil	30 °46' 30.6	27 ° 11' 26.9	1679
LG2 2	33b	Lady Grey	TRc bed rock	30 °46' 30.6	27 ° 11' 26.9	1679
N.E 3	35	New England	Jdr soil	30 °52' 09.0	27 °28' 40.5	1754
B.E 4	36	Barkly East	Jdr bedrock	30°04' 15.8	27 ° 39' 26.9	1790
KPS 7	37	Barkly East	Jdr bedrock	30°57' 07.9"	27° 27' 41.4"	1606
8A	38a	Barkly East	Jdr topsoil	30°51' 32.2"	27° 24' 37.0"	1892
8B	38b	Barkly East	Jdr subsoil	30°51' 32.2"	27°2 4' 37.0"	1892
8C	38c	Barkly East	Jdr Weatherd Bed Rock	30°51' 32.2"	27°24' 37.0"	1892
8D	38d	Barkly East	Jdr bed rock	30°51' 32.2"	27° 24' 37.0"	1892
9 basalt	42	Dordrecht	Jdr soil	30°50' 42.5"	27° 1 7' 05.0"	1916
10 mud	43	Dordrecht	TRe rock	30°48' 32.3"	27° 15' 28.3"	1660
11A	44a	Dordrecht	TRe topsoil	30°46' 58.8"	27° 11 ' 17.5"	1697
11B	44b	Dordrecht	TRe bed rock	30°46' 58.8"	27 ° 1 1' 17.5"	1697
12A	46a	Blue Gum	TRe topsoil	30°32' 03.2"	27 °18' 11.4"	1488
12B	46b	Blue Gum	TRe Weathered Bed Rock	30°32' 03.2"	27 °18' 11.4"	1488
12C	46c	Blue Gum	TRe bed rock	30°32' 03.2"	27 °18 ' 11.4"	1488
13SP	49	Sterkspruit	TRm topsoil	30 °26' 08.8"	27 ° 22' 43.3"	1378
15A O.F.S.B	50a	Zastron	TRe topsoil	30 °22' 19.5"	27° 16' 42.4"	1515
15B O.F.S.B	50b	Zastron	TRe Weathered Bed Rock	30 °22' 19.5"	27 °16' 42.4"	1515
15C O.F.S.B	50c	Zastron	TRe sub soil	30 °22' 19.5"	27° 16' 42.4"	1515
15D O.F.S.B	50d	Zastron	TRe Weathered Bed Rock	30 °22' 19.5"	27° 16' 42.4"	1515
16soil hori	54	Rouxville	TRm topsoil	30 °22' 08.4"	26 °46' 24.4"	1417
17A	55a	Kleinspirit	TRt topsoil	30 °19' 05.1"	26 ° 42' 56.1"	1374
17B	55b	Kleinspirit	TRt Weathered Bed Rock	30 °19' 05.1"	26°42' 56.1"	1374
17C	55c	Kleinspirit	TRt rock	30 °19' 05.1"	26° 42' 56.1"	1374
RB 19	58	Reddersburg	TRt topsoil	29 °38' 07.1"	26 °10' 49.2"	1407
20	76	Reddersburg	TRt soil sample			
LM-07	59		TRt soil sample			

Source River	Sample name	Sample no	Nearby town	Suspended load (g/l) 2006	g/l 2007	Latitude	Longitude	Elevation m
<b>Orange River</b>	Bundi	Bundi	Violsdrif		0.058 g/l	28°41'08.6"	17°33'48.5"	150
	AN1	AN1	Aliwal North	2.6 g/l	0.46 g/l	30°41'10.5"	26°42'20.7"	1306
	FSB	FSB	Free State border bridge	3.4 g/l		30°24'19.6"	27°20'14.1"	1368
<b>Caledon River</b>	Caledon	CLDN	N6 Bridge	3.0 g/l	0.52 g/l	30°16'44.0"	26°39'16.7"	1329
<b>Vaal River</b>		Vaal	Douglas		0.022 g/l	29°04'17.9"	23°44' 17.9"	
<b>Kraai River</b>		Kraai B.E	Barkly East	0.05 g/l		30°57' 08.6"	27°36 ' 24.3"	1754
		Kraai N.E	New England	0.22 g/l		30 °52' 09.0"	27°2 ' 8' 40.5"	1754
<b>RIVER BANK DEPOSITS 2007</b>								
<b>Caledon River</b>								
	CR16a	CLDNc RBa	Clocolan	top soil		28° 56' 51,1"	27°43' 44,2"	1521
	CR16b	CLDNc RBb	Clocolan	river bank deposit		28° 56' 51,1"	27°43' 44,2"	1521
	Caledon River Bank	CLDN RB	N6 Bridge	almost all sand deposit		30°16'44.0"	26°39'16.7"	1329
	Caledon 2 <sup>nd</sup> samples.	CLDN RB Clay	N6 Bridge	clay rich river bank sample		30°16'44.0"	26°39'16.7"	1329
<b>Vaal River</b>	Vaal Windsorton	Vaal RB	Windsorton	sandy river bank deposit		29°04'17.9"	23°44' 17.9"	
<b>Orange River</b>	AL North clay River Bank 4 <sup>th</sup> Jan	AN1 RB silt	Aliwal north	clay layer on river bank		30°41'10.5"	26°42'20.7"	1306
	AL North Clay River Bank	AN1 RB Mud	Aliwal north	fine clay and mud layer		30°41'10.5"	26°42'20.7"	1306
	AL North Surface mud	AN1 RB Clay	Aliwal north	clay layer on sandy beds		30°41'10.5"	26°42'20.7"	1306
<b>Paleoflood deposits</b>								
<b>Caledon River</b>	Caledon Paleoflood N6	CLDN P	N6 Bridge	very sandy homogenous sed		30°16'44.0"	26°39'16.7"	1329
<b>Vaal River</b>	Vaal Paleoflood(Douglas)	Vaal P	Douglas	sub surface deposit in dry river bed				
<b>Orange River</b>	AL North Paleoflood	AN1 P	Aliwal north	fine silt sampled in between tree roots		30°41'10.5"	26°42'20.7"	1306