Morphometric analysis of drainage basins subject to diverse geotectonic controls: the case of the Gamtoos and Crocodile drainage basins, South Africa

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Dissertation accepted in fulfilment of the requirements for the degree *Masters of Science in Environmental Sciences and Management* at the North West University

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DECLARATION

I, Owosuyi Emmanuel Adeniyi (Student number: 26352222), hereby declare that this dissertation entitled "Morphometric analysis of drainage basins subject to diverse geotectonic controls: the case study of the Gamtoos and Crocodile drainage basins, South Africa" is my own original work. Unless specifically stated, all references listed have been consulted. The dissertation is being submitted in fulfilment of the requirements for the degree of MSc in Environmental Science and Management, at the North-West University, Mafikeng Campus, South Africa. I further declare that this work has not previously been submitted by me for a degree at any other university.

Signed:

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Date: 30 January 2018

This dissertation has been submitted with my approval as the supervisor and I certify that the requirements for the applicable MSc degree rules and regulations have been fulfilled.

Signed: ....

Supervisor

Date: ....

DEDICATION

This work is dedicated to the memory of my father (Late Pa. Samuel Olajide Owosuyi). It is also dedicated to my mother (Janet Owosuyi), to my lovely wife (Ifeoma Laura Owosuyi), to my son (Oluwademilade Owosuyi), and daughter (Onyinyechi Owosuyi). Thank you all for having my back.

This work is also dedicated to my 'other mother' (Mrs Mary Ofili), thank you for always being there.

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Lastly, I would like to extend my sincere thanks to my family, my in-laws, friends and colleagues who have supported me throughout my study period. Without their love and support, this would have been a very difficult task to complete.

ABSTRACT

Morphometric analysis represents a method to describe basin processes and examine basin characteristics to enable the structure, process and evolution of the landscape to be investigated. This approach has potential to yield insights into the long-term landscape evolution in South Africa. However, recent research has shown that care must be taken in the application of morphometric analyses to constrain tectonic or climatic influence in the evolution of ancient landscapes. The study aimed to evaluate the potential of morphometric properties to help better understand the process of landscape evolution using drainage basins with contrasting geotectonic histories; the Gamtoos and Crocodile basins. ASTER digital elevation data was used to extract selected areal, linear and relief morphometric properties of the study basins in Geographical Information Systems (GIS). Lithology and structural geology data were used to analyse and interpret spatial patterns of the morphometric properties investigated.

The study found that the variation of morphometric properties was not systematic and consistent across the study basins. Not all the spatial variation of the selected morphometric properties was consistently explained by the geotectonic data. The role of bedrock type could only explain the variation of drainage density and texture across all study regions. Only the drainage pattern and shape of the stream courses were able to explain the impact of inherited tectonic structures in the evolution of drainage basin in the three study areas. The analysis of the linear properties of the drainage network, to some extent, gives evidence of possible large scale forcing factors in the Cape Fold Belt in the form of tectonic uplift which is absent in the Crocodile and Central Karoo regions. However, the rest of morphometric properties are not consistent with expectations. The major cause of this is most likely signal shredding or overprinting, whereby the evidence of the past geological processes is lost over time in ancient landscapes making impossible to infer the corresponding trajectory of the evolution of the given landscape. Also, the morphometric properties might be reflecting a composite effect of multiple factors and recent geomorphic events than the inherited structural fabric.

The study did not find enough evidence to contradict Richardson *et al.,* (2016) with regard to the utility of morphometric analysis in landscape evolution studies in the Cape Fold Belt. In view of the findings, this study recommends: further studies to examine the variation of all the morphometric properties at various nested scales to assess scale effects of some of the investigated morphometric properties, the use of a more extensive list of morphometric properties, especially those that have been successfully used in similar studies and the use of

a combination of the GIS and remote sensing based studies with paleogeomophological techniques, such as dating techniques of surfaces.

Key words: drainage basin morphometry, landscape evolution, structural geomorphology, Cape Fold Belt, structural control

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DEFINITION OF KEY CONCEPTS

Drainage basin: a topographic area that is drained by a stream and its tributaries.

Morphometry: measurement and mathematical analysis of the configuration of the earth's surface, shape and dimensions of its landforms.

Drainage basin morphometry: the quantitative description of the linear, areal and relief characteristics of a basin.

Geotectonic or structural control: reflection of the influence of tectonic displacement, geological deformation, stratigraphic arrangement of rock strata and lithology on landform development and evolution.

Landscape: is part of the Earth's surface with a collection of landforms characteristic of the area, e.g. karst landscapes and desert landscapes,

Landscape evolution: the response of landscapes to endogenic and exogenic forces.

ABBREVIATIONS

ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
CFB	Cape Fold Belt
DEM	Digital elevation model
DD	Drainage Density
GIS	Geographical Information Systems
HI	Hypsometric Integral
HC	Hypsometric curve
NASA	National Aeronautics and Space Administration
USGS	United States Geological Survey

CHAPTER 1: INTRODUCTION

1.1 Introduction

The main objective of this study is to evaluate the potential of morphometric analyses to help better understand landscape evolution. The study uses two drainage basins with different geotectonic histories, the Gamtoos drainage basin, part of which has been extensively affected by tectonic forces and the Crocodile drainage basin which represents a drainage basin without apparent structural control. This study is motivated by the need to test the suitability of morphometric characterization in ancient landscapes and providing further case studies in the use of morphometric analyses to interpret landscape evolution. The chapter introduces the study by offering a background of the research topic, research problem statement and the significance of the study among others. It also outlines the research hypothesis, research questions, general objective and specific objectives.

1.2 Background to the study

The natural landscape of a particular area is a direct outcome of the interaction of rock, sediment type, structural configuration, climate, sea level change and isostatic adjustment (Dipietro, 2012). These processes associate over time to maintain and change the natural landscape of any given area. An understanding of the interaction amongst these factors provides answers about the form and evolution of the present landscapes. Streams and rivers are very important elements in landscape evolution (Kirchner, 1993; Kondolf *et al.*, 2003). According to Schumm and Lichty (1965) cited in Splintera *et al.* (2011), different variables form and control drainage basin characteristics over time and space and the study of drainage basins may help understand these variables. For example, the patterns formed by stream channels may reflect regional tectonics (Burbank, 1992) and local geologic structure (Hattingh and Goedhart, 1997; Manjoro, 2015), as well as prevailing erosional mechanisms (Dunne, 1980) and climate (Bootsman, 1997; Daniel, 1981). Thus, one of the ways of understanding the evolution of landscapes is by investigating drainage basins.

Drainage basins are basic elements of fluvial landscapes. Morphometric analyses of drainage basins represents a relatively simple process used to examine basin attributes (Mesa, 2006) and compare different basins. Detailed morphometric analysis of drainage basins (e.g. drainage pattern, hypsometry, stream order, etc.) is useful in understanding the relative importance of macroscale and local factors in the evolution of a given landscape (Nag and

Chakraborty, 2003). Earliest research on basin morphometry started with researchers like Horton (1932, 1945), Miller (1953), Smith (1950), and Strahler (1964). Using drainage basins in morphometric investigation is appropriate due to the fact that all hydrologic and geomorphic processes happens inside drainage basins (Malik *et al.*, 2011).

1.3 Problem Statement

There is inadequate basic morphometric investigation of the South African drainage basins (Richardson *et al.*, 2016). This is despite the approach having the prospect of providing better understanding of the evolution of landscapes. However, as indicated by Richardson *et al.* (2016) while morphometric analysis can be valuable in the evaluation of how landscapes evolved, care must be taken in its use in ancient landscapes. This is due to the presence of inherited tectonic structures and signal shredding or overprinting. Signal shredding or overprinting (Allen, 2008; Jerolmack and Paola, 2010; Twidale, 2007), whereby the evidence of the past geological structure is lost due to climate oscillations and geodynamics leading to inability to infer the corresponding trajectory of the evolution of the given landscape. While Richardson *et al.* (2016)'s findings were remarkable and with potential to change the way we view and study landscape evolution, there is need for further case studies and interrogation of the utility of morphometric analysis of drainage basins to enable the better interpretation of landscape evolution in South Africa. Thus this study aims to evaluate the potential of morphometric analyses to help better understand landscape evolution in South Africa. Two drainage basins with suspected divergent trajectories of landscape evolution and geotectonic or deformation histories are used for this study.

1.4 Research hypothesis

The study set out to test the following hypothesis:

- Morphometric analyses of drainage basins can explain the trajectory of landscape evolution in ancient landscapes by revealing the role of bedrock type, inherited tectonic structures and macroscale forcings.

1.5 General objective

The general objective of this study is to evaluate the potential of morphometric analyses to help better understand landscape evolution in South Africa on the basis of two case studies.

1.6 Specific objectives

The specific objectives of this study are to:

1. Extract selected relief, area and linear morphometric properties for the study basins.
2. Document variation in morphometric properties between the basins.
3. Explain the observed variation using existing geotectonic data and
4. Evaluate the suitability of morphometric properties for the characterization of ancient landscapes.

1.7 Research questions

The key questions that will be answered in the course of this research are as follows:

1. What relief, area and linear morphometric properties may be used to characterize the study basins?
2. How does these morphometric properties vary within and between the basins?
3. How can the observed variations be explained using existing geotectonic data?
4. To what extent can morphometric characterization of drainage basins provide insight into the history of the geomorphic development of the study basins?

1.8 Significance and justification of the study

Morphometric characterization of drainage basins has demonstrated potential to offer valuable insight into the landscape development. For example, it has been demonstrated that the drainage basin hypsometry is scale-dependent (Walcott and Summerfield, 2008) and may be used to constrain differences in tectonic uplift rates and changes in resistance to erosion of diverse lithological units (Lifton and Chase, 1992; Willgoose and Hancock, 1998; Chen *et al*., 2003). Richardson *et al*. (2016) observed that fundamental morphometric analysis of the South African basins is lacking. Therefore, it is necessary for more case studies, like the present study, to better understand the use of morphometric analysis in interpreting landscapes in South Africa. Thus, this study contributes to the debate on the utility of morphometric analysis.

1.9 Delimitation of study

To enable the evaluation of the potential of morphometric analyses to better understand landscape evolution, this study uses two drainage basins with different geotectonic histories. These are the Gamtoos drainage basin, an ancient discordant drainage basin in the Cape Fold Belt region affected by various structural controls and the Crocodile drainage basin, which represents a stable basin without apparent structural control. The drainage basins were also selected because of their differences in geological substrate.

The use of the term structure in this study refers to all the elements that relate to the disposition of the landscape as a result of crustal deformation. These are: nature and spatial arrangement of faults or inferred joints, nature and distribution of folded strata, plunge, strike and dip angles, bed rock lithology and the stratigraphic arrangement of rocks (Gunnell and Harbor (2008); Bourne and Twidale (2011) and Manjoro (2015).

Various factors influence the trajectory of landscape evolution in a given drainage basin. In this study only the following the factors which may be easily investigated using morphometric characterization were examined; bedrock type, inherited tectonic structures and large scale forcing factors. Although climate plays an important role in landscape evolution, it was not investigated in this study as it was not possible to isolate the paleoclimatic regimes of the study areas.

In terms of morphometric properties, only those linear, areal and relief morphometric properties that have been used successfully in other parts of the world to investigate landscape evolution were selected. Morphometric analysis was done for each whole study drainage basin and for all 4th order sub-basins based on previous work (e.g. Chen *et al.,* 2003; Richardson *et al*., 2016). For the Gamtoos drainage basin where there are two distinct physiographic regions, the analysis was additionally separated by each region.

1.10 Assumptions

The study is based on the following assumptions:

1. The process of landscape evolution takes millions of years to happen,
2. The trajectory of landscape evolution of a given drainage basin is influenced by the bed rock type, inherited tectonic structures and large scale scale forcing factors acting regionally,
3. Environmental signal shredding or overprinting (Allen, 2008; Jerolmack and Paola, 2010; Twidale, 2007), may obliterate the effect of bed rock type, inherited tectonic structures and large scale scale forcing factors depending on the action of exogenic factors in a particular ragion,
4. Morphometric analysis of a drainage basin or a landscape may reveal the effect of bed rock type, inherited tectonic structures and large scale scale forcing factors in a given drainage basin or landscape,

5. The role of climate in landscape evolution is important but difficult to constrain using morphometric analysis.

1.11 Description of the study area

This section provides information on the tectonic setting, lithostratigraphy, geomorphology and climate of the two study basins: the Gamtoos and Crocodile drainage basins (Figure 1.1A). The Gamtoos drainage basin (34,635 km^2 in size) is located in the southern margin of South Africa, extending from latitude 22°S to 25.2°S and longitude 31°E to 33.9°E. The Crocodile drainage basin (29,349 km^2 in size), extends from latitude 24°S to 26.1°S and longitude 26°E to 28.4°E. It is part of the Limpopo river basin located in the north-western part of South Africa.

1.11.1 Tectonic setting and lithostratigraphy

The CFB is a well-defined fold and thrust belt that is situated at the southern margin of the South Africa (see Figure 1.2A). The CFB contains three structural provinces: the western branch (from Vanrhynsdorp to Ceres), a syntaxis around Worcester and the southern branch (from Touwsrivier to Port Alfred) (de Mielke and de Wit 2009; Booth, 2011).The Gamtoos drainage basin is found in the southern domain. The most conspicuous structural element in the drainage basin is the Gamtoos fault, which changes in orientation from Eastern part of the South-East, to Western part of North-West in the northern portion of the area to a North-South strike further downwards in the southern part (Thomson, 1999). Two schools of thought exist about the cause of the change in orientation of the strike direction of the fault. The first one (Lock, 1980; Malan *et al.*, 1990 and Shone *et al.*, 1990) suggests that the change in strike is as a result of the Cape Fold Belt tectonism and the influence of its flat-lying thrust sheets affecting the listric makeup of the Gamtoos fault. The second school of thought (Ben-Abraham *et al.*, 1993) attributes the change in fault strike to the Agulhas Falkland fracture zone movement that took place during the separation of Gondwana. Most rocks in the lower region of the drainage basin are fault or fold bearing. However, the Cape Fold Belt is currently tectonically quiescent with low seismicity (Bierman *et al.,* 2014).

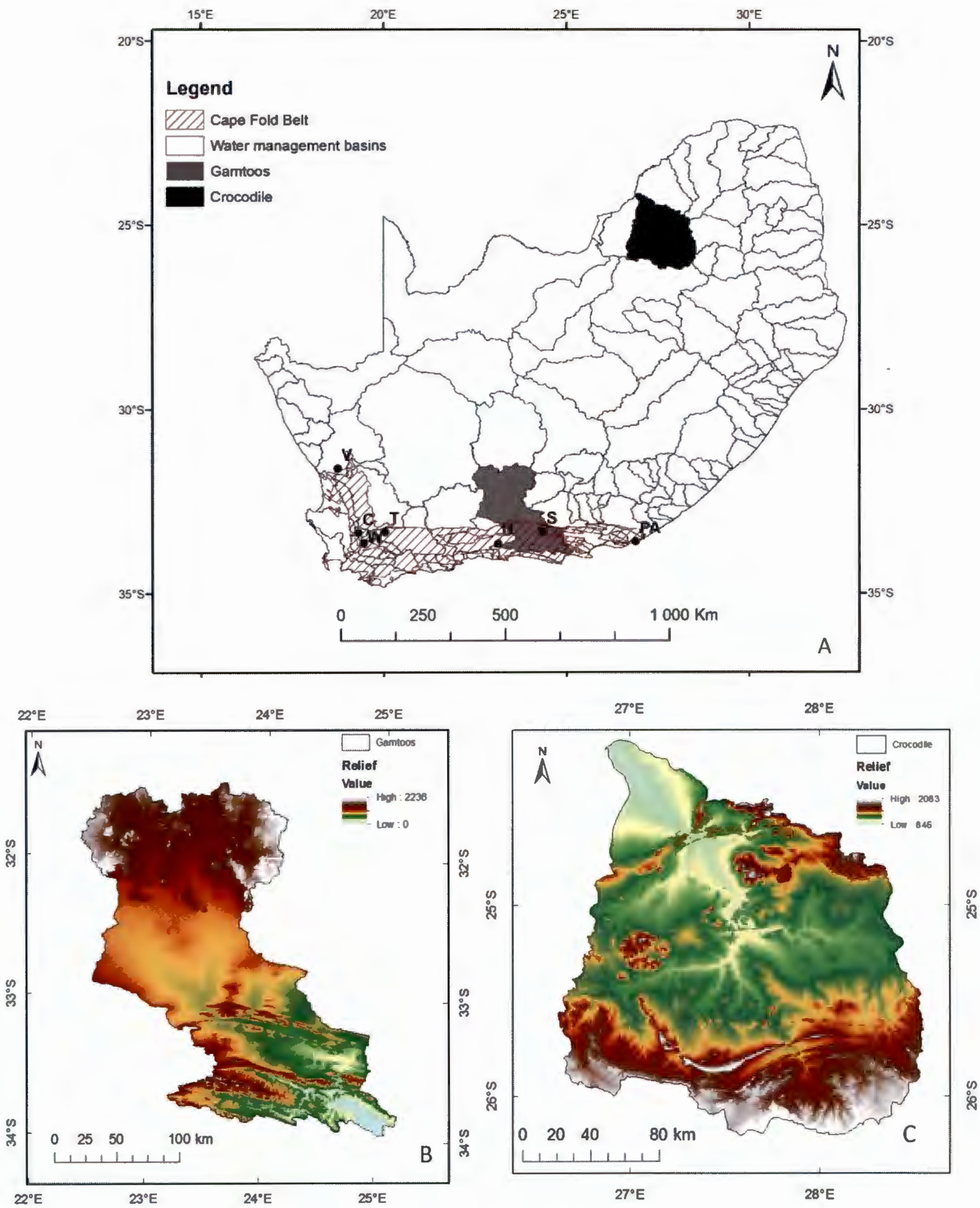


Figure 1.1. The general location (A) and the topography of the Gamtoos (B) and Crocodile drainage basins (C).

Based on the lithostratigraphy, the Gamtoos drainage basin consist of two distinct physiographic regions, namely the Central Karoo region and Cape Fold Belt region (see Figure 1.2B).

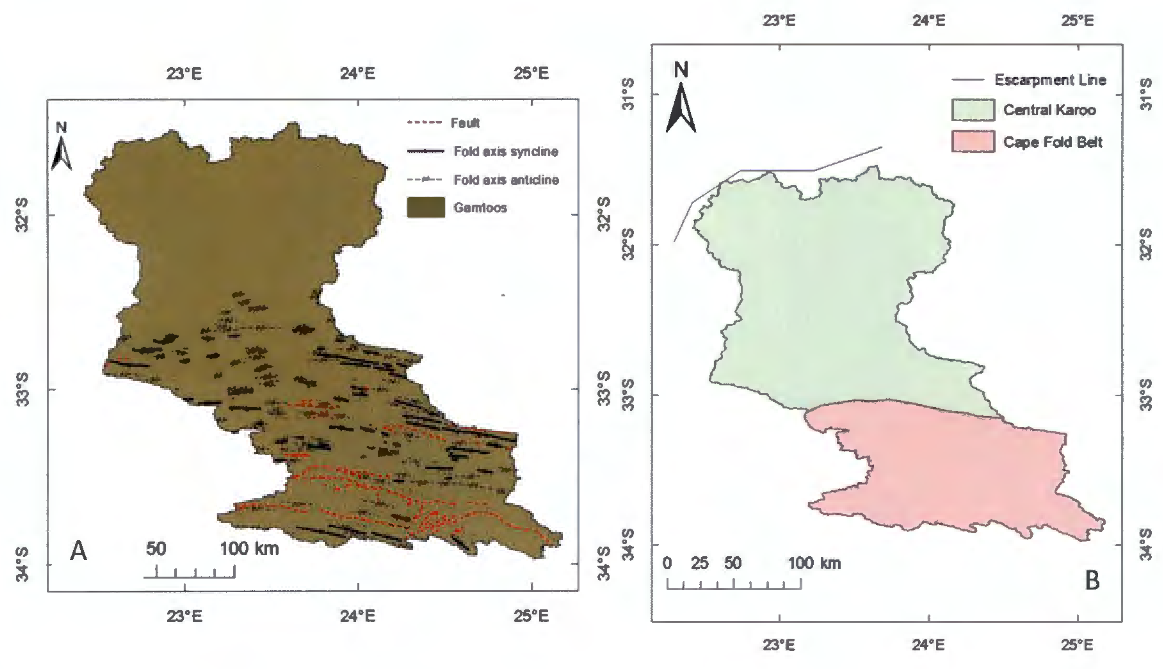


Figure 1.2. Selected structural features of the Gamtoos drainage basin (A) and its physiographic regions (B).

Figure 1.3 shows the general geology of the drainage basin. The Cape Fold Belt region is underlain mainly by rocks of the Witterberg, Bookeveld and Table Mountain Groups. The Table Mountain Group consists mostly of medium-grained quartzites, shale and sandstone. The rocks of the Bokkeveld Group are predominantly shale with a small proportion of feldspathic sandstone and quartzites (Shone and Booth, 2005). On the other hand the Witterbergg group predominantly comprises of quartzitic sandstone and shale (Broquet, 1992). The Table Mountain and Bokkeveld groups constitute the largest portion of the lithostratigraphy of the region covered by the Cape Supergroup rocks. Most parts of the rocks of the Cape Fold Belt regions have been exposed to burial or regional metamorphism, causing the rocks to be resistant to erosion (Richardson *et al.*, 2016).

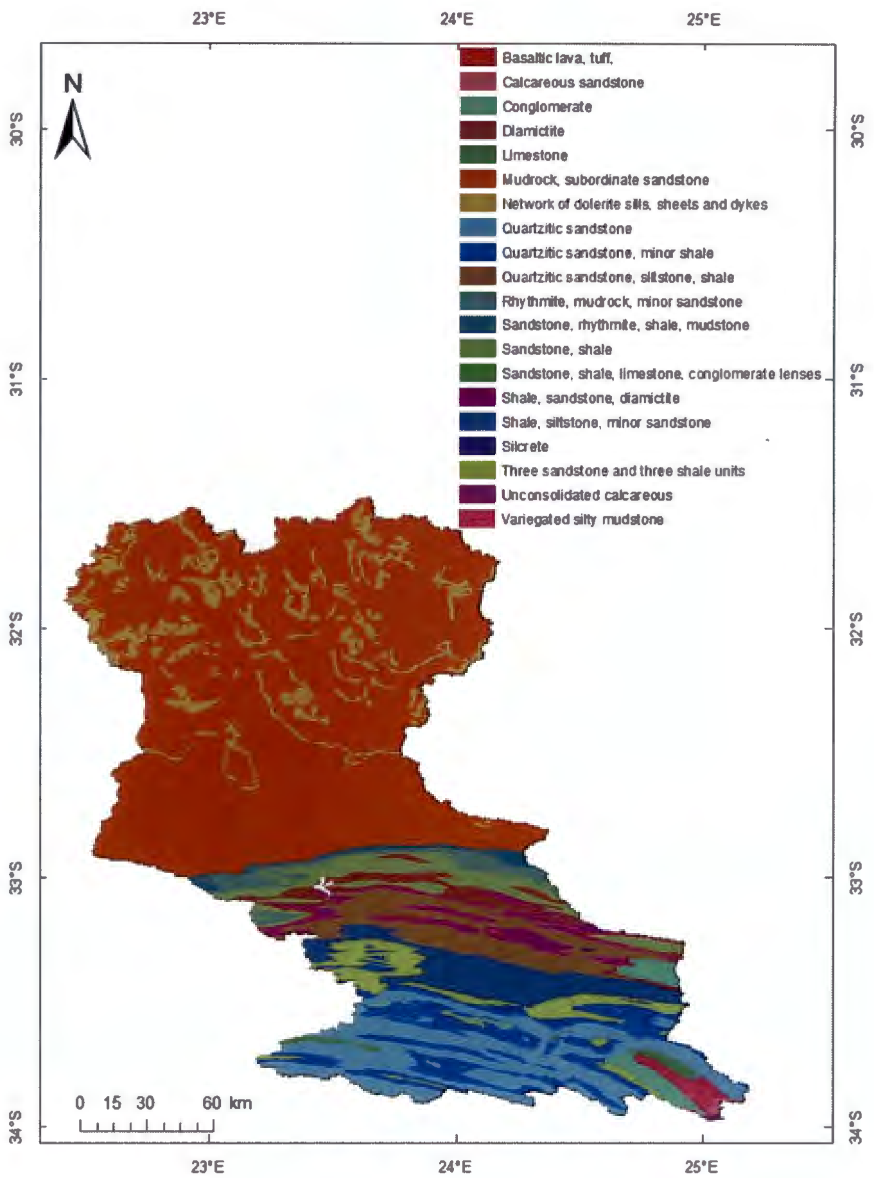


Figure 1.3. General geology map of the Gamtoos drainage basin.

The lithostratigraphy of the Central Karoo region is dominated by the Alelaide Supergroup and the Beaufort Group consisting of mudrock and subordinate sandstone. Various igneous intrusions forming rocks of the Karoo Dolerite suite appear in the upper part of the sub-region (Figure 1.3). The supergroup consists of a sequence of units, mostly of non-marine origin, deposited between the Late Carboniferous and Early Jurassic, a period of about 120 million years. Its strata consist mostly of a sequence of shale and mudstone with some interbedded lenticular sandstone (Broquet, 1992).

1.11.1.1 The Crocodile drainage basin

The Crocodile drainage basin has diverse geology dominated by the Bushveld igneous complex, which is a volcanic intrusive feature (see Figure 1.4). In relation to stratigraphy, the Rustenburg formation underlain by the Pretoria, Transvaal and the Rooiberg series cuts across the middle of the drainage basin. Overlaying the Rustenburg formation is the Bushveld

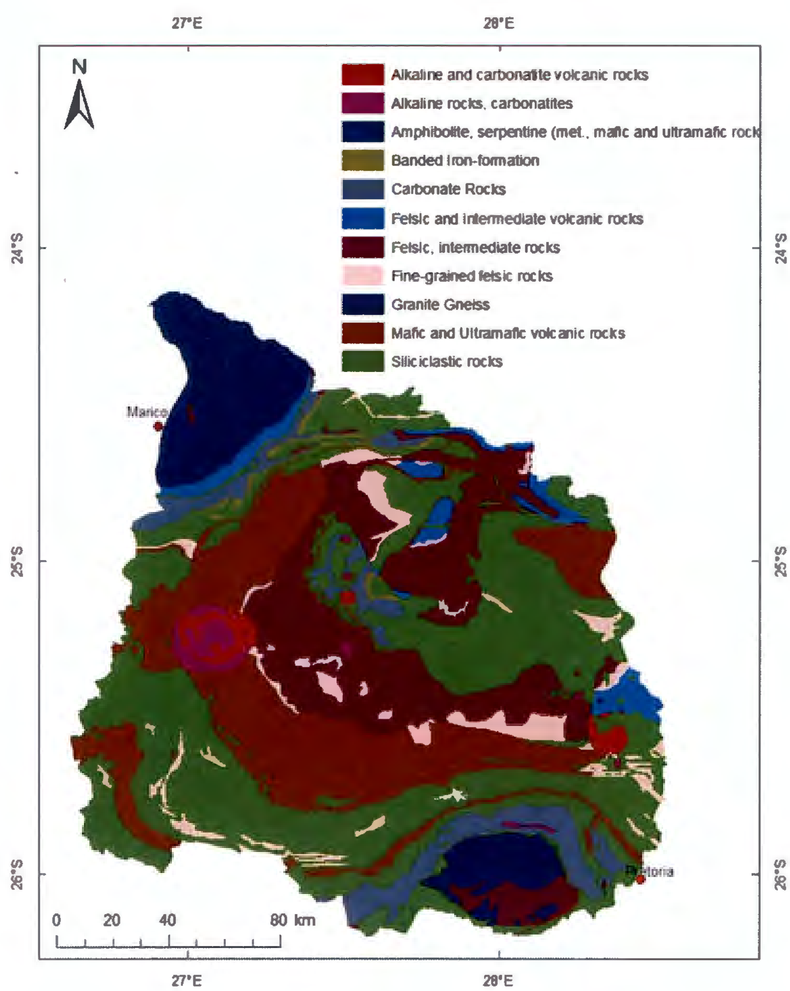


Figure 1.4. General geology map of the Crocodile drainage basin.

complex, the Karoo series and the Lebombo series. The rock formations in this complex are very rich in minerals. Dolomitic chert-rich rocks can be seen in a band running from east to west between Rietvlei Dam and Krugersdorp (CSIR, 1981). In the upper part of the catchment are gold-bearing seams of the Witwatersrand Ridge. Sedimentary rocks of the Crocodile drainage basin include shale, siltstone, mudstone, and sandstone, with the quartizites of the Magaliesberg Mountain Range being the most noticeable feature (DWAF, 2004). Outcrops of dolomites are found between Johannesburg and Pretoria, and in the central part of the drainage basin. Minor occurrence of alluvial deposits can also be found in the drainage basin.

1.11.2 Geomorphology and climate

The geomorphology and climatic conditions in the Gamtoos and Crocodile drainage basins are presented below.

1.11.2.1 The Gamtoos Drainage basin

The Gamtoos drainage basin has a rugged and deeply folded topography. The Southeast trending plain is surrounded by steep hills that increase in altitude further inland (see Figure 1.1B). The highest elevation is 2 789m above sea level. The Gamtoos river system is formed by the following tributaries the Groot, the Kouga, the Klein and Buffels rivers. The Gamtoos river lies south of the Kango-Gamtoos line of fault. The Kouga and Groot rivers, the two major tributaries of the Gamtoos and they run across quartzitic sandstone of the Table Mountain Group, which make up the Kouga and Baviaanskloof mountain range. The Gamtoos river flows through a 90km course along a flat alluvial plain bounded by less resistant Enon conglomerate.

Four rainfall zones are observed in the Gamtoos drainage basin. Inland areas have lower rainfall than the coastal areas. The average rainfall is about 530 mm. The annual minimum temperature is 8°C and occurs in July. The maximum annual temperature is 38°C and occurs in January CSIR, 1981; DWAF, 2004). The mean run-off from the Gamtoos drainage basin is approximately $485 \times 10^6 m^3$ (Nobel and Hemens, 1978).

1.11.2.2 The Crocodile Drainage basin

The Crocodile river source is in the Witwatersrand mountain range. The elevation for the drainage basin ranges from 855m to 2135m (Figure 1.1C). The Crocodile river and a few of its major tributaries rise in the south of the drainage basin as gentle rolling hills on the Highveld Plateau in Witwatersrand at altitude close to 2000m.The rivers flow across the Daspoort Ridge up to the Magaliesburg mountain range at the Hartbeespoort Dam with an altitude of 1200m. Further meandering of the Crocodile River across a flat weathered volcanic landscape continues past the Pilansberg volcano and over the Thabazimbi Mountains down its confluence with the Groot Marico. At this point the river becomes the Limpopo River at an altitude of 900m (DWAF, 2004). The Crocodile tributaries include, Magalies, Elands, Bierspruit and the Sands.

The maximum temperature of 40°C occurs in January while the minimum temperature is 15°C and occurs in July (DWAF, 2004). The Crocodile drainage basin experiences an annual average rainfall of 750mm. The mean run-off for the Crocodile drainage basin is $855x10^6m^3$ (CSIR, 1981).

1.12 Outline of the dissertation

This dissertation is divided into five chapters. Chapter one offers a background of the study and explains the research problem. It also outlines the research hypothesis and objectives and a description of the study area. In Chapter two, relevant literature is reviewed to understand landscape evolution and the evolution of South African landscapes in particular. The chapter also provides a critical background and analysis of the drainage basin morphometry and the corresponding important indices used in this study. Chapter three outlines the data used in this study and explains and justifies the research techniques used. Chapter four presents the results and offers interpretation and an overarching discussion of the research findings for the two study drainage basins. Chapter five presents the conclusions and recommendations for the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter offers a theoretical background of the research. The following aspects are given special attention: a critique of classical theoretical work that explains landscape evolution, a discussion on the evolution of South African landscapes and an examination of the fundamental aspects of drainage basin morphometry.

2.2 Evolution of landscapes

The natural landscape is part of the Earth's surface with a collection of landforms characteristic of the area, e.g. karst landscapes and desert landscapes. There is continuous change taking place in every landscape in response to endogenic forces (volcanism, uplift, isostacy, folding and faulting among others) and exogenic forces (erosion, transport, deposition, weathering and mass wasting) (Bauer and Kilburn, 2009). This interaction produces the different landscapes seen across the globe.

Different ideas have been advanced to explain the role of tectonics and climatic factors in the evolution of landscapes. Early examples of research into the role of structure and climate controls on landscape evolution started with Davis (1902). According to him, the sequence through which landscape evolves is a function of a trio of geographic controls, namely: structure (that is the lithology and geological deformation), process (geomorphic procedures that act on the earth crust to produce the landscape) and the passage of time. A number of earth scientists accepted wholly or in part the Davis's structure-process-time framework (Jenny, 1941; Hole and Johnson, 1994; Retallack, 1994; Holliday, 1994), some have pointed out the role of reverse interaction between climate and tectonics (see King 1962, Penck 1924, Wobus *et al*., 2003, Thielde *et al*., 2005, Grujic *et al*., 2006, Burbank *et al*., 2003). Others have questioned the consistency of the structure-process-time trinity in fully explaining the role multiple controls and processes play in landscape evolution.

Considerable research has been undertaken on the role of structure in drainage development (Summerfield, 1991; Macka, 2003; Twidale, 1980, 2004; Clark *et al*., 2004; Raj, 2007: Gunnell and Harbor, 2008; Babault *et al.,* 2013; Manjoro, 2015). There is consensus on the relationship between the structure and stream orientation, drainage pattern and direction of river channels (Hodgkinson *et al*., 2006; Twidale, 1980, 2004; Scheiddegger,

1965. The challenge is to be able to identify the best techniques that may help assess and understand the trajectory of landscape evolution in a particular area.

2.3 Development of South African landscapes

Research on South African landscape has a long history (Grab and Knight, 2015). Du Toit, (1937) using Continental Drift Theory explained the breakup of the Gondwana as one of the factors shaping the current landscapes. On the other hand, King (1962) hypothesised what he called the macroscale cycle of land surface erosion where climate enforced the landscape to respond to weathering and erosion activities. Traditionally, the evolution of the South African landscapes is argued based on two contemporary viewpoints namely; its geology and geomorphology (Grab and Knight, 2015). The South African landscape is a product of the ancient Gondwana break up. A substantial amount of literature has been published on the geological evolution of South Africa landscapes. The structural framework for the South African continental margin was established during the formation of the retro-arc Permo-Triassic Cape Fold Belt (Halbich, 1983). Subsequently, Late Jurassic to early Cretaceous tensional fragmentation of Gondwana resulted in major easterly-trending, southward dipping normal faults, sub-parallel to the present Southern Cape coastline. Tankard *et al*., (1982), identified five stages in the geological formation of South Africa. Noffke *et al., (*2006) demonstrated that the initial Archean rocks that lie inside the Barberton area of South Africa symbolise one of the world's renowned Greenstone Belt and composed of metamorphosed volcanic-sedimentary sequence with an age of between 2.9-3.2 billion years ago. The oldest known glaciation (2.9 billion years ago), as evidenced by diamictites are contained within stratified siltstone found in the country (Young *et al.,* 1998).

According to Partridge and Maud (2000), the evolution of the Kaapvaal Craton took place in the Neogene period. The craton is composed predominantly of gneissic rocks (Partridge and Maud, 2000). On the other hand some the Karoo Basin was formed in the South-Western Gondwana during the Carboniferous Era, with successive infilling of the drainage basin yielding stratigraphic thickness of up to 12 km (Grab and Knight, 2015). The Karoo foreland basin is surrounded in the Northern part by the Cargonia highlands, and in the Southern part by the Cape Fold Belt (Isbell *et al.,* 2008). Karoo sedimentation ended about 183 million years ago during the basaltic outpouring that took place around that time. The intrusion of the Karoo sequence also happened because of volcanicity that occurred with the continental drift to create dolerite dykes and sills (Eales *et al.,* 1984). The present day outline of the coast in Southern part of Africa emerged when the South America, the Falkland

Plateau, and the Antarctica detached from the southern part of Africa around 129-121(Ma) million years ago (Fouche *et al.*,1992). The above discussion gives an overview of the geotectonic events in South Africa.

2.4 Drainage basin morphometry

A drainage basin is a fundamental geomorphic system or unit of study of geomorphic and hydrologic processes (Ritter *et al.,* 1995). Drainage basins preserve records of their development and progression, owing to the fact that majority of the geomorphic processes occur within the boundaries of drainage basins (Romshoo *et al.*, 2014; Dar *et al.*, 2014). According to Ritter *et al.,* 1995) the features of a basin can be considered a subsystem, each having its own unique sets of processes, geology, energy gain and losses. This, therefore, makes it possible to analyse hydrologic and geomorphic events on a basin scale. For many years, the drainage basin has been the focus of research aiming to understand the geometric characteristics of master channels and their tributary networks. These studies have shown that patterns of basin morphometry can be used to describe and predict the corresponding geomorphic processes and geologic evolution (Gardiner, 1978). In the following section the most common morphometric properties are presented.

2.4.1 Linear morphometry

These are linear expressions of a drainage basin's characteristics, which include drainage pattern, stream ordering, stream length, stream length ratio and bifurcation ratio among others. Six major drainage patterns (dendritic, trellis, rectangular, radial, annular, and parallel) have been recognized. The groundwork for drainage pattern analyses was laid by Zernitz (1932). Drainage patterns are an important indicator of structural influence (Twidale and Bourne, 2011; Kale *et al.,* 2014). The dendritic drainage pattern which characterized by streams irregularly branch out in all directions and the tributaries join the main stream at acute angles, develops on rock of uniform resistance to erosion and in the absence of structural control (Twidale, 2004; Zernitz,1932). According to Twidale (2004), the rectangular pattern is directly conditioned by right-angled jointing or faulting of rocks. However, Manjoro (2015) found that anticline breaching may also result in rectangular drainage in the CFB. Trellis patterns are typical of zones of roughly parallel or only gently arcuate outcrops associated with the flanks of anticlines and synclines within folded sedimentary sequences. The effect of tectonic structure is revealed by the dominance of patterns such as trellis or rectangular patterns.

Among the linear morphometric properties, stream order expresses the hierarchy of a particular stream in the overall stream network in a basin. The classification of stream orders is the first step in the analyses of drainage basins (Malik *et al.*, 2011). There are three major stream ordering techniques. The method suggested by Strahler (1964) is the most commonly used. Macka (2003) and Manjoro (2015) noted that higher order streams reveal the effect of geologic structure while lower order streams respond to local slope. Stream length is calculated from the mouth of a river to the drainage divide. The stream length ratio of a basin is described as the ratio of the mean length of the one order to the next lower order of the stream segments. The bifurcation ratio (BR) according to Schumn (1956) is a relative ratio of the amount of the stream segments of given order to the amount of segments of the next higher order. The BR values of a drainage basin range from 0 to 10. BR values between 0 and 5 suggest that the area has less structural control, while for drainage basins with BR values from 5 to10 indicate strong structural disturbance (Strahler, 1964; Nag, 1998; Som *et al.*, 1998; Vittala *et al.*, 2004; Chopra *et al.*, 2005).

2.4.2 Areal Morphometry

This aspect measures the two dimensional properties of a drainage basin. It includes drainage density, drainage texture, stream frequency, form factor, circularity ratio, elongation ratio and length of overland flow, among others. Drainage density (DD) is described as the total stream length per unit area and represents the degree of fluvial dissection (Lin and Oguchi, 2004). DD reveals the closeness of spacing of channels (Horton, 1932) and gives a numerical measurement of the landscape dissection and runoff potential (Rekha *et al.*, 2011). The DD of a basin is associated with the climatic conditions, rock types, relief, infiltration capacity, vegetative covers and run-off intensity of the drainage basin

Drainage texture is the relative spacing of total number of stream segments of a given length per unit area (Horton, 1945). Impermeable areas show larger values of drainage texture when compared with permeable areas. Horton (1945) noted that infiltration capacity is the single most critical factor that controls the texture of drainage basins. On the other hand, the circularity ratio and elongation ratio are related measures of the drainage basin shape. Miller (1953) defined circularity ratio as the ratio of the area of a drainage basin to the area of the circle having same circumference as the perimeter of the drainage basin. The value of circularity ratio varies from 0 (in a line) to 1 (in a circle). In cases where the value of drainage texture is less than 2, the drainage basin texture is referred to as a very coarse, from 2 and 4, coarse, between 4 and 6 moderate, from 6 and 8 fine grained and for values greater than 8, very fine grain (Smith, 1950). Similarly, elongation ratio is calculated as the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the drainage basin. The elongation ratio value range from 0.45 to 1.12. The elongation ratio values are generally influenced by climatic conditions and rock types (Singh and Singh, 1997; Schumm, 1956; Strahler, 1964).

2.4.3 Relief Morphometry

The relief characteristics of drainage basins relate the three dimensional features of the basin. Examples of relief morphometric indices are basin relief, maximum basin relief, slope gradient, ruggedness number and hypsometry among others. Basin relief is the differences in elevation between the highest and the lowest points on the valley floor of a basin (Strahler, 1952). Basin relief is an important factor in understanding the denudational characteristics of the basin and plays a significant role in landforms development, drainage development, surface and sub-surface water flow, permeability and erosional properties of the terrain (Magesh *et al.,* 2011). The ratio of the maximum relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line is termed as relief ratio (Schumn, 1956). The relief ratio values increase as the drainage area decreases and size of the drainage basin decreases (Gottaschalk, 1964). The ruggedness number is a dimensionless number that expresses the geometric characteristics of a drainage system; derived from the product of maximum basin relief and drainage density within the drainage basin. The ruggedness number is particularly useful, because it summarizes the interaction of relief and dissection such that highly dissected basins of low relief are as rugged as moderately dissected basins of high relief. According to Schumm (1956) ruggedness number indicates the structural complexity of the terrain.

On the other hand, basin hypsometry examines the distribution of horizontal cross-sectional area of a landmass with respect to elevation (Strahler, 1952) (see Figure 2.1). Hypsometric analysis has been used to investigate the geomorphic form of landscapes, landscape evolution including elucidating the link between geological structure and fluvial geomorphology (Strahler 1952; Hurtrez et al 1999, Lifton and Chase 1992). The hypsometry of a basin is displayed graphically as a hypsometric curve (HC) and quantitatively as the hypsometric integral (HI). The HC is created by plotting the proportion of total basin height against the proportion of total basin area. It represents the volume of rock mass in the catchment and the amount of erosion that has taken place in the catchment against the remaining mass (Hurtrez, 1999). Hypsometric curves help compare drainage basins that are different in extent and steepness, assessing geomorphic maturity of basins and landforms and ascertaining links between erosion processes, basin geometry and drainage network form. The form of hypsometric curve provides critical information about the basin (Luo, 1998). Strahler, (1952, 1957, and 1964) used the hypsometric curve shapes to categorize landforms and their stage of evolution; where the young stage is characterized by a convex upward hypsometric curve, mature by an S-shaped curve while the old/senile by a concave shape. In addition, lithology and structural differences between basins usually accounts for different curve shapes (Keller and Pinter, 1996).

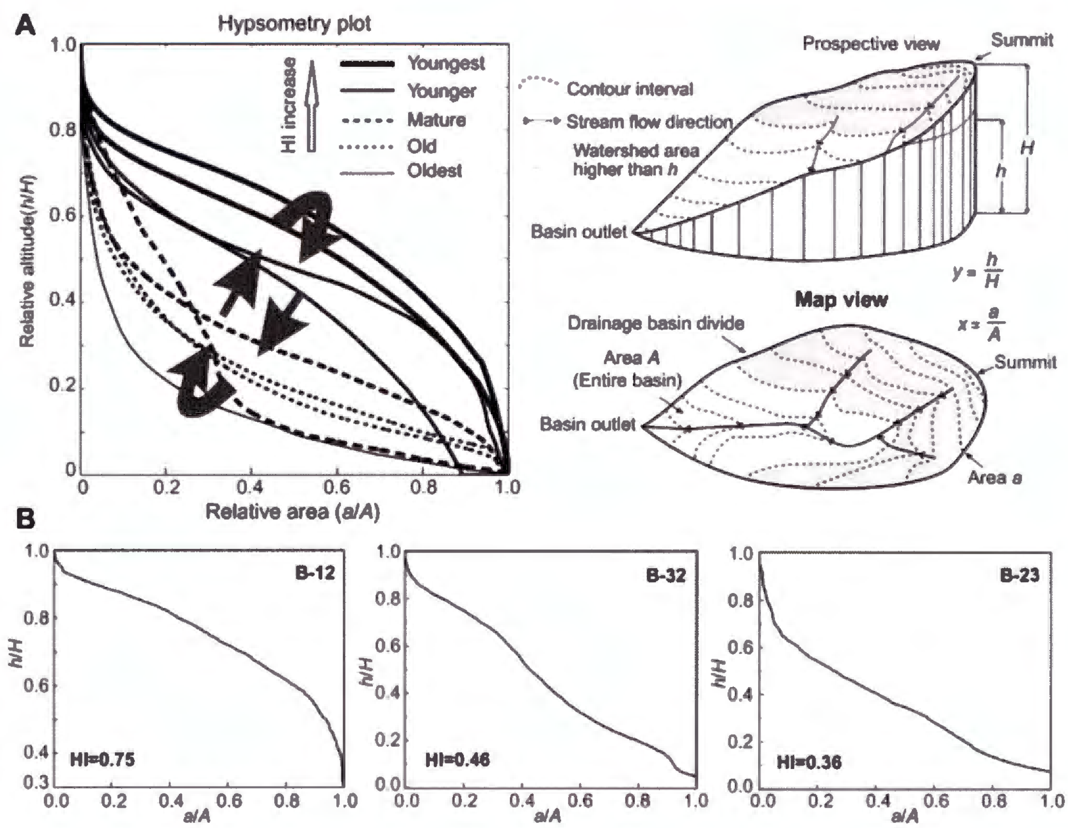


Figure 2.1. The hypsometric curve (plot). A: derivation and interpretation of the shape of the hypsometric curves and B, relationship between the hypsometric curve and the hypsometric integral (Singh *et al.,* 2008).

The Hypsometric Integral (HI), is a simple morphological index of the elevation distribution within the area considered (Ohmori, 1993). The values of the HI lie within the range of 0 to 1, with the monadnock (old) in which the watershed is fully stabilized (HI

$\leq$0.3); equilibrium or mature stage (0.3$\leq$HI$\leq$0.6); and inequilibrium or young stage (HI$\geq$0.6), in which the watershed is highly susceptible to erosion (Strahler, 1952).

There are various methods that can be used to estimate HI. The most common technique is the elevation-relief ratio method (Pike and Wilson,1971), which is based on topographic information from maps or digital elevation models, with the latter being the most commonly used.

$$HI = H_{mean} - H_{min} / H_{max} - H_{min}$$

Where H_{max}, H_{min} and H_{mean} are the maximum, minimum and the mean elevation values in the basin respectively, they are measured in meters (M). Many studies have shown that drainage basin hypsometry robust against variations of DEM resolution (Hurtrez *et al.*, 1999; Keller and Pinter, 2002).

Drainage basin hypsometry is sensitive to both tectonic uplift rates (Lifton and Chase, 1992; Hurtrez and Lucazeaum, 1999; Chen *et al.*, 2003) and variations in erosional resistance of different lithological units (Sarpa *et al.*, 2009). However, basin hypsometry has also been found to be related to the size and shape of basins (scale effect) (Lifton and Chase, 1992; Moglen and Bras, 1995) and relief of the sampled area (Chen *et al.*, 2003; Huang and Niemann, 2006) as well as factors such as the type of dominant erosional process (Walcott and Summerfield, 2008).

Appendix 1 shows some of the most common linear, areal and relief morphometric properties and their calculation. This study will extract some of these indices and analyse their variation and controls in the study areas.

2.5 Summary

In the course of this chapter a review of relevant research on the evolution of landscapes was done, looking at existing knowledge about the structure-process–time framework. Also in this chapter a review on the development of the South African landscapes was done. The chapter examined and set the theoretical foundation to understand drainage basin morphometry. Although, different theories and ideas exist about how ancient landscapes evolved, based on interactions of the processes leading to their formation, it is necessary to be able to ascertain the best technique that will give better understanding of these processes. The next chapter outlines the research methodology.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

The chapter explains how the study basins were selected. It also describes and justifies the selection of the data sets used and also explains all the technical procedures used for data extraction and interpretation.

3.2 Selection of study basins

Two drainage basins with diverse geotectonic histories were selected for this study. The first basin, the Gamtoos (34,635 km^2 in size) represents an ancient landscape, part of which has been exposed to different incidents of crustal shortening and stretching (Malan *et al.*, 1990; Booth and Shone, 2000; Broad *et al.*, 2006). The second basin, the Crocodile (29,349 km^2 in size), was selected purposively from the drainage basins for which detailed geological and structural data was available from the Council of Geosciences. This basin needed to be geologically and structurally different from the first one for comparison purposes, in particular its morphometric characteristics and implications on the explanation of landscape evolution. The Gamtoos drainage basin is distinguished from the Crocodile in that the latter was not exposed to crustal shortening and stretching.

3.3 Data sources

The study was based on the analysis of geology and digital elevation data. In the following sections, the specific data sets are described.

3.3.1 Lithostratigraphy and structural geology data

An extensive GIS database consisting of lithostratigraphy and structural geology data at scales of 1: 250 000 and 1: 000 000 were obtained from Council of Geosciences, South Africa. The data which were in vector format showed geological lines (for example, geological contacts, inferred and observed faults and their types, dykes, location and characteristics of veins, different types of lineaments), lithologic units (for example, rock formations, rock ages), structural lines (for example, joints and fold axes, domes) and point data indicating structural geological markers (for example, plunging angle of fold axis, strike and dips of rock strata, azimuth of dykes) and rock type for the two study areas. Appendix 2 shows an example of a style sheet of one of the geology datasets used to illustrate the amount of detail available in the geology data. The 1: 000 000 scale data was used for plotting maps as the legend was not too detailed. However, the 1: 250 000 data was used for detailed visual analysis. Details of how the above mentioned data sets were used will be explained in the following section.

3.3.2 Digital Elevation Data

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital terrain data tiles at a spatial resolution 30m were acquired on the 23rd June 2016 from the website of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov). The data were transformed to Universal Transverse Mercator World Geodetic System (WGS) 1984 coordinate system so that the data could be overlaid with the existing geology data. The tiles were mosaicked in ERDAS® IMAGINE 2017 software before being subset to the extents of the two drainage basins. The DEM of the Gamtoos drainage basin was further subset into two: the Cape Fold Belt physiographic and Central Karoo regions so that the analysis could be separated by geotectonic history of these regions.

3.3.3 South Africa Water Management basins

A GIS map of the water management basins of South Africa was downloaded from the Department of Water and Sanitation (http://www.dwaf.gov.za/iwqs/gis_data.html). The data was used to extract the extents of the two study areas for use to subset the rest of the data sets.

3.4 Methods

This section presents a description of the methodology used to extract data and to interpret the results to achieve the specific objectives of the study.

3.4.1 Extraction of the drainage network and sub-drainage basins

Hydrological analysis was done using ArcHydro, a set of data models and tools developed by Maidment (2002) and operate within ArcGIS to support geospatial and temporal data analyses related to hydrology. The ASTER DEM was used to delineate and characterize the drainage basins using standard procedures (Figure 3.1). A minimum threshold area of 3.35 km^2 was used to define a stream following (Ghosh *et al.*, 2015; Richardson *et al.*, 2016). Note that this definition of stream has nothing to do with flow characteristics (perennial or ephemeral) but it defines a landscape feature that has potential to transfer water and sediments in the drainage basin based on the size of its contributing catchment area. The Strahler stream ordering scheme (Strahler, 1957) was used for stream ordering.

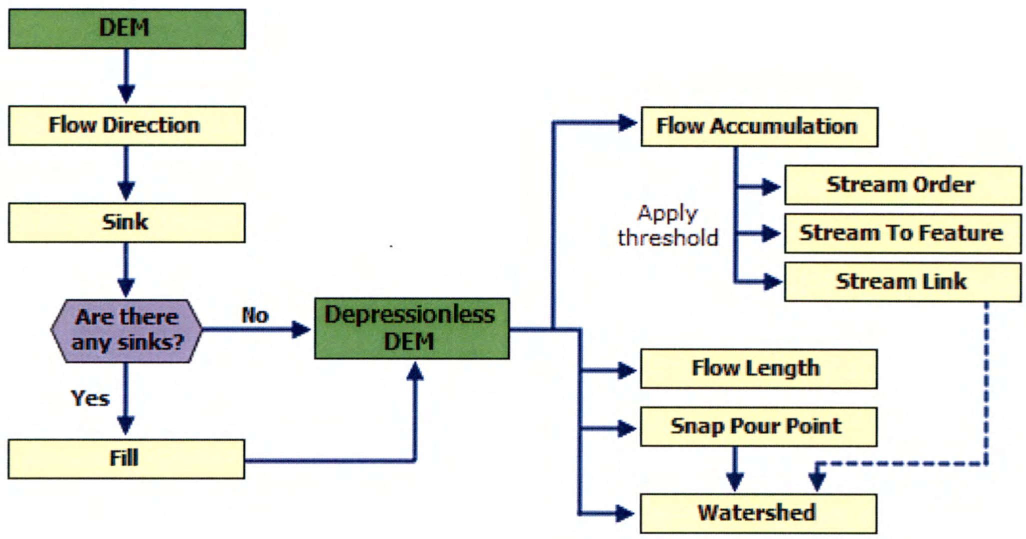


Figure 3.1. Methodological flow chart for the delineation and characterization of the drainage network and drainage basins.

3.4.1 Extraction of the morphometric properties

The main tributaries in each basin were identified from published work and their sub-basins extracted and characterized as explained above. Similarly, all fourth order basins were extracted and characterized in terms of the morphometric properties of interest. Third or fourth order basins have been widely used to assess the spatial distribution of basin properties in basin morphometry studies (Chen *et al.*, 2003; Richardson *et al.*, 2016). However, the choice of the scale of analysis depends on the objective of the study or whether there is suspected scale dependence of the property under analysis (Walcott and Summerfield, 2008). In the study region Manjoro (2015) found that the effect of structure of some morphometric characteristics of the stream networks, for example, orientation was better observed in higher order streams as opposed to first order streams. Thus fourth order basins were used.

For linear and areal morphometry, the stream network and drainage basin attribute databases were exported from ArcGIS to Microsoft Excel where the calculation of selected properties using appropriate formulae (see Appendix 1) was done. The properties were calculated for the entire Crocodile drainage basin and separately for the two distinct physiographic regions of the Gamtoos drainage basin. Additionally this was done for all extracted 4th order basins (Figure 3.2). A total of 14 different relief, areal and linear indices were extracted for the two drainage basins (see Appendix 1).

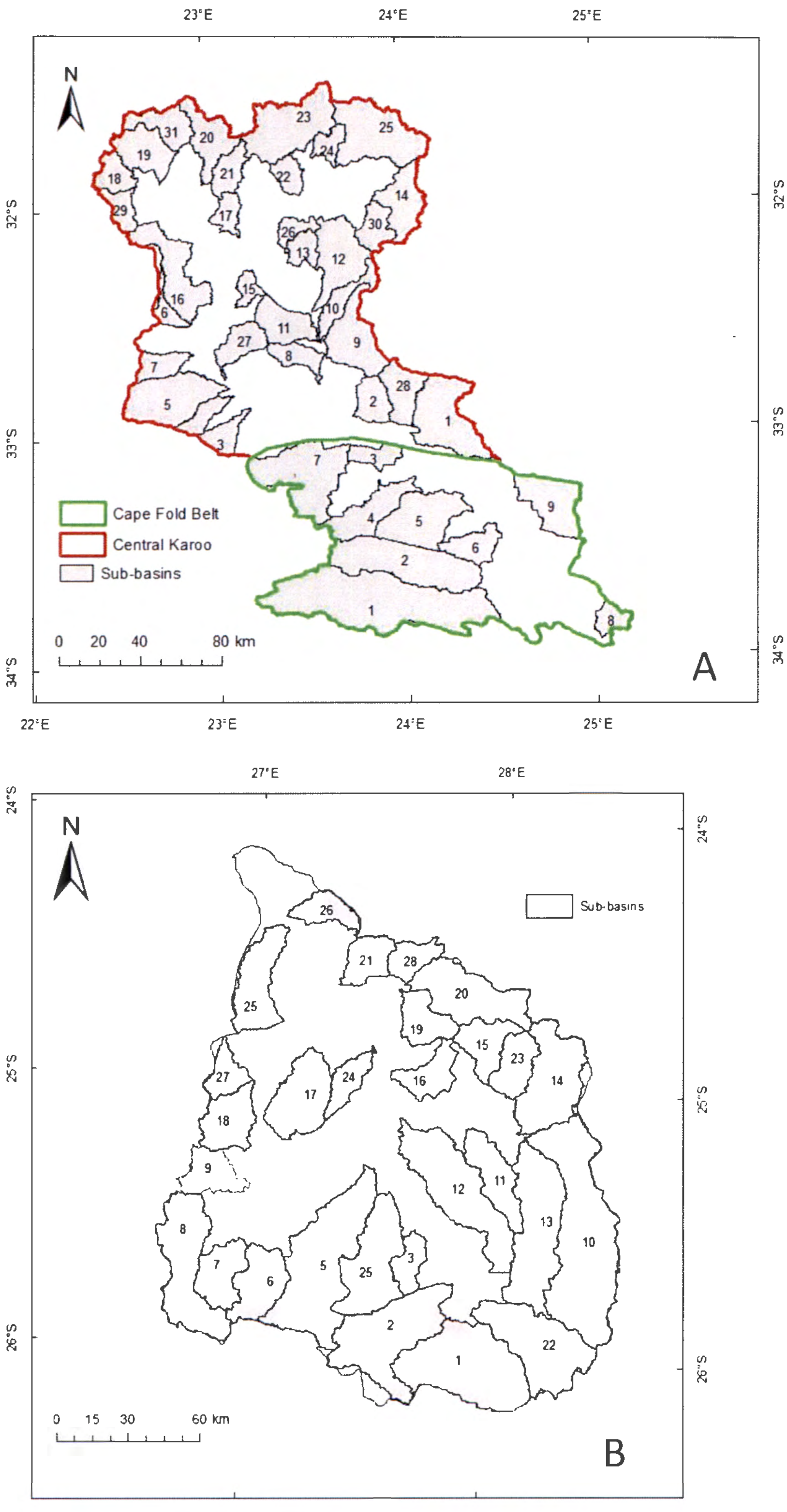


Figure 3.2. The 4th order drainage sub-basins delineated in the Gamtoos (A) and the Crocodile (B) drainage basins. The numbers indicate each sub-basin.

For relief morphometry the information was obtained from the DEM attributes in ArcGIS for each drainage basin extracted previously. In terms of hypsometric properties, the minimum and maximum elevation values were extracted in ArcMap by looking at the table of contents of the DEM. Calculation of the HI were done in Excel. The HC for each fourth order basin was plotted using the Binned Hypsometry Spreadsheet technique (http://gis4geomorphology.com/hypsometric-index-integral/).

Long profiles of the main tributaries of the two drainage basins (see Appendix x) were extracted using ArcGIS by digitising the stream network and then extracting the elevation values along the digitized network and graphically plotting them in Excel. Long profile analysis was important because it allowed the examination of fluvial incision, structural and lithological controls. This was done by highlighting the relationship between knick points and main lithological (bedrock types and igneous intrusions) and structural elements (faults and fold axes) among others.

The above explained procedures were used to extract the selected morphometric properties of the drainage basins to achieve the first specific objectives: to extract selected relief, area and linear morphometric indices for the study basins. To archive the second objective to document variation in the selected morphometric indices between the basins, selected maps were plotted, for example, to show the spatial variation of the hypsometric integrals. Most of the variations were described from the visual analysis of the maps. The impact of structure and lithology on the long profile characteristics was examined by plotting the lithology, fold, faults and dykes together.

3.4.3 Morphostructral analysis

In order to achieve the third specific objective: to explain the observed variation using existing geotectonic data, a morphostructural approach (Stokes *et al.,* 2008; Manjoro, 2015) was used. This approach is based on a detailed GIS overlay and visual analysis of structural, geology, topographic and hydrological data sets to investigate relationships. For example, the influence of structure on drainage was examined by overlaying the drainage network with fold axes, faults and shaded DEM. The impact of lithology of selected morphometric properties was examined likewise. Insight into the suitability of morphometric properties in characterizing geomorphic evolution of the basin was obtained by assessing the extent to which the role of bedrock type, inherited tectonic structures and large scale forcing factors were explained by the morphometric characteristics. Figure 3.3 shows the methodological flow chart.

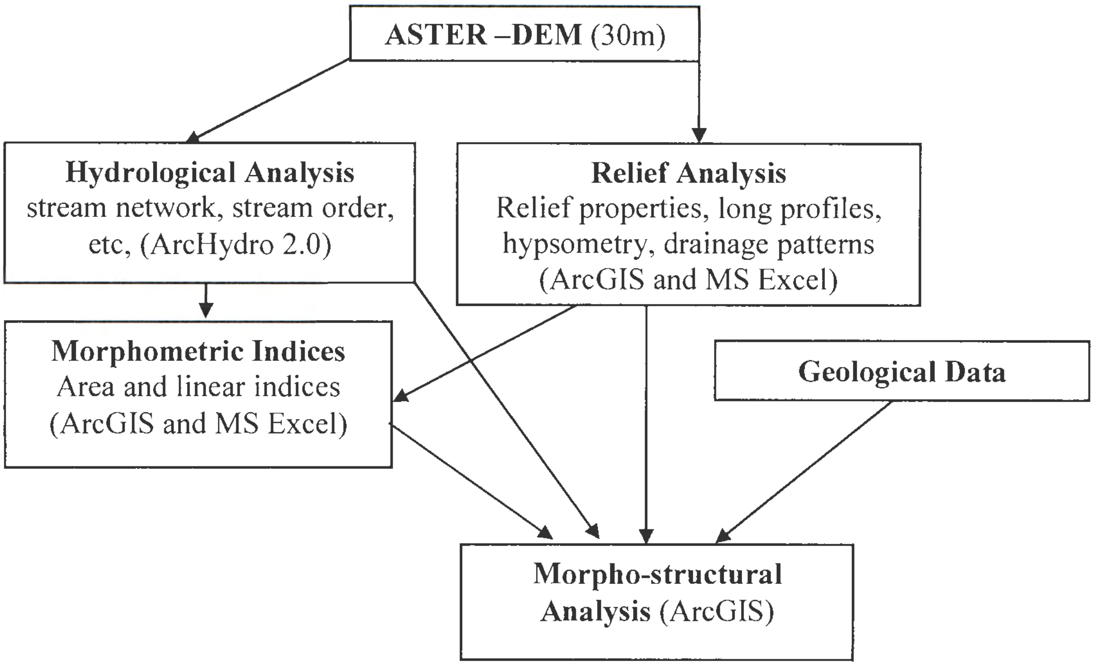


Figure 3.3. The methodological flow chart of the study.

3.5 Summary

This chapter outlined the data and explained the methodological steps for the extraction of drainage networks, morphometric properties, and the morphostructural analysis of the drainage basins. The next chapter presents the results of the morphometric analyses of the drainage basins.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The aim of this chapter is to present and discuss the research results. The results are presented first and the discussion on whether the morphometric characterization undertaken has been able to explain the geomorphic evolution of the two drainage basins will be done last in Chapter.

4.2 Results

The selected linear, areal and relief morphometric properties of the two physiographic regions of the Gamtoos drainage basin and those of the Crocodile drainage basin will be presented in this section. The spatial variation of the morphometric properties will be examined and interpreted using the available geotectonic data.

4.2.1 Linear morphometry of the Gamtoos and Crocodile drainage basins

The linear morphometric properties of the two physiographic regions of the Gamtoos and the Crocodile drainage basins are presented in Table 4.1. In both regions of the Gamtoos drainage basin and in the Crocodile drainage basin, stream order is inversely proportional to stream number and total stream length. The bifurcation ratio (BR) values ranged from 3 to 5.6 (with mean BR of 3.49) for the Central Karoo region, from 1 to 8 (with a mean BR of 4.12) for the Cape Fold Belt region and 1 to 5.64 (with a mean BR of 3.58) in the Crocodile drainage basin. It is evident that Cape Fold Belt region has the highest average BR values. According to Som *et al.*(1998), Vittala *et al.*(2004) and Chopra *et al.*(2005) BR values between 0 and 5 suggest that the area has less structural control while values above 5 indicate tectonically active areas. The results point at little structural control of BR values in both basins. The implication of this will be discussed in section 4.3.

Regarding the drainage pattern, the Central Karoo region and the Crocodile drainage basins show a predominantly dendritic drainage pattern (Figure 4.1). According to Twidale, (2004) and Zernitz (1932), this pattern develops on horizontal rock beds of uniform resistance to erosion and in the absence of structural control. This is true of the Central Karoo region which is largely underlain by mudrock and subordinate sandstone without any structural control (Figure 1.2A and Figure 1.3).

Table 4.1. Selected linear morphometric properties of the Gamtoos and Crocodile drainage basins

Stream order	Stream number	Total stream length (km)	Average stream length (km)	Bifurcation ratio	Mean BR
Gamtoos drainage basin: Cape Fold Belt region					
1	1170	2938.39	2.51	5.90	4.12
2	198	1358.11	6.86	4.21	
3	47	613.30	13.05	5.88	
4	8	410.97	51.37	8	
5	1	269.63	269.63	1	
6	1	78.94	78.94	-	
Gamtoos drainage basin: Central Karoo region					
1	2316	6224.68	2.69	5.62	3.49
2	412	3077.31	7.47	3.89	
3	106	1462.52	13.08	3.93	
4	27	704.02	26.08	4.5	
5	6	256.44	42.70	3	
6	2	399.27	199.63	-	
Crocodile drainage basin					
1	2539	6991.20	2.75	5.64	3.58
2	450	3605.55	8.01	4.37	
3	103	1440.05	13.98	4.48	
4	23	999.76	43.47	4.6	
5	5	302.69	60.54	5	
6	1	141.73	141.73	1	
7	1	163.01	163.01	-	

In the Crocodile drainage basin although there are diverse rock types (Figures 1.4) there are all largely resistant rocks except for a small cover of carbonate rocks in the southern and northern sections. The drainage pattern of the Cape Fold Belt region is predominantly trellis followed by the sub-rectangular pattern (Figure 4.1B).

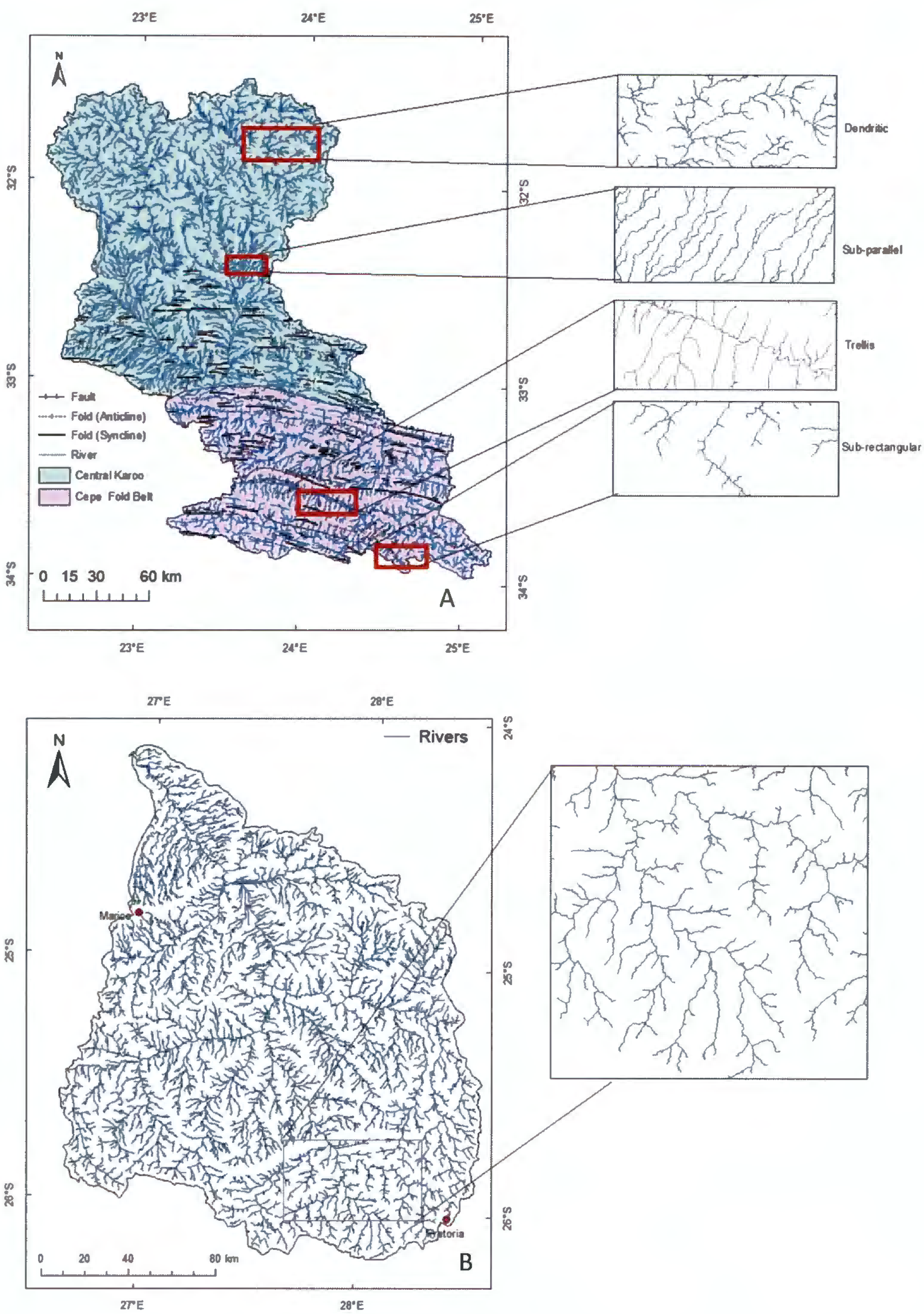


Figure 4.1. Drainage patterns in the Gamtoos (A) and Crocodile (B) drainage basins.

Structural control is evident in the Cape Fold Belt region as short by right-angled jointing or faulting of rocks in the southern most areas. Sub-rectangular drainage in this region is also affected by folding, and particularly anticline breaching causing rectangular drainage as found by Manjoro (2015) in the western domain of the CFB. The dominance of the trellis in the CFB is related to the inherent homoclinal setting of the rock beds in the whole of the Cape Fold Belt (e.g. Hattingh and Goedhart, 1997), where there is a sequence or resistant quartizitic sandstone and less resistant mudstone creates conditions for the development of short dip stream and longer strike valleys that define a trellis drainage pattern. Thus there are multiple structural controls of drainage development in the CFB region of the Gamtoos drainage basin.

4.2.2 Areal morphometry of the Gamtoos and Crocodile drainage basins

The following areal properties were analysed: drainage density, drainage texture and circularity ratio, (Table 4.2). Drainage density was highest in the Central Karoo region with a value of 0.54km/km^2 and both the Cape Fold Belt region and the Crocodile drainage basin have a drainage density value of 0.46km/km^2. The drainage texture values mirror those of drainage density with the highest values found in the Central Karoo region. Drainage density values are surrogates of the level of landscape dissection and runoff potential of a drainage basin (Rekha *et al.*, 2011).

Table 4.2. Areal morphometric properties of the Gamtoos and Crocodile drainage basins

Parameters	**Gamtoos drainage basin**		**Crocodile drainage basin**
	Central Karoo	**Cape Fold Belt**	
Basin Area	22496.63km^2	12261.73km^2	29629.90km^2
Drainage Density	0.56km/km^2	0.46km/km^2	0.46km/km^2
Drainage Texture	3.06	1.94	0.35
Circulatory Ratio	0.32	0.28	0.42

The circularity ratio reflects the drainage basin shape. This ratio ranged between 0.28 to 0.42 in the three study areas with the highest values in the Crocodile drainage basin (0.42) (Table 4.2). According to Smith (1950), the nearer the value is to 0 it means that the basin is linear and if it nears 1 it means that the basin is circular Basins affected with marked geological deformation have near linear basin shapes (lower circularity ratio) due to the confining nature of folding and faulting.

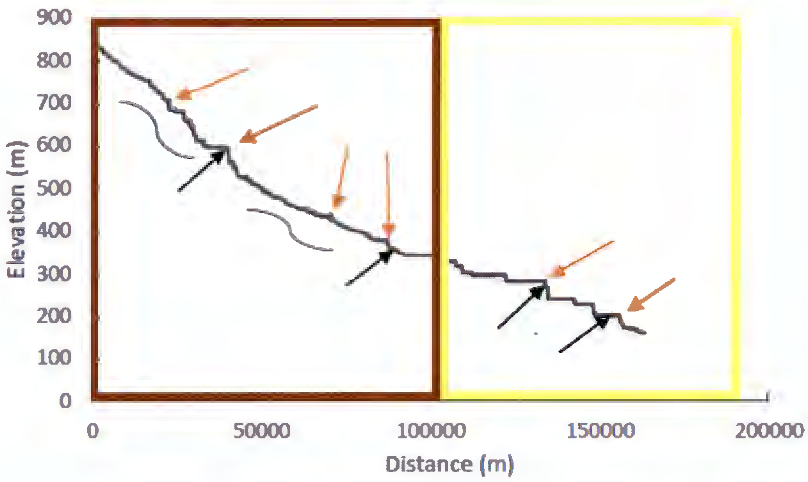
4.2.3 Relief morphometry of the Gamtoos and Crocodile drainage basins

The relief characteristics of the drainage basins were investigated by examining the basin relief, maximum basin relief, hypsometric properties and the stream long profiles. Basin relief reflects the differences in elevation between the highest and the lowest points on the valley floor of a basin (Schumm, 1956) and the basin relief value is highest in the Central Karoo region and lowest in the Crocodile drainage basin (Table 4.3). The Central Karoo region also has the highest maximum basin height. The headwaters of the Central Karoo region occurs at the edge of the Great Escarpment (see Figure 1.1.A and 1.3.B) explaining the high maximum basin height. Maximum basin relief and basin relief are important relief indices as they indicate the general steepness of a basin and erosion potential.

Table 4.3. Selected relief morphometric parameters of the Gamtoos and the Crocodile drainage basins

Parameters	Gamtoos drainage basin		Crocodile drainage Basin
	Central Karoo	Cape Fold Belt	
Basin Relief	2 789m	1 740m	1251m
Relief Ratio	0.01	0.01	0.01
Maximum Basin Height	2 236m	1 744m	2083m
Minimum Basin Height	553m	4m	832m

In addition to the above relief morphometric properties, long profile analysis (Figure 4.2 and 4.3) was undertaken to infer the structural and lithological controls of drainage in the basin. The long profiles of the main tributaries of the Gamtoos drainage basin show a lack of single-graded form as opposed to those of the Crocodile drainage basin. In the Gamtoos drainage basin knick points appear along various points of the profiles.


Elevation (m)
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400
500
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700
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900
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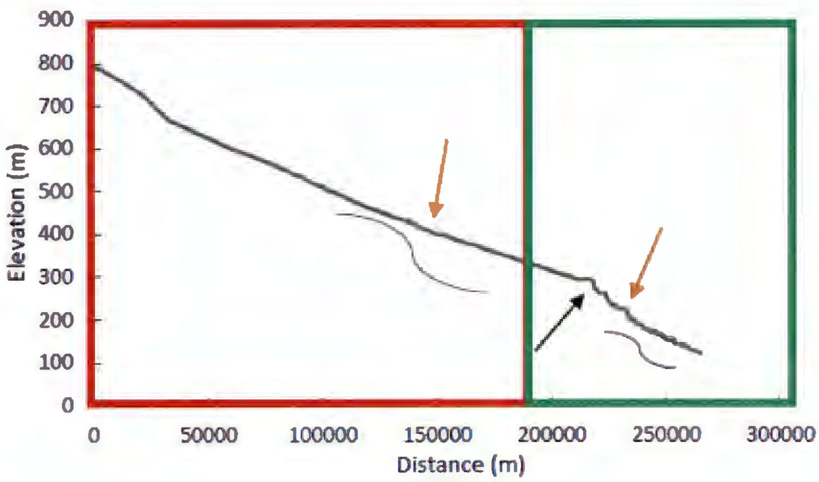
50000
100000
150000
200000
Distance (m)

(A)


Elevation (m)
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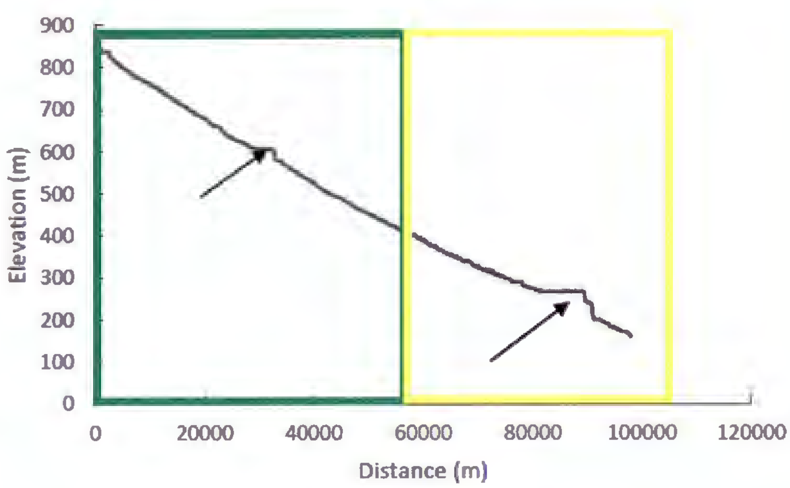
Distance (m)

(B)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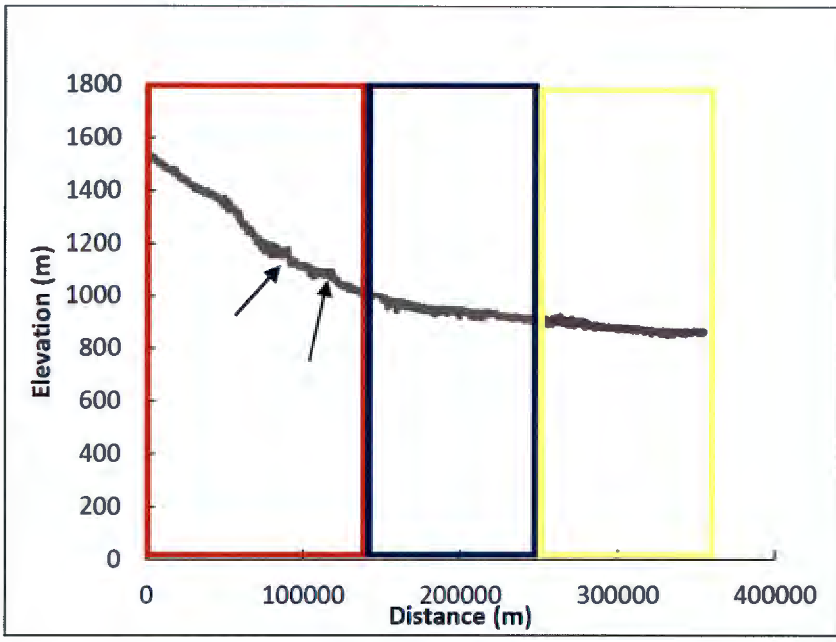
(C)

LEGEND			
	Nardouw Supergroup rocks		Ecca Group rocks
	Witerberg Group rocks		Adelaide Supergroup rocks
	Table Mountain Group rocks		Knickpoints
	Fault		Folds axis

Figure 4.2. Long profile of major rivers and tributaries in the Gamtoos drainage basin: (A) Kouga River, (B) Groot River and (C) Baviaans River.

Generally the tributaries of the Crocodile river have fewer knick points and two of the tributaries have no knick point at all. The shape of long profiles are generally convex in the head waters with the rest being convex and straight in the Gamtoos, while those of the Crocodile basin generally have convex head waters and concave mid and lower parts. Most of the knick points in the Gamtoos drainage basin correspond to faults and fold axes. None of the knick points in the drainage basin coincide with lithological boundaries. In the Crocodile drainage basin there were no apparent controls of the knick points for most of the tributaries.

Drainage basin hypsometry was examined through the hypsometric integral (HI) and hypsometric curve (HC) to assess the denudational or evolutionary stage of the drainage basin following Sarkar and Patel (2011). Table 4.4 shows the hypsometric integral and other selected basin parameters for each 4th order basin. The HI value of the whole Gamtoos drainage basin is 0.30 which according to Sarkar and Patel (2011) denotes an early old age basin. The majority of the HI values in the Cape Fold Belt region range between ($0.35 \geq HI > 0.25$) corresponding to the early old age according (Sarkar and Patel, 2011). On the other hand in the Central Karoo region, most of the HI values of the sub-basins are early old age ($0.35 \geq HI > 0.25$) and senile stage (<0.25). On the other hand, the HI value of the whole Crocodile drainage basin is 0.37 (early old age). Most of the sub-basins in Crocodile a drainage basin the senile stage (<0.25) and early old ($0.35 \geq HI > 0.25$).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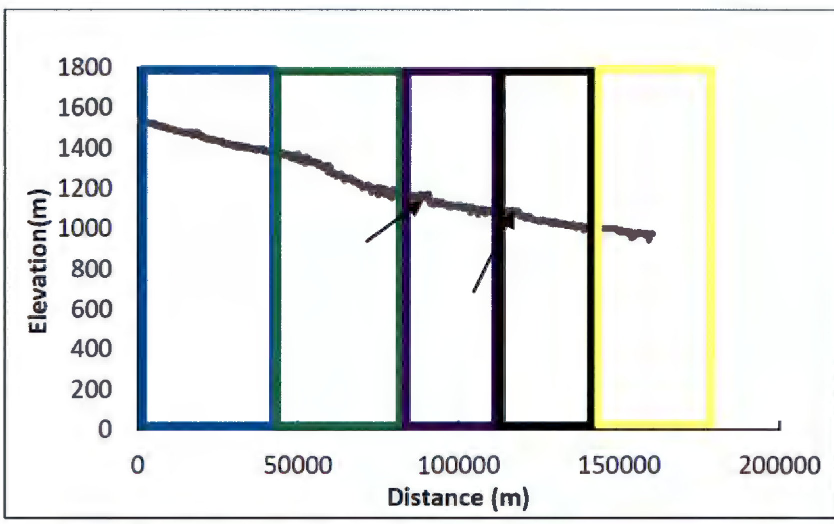
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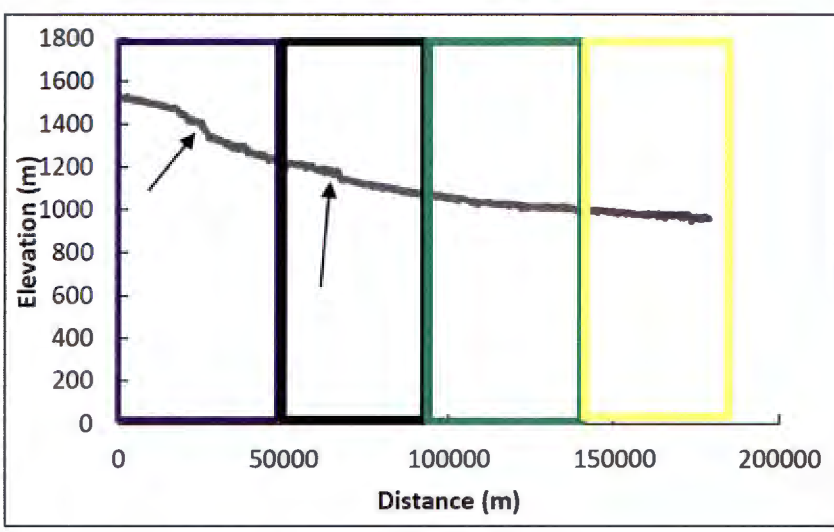
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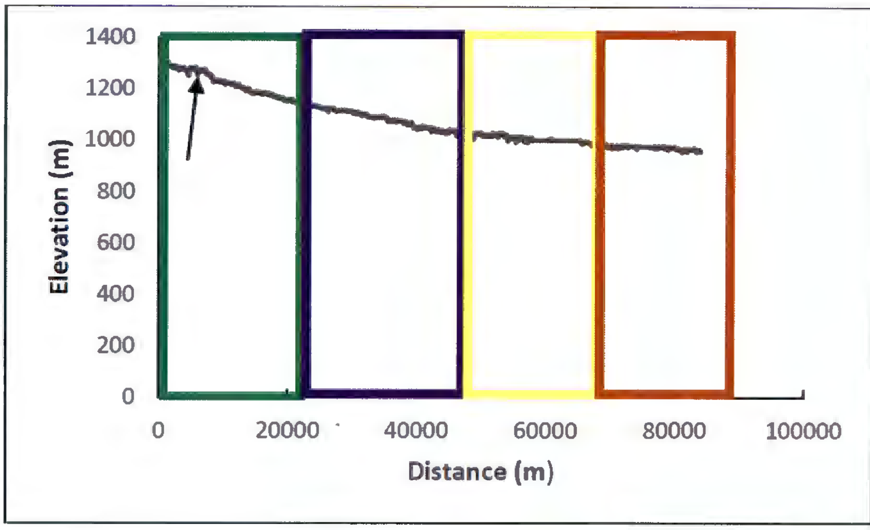
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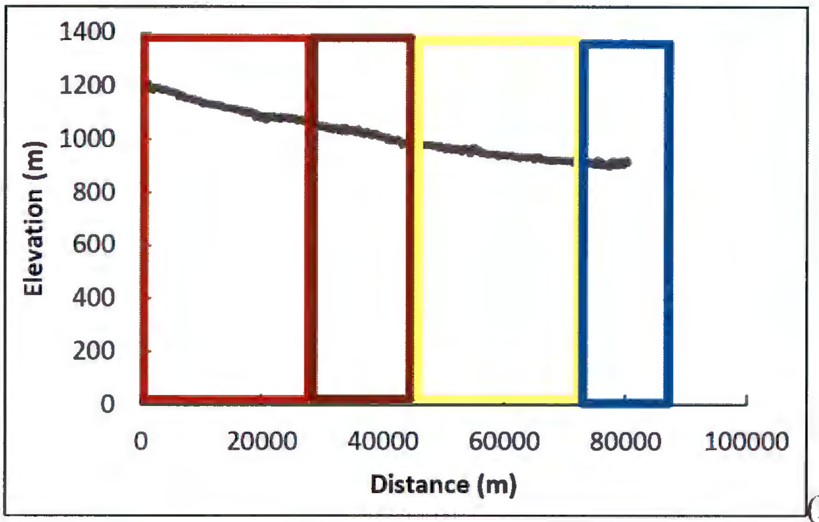
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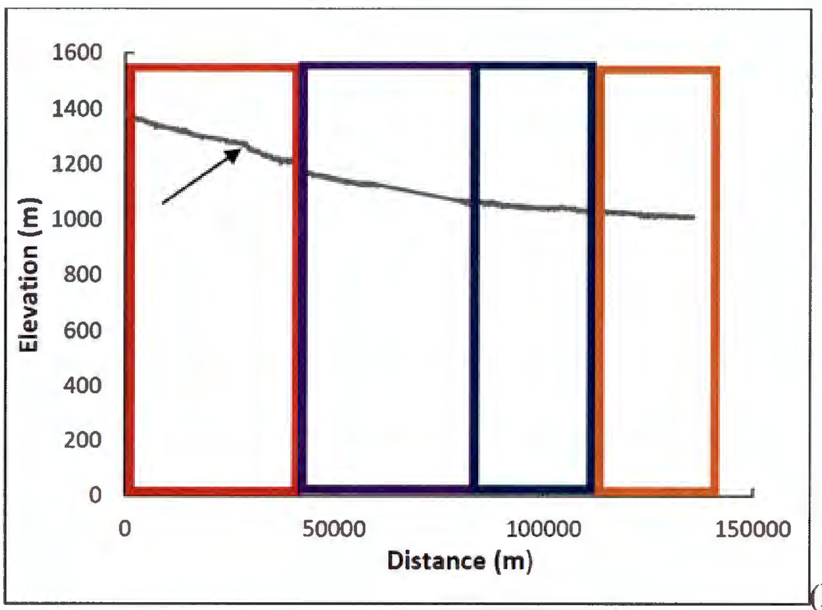
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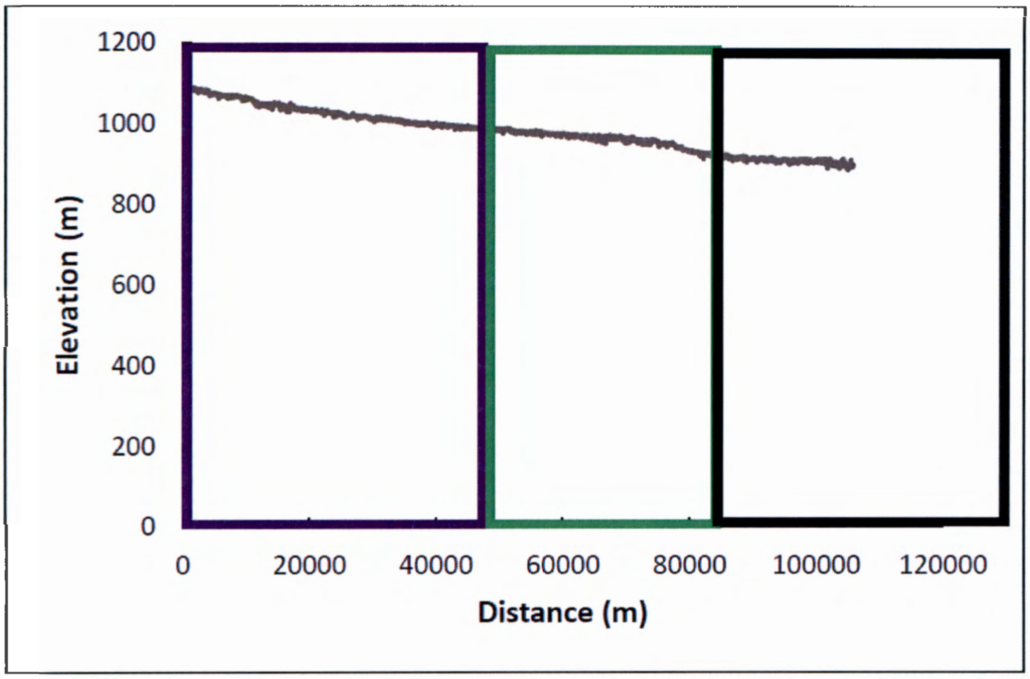


(G)

LEGEND			
	Swazian Erathem rocks		Malmani Supergroup rocks
	Rustenburg Series rocks		Pyramid Gabbro Nortite rocks
	Karoo Supergroup rocks		Silverton Formation rocks
	Pretoria Group rocks	↗	Knickpoints

Figure 4.3. Long profiles of the main tributaries of the Crocodile River: (A) Crocodile 1, (B) Crocodile 2, (C) Elands, (D) Magalise, (E) Sands, (F) Pienears and (G) Bierspruit

The hypsometric integral signifies the geologic stages of development in the 'Davisian cycle of erosion' (Strahler, 1952). The cycle of erosion defines the stages a landform passes through until it reaches a base level. It evident that that most sub-basins in the Cape Fold Belt region correspond to the early old age, which is indicative stabilized basin with less erosion proneness (Singh *et al*, 2008; Sarkar and Patel, 2011). In the Central Karoo region most of the sub-basins are in the early old age and senile stage, while in the Crocodile basin most are in the senile and early old age. None of the three study areas is in the young stage (inequilibrium stage) where the basin is highly erosive. The HI analysis shows that there is no marked difference in the stage of development in the 'Davisian cycle of erosion'. It was expected that rock types and structure among other factors would clearly separate sub-basins into distinct groups. Further discussion on this will be done in Section 4.3.

Table 4.4. Hypsometric integral and other selected parameters for each 4th order sub-basin investigated in the drainage basins.

Cape Fold Belt region						
Basin Number	**Basin Area**	**Mean Elevation**	**Dissection**	**Relief**	**HI**	**Relative age based on Sarkar and Patel (2011)**
1	1937.49	682.11	686.11	1748	0.39	Late Mature
2	1934.82	815.71	533.71	1462	0.37	Late Mature
3	223.22	871.49	307	1005	0.31	Early Old
4	578.59	837.49	300.49	1081	0.28	Early Old
5	836.42	646.95	241.95	1190	0.21	Senile
6	344.10	631.26	260.26	1200	0.22	Senile
7	41.89	364.22	48.22	150	0.33	Early Old
8	190.74	247.46	242.46	817	0.30	Early Old
9	648.95	528.16	234.16	737	0.32	Early Od
Central Karoo region						
1	945.43	727.49	174.49	525	0.35	Early Old
2	322.40	846.40	138.46	455	0.31	Early Old
3	238.40	866.57	112.57	232	0.49	Early Mature
4	210.15	879.66	110.66	253	0.44	Late Mature
5	874.20	907.41	128.41	326	0.40	Late Mature
6	154.74	909.92	67.92	316	0.22	Senile
7	260.27	868.44	50.44	147	0.35	Early Old
8	257.50	825.95	69.95	163	0.43	Late Mature
9	696.93	863.62	75.62	977	0.08	Senile
10	310.25	1031.76	228.76	1115	0.21	Senile
11	451.41	866.70	64.70	434	0.15	Senile
12	738.36	1118.39	280.39	1080	0.26	Early Old

13	210.79	1012.66	97.66	518	0.19	Senile
14	538.93	1549	333.76	1020	0.33	Early Old
15	145.84	922.54	37.54	246	0.16	Senile
16	738.07	1060.35	218.35	1100	0.20	Senile
17	205.56	1143.42	134.42	541	0.25	Senile
18	277	1486.57	160.57	474	0.34	Early Old
19	515.52	1390.65	177.65	617	0.29	Early Old
20	511.40	1307.47	232.47	711	0.33	Early Old
21	292.30	1277.71	204.71	565	0.37	Late Mature
22	209.52	1179.93	140.93	634	0.23	Senile
23	1005.92	1296.7	182.70	710	0.26	Early Old
24	189.77	1279.27	169.27	531	0.32	Early Old
25	1030.78	1460.40	282.40	871	0.33	Early Old
26	168.17	1076.56	128.56	680	0.19	Senile
27	336.03	849.52	67.52	161	0.42	Late Mature
28	432.89	819.12	122.12	353	0.35	Late Mature
29	226.89	1534.34	208.34	562	0.37	Late Mature
30	300.74	1505.06	405.06	1115	0.37	Late Mature
31	396.61	1357.45	154.45	583	0.27	Early Old
Crocodile drainage basin						
1	1417.85	1517.19	302.19	623	0.49	Early Mature
2	1180.62	1476.20	305.20	687	0.45	Early Mature
3	240.22	1189.24	144.24	672	0.22	Senile Stage
4	879.07	1182.71	185.7	859	0.22	Senile Stage
5	1555.6	1218.86	251.86	889	0.29	Early Old
6	530.99	1337.37	245.37	597	0.42	Late Mature
7	442.27	1386.49	285.49	565	0.51	Early Mature
8	995.98	1375.58	319.58	668	0.48	Early Mature
9	362.54	1133.76	100.76	447	0.23	Senile Stage
10	1978.17	1246.31	228.31	631	0.37	Late Mature
11	494.85	1089.27	89.27	355	0.26	Early Old
12	1168	1107.32	154.32	697	0.23	Senile

13	1174	1206.55	197.55	592	0.34	Early Old
14	900.90	1169.25	160.25	630	0.26	Early Old
15	384.90	1181.18	153.18	546	0.28	Early Old
16	335.28	1155.38	218.38	712	0.31	Early Old
17	678,29	1075.81	115.81	717	0.17	Senile Stage
18	463.65	1131.74	120.74	506	0.24	Senile Stage
19	361.89	1230.37	286.37	705	0.41	Late Mature
20	831.53	1228.78	261.78	881	0.30	Early Old
21	324.54	1098.29	186.29	851	0.22	Senile Stage
22	1053.98	1512.92	301.92	597	0.51	Early Mature
23	370.60	1150	122	546	0.23	Senile
24	254.23	1050.81	126.81	504	0.26	Early Old
25	613.27	1022.63	144.63	642	0.23	Senile
26	268.92	965.84	92.84	520	0.18	Senile
27	243.94	1100.49	87.49	289	0.30	Early Old
28	252.67	1227.97	260.97	1116	0.23	Senile

The spatial distribution of the HI values in each sub-basin is shown in Figures 4.4. The senile (HI<0.25) and early old age early old ($0.35 \geq HI > 0.25$) drainage basins are mostly found in less resistant lithology in the Central Karoo region and in both resistant and less lithologies in the CFB region and Crocodile drainage basin.

To account for the spatial distribution of the HI values selected basin parameters that may exert control on HI (e.g. basin area (scale), dissection, mean elevation and relief) were analysed (Table 4.4). Figure 4.8 assesses the relationship between these basin parameters and the HI. The coefficients of determination of the relationship between HI and basin scale in both the Central Karoo and the Cape Fold Belt regions shows that the HI variation is not controlled by scale (R^2=0.0065 and R^2=0.0022, respectively). It was also found that it is neither dependent on basin relief (R^2=0.0248 and R^2=0.0254, respectively) or basin dissection (R^2=0.0065 and R^2=0.0022, respectively) in both regions. In the Crocodile drainage basin, HI is not scale dependent.

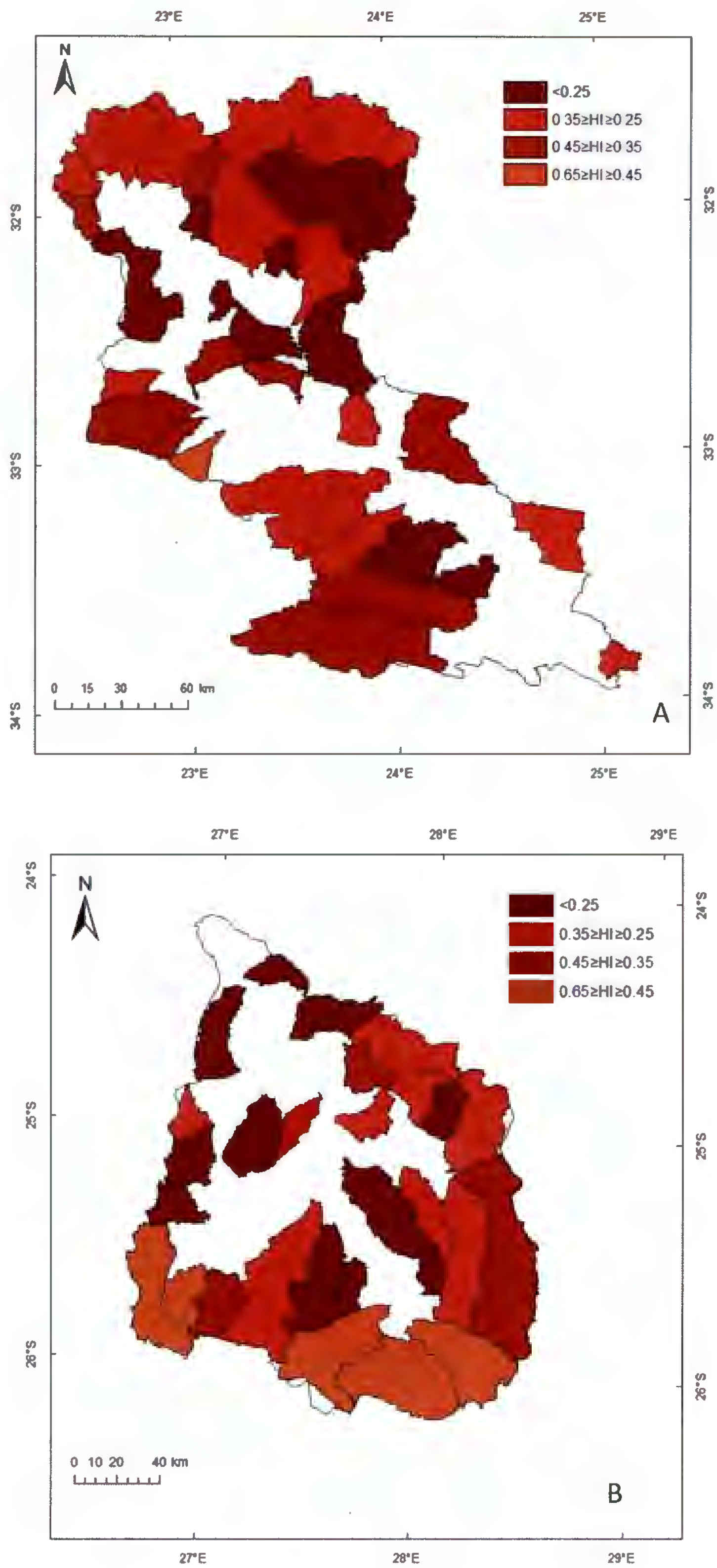


Figure 4.4. Spatial distribution of the hypsometric integrals for the Gamtoos (A) and Crocodile (B) drainage basins.

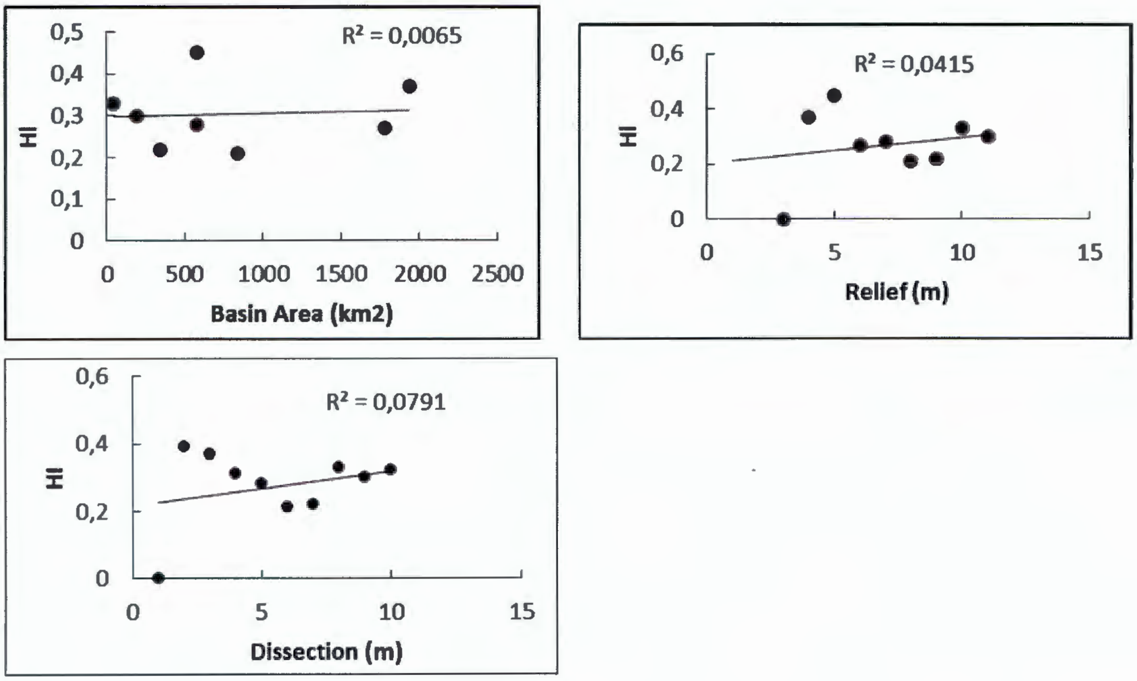


Figure 4.5. Scatter plot of HI against basin size, basin relief and dissection for the Cape Fold Belt region

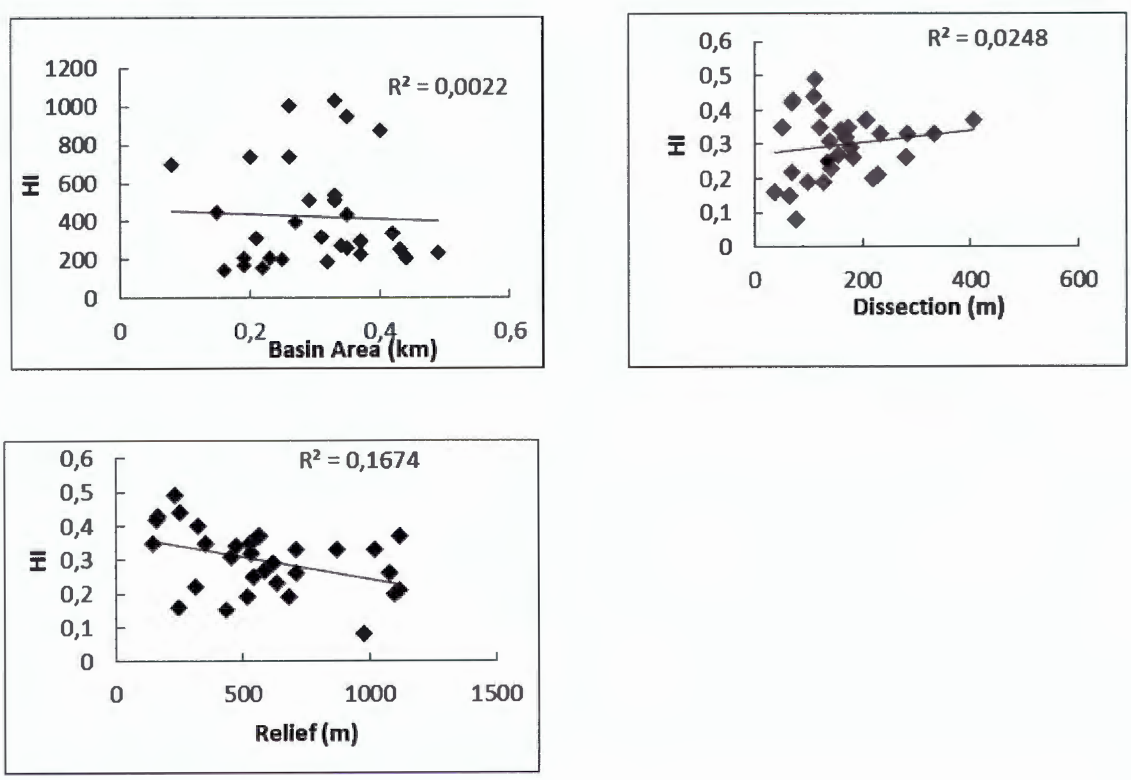


Figure 4.6. Scatter plot of the HI and basin size, basin relief and dissection for the Central Karoo physiographic region.

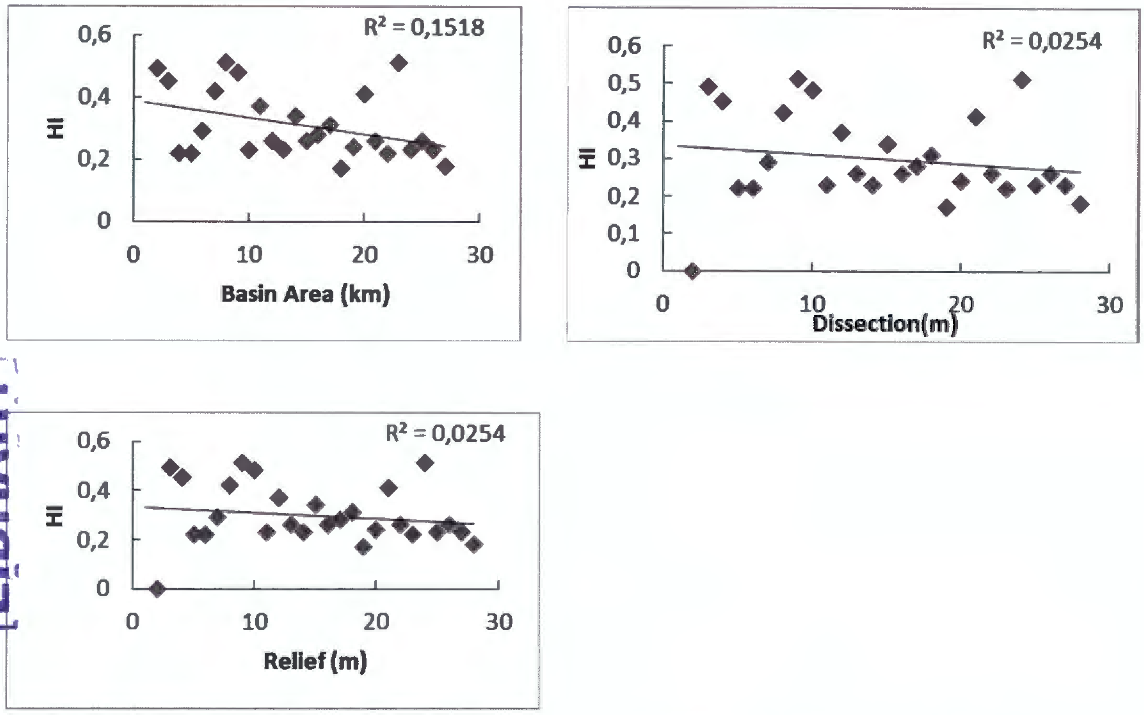
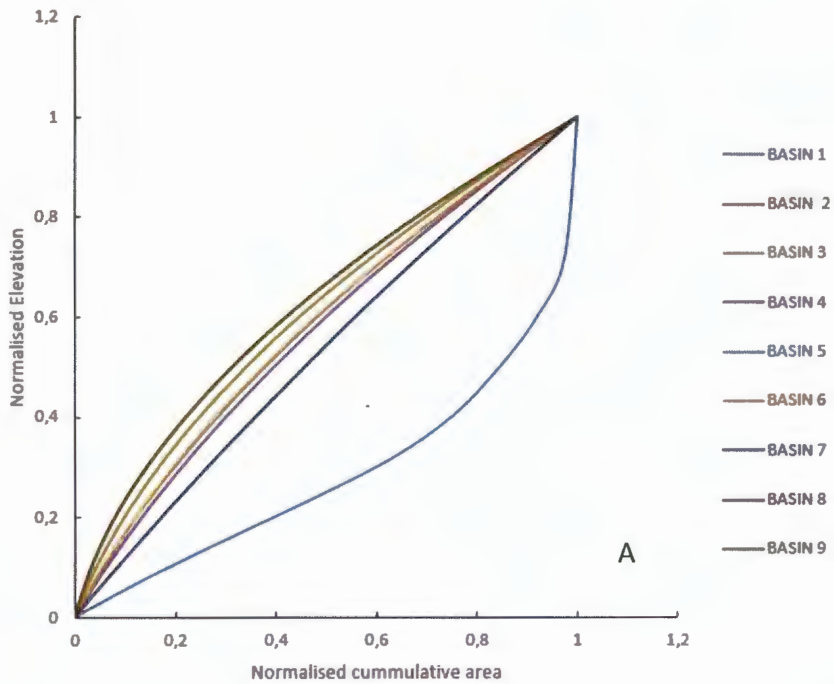


Figure 4.7. Scatter plot of HI against basin size, basin relief and dissection for the Crocodile Drainage basin.

The result indicate that HI is neither dependent on basin relief or dissection (Figure 4.10). Thus in all study areas there was no relationship between the hypsometric integral values and the basin parameters.

The hypsometric analysis of each sub-basin also included the plotting and examination of the hypsometric curves (HC). Figure 4.8 shows the HC of all the 4^{th} order sub-basins in the Cape Fold Belt (A), Central Karoo regions (B) and the Crocodile Drainage basin. For the Cape Fold Belt region, most of the HC are convex (seven curves), with only two exceptions. In the Central Karoo region thirteen HC of the sub-basins shapes are sinusoidal (S-shaped), ten were convex and eight concave in shape. Most hypsometric curves in the Crocodile basin are sinusoidal (thirteen curves). Nine basins have a convex shape, while six have concave shapes.

The form of the hypsometric curve in the same way as the hypsometric integral value provides critical information about a basin (Luo, 1998) and their stage of landform development (Strahler, 1964; Braga *et al.*, 2003). The analysis of the HC indicates that most of the basins in the Cape Fold Belt region typify a relatively high elevation terrain equivalent to what Davis (1899) called a youthful topography. These youthful basin in the study area are


Normalised Elevation
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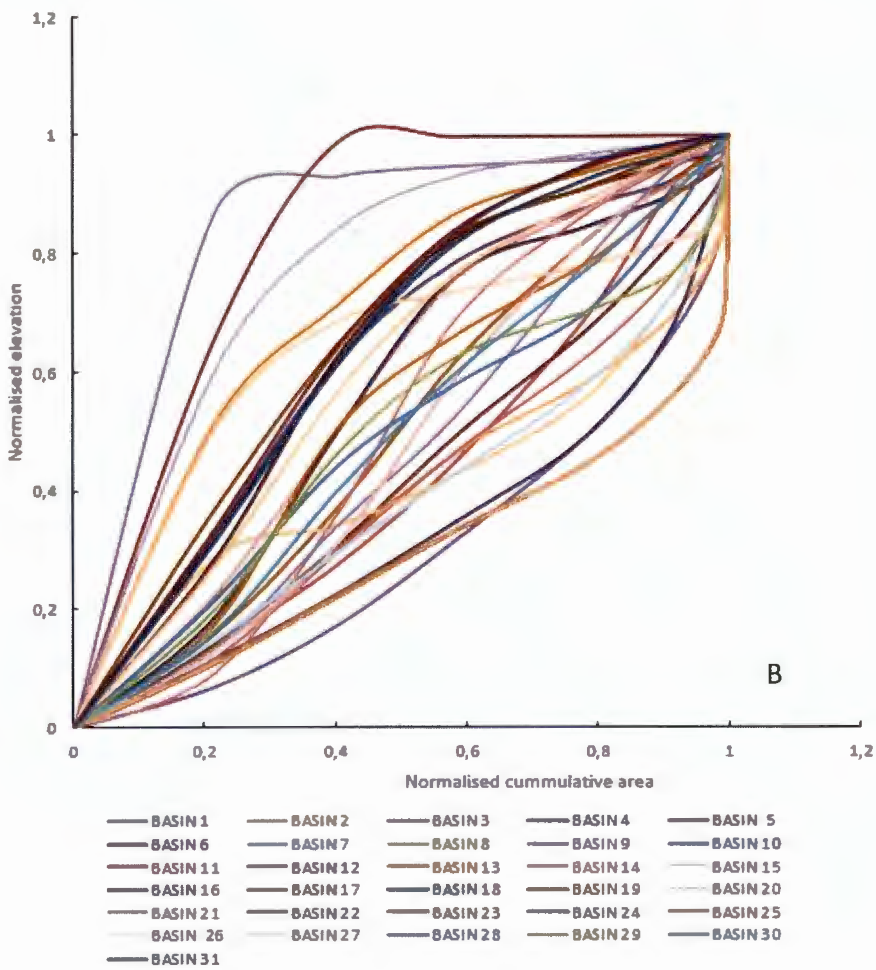
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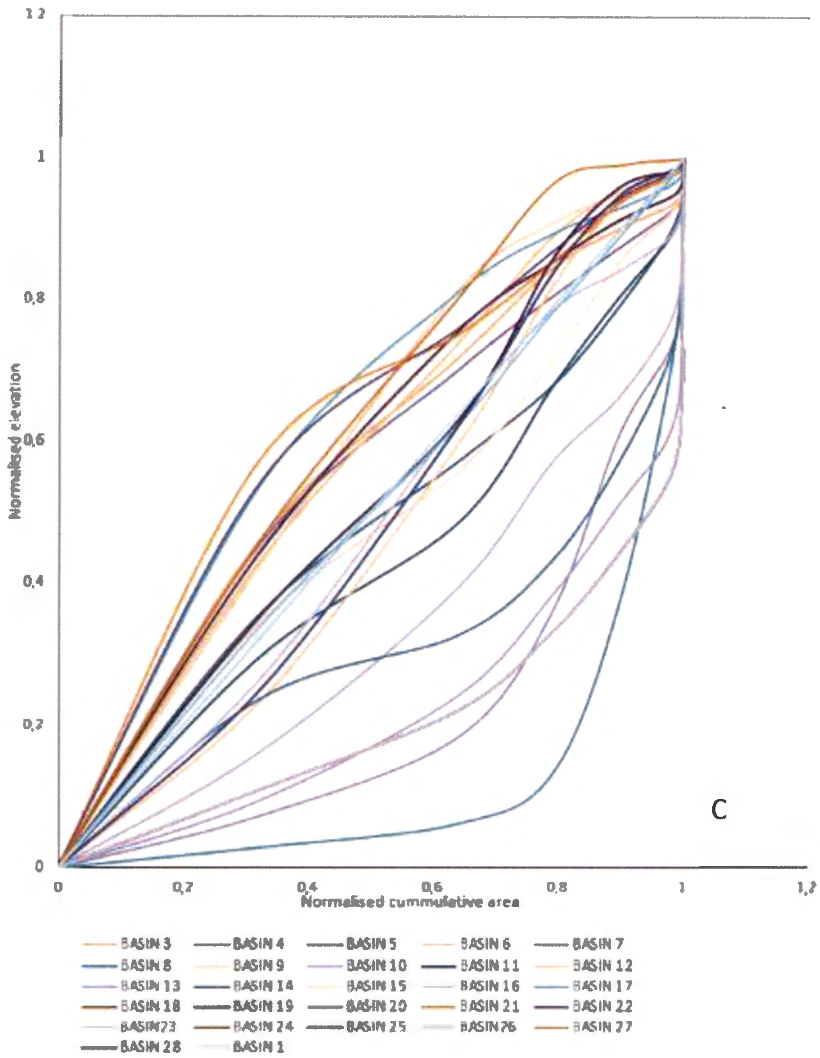

Figure 4.8. Hypsometric curves for all the 4th order sub-basins in the Cape Fold Belt (A), Central Karoo regions (B) and the Crocodile Drainage basin (C)

found in areas where resistant lithologies such as sandstone are dominant (Figure 1.3). Most of the Central Karoo basins are in the mature followed by youthful stage. Those in the mature stage are found in areas with less resistant lithologies such as mudstone in association with sandstone (Figure 1.3). In the Crocodile drainage basin most of the sub-basins are in the mature and youthful stage. Generally this basin is predominantly made up of relatively resistant bedrock (Figure 1.4). Geological deformation had no effect on either HI or HC as there is no unique pattern of hypsometry in the affected areas. A discussion of the implications of the results and relationships with the observations from HI will be discussed in the next section.

4.3. Discussion

This section interprets the key findings and discusses whether the morphometric characterization undertaken for the two basins has been able to explain the geomorphic evolution of the two basins. This will be done by examining the extent to which the morphometric approach is successful in revealing the fundamental controls on the evolution of drainage basins, that is: bedrock type, inherited tectonic structures and large scale forcing factors.

4.3.1 Does basin morphometry explain the impact of bedrock type in the drainage basins?

The impact of bedrock type on drainage development and evolution of drainage basins has been examined by many geomorphologists (Richardson *et al.,* 2016; Hurtrez and Lucazear, 1999). This impact can best be seen in the shape of hypsometric curves (Richardson *et al.,* 2016). However, in this study the relationship between erosion resistance of the bedrock and hypsometry was not consistent across all study regions and drainage basins. For example, while the hypsometric integral was lowest (youthfulness) in the less resistant Devonian rocks of the Cape Supergroup in the Central Karoo region, in the rest of the study areas, this relationship was not applicable. Also, the hypsometric integrals and hypsometric curves were not consistent in indicating the stage of geomorphic development of the study basins. For example, less resistant bedrocks are expected to be more easily eroded resulting in a concave hypsometric curves (Richardson *et al.*, 2016), which is a sign of maturity.

The circulatory ratio is lowest in the Cape Fold Belt and that is consistent with bedrock effects in folded strata. Folded rock beds in South Africa and the Cape Fold beds are known to produce a homoclinal sequence of resistant sandstone and less resistant mudstone (Manjoro, 2015; Hattingh and Goedhart, 1997). This sequence has a confining effect to drainage basin shape possibly leading to lower circulatory ratios. Similarly, basin drainage density and drainage texture reflect the bed rock type, with the highest drainage density associated with less resistant bedrock of the Karoo Supergroup rocks. This means that this region is the most dissected of the three study areas. The high drainage density of Karoo Supergroup rocks was also observed by Richardson *et al.,* 2016) in the Gouritz drainage basin in the south east of South Africa. These authors attributed the less resistance of the bedrock to the absence of burial metamorphism which took place in the areas of the Cape Fold Belt making the rocks more resistant. The rocks of the Crocodile drainage basin and CFB are generally more resistant than the Central Karoo rocks. None of the longitudinal profiles demonstrated bedrock effects as observed in other studies in South Africa (Tooth *et al.*, 2004; Richardson *et al.*, 2016). None of the knick points were associated with lithologic boundaries.

In the Cape Fold Belt most of the abrupt changes in stream direction (also called angular turns), responding to underlying geological structure. Because these areas are predominantly underlain by quartizitic sandstone, which is generally fractured and jointed (Plummer and Carlson, 2012), the AT could be a results of that and to some extent faulting. It is clear that only the variations of the following morphometric properties; circulatory ratio, drainage density, drainage texture and to some extent straight stream planforms explain the impact of bed rock type. Drainage basin hypsometry could not be explained by most of the analysed morphometric properties.

4.3.2 Does basin morphometry explain the impact of inherited tectonic structures in the drainage basins?

Structural configuration of a bedrock greatly influences its drainage development and particularly the drainage patterns (Bourne and Twidale, 2011; Raj, 2007) and river long profiles (Schedegger, 1965; Twidale, 2004). The Cape Fold Belt region of the Gamtoos drainage basin is the only one of the three study areas that was exposed to crustal shortening and stretching including thrust faulting (Booth and Shone, 2000; Broad *et al.*, 2006). The impact of these inherited tectonic structures manifests mainly through the trellis and sub-rectangular drainage (see Figure 4.1A). However, in the rest of the study regions, Central Karoo region where there is no inherited tectonic structure, the main drainage patterns are dendritic and sub-parallel, while the Crocodile drainage basin is mostly dendritic.

Another remarkable control of inherited tectonic structures is evident in most of the Cape Fold Belt region where stream channels ran parallel to or along regional lineaments such as fault, fold axis and associated features such as strike valleys. The data show that most of the stream courses are evidently aligned with the fold axes in the central and South of the CFB region. Also, some of the abrupt changes in stream direction seemed to respond to underlying geological structure.

Although drainage patterns in the three study areas were consistent with the absence or presence of major structural controls, the bifurcation ratio was not. The bifurcation ratio were all below 5 in the three study areas with the Cape Fold Belt region having the highest average BR values. According to Som *et al.*, 1998, Vittala *et al.*, 2004 and Chopra *et al.*, 2005, BR values between 0 and 5 suggest that the area has less structural control while values above 5 indicate tectonically active areas. Thus these results point at little or no influence of the inherited tectonic structures on BR values in both basins. Morphometric properties were only able to explain the impact of inherited tectonic structures on drainage pattern and most the linear stream courses in the CBF region.

4.3.3 Does basin morphometry explain the role of large scale forcing factors in the drainage basins?

Large scale forcings include factors such as uplift and rejuvenation of landscapes Richardson *et al.*, 2016). Hypsometric curves have been used to infer large-scale forcing factors in drainage basins (Montgomery *et al.*, 2001). For example, rejuvenation can be caused tectonic changes such as uplift, fall in sea level and river capture (Plummer and Carlson, 2012). The S-shaped hypsometric curves have been used to indicate rejuvenation of a basin (Ohmori, 1993). The Crocodile basin where most of the curves are the S-shaped did not show signs of rejuvenation or uplift such as many knick points and incised bedrock channels (Richarson *et al.*, 2016). The Central Karoo region has a mix of the S-shaped and convex hypsometric curves in adjacent drainage basins, which makes it difficult to attribute the differences to large scale forcings.

However, drainage rejuvenation signs, for example, in the form of stream capture can be inferred from the drainage network in the Cape Fold Belt region (Figure 4.1A), particularly with reference to angular stream turns. Angular stream turns are commonly used as an indicator of stream capture (in such cases they are called elbows of capture or fluvial elbows), especially where they occur in folded bedrock. Hattingh (2008) in a study in the southern domain of the CFB observed that angular turns occurred in combination with abandoned river terraces and wind gaps, signalling stream capture.

Even though hypsometric curves and integrals are known to reveal large scale forcing factors (Ohmori, 1993; Richardson *et al.*, 2016), the hypsometric evidence in this study does not support the existence of does not support the does not explain the existence of large scale forcings like uplift. While the issue of the tectonic uplift of southern Africa is much debated issue (Tinker *et al.*, 2008; Decker *et al.*, 2013) research has shown that hypsometric evidence does not reveal the role of uplift. This is because the tectonic activity was very slow and it occurred a long time ago (Walcott and Summerfield, 2008) leading to the tectonic pulse being no longer expressed physiographically (Richardson *et al*., 2016).

Analysis of the linear properties of the drainage network to some extent gives evidence of possible large scale forcing factors in the Cape Fold Belt in the form of tectonic uplift which is absent in the Crocodile and Central Karoo regions. However, the rest of morphometric properties are not consistent with this.

4.4 Implications and application of morphometric properties to ancient landscapes

In order to properly assess and evaluate the morphometric properties of the two contrasting drainage basins, a proper understanding of their history and origin is required. As previously seen in the plotted hypsometric curves and other indices, with exception of the drainage patterns and bifurcation ratio, most of the obtained values were not consistent with what was expected. In the Cape Fold belt region for instance, the shape of the HC indicates that the drainage basins are generally at the young age (Strahler, 1957). However, the HI values indicated the opposite; that most of the drainage basins in the region are in the early old to senile age (Singh *et al*,. 2008; Sarkar and Patel, 2011). The HC and HI interpretations were consistent as they both indicated that most basins in the Central Karoo region are in the mature to old stage of development. The same applied to the Crocodile region where the values of the HI and the shapes of the HC were consistent in predicting the stages of geomorphic development (mature to old). However, drainage pattern analysis was consistent with expectation as it showed striking differences in the study basins due to the existence of structural control in the Cape Fold Belt and its absence in the Crocodile and the Central Karoo region. This also extends to the linear characteristics such as stream shapes. Most of the morphometric properties did not explain the expected trajectory landforms development of the three study basins.

Richardson *et al*.(2016) observed that morphometric properties only record the composite effect of multiple factors and recent geomorphic events, as opposed to the inherited structure and forcing factors. This leads to the loss of signal of the inherited tectonic structure through overprinting or truncation (Romans *et al*., 2015). The findings of this study are consistent with Richardson *et al*. (2016). It is difficult to relate Gondwana rifting to the obtained morphometric parameters.

In light of this, it may be not appropriate to depend of morphometric analysis only to test the theories of landscape evolution. It may require more than a single approach.

4.5 Summary

The chapter presented the linear, areal and relief morphometric characteristics of the Gamtoos and the Crocodile drainage basins. A detailed discussion and interpretation of the major patterns of the morphometric properties of the two drainage basins was undertaken. It was observed that the variation in the morphometric properties of the study areas may be attributed, to some extent, to various factors which include; bedrock type, inherited tectonic structures and large scale forcing factors. However, the variation was not systematic and consistent across the basins, which makes it difficult to depend on drainage basin morphometry only to unravel landscape evolution in the study areas. The next chapter presents the conclusion and recommendations.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5 .1 Introduction

This study evaluated the potential of morphometric analysis to understand landscape evolution of basins with contrasting geotectonic histories. Using the ASTER DEM selected areal, linear and relief morphometric properties were extracted from the two physiographic regions of the Gamtoos drainage basin and from the entire Crocodile drainage basin. Lithostratigraphy and structural geology datasets were used to carry out morphostructural analysis of the two study areas. The study provided insight into the extent to which morphometric properties can be used to understand the geomorphic evolution of drainage basins. In addition, the role geotectonics in geomorphic evolution of drainage basins was also evaluated.

5.2 Conclusions

Basic morphometric investigation of the South African drainage basins may provide better understanding of the evolution of landscapes. However, as indicated by Richardson *et al.* (2016) while morphometric analysis can be valuable in the evaluation of how landscapes evolved, care must be taken in its use in ancient landscapes. This study set out to evaluate the potential of morphometric analyses to help better understand landscape evolution in South Africa on the basis of two case studies with diverse geotectonic controls. The study assessed the variation of various linear, areal and relief properties of the three study areas.

The study shows that the spatial variation of the selected morphometric properties was not consistently explained by the geotectonic data. The role of bedrock type could only explain drainage density and texture across all study regions. Only the drainage pattern and shape of the stream courses were able to explain the impact of inherited tectonic structures in the evolution of drainage basin in the three study areas. The analysis of the linear properties of the drainage network to some extent gives evidence of possible large scale forcing factors in the Cape Fold Belt in the form of tectonic uplift which is absent in the Crocodile and Central Karoo regions. However, the rest of morphometric properties are not consistent with expectations. The major cause of this is most likely signal shredding or overprinting, whereby the evidence of the past geological processes is lost over time in ancient landscapes making impossible to infer the corresponding trajectory of the evolution of the given landscape. Also, the morphometric properties might be reflecting a composite effect of multiple factors and recent geomorphic events than the inherited structural fabric. The findings confirm did not find enough evidence to contradict Richardson *et al.* (2016) with regard to the utility of morphometric analysis in landscape evolution studies in the Cape Fold Belt.

6.3 Recommendations

In view of the findings, this study recommends the following:

- Further studies need to be undertaken to examine the variation of all the morphometric properties at various nested scales to assess scale effects of some of the investigated morphometric properties.
- Although the technical expertise and analytical facilities available to each researcher influences the type and number of morphometric properties that can be investigated, a more extensive list of morphometric properties may be used, especially those that have been successfully used in similar studies.
- Desktop landscape evolution studies based on GIS and remote sensing techniques only may not be enough but need to be augmented by paleogeological and paleogeomophological techniques, such as dating techniques of surfaces.

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APPENDICES

Appendix 1. Common morphometric properties and their calculation (Source: Ker-ord *et al.*, 2013)

No.	Aspects	Parameters	Formulae	References
1	Linear Aspects	Stream Order (U)	Hierarchial rank	Strahler (1964)
2		Stream Length (Lu)	Length of the stream	Horton (1945)
3		Mean Stream Length (Lsm)	Lsm = Lu/Nu Where, Lsm = mean stream length Lu = total stream length of order 'u' Nu = total no. of stream segments of order 'u'	Strahler (1964)
4		Stream Length Ratio (RL)	RL = Lu/(Lu-1) Where, RL = stream length ratio Lu = total stream length of order 'u' Lu-1 = total stream length of its next lower order	Horton (1945)
5		Bifurcation Ratio (Rb)	Rb = Nu/(Nu+1) Where, Rb = bifurcation ratio Nu = total no. of stream segments of order 'u' Nu+1 = no. of stream segments of next higher order	Schumm (1956)
6		Mean Bifurcation Ratio (Rbm)	Rb = average of bifurcation ratios of all orders	Strahler (1957)
7	Areal Aspects	Drainage Density (Dd)	Dd = Lu/A Where, Dd = drainage density Lu = total stream length of all orders A = area of the basin (km^2)	Horton (1932)
8		Drainage Texture (Rt)	Rt = Nu/P Where, Rt = drainage texture Nu = total no. of streams of all orders P = perimeter (km)	Horton (1945) Smith (1950)
9		Stream Frequency (Fs)	Fs = Nu/A Where, Fs = stream frequency Nu = total no. of streams of all orders A = area of the basin (km^2)	Horton (1932)
10		Form Factor (Rf)	$Rf = A/Lb^2$ Where, Rf = form factor A = area of the basin (km^2) Lb^2 = square of basin length	Horton (1932)
11		Elongation Ratio (Re)	$Re = 2\sqrt{(A/\pi)}/Lb$ Where, Re = elongation ratio A = area of the basin (km^2) π = 'Pi' value (3.142817) Lb = basin length	Schumm (1956)
12		Circularity Ratio (Rc)	$Rc = 4*\pi*A/P^2$ Where, Rc = circularity ratio π = 'Pi' value (3.142817) A = area of the basin (km^2) P^2 = square of perimeter (km)	Miller (1953)
13		Length of Overland Flow (Lg)	Lg = 1/Dd*2 Where, Lg = length of overland flow Dd = drainage density	Horton (1945)
14	Relief Aspects	Watershed Relief (H)	vertical distance between the lowest and highest points of watershed (highest – lowest)	Schumm (1956)
15		Relief Ratio (Rh)	Rh = H/Lb Where, Rh = relief ratio H = watershed relief Lb = basin length	Schumm (1956)
16		Ruggedness Number (Rn)	Rn = H*Dd Where, Rn = ruggedness number H = watershed relief Dd = drainage density	Schumm (1956)

Appendix 2: Geology map style sheet showing some of the detailed data layers available and obtained from the Council of Geosciences.

Stylesheet: Carto2004

Shapefile: Line1

MXD-file: Line1.mxd

Geological lines (on Tectcon)

Feature class consists of geological contact lines that seperate lithostratigraphic, chronostratigraphic and lithologic units, as well as all tectonic lines that can also act as contact lines, e.g. faults, thrusts, shears, etc., even if these do not seperate different polygons.

1	Geological contact, observed
2	Geological contact, inferred
83	Geological contact, unconformable (v points towards younger rocks)
10	Fault, observed
15	Fault, inferred
13	Fault, thrust, observed
18	Fault, thrust, inferred
11	Fault, normal, observed
16	Fault, normal inferred
9	Fault, strike slip, left lateral, observed
14	Fault, strike slip, right lateral, observed
19	Fault, strike slip, right lateral, inferred
153	Fault, strike slip, left lateral, inferred
100	Fault, high angle, reverse, observed
101	Fault, high angle, reverse, inferred
82	Fault, brecciated
178	Fault, slump, syn-sedimentary
69	Shear zone
102	Mylonite zone
5	Edge of the map
3	Non-print line
4	Edge of water body; coast line
65	Dam wall
53	International border

Stylesheet:Carto2004

Shapefile: Line2

MXD-file: Line2.mxd

Geological lines (on Geollin)

Contains such non-stratiform lithostratigraphic or lithologic units which, at the scale of the map, can only be depicted as lines, e.g., dykes or veins. At a larger scale these would have been shown as narrow polygons. The description is only an indication what the symbol can be used for and should not be used as a "database", the uq_geol links it to a database in Oracle

71	Seam, undifferentiated
118	Reef, Merensky;Plat
73	Layer, undifferentiated
116	Layer, magnetitite
117	Layer, chromitite
112	Bed, contorted
6	Bed, amydaloidal lava
130	Bed, ropy lava
131	Bed, conglomerate
132	Bed, iron formation
133	Bed, tillite/diamictite
163	Bed, marker at contact
72	Bed, undifferentiated
84	Dyke, garnetiferous
85	Dyke, diopsite
86	Dyke, amphibolite
70	Dyke, undifferentiated
74	Dyke, dolerite
87	Dyke, dolerite, inferred
75	Dyke, syenite
76	Dyke, diabase
89	Dyke, diabase, inferred
77	Dyke, quartz porphyry
78	Dyke, basic
79	Dyke, kimberlite
173	Dyke, granophyre
167	Dyke, epidiorite

Stylesheet: Carto2004

Shapefile: Line3

MXD-file: Line3.mxd

Geological lines (on Geollin)

Contains such non-stratiform lithostratigraphic or lithologic units which, at the scale of the map, can only be depicted as lines, e.g., dykes or veins. At a larger scale these would have been shown as narrow polygons. The description is only an indication what the symbol can be used for and should not be used as a "database", the uq_geol links it to a database in Oracle

80	Dyke, alkaline
88	Dyke
25	Vein, undifferentiated
26	Vein, quartz
27	Vein, iron rich
28	Vein, applite
29	Vein, pegmatite
30	Vein, granophyre
31	Vein, breccia
174	Dyke?

Stylesheet: Carto2004

Shapefile: Line4

MXD-file: Line4.mxd

Structural lines (on Struclin)

Contains all those structural lines that cannot form geological contacts, e.g. various lineaments, fold-axes, form-lines, etc.

20	Lineament, undifferentiated
21	Lineament, possible dyke
137	Lineament, possible fault
172	Lineament, possible shear
22	Lineament, aeromagnetic
136	Lineament, aeromagnetic, possible dyke
134	Lineament, aeromagnetic, possible remanent dyke
135	Lineament, aeromagnetic, possible fault
115	Lineament, aerial photograph
128	Lineament, aerial photograph, possible dyke
23	Lineament, satellite imagery
24	Lineament, aerial photo and satellite imagery
68	Lineament, magnetic, surface survey
103	Form line
32	Joint
33	Fold axis, undifferentiated
34	Fold axis, anticlinal
143	Fold axis, anticlinal, inferred
138	Fold axis, anticlinal, plunging
148	Fold axis, anticlinal, plunging, inferred
35	Fold axis, synclinal
144	Fold axis, synclinal, inferred
139	Fold axis, synclinal, plunging
149	Fold axis, synclinal, plunging, inferred

Stylesheet: Carto2004

Shapefile: Line5

MXD-file: Line5.mxd

Structural lines (on Struclin)

Contains all those lines that cannot form geological contacts, e.g. various lineaments, fold-axes, form-lines, etc.

36	Fold axis, antiformal
145	Fold axis, antiformal, inferred
140	Fold axis, antiformal, plunging
150	Fold axis, antiformal, plunging, inferred
37	Fold axis, synformal
146	Fold axis, synformal, inferred
141	Fold axis, synformal, plunging
151	Fold axis, synformal, plunging, inferred
38	Fold axis, monoclinal
147	Fold axis, monoclinal, inferred
142	Fold axis, monoclinal, plunging
152	Fold axis, monoclinal, plunging, inferred
175	Fold axis, monoclinal, plunging right
176	Fold axis, monoclinal, plunging right, inferred
154	Fold axis, anticlinal, overturned
158	Fold axis, anticlinal, overturned, inferred
187	Fold axis, anticlinal, overturned, plunging right
188	Fold axis, anticlinal, overturned, plunging left
193	Fold axis, anticlinal, overturned, plunging
155	Fold axis, synclinal, overturned
159	Fold axis, synclinal, overturned, inferred
190	Fold axis, synclinal, overturned, plunging right
191	Fold axis, synclinal, overturned, plunging left
192	Fold axis, synclinal, overturned, plunging
185	Dome
186	Basin

Stylesheet:Carto2004

Shapefile: Point3

MXD-file: Point3.mxd

Structural geological markers (on Strucpt)

Contains structural observation points such as dip or foliation measurements.

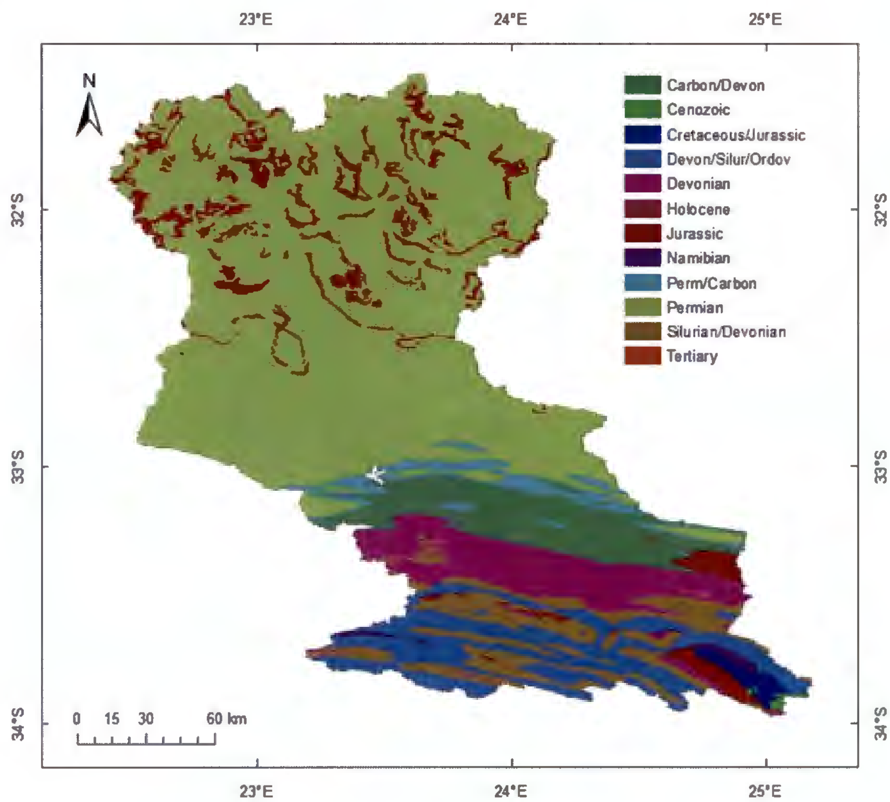
Structural observation points with strike and plunging fold axis

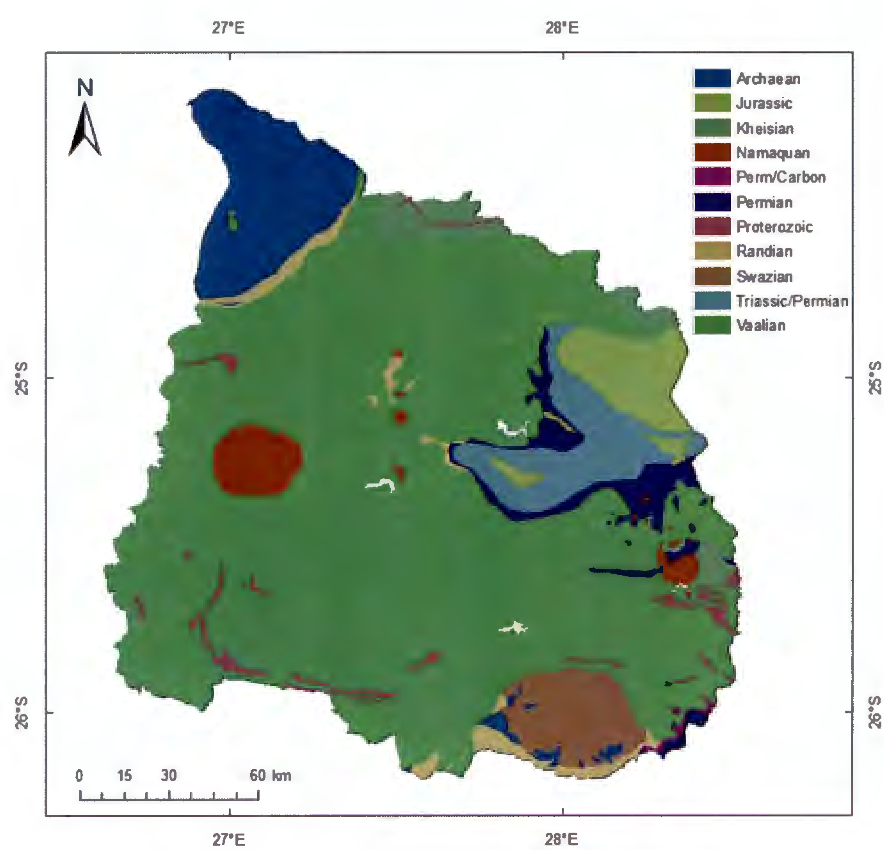
200	Fold axis, synclinal, plunging	(Azimuth = Strike)
199	Fold axis, anticlinal, plunging	(Azimuth = Strike)
201	Fold axis, monoclinal, plunging left	(Azimuth = Strike)
229	Fold axis, monoclinal, plunging right	(Azimuth = Strike)
203	Fold axis, anticlinal, overturned, plunging	(Azimuth = Strike)
202	Fold axis, synclinal, overturned, plunging	(Azimuth = Strike)
206	Fold axis, antiformal, plunging	(Azimuth = Strike)
207	Fold axis, synformal, plunging	(Azimuth = Strike)

Structural observation points with an azimuth and possible dip value

52	Bedding, facing direction	Azimuth = facing direction
179	Bedding (dip < 30 degrees), dip direction; 1:1 000 000 map	
180	Bedding (dip 31 to 60 degrees), dip direction; 1:1 000 000 map	
181	Bedding (dip 61 to 90 degrees), dip direction; 1:1 000 000 map	
15	Bedding, overturned, dip direction	(Azimuth = dip direction)
49	Lineation, direction and plunge	(Azimuth = plunge direction)
93	Fold axis, direction of plunge	(Azimuth = plunge direction)

Appendix 3. Rock ages in the two basins





Appendix 4. The drainage maps of the Gamtoos and Crocodile drainage basins showing the selected tributaries for long profiles.