Testing the applicability of morphometric characterisation in discordant catchments to ancient landscapes: a case study from southern Africa

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Abstract

The ancient landscapes south of the Great Escarpment in southern Africa preserve large-scale geomorphological features despite their antiquity. This study applies and evaluates morphometric indices (such as hypsometry, long profile analysis, stream gradient index, and linear / areal catchment characteristics) to the Gouritz catchment, a large discordant catchment in the Western Cape. Spatial variation of morphometric indices were assessed across catchment (trunk rivers) and subcatchment scales. The hypsometric curve of the catchment is sinusoidal, and a range of curve profiles are evident at subcatchment scale. Hypsometric integrals do not correlate to catchment properties such as area, circularity, relief, and dissection; and stream length gradients do not follow expected patterns, with the highest values seen in the mid-catchment areas. Rock type variation is interpreted to be the key control on morphometric indices within the Gouritz catchment, especially hypsometry and stream length gradient. External controls, such as tectonics and climate, were likely diminished because of the long duration of catchment development in this location. While morphometric indices can be a useful procedure in the evaluation of landscape evolution, this study shows that care must be taken in the application of morphometric indices to constrain tectonic or climatic variation in ancient landscapes because of inherited tectonic structures and signal shredding. More widely, we consider that ancient landscapes offer a valuable insight into long-term environmental change, but refinements to geomorphometric approaches are needed.

Keywords: morphometry; ancient landscapes; GIS; rock type

1. Introduction

The physiography of South Africa has received much attention owing to its distinctive topography and ancient setting, but the timing and processes involved in landscape evolution remain contentious in several respects. Major river networks within southern South Africa have evolved since the Mesozoic breakup of Gondwana (Moore and Blenkinsop, 2002; Hattingh, 2008), and their development has been synchronous with large-scale (6-7 km) exhumation of the southern African continental crust (Tinker et al., 2008a). However, the tectonic uplift history of southern Africa is poorly constrained, especially the causes and magnitude of uplift (Gallagher and Brown, 1999; Brown et al., 2002; Tinker et al., 2008a; Kounov et al., 2009; Decker et al., 2013). Previous macroscale geomorphological research in southern South Africa has focussed on the formation of the Great Escarpment (e.g., King, 1953; Partridge and Maud, 1987; Brown et al., 2002), and the development of the Orange River (e.g., Dingle and Hendey, 1984). Furthermore, the timing of the main phase of landscape development in South Africa has been argued to be either

Cenozoic (Du Toit, 1937, 1954; King, 1951; Burke, 1996) or Mesozoic (Partridge, 1998; Brown et al., 2002; Doucouré and de Wit, 2003; de Wit, 2007).

Long-lived ancient landscapes (Bishop, 2007) have been argued for many ‘Gondwana landscapes’ (Fairbridge, 1968) related to large parts of the planet, including cratonic areas and passive continental margins, such as Australia (e.g., Ollier, 1991; Ollier and Pain, 2000; Twidale, 2007a,b), southern South Africa (e.g., Du Toit, 1954; King, 1956a), and South America (e.g., King, 1956b; Carignano et al., 1999; Demoulin et al., 2005; Panario et al., 2014; Peulvast and Bétard, 2015). Long-lived landforms and surfaces have also been argued to form parts of Russia (Gorelov et al., 1970), India (Gunnell et al., 2007), Sweden (Lidmar-Bergström, 1988), and western France (Bessin et al., 2015). Ancient landscapes have the potential to offer insights into the temporal variation of controls such as tectonic uplift or climate. However, deciphering these factors is problematic within ancient catchments because the imprint of certain forcing factors on catchment morphology may no longer be present owing to long-term erosion. The loss of forcing signals can also be seen with regards to sediment transport, which mediates landscape response (Jerolmack and Paola, 2010). The catchments draining southward from the Great Escarpment in the Western Cape have been subject to cosmogenic (Scharf et al., 2013) and apatite fission track analyses (Tinker et al., 2008a) to determine rates of fluvial erosion and exhumation, respectively; but these data have not been through a detailed geomorphological assessment (Rogers, 1903; Partridge and Maud, 1987). Fundamental morphometric analyses of South African drainage basins have yet to be attempted, although this approach has the potential to yield insights into the long-term landscape evolution as shown by the Walcott and Summerfield (2008) hypsometry study in the Eastern Cape.

Geomorphometry employs a range of morphometric indices to help characterise the history of a drainage basin (Horton, 1932; Miller, 1953; Schumm, 1956; Chorley, 1957; Strahler, 1964). Morphometric indices include river network analysis, hypsometry, and analysis of the stream profile. River networks are used to infer the tectonic and climatic history of a region (e.g., Montgomery et al., 2001; Walcott and Summerfield, 2008; Antón et al., 2014), as river form is closely linked to these extrinsic factors. However, river networks are also governed by intrinsic factors such as network reorganisation through stream capture (Davis, 1889), bedrock geology (Tinkler and Wohl, 1998; Duvall et al., 2004), and sediment flux (Richards, 1982; Sklar and Dietrich, 2001). Many studies of morphometric indices relate to tectonically active areas (e.g., Snyder et al., 2000; Zhang et al., 2013; Antón et al., 2014; Ghosh et al., 2014). However, these indices are rarely applied to tectonically quiescent areas or ancient landscapes. An example of a morphometric approach to ancient landscape development is by Walcott and Summerfield (2008) who assessed the variation in hypsometric integral within catchments draining the Drakensberg mountain range in eastern South Africa. They argued that variation in hypsometric integral within streams of order 5 or less is because of differences in bedrock type resistance as well as moderate crustal displacement, whereas the larger stream orders (>6) are independent of rock type or tectonic control.

In this study, we test if morphometric indices can offer further insight into the history of the understudied ancient landscapes of southern South Africa, which have undergone reorganisation because of the exhumation of the resistant Cape Fold Belt and retreat of the Great Escarpment. Therefore, inherited structures are expected to play an important role in landscape evolution of the Gouritz catchment. We aim to address the following objectives: (i) to extract morphometric indices for an antecedent and tectonically quiescent drainage basin, the Gouritz Catchment; (ii) to document spatial variation in morphometric indices within the main tributaries; (iii) to test the prevailing conceptual models in the literature of external (e.g., Montgomery et al., 2001; Keller and Pinter, 2002; Manjoro, 2015) and internal controls (e.g., Tooth et al., 2004; Walcott and Summerfield, 2008; Jansen et al., 2010) on geomorphometry and landscape evolution; and (iv) to assess the broader suitability of morphometric indices for characterisation of ancient landscapes.

2. The Gouritz catchment

The Gouritz catchment is located within the Western Cape Province of South Africa (Fig. 1) and is one of several antecedent systems draining from the Great Escarpment that cut across the west-east trending Cape Fold Belt (CFB) mountains to the Atlantic and Indian Oceans. Antecedence in the Western Cape is shown by the large-scale discordance of the main trunk rivers (Rogers, 1903), which completely dissect the resistant CFB and have deeply incised meanders into quartzites (up to 1 km in depth). The main catchment evolutionary events include the breakup of Gondwana in the Mesozoic (Summerfield, 1991; Goudie, 2005) and the large-scale incision in the Cretaceous resulting in the exhumation of the CFB (Tinker et al., 2008a) and the Karoo basin-fill. As such, the retreat and development of the Great Escarpment (Fleming et al., 1999; Cockburn et al., 2000; Brown et al., 2002; Moore and Blenkinsop, 2006) has an important control on catchment evolution and stream capture of the Orange River catchment. King’s (e.g., King, 1963, 1972) view of the escarpment forming at the coastline and retreating uniformally since the breakup of Gondwana has been disproved by numerical models (e.g., Gilchrist and Summerfield, 1990; van der Beek et al., 2002) and dating techniques (e.g., Fleming et al., 1999; Brown et al., 2002). On the basis of apatite fission track data, researchers have proposed that the Great Escarpment has retreated a *maximum* of 29 km to its current position since the Cretaceous (Brown et al., 2002), which would have affected the headwaters of the Gouritz catchment.

The Gouritz catchment has an area of 6.45 x 10^4 km^2 and a stream order of 7 (Strahler, 1957). The basin is composed of six main tributaries: the Traka, Touws, Buffels, Olifants, Dwyka, and Gamka rivers (Fig. 1). The source regions for many of the main tributaries are hillslopes to the south of the Great Escarpment, with the Gouritz system reaching the ocean at Gouritzmond (Fig. 1). The majority of the rivers are bedrock or mixed bedrock-alluvial in nature, with common steep-sided valleys and bedrock-confined gorges.

The Great Escarpment separates an interior plateau of low relief and high elevation from a coastal region of high relief and low average elevation (Fleming et al., 1999; Tinker et al., 2008b; Moore et al., 2009). The Gouritz catchment also contains a segment of the exhumed CFB, which is a compressional mountain range that formed in the late Permian and Triassic (Tankard et al., 2009; Flint et al., 2011). Physiographically, and based on variation in elevation and landscape morphology, the drainage basin can be divided into the following units: escarpment, central Karoo, Cape Fold Belt, and coastal (Fig. 2A). The application of Hammond's topographic analysis (Fig. 2B) to the Gouritz catchment reveals that the area is dominated by (i) plains that usually carry a thin (<1 m) sedimentary cover, which decreases toward the north, and that include dissected pediment surfaces; and (ii) mountains where bedrock crops out in the CFB and escarpment regions with a thin regolith, if present.

The present day climate of the Gouritz catchment is primarily semiarid (Dean et al., 1995) with mean annual precipitation of 262 mm (CSIR, 2007). The region has a clear split between summer and winter rainfall regimes, with late summer to winter rainfall in the Great Escarpment and central Karoo region, winter rainfall in the western CFB, late summer to winter rainfall in the southern CFB, and summer and winter rainfall in the coastal areas (CSIR, 2007). The lower part of the catchment in the coastal region has a Mediterranean-type climate (Midgley et al., 2003). Orographic rainfall over the CFB provides much of the discharge (Midgley et al., 2003), with the other main source being intense thunderstorms that usually form on the escarpment and move south over the central Karoo. Smaller tributaries in the upper reaches of many of the larger trunk rivers are ephemeral. South of the CFB, trunk rivers are perennial with the main tributaries transporting boulders to sand-grade material as bedload, although no sediment transport data is available. The climatic history of southern South Africa is poorly constrained. Since the Cretaceous (and the development of the major drainage systems), we see a general trend toward a more arid environment (Bakker and Mercer, 1986), with variation in intensity in the winter or summer rainfall regime (Bar-Matthews et al., 2010) as well as the fire regime (Seydack et al., 2007).

The substrate of Gouritz catchment is predominantly Palaeozoic rocks of the Cape and Karoo Supergroups, composed of various mudstone and sandstone units (Fig. 1). Small inliers of the Kansa Group (conglomerate, shale, mudstone) are found in the CFB. Resistant lithologies (Fig. 3) within the Gouritz catchment include the Precambrian Cango Cave Group, which comprises metasediments (limestones, arenites, mudrocks), the Table Mountain Group quartzites, and Jurassic dolerite intrusions dominantly toward the north and granite plutons in coastal areas of the catchment (Fig. 1). The Mesozoic Uitenhage Group comprised mainly of conglomeratic and sandy units represents the youngest resistant rock type within the basin.

The structural geology of the drainage basin is dominated by large-scale (~11 km wavelength; Tankard et al., 2009) E-W trending folds that decrease in amplitude toward the north (Paton, 2006, Spikings et al., 2015). The folds formed along the southwestern margin of Gondwana during Paleozoic-Mesozoic convergence (e.g., Tankard et al., 2009). The Gouritz catchment contains two large anticlines, the Swartberg and Langeberg (CFB), which are cut by large Mesozoic normal faults (Paton, 2006), the Swartberg and Worcester faults, respectively (Fig. 1).

The Gouritz catchment is currently tectonically quiescent, with a lack of fault scarps, low seismicity (Bierman et al., 2014), and low rates of sediment supply (Kounov et al., 2007; Scharf et al., 2013). The tectonic history of the area is contentious (Gallagher and Brown, 1999; Brown et al., 2002; Tinker et al., 2008a; Kounov et al., 2009; Decker et al., 2013). Researchers have debated about the events causing the large-scale denudation in the Cretaceous, with ideas often related to plume activity in the early Cretaceous (Moore et al., 2009). Burke (1996) proposed that the most recent uplift occurred around 30 Ma ago because of a thermal anomaly, whereas Partridge and Maud (1997) argued for a later period of activity in the Miocene (~250 m uplift) and again in the Quaternary (900 m uplift). The large-scale exhumation across southern South Africa could still be driving eperiogenic uplift (Tinker et al., 2008a).

3. Methodology

Catchment topography from a digital elevation model (DEM) based on ASTER (30 m) data, was reprojected into WGS 1984 world Mercator coordinates. Catchment boundaries were extracted using the default hydrology toolbox in ArcGIS 10.1, in which the DEM was manually filled in order to remove any holes within the DEM to allow for flow path extraction. Following Abedlkareem et al. (2012) and Ghosh et al. (2014), a minimum upstream drainage area threshold of 3.35 km^2 was used to delineate the drainage network, showing perennial and ephemeral rivers. Stratigraphic unit, rock type, and structural geological data sets were obtained digitally from the Council of Geoscience, at a scale of 1:250,000.

3.1. Drainage characterisation and landforms

Zernitz (1932) laid the foundation of drainage pattern analyses, argued that structure and slope determine the spatial arrangement of rivers, and determined six river patterns (dendritic, trellis, rectangular, radial, annular, and parallel). A more refined classification was provided by Howard (1967) with additional subclassifications, which included subdendritic, pinnate, anastomotic, and distributary. Drainage patterns are fundamental in determining structural change at a local and regional scale (Hills, 1963) with analyses used primarily in tectonic settings (e.g., Gupta, 1997; Friend et al., 2009).

The drainage pattern of the Gouritz Catchment was assessed and assigned drainage categories in order to assess controls on the catchment (Zernitz, 1932) at a regional scale (Knighton, 1998). The impact of tectonic structures is shown by the dominance of trellis or parallel patterns. Tectonic structure has been shown to be important in catchments draining the western domain of the CFB (Manjoro, 2015): 49% of the catchment area of the Gouritz drains the southern domain of the CFB.

3.2. Morphometric indices

3.2.1. Long profile

Long profiles of the main trunk rivers were extracted using ArcGIS by digitising the stream network with 10-m vertical spacing along the stream. Assessing long profiles of rivers allows quantitative analysis of fluvial incision and lithological controls (Hack, 1973). The analysis of long profiles can highlight knickpoints, which are the principal method of channel lowering within bedrock channels (Whipple, 2004). In this study, long profiles were further quantified using the stream gradient index (Hack, 1973), which would be expected to be approximately constant along a graded long profile in a homogenous lithology. Deviations from the average value were therefore assumed to be caused by forcing factors (Antón et al., 2014) such as tectonics (Keller and Pinter, 2002), lithology (Hack, 1973), or migrating knickpoints (Bishop et al., 2005).

3.2.2. Stream gradient index

Long profile geometry was used to assess the level of grading within a river by employing the stream gradient index (SL; Hack, 1973) and was calculated as

$$SL = (\Delta H / \Delta Lr) \Delta Lsc \qquad (1)$$

where *ΔH* is change in altitude, *ΔLr* is length of the reach, and *ΔLsc* is the horizontal flow path length from the watershed divide to the midpoint of the reach. The stream length gradient was calculated in 50-m reaches for the main trunk rivers, the data were then normalised (to a value between zero and one, using the range of values collected from all trunk rivers) to allow comparison between the trunk rivers.

3.2.3. Morphometric indices

Morphometric indices permit the quantitative assessment of, and comparison between, landscapes and can highlight anomalies along the river network. Linear measurements such as stream order, stream length, and bifurcation ratio (Horton, 1945) were extracted using ArcGIS. Areal measurements such as basin area, drainage density (Horton, 1945), and circularity (the ratio of the perimeter of the basin to the perimeter of a circle with the same area) were also extracted. Drainage density was extracted for the entire catchment and also for the main rock types within the catchment (Fig. 1) in order to assess the impact of different bedrock resistances to the drainage pattern.

3.2.4. Hypsometry

Hypsometry describes the area distribution of elevation within a catchment. Strahler (1952) defined the hypsometric integral (HI) as the differences in sinuosity of curve form and the proportionate area below the curve. Strahler (1952) argued that catchments where HI > 0.6 are in disequilibrium (youth) and the catchment shows rapid slope transformation as the drainage system expands, and where HI is between 0.4 and 0.6 catchments are in equilibrium (mature). Below 0.4 the catchments are argued to be in a monadnock phase (old age; Strahler, 1952). More recently hypsometry has been used for a wide range of applications, including the evolution of landscapes (Hancock and Willgoose, 2001), the effect of climate (Montgomery et al., 2001), and the influence of tectonics on catchments (Ohmori, 1993). Hypsometric curves have been used to decipher the forcing factors in catchments (Strahler, 1952; Montgomery et al., 2001; Walcott and Summerfield, 2008). However, the influence of drainage basin properties such as area, circularity, relief, and dissection on the HI has received mixed results, with researchers arguing for correlation (Hurtrez et al., 1999; Chen et al., 2003) and no correlation (Walcott and Summerfield, 2008). Strahler (1952) argued that catchments try to maintain a convex or sinusoidal curve, with erosion of the transitory concave monadnock phase returning the curve to a sinusoidal curve.

In this study, hypsometric data (hypsometric integral (Eq. 2) and curve) were extracted by an ArcGIS tool (Hypsometric Tools by Davis, 2010) for the whole catchment and then western-draining subcatchments. The western-draining catchments are defined as those that drain the western part of the Gouritz catchment, delineated at the confluence with the main trunk river (Gamka River). These subcatchments were chosen to investigate the variation in hypsometric integral and curve shape with respect to the location of the catchment and the stream order. Only analysing the western-draining subcatchments is justified because the Gouritz catchment is nearly symmetrical (Fig. 1) and because the geology is broadly similar in the western and eastern portions of the catchment (Fig. 1). Hypsometric integrals were then compared to basin properties including circularity, area, relief (Eq. 3), dissection (Eq. 4), and key rock types and geological structure.

$$H.I. = \frac{mean\ elevation - minimum\ elevation}{maximum\ elevation - minimum\ elevation} \quad (2)$$

$$Relief = maximum\ elevation - minimum\ elevation \quad (3)$$

$$Dissection = mean\ elevation - minimum\ elevation \quad (4)$$

4. Results

4.1. Catchment characteristics

Overall, the Gouritz catchment exhibits a dendritic drainage pattern (Fig. 1), but spatial variation is seen within the subcatchments in different physiographic regions. Dendritic patterns are present within the central Karoo and escarpment regions, where the Karoo Supergroup crops out, which is an area dominated by irregular plains with low relief (Fig. 2B). Within the CFB, trellis drainage patterns are found (Fig. 4A). The coastal region is dominated by small dendritic catchments (Fig. 4A).

The Gouritz catchment is a stream order 7 catchment (Strahler, 1952) and has a drainage density of 0.454 km/km^2. Drainage density is lowest on quartzite bedrock, the most resistant rock type (Fig. 3), and is the highest on the more easily eroded Karoo Supergroup sandstones and mudstones (Table 1). Physiographically, the CFB- and escarpment-draining subcatchments have the greatest variation in elevation. The CFB is dominated by streams of a lower order which drain the majority of the slopes, with the high order (>4) streams cutting straight through the mountain chain. The lower order streams (<3) are normally straight with meandering dominating in stream order >4 (Fig. 4). Deeply incised meander bends are found in some of the main trunk rivers that cut across the CFB, e.g. Gamka-Gouritz River. Several rivers show right angles in their courses and evidence of beheading (Figs. 4B, C) and are remnants of stream capture sites, of which many are expected in such a long-lived catchment. The mean bifurcation ratio of the catchment is 3.39; however, variation within individual stream orders is seen, with a range from 2 to 6.

4.2. Morphometric indices

4.2.1. Long profiles

The long profiles of the main tributaries of the Gouritz catchment show a lack of single-graded form. Overall, the long profiles are concave in the headwater regions and fairly straight in the CFB (Fig. 5). Concave long profiles are mainly found in the physiographic regions of the Great Escarpment and central Karoo regions but are also found in the transverse Olifants and Traka rivers whose headwaters form in the

Cape Fold Belt (Fig. 5). Knickpoints are present along the long profiles (Fig. 5), which in some cases relate to artificially dammed lakes. These dams were preferentially sited at the upstream side of narrow canyons, with the knickpoints corresponding to lithostratigraphic boundaries between quartzite and other Cape Supergroup rock types or the Uitenhage Group. Dolerite intrusions (Dwyka and Gamka rivers) do not always exhibit knickpoints. A detailed study of the Swartberg mountains indicates that in the smaller mountain-draining catchments (stream order <3) knickpoints are prevalent and commonly are tied to lithostratigraphic boundaries involving quartzite (Figs. 3, 6).

4.2.2 Stream gradient index

Figure 6 shows the variation of stream gradient indices within the Gouritz catchment. The data were normalised with a value of 1 indicating high stream gradients; a full range of SL are seen within the catchment. The headwaters of all the trunk rivers have low SL, with values below 0.2, which is exceptionally low and shows an increase downstream. The rivers that cross the central Karoo (Buffels, Gamka, and Dwyka rivers) show gradients between 0 and 0.4. This area is characterised by flat plains and is dominated by the relatively easily eroded Karoo Supergroup rock types. The CFB, which all the main trunk rivers either run parallel to or transverse (Fig. 1), shows the highest variation in SL, with values between 0.2 and 1. The CFB is dominated by the Cape Supergroup, with resistant quartzites and metamorphosed sandstones as well as the resistant Uitenhage Group and Cango Cave Group rock types. Stream gradient indices then decrease in the coastal region with the SL of the majority of reaches below 0.2, where the Cape Supergroup outcrops are dominated by mudstones. Stream gradient is unaffected by large-scale faults (mapped at 1:25,000).

4.2.3. Hypsometry

The hypsometric integral of the Gouritz catchment is 0.34, and the hypsometric curve for the catchment is sinusoidal (Fig. 7). The overall drainage basin has a circularity of 0.16, which indicates the drainage basin shape is highly irregular. In order to understand how hypsometry varies throughout the drainage basin, the western-draining catchments of the main trunk river (Gamka River) were assessed in detail.

Western-draining catchments range in stream order from 1 to 6 and have a mean basin area of 728.10 km^2 (ranging from 4.37 to 19,054.91 km^2). In Fig. 8, hypsometric integrals are plotted against catchment characteristics. The R^2 value shows no correlation between the hypsometric integral and each variable: hypsometric integral and circularity = 0.0053, hypsometric integral and area = 0.0872, hypsometric integral and dissection = 0.0321, and hypsometric integral and relief = 0.1761. The hypsometric integral, therefore, appears to be independent of catchment factors. The hypsometric integral on average decreases with increasing stream order (Table 3). The central Karoo catchments have the highest mean hypsometric integral, and the coastal catchments the lowest (Table 4).

Some patterns between stream order and geomorphological location are apparent. Catchment area increases with stream order, with larger basins having lower hypsometric integrals (Fig. 8A). Higher order streams (>4) on average have a lower circularity and data is less scattered than lower order streams (<3; Fig. 8B). The lower circularity value of higher stream order catchments relates to a more complicated drainage network and watershed shape. Lower order streams (<3) have a wider range of dissection and relief (Figs. 8C, D); this seems to be a function of location with many of these streams draining the CFB. The central Karoo catchments are more homogenous and less scattered, with low levels of dissection and relief, and the area is characterised by large flat areas (Fig. 2B). The escarpment represents the headwaters of many of the central Karoo catchments, and only represents a small proportion of the total catchment area. Hypsometric integrals do not correlate with the distance of the catchment from the river mouth (Fig. 8E; R^2 = 0.05). Figure 8E also shows how the range of integrals decreases toward the escarpment, whilst the drainage density increases (i.e., density of data points increases).

Hypsometric curves: The hypsometric curves from subcatchments within the Gouritz catchment can be classified as sinusoidal, straight, concave, and convex (Fig. 9A). Overall, the Gouritz catchment has a sinusoidal curve (Fig. 7), whereas at subcatchment scale, the majority of curves are concave (Fig. 9A). The concave curves can be seen in a range of stream orders (stream order 1 to 6), whereas the convex, straight, and sinusoidal catchments are associated with the lower stream orders (<3) (Fig. 9). No systematic variation in the curve shape is seen toward the escarpment (Fig. 9B) or within each geomorphological region.

Curve shapes were quantified to assess whether the observed variation could be attributed to internal or external catchment controls. Figure 9C shows the percentage area of the catchment that lies below half the maximum elevation within the western-draining catchments. The more dissected a basin is, the higher the area of the catchment below the maximum value within the basin. The coastal catchments are highly dissected, with the majority of catchments having >90% of area lower than 50% of the maximum height. The CFB has similar levels of dissection where many catchments have >80% of area lower than 50% of the maximum height. Dissection also increases toward the escarpment where, on average, the lowest percentage of area below 50% of the maximum height is within the central Karoo catchments, where average elevation is high and slope angles are low.

Figure 10 shows the influence of rock type on hypsometric curves of stream order 1 to 6 streams. The presence of resistant rock types (Fig. 3), such as the Cango Cave Group and igneous intrusions at the higher elevations of the catchment, allows elevation to be preserved causing a disturbance of the hypsometric curve. The hypsometric curve in these locations has a lower slope than the catchments without resistant rock types, with a higher proportion of area preserved in the higher elevations (e.g. Figs. 10A, E). Hypsometric curve slope also decreases when resistant rock types are found at lower elevations (e.g. igneous intrusions, Uitenhage, and Cango Cave groups; Fig. 10D). At the lower elevations of catchments the influence of resistant rock types decreases, e.g. below 50% of the maximum elevation, especially in the larger catchments. The presence of quartzite does not impact the curve shape significantly (Figs. 10C, D). Curve shape variation within catchments dominated by the Karoo Supergroup cannot be attributed to different rock types, although the lithostratigraphic groups within the Karoo Supergroup have different proportions of mudstone and sandstone (Fig. 10B). Some catchments have a large change in slope at the lower elevations (Figs. 10D, F), which does not correspond to a change in the proportions of rock type.

5. Discussion

When assessing the dominant controls on the development of an ancient landscape, uncertainty remains in the timing and effects of external forcing factors; and the long timescales involved mean that external signals can be overprinted. Nonetheless, the

Gouritz catchment is an ideal test of a morphometric approach to considering the dominant controls on the evolution of long-lived drainage basins.

5.1. Impact of bedrock type

The impact of bedrock type is seen in the hypsometric curves, where the high relief of some subcatchments is related to the resistant dolerite intrusions and Cango Cave Group bedrock (Figs. 3, 10A, E). The deviation in curves dominated by the Cape (including quartzites) and Karoo supergroups cannot be related to rock type, and the resistance of the units appears to be fairly similar (Fig. 3). However, parameters such as bed thickness, bed orientation (strike and dip), and the extent of jointing – which have not been taken into account in this study – also impacts the resistance of bedrock to erosion (Walcott and Summerfield, 2008). Cape Supergroup rocks have also been metamorphosed, which can cause rocks of different compositions to have more similar resistance to erosion (Zernitz, 1935).

The level of dissection within catchments as shown by the hypsometric curves can also be attributed to variation in bedrock type; many of the coastal catchments are underlain by mudstones (Bokkeveld Group, Cape Supergroup), which are more easily eroded (Fig. 3), resulting in a concave curve. The CFB-draining subcatchments are dominated by resistant metamorphosed bedrock, associated with lower rates of erosion (Scharf et al., 2013) and, therefore, a longer duration of evolution resulting in sinusoidal or straight curves (Figs. 9A, B). In the CFB area, the catchments are lower order streams (<3), and the impact of bedrock type appears to be more dominant (Fig. 4A). The wide range in circularity values in the CFB-draining subcatchments also indicates a larger structural and lithological control within these mountainous catchments (Fig. 8A).

The impact of bedrock type appears to be stream-order dependent; knickpoints are pinned to contacts between rock types of different resistance within the subcatchments (Fig. 6). The large trunk rivers do not show this relationship as such pronounced changes in stream profile, which could be a function of temporal development; however, the profiles are straighter in the CFB area because of the high rock resistance (Figs. 3, 5). Bedrock type also impacts on drainage densities. The Karoo Supergroup rocks have the highest drainage densities (Table 1), and these rocks have been less affected by burial metamorphism. The more resistant rocks have lower drainage densities owing to the time taken for incision and the formation of a drainage network. Dolerite has been shown to play a key role in catchment development within South Africa (Tooth et al., 2004). In the upper Gouritz catchment, where dolerite is dominantly found, low stream gradients are present and the impact differs from Tooth et al. (2004) as the dolerite intrusions are not always represented as knickpoints along the long profile (Fig. 5). This could be because of the limited thickness of the dolerite intrusions in the Gouritz catchment in comparison to those exhumed in the South African Highveld (Tooth et al., 2004).

Quartzite has been argued to be the most dominant rock type on catchment dynamics (Jansen et al., 2010); however, in this study the presence of quartzites does not always vary morphometric indices. Typically, high SLs are located in the upper reaches of catchments (Antón et al., 2014); however, this is not the case for the Gouritz catchment (Fig. 6). The highest values are seen within the CFB, with low values at headwater regions. The highest values of SL are not always associated with the rivers crossing quarzitic lithologies, but mainly with the Uitenhage Group. When assessing the major trunk streams at reach level, quartzite does not have strong control. This is because the main trunk rivers breach the quartzite in only seven locations (Fig. 6), where deeply dissected gorges have formed resulting in high gradients and meandering in these locations. The majority of the river courses transverse other rock types such as the resistant Cango Cave Group, where high stream gradients and meanders are present (Fig. 6). The large degree of variation in stream length gradient within the Cape Supergroup rock types could be explained by the variation of bed thickness, bedding orientation, and jointing, as well as the degree of metamorphism.

5.2. Impact of inherited tectonic structures

The impact of tectonic structures within the Gouritz catchment is primarily exhibited in the drainage pattern of the lower order streams (order 2 and 3; Fig. 4A). Bifurcation ratios above 5 normally indicate a structural control (Strahler, 1957). However, in the case of the large trunk rivers of the Gouritz catchment (stream order 4 and 6), the higher stream orders dissect the CFB and are not directed or deflected by the E-W trending structures; this discordance supports their interpretation as antecedent systems (Rogers, 1903). Additional evidence of antecedence is shown by the combination of high gradients and meander forms into resistant lithologies within the CFB (Fig. 3). The CFB folds have the greatest control on subcatchments; this is especially evident in a stream order 2 river in Fig. 4B that has a linear planform and stream order 3 rivers in Fig. 4A. The strong structural control within the catchment with regards to bifurcation ratio is, therefore, the antecedence of the major tributaries (Rogers, 1903), which explains the higher bifurcation ratios in stream order 4 and 6 streams.

Across the catchment, the CFB represents a large proportion of elevation resulting in the plateau in the hypsometric curve (Fig. 7). The CFB has low rates of erosion, with the resistant rock types allowing the post-orogenic feature to persist (Scharf et al., 2013). Additional preservation of elevation is caused by the widespread presence of fossilised plains, pediments (Kounov et al., 2015), and presence of the Great Escarpment (Fig. 2B). Exceptionally low SL in the ephemeral headwaters indicates the importance of the flat top nature of the Great Escarpment (Fig. 2B). South Africa formed a central part of Gondwana and was a super-elevated continent (Patridge and Maud, 1987; Rust and Summerfield, 1990); during rifting in the Mesozoic, reorganisation of seaward-draining catchments such as the Gouritz occurred. The headwaters of the Gouritz incised the escarpment face and now drain a portion of the flat area on the escarpment inherited from the breakup of Gondwana. The concave nature of the headwaters shown in the long profiles (Fig. 5) indicates the large change in elevation between the flat top of the Great Escarpment and the central Karoo, which sits ~700 m below the escarpment.

Large-scale extensional faults (Fig. 1) do not appear to have an important control within the catchments, either within the hypsometric curves or the morphometric indices. However, the rock types within the catchment, especially the CFB, are pervasively jointed and faulted, and therefore, must be an important control at a small scale (Manjoro, 2014).

5.3. Large-scale forcing factors

Variation in morphometric indices (circularity, SL, and hypsometry) indicate that the Gouritz catchment has had a complicated development history (Fig. 11). Commonly, hypsometric curves are used to elucidate large-scale forcing factors in catchments (Montgomery et al., 2001).The sinusoidal shape of the Gouritz catchment (Fig. 9) is often related to rejuvenation (Ohmori, 1993). The uplift in South Africa is contentious (Gallagher and Brown, 1999; Brown et al., 2002; Tinker et al., 2008a; Kounov et al., 2009; Decker et al., 2013), however Walcott and Summerfield (2008) argued that if tectonic activity did occur within South Africa, it was either at a low rate or a long time ago because the hypsometry of the catchments are concave-up with low integral values, and the tectonic pulse is no longer expressed physiographically (Fig. 11). Summerfield (1991) related sinusoidal curves extracted from rivers in South Africa to coastal upwarp. The lower curve portion of the Gouritz catchment is not underlain by resistant lithologies, and the sinuous nature at these low elevations could be related to coastal upwarp. Strahler (1952) argued that fluvial equilibrium is shown by hypsometric integrals between 0.4 and 0.6. However, this is not always the case, as shown by this study, and caution is needed in the application of hypsometric integrals.

In the western-draining catchments, many of the hypsometric curves are convex, with variation in shape occuring in adjacent catchments. This suggests that either different forcing factors are affecting the catchments or they are reacting to the same forcing factors in different ways. Within smaller subcatchments, stream capture has been shown to cause rejuvenation and can occur as an allogenic process (Prince et al., 2011). Stream capture can explain the variation in some of the subcatchments; however, it is not sufficient to explain such large-scale processes for the entire drainage basin.

Hurtrez et al. (1999) and Chen et al. (2003) proposed that the hypsometry of catchments correlates to catchment properties. However, the lack of correlation between the hypsometric integral and catchment properties in this study does not support these findings but does support those by Walcott and Summerfield (2008) who also worked in ancient settings. When assessing variation in the western-draining catchments, the hypsometric integral values generally decrease toward the escarpment but show large variation. Regardless of stream order or location, correlation between catchment properties and the hypsometric integral is poor, which was also identified by Walcott and Summerfield (2008). Variation is larger between smaller subcatchments (<4), which is attributed to the smaller subcatchments having had less time to develop or to structural/rock type control having a larger influence on the smaller basins.

5.4. Implications and application of morphometric indices to ancient settings

The Gouritz catchment has had a long history of development since the Mesozoic breakup of Gondwana and the concomitant Cretaceous exhumation of southern South Africa. When assessing morphometric indices, this history needs to be understood, especially as large catchments like the Gouritz do not evolve in a uniform manner (Grimaud et al., 2014) as indicated by the variation in trunk river morphometric indices.

The long-lived nature of ancient catchments causes morphometric indices to record the composite effects of multiple factors. This is seen within the hypsometric curve of the Gouritz catchment whereby the middle portion appears to record rock type controls related to inherited structure (Fig. 7) and the lower portion tectonic impacts. Over long timescales, signals can be lost, overprinted, or truncated (Fig. 11), which can also be recorded in the sedimentary history of basins (Jerolmack and Paola, 2010; Covault et al., 2013; Romans et al., 2015). The large-scale tectonic event of Gondwana rifting and the debated tectonic uplift history of the catchment since rifting cannot directly be related to morphometric indices in this study (e.g., Walcott and Summerfield, 2008). This is because of the long time for the catchment to respond to and erode the resulting geomorphological impression of the tectonic pulse, coupled with overprinting of other signals (both internal and external; Allen, 2008) and the poorly constrained history of the Gouritz catchment. This is complicated by the lack of understanding of the timescale at which tectonic or climatic factors affect catchments after their initiation and of the response time within the catchment (e.g. Allen, 2008). Overall, the prevailing theories of tectonic and climatic impacts on landscape development cannot be tested properly using morphometric indices in this ancient landscape. The Gouritz catchment has preserved drainage structures (*sensu* Hack, 1960) because of the relatively constant climate since the end of the Cretaceous and lack of tectonic activity. The current planform of the Gouritz is closely linked to rock type, as shown by the hypsometric curves, with steep relief, knickpoints, and high SL in the CFB and subdued relief in the less resistant Karoo Supergroup rock types. Nonetheless, a range of controls will have shaped the Gouritz catchment. However, bedrock geology within these ancient catchments is judged to be the dominant control on the morphometrics as it is the longest lived *relatively* constant boundary condition in comparison to tectonic or climatic change (Fig. 11).

6. Conclusion

Morphometric indices, including stream length gradient and hypsometric integrals, were extracted from the tectonically quiescent Gouritz catchment and confirm that the catchment has had a complicated extended geomorphological history. This is expected for a catchment that has developed since the Jurassic break-up of Gondwana and large-scale exhumation from the Cretaceous onward. Nonetheless with a combined geological-geomorphological approach and analysis across different spatial scales, we are able to decipher that at a catchment scale, indices such as hypsometry are affected by resistant rock types, whereby resistant units preserve topography at a subcatchment and catchment scale. The influence of rock type is scale dependent on river channel long profiles and is more prevalent in catchments of stream orders <4; knickpoints are pinned on boundaries between quartzites and less resistant rock types. Within the larger trunk rivers, stream length gradient is mainly affected by the Uitenhage Group with low values experienced in the upper reaches of the catchment. The trunk rivers dissect the CFB because of their antecedence. Contacts between quartzite and less resistant rock types in these locations are not shown as knickpoints or the highest stream length gradient values, indicating a long duration of development. Control by inherited tectonic structures in this study is therefore mainly seen within smaller subcatchments that drain the CFB as shown by the range in circularity values and within the long profiles of the rivers that cross the CFB

Hypsometric curve shape is normally related to external variation in climate or tectonics; however, the sinusoidal hypsometric curve of the Gouritz catchment can be attributed to elevation preservation owing to resistant lithologies and to the preservation of pediments because of low erosion rates. Tectonic influence caused by mantle plumes would cause systematic variation in indices, which is not seen as shown by the lack of correlation between catchment location or stream order. However, large scale differential uplift related to exhumation in the Cretaceous and coastal upwarp because of Mesozoic rifting could still be impacting catchment development, but these controls are hard to distinguish. Within smaller subcatchments, variation in hypsometric curve can be attributed to stream capture in some locations.

Overall, morphometric indices allow a first-order characterisation of ancient landscapes and highlight the importance of resistant lithologies. In long-lived catchments, the influence of tectonic activity cannot clearly be ascribed to variation in morphometric indices and appear to be subdued and shredded by the impact of resistant rock types. Caution must therefore be taken when comparing morphometric indices within different tectonic regimes and with different durations of development. Future work should investigate how morphometric indices vary over time in such tectonically quiescent and/or ancient regions and examine how long a tectonic or climatic pulse can be preserved within different environments.

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Figure Captions

Table 1

Variation in drainage density for the main lithological groups of the Gouritz catchment

Lithology	**Drainage density (km/km^2)**
Igneous intrusions	0.28
Quartzites	0.23
Cango Cave group	0.37
Uitenhage group	0.35
Karoo Supergroup	0.44
Cape Supergroup	0.37

Table 2

Linear aspects of the Gouritz catchment

Stream order	**Stream number**	**Average stream length (km)**	**Bifurcation ratio**
1	2811	5.36	3.45
2	814	9.29	3.86

3	211	17.51	3.91
4	54	30.01	6.00
5	9	117.77	4.50
6	2	52.44	2.00
7	1	355.96	
Mean			3.39

Table 3

Variation in hypsometric integral in the western-draining catchments with stream order

Stream order	N	Highest hypsometric integral	Lowest hypsometric integral	Mean	Range	Standard deviation
1	18	0.53	0.32	0.43	0.21	0.62
2	13	0.69	0.27	0.43	0.42	0.11
3	13	0.51	0.23	0.38	0.27	0.75
4	3	0.38	0.18	0.30	0.20	0.10
5	1			0.24		
6	2			0.30		

Table 4

Variation in hypsometric integral with catchment location

Location	N	Highest hypsometric integral	Lowest hypsometric integral	Mean	Range	Standard deviation
Coastal	7	0.69	0.19	0.35	0.50	0.17
Cape Fold Belt	14	0.56	0.30	0.41	0.26	0.07
Central Karoo	28	0.53	0.25	0.41	0.28	0.07

Fig. 1.*The location of the Gouritz catchment in southern South Africa and the six major tributaries and major extension faults. A simplified geological map is also shown highlighting the main rock types.*

Fig. 2.*(A) Topography variation within the Gouritz catchment showing the main physiographic regions; (B) Hammond's landform classification map indicating the catchment is dominated by plains and mountains.*

Fig. 3. *Relative resistance of rock types within the Gouritz catchment. Quartzite (Table Mountain Group) and dolerites are the most resistant rock types. The values indicate Schmidt hammer results from the study area, italicised numbers are from*

published studies of the same rock type (1 – Özbek, 2009; 2 – Dardis and Beckedahl 1991; 3 – Goudie, 2006; 4 – Shelton, 2015; 5 - Goudie et al., 1990).

Fig. 4.*(A) Drainage pattern of the Cape Fold Belt and Coastal physiographic region, showing stream order 3 streams categorised by shape. See Fig. 1 for location. (B) and (C) show evidence of stream capture and linear streams confined by folding.*

Fig. 5. *Long profiles of the Gouritz catchment and main tributaries: (A) Buffels River, (B) Touws River, (C) Olifants River, (D) Traka River, (E) Gamka River and (F) Dwyka River.*

Fig. 6. *Normalised stream length gradient and the relationship to simplified geology within the Gouritz catchment. The locations of knickpoints within the smaller catchments of the Swartberg range are also shown.*

Fig. 7*. The sinusoidal hypsometric curve of the Gouritz catchment.*

Fig. 8. *Relationship between location, catchment properties, and hypsometric integral: (A) area, (B) circularity, (C) relief, (D) dissection, and (E) distance from mouth of Gouritz River. The R^2 values indicate no correlation between catchment properties and hypsometric integral.*

Fig. 9. *(A) Distribution of 'type' curves (straight, convex, concave, and sinusoidal) where RA is relative area and RE is relative elevation; (B) variation in curve shape toward the escarpment. Data extracted from every fifth catchment: (C) area of catchments below 50% of the maximum elevation within the basin; (D) the average lengths of stream order 1 to 6 streams draining the Western Cape.*

Fig. 10. *Hypsometric curves and lithostratigraphic units for stream order 1-6 (A-F) catchments draining the western side of the Gouritz catchment. Inflection points in the curve are highlighted. The numbers indicate the gradient of each section, delineated by a change in curve shape.*

Fig. 11. *Synthesis diagram showing the differences between young and ancient catchments and the impact on morphometric indices. Within young landscapes, recent tectonic activity is represented as knickpoints and straight hypsometric curves. However, in ancient catchments this signal is diminished, resulting in pinned knickpoints on lithological divides, sinusoidal curves, and composite effects of multiple factors that make it hard to distinguish dominant controls.*

Figure 1

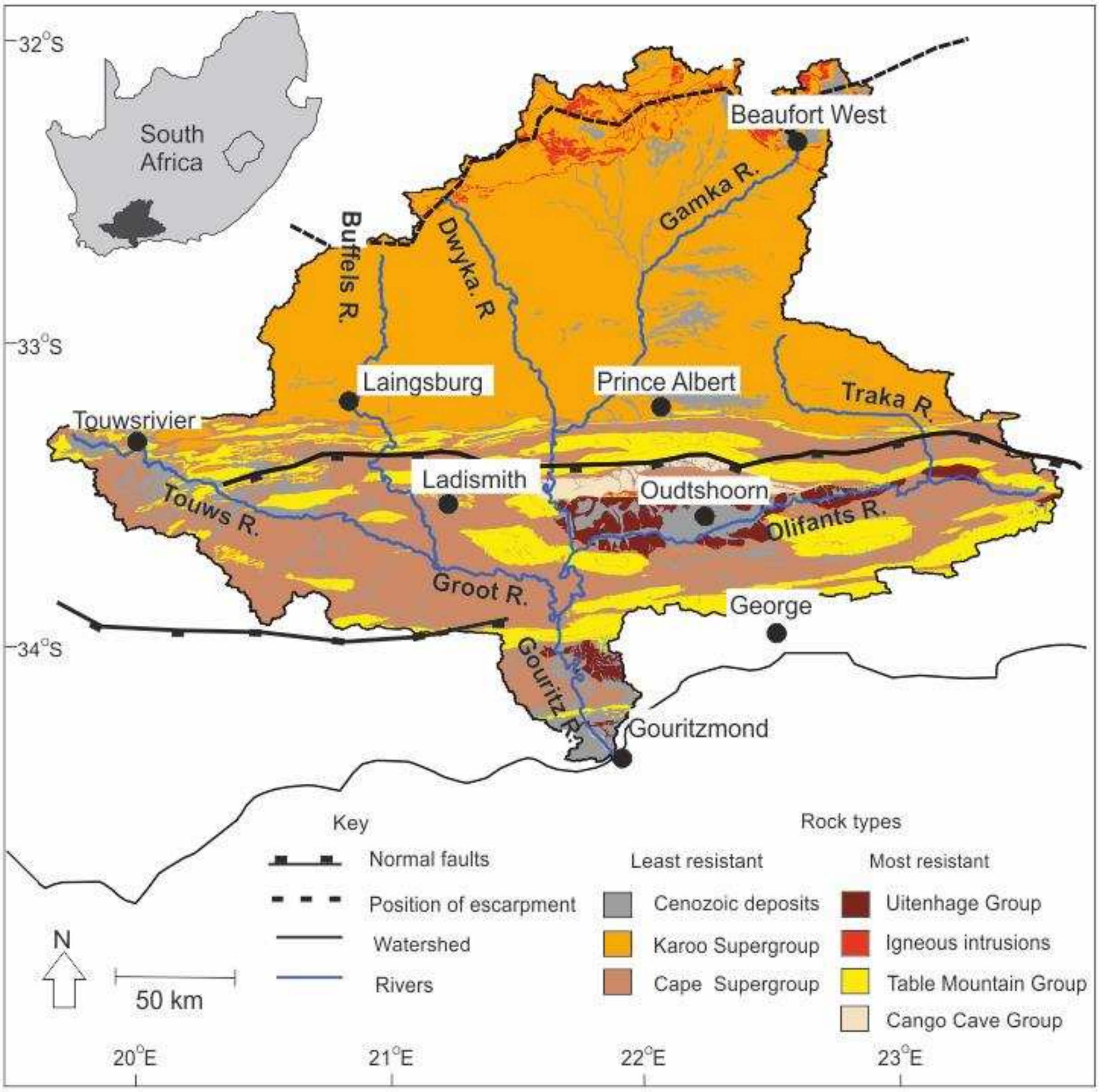

32°S
33°S
34°S
South Africa
Beaufort West
Gamka R.
Buffels R.
Dwyka. R
Laingsburg
Prince Albert
Traka R.
Touwsrivier
Ladismith
Oudtshoorn
Olifants R.
Touws R.
Groot R.
George
Gouritz R.
Gouritzmond
Key
Normal faults
Position of escarpment
Watershed
Rivers
Rock types
Least resistant
Cenozoic deposits
Karoo Supergroup
Cape Supergroup
Most resistant
Uitenhage Group
Igneous intrusions
Table Mountain Group
Cango Cave Group
N
50 km
20°E
21°E
22°E
23°E

Figure 2

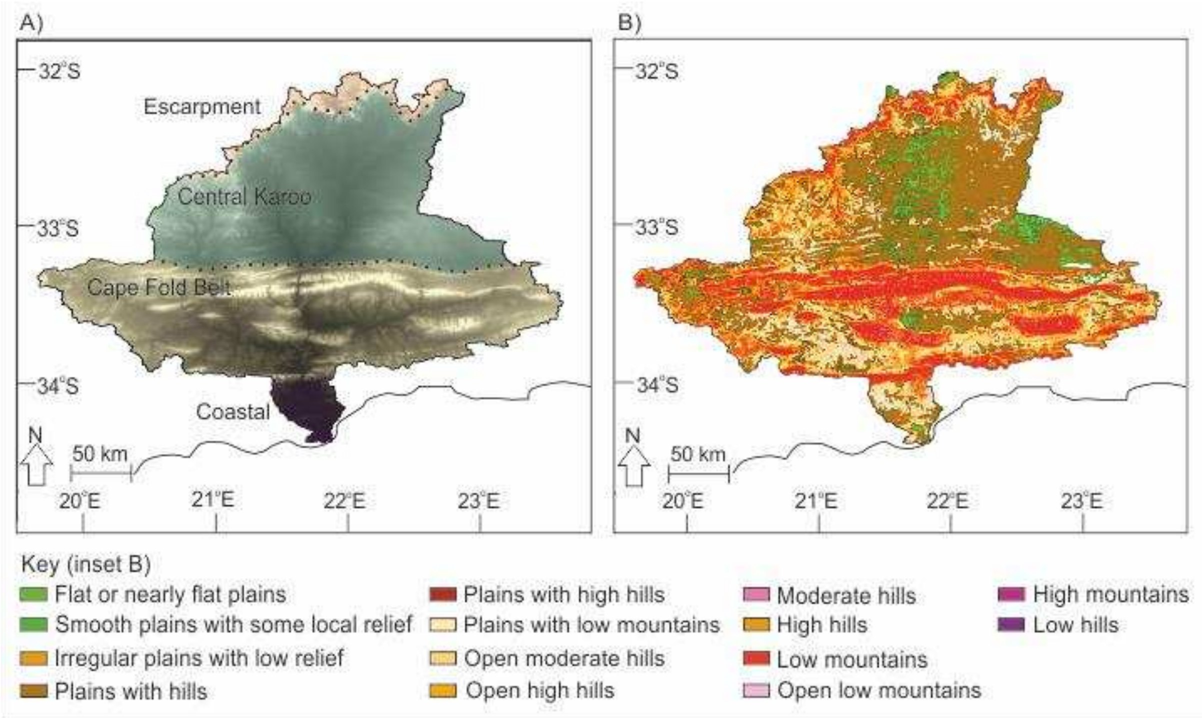

A)
32°S
33°S
34°S
Escarpment
Central Karoo
Cape Fold Belt
Coastal
N
50 km
20°E
21°E
22°E
23°E
B)
32°S
33°S
34°S
N
50 km
20°E
21°E
22°E
23°E
Key (inset B)
Flat or nearly flat plains
Smooth plains with some local relief
Irregular plains with low relief
Plains with hills
Plains with high hills
Plains with low mountains
Open moderate hills
Open high hills
Moderate hills
High hills
Low mountains
Open low mountains
High mountains
Low hills

Figure 3

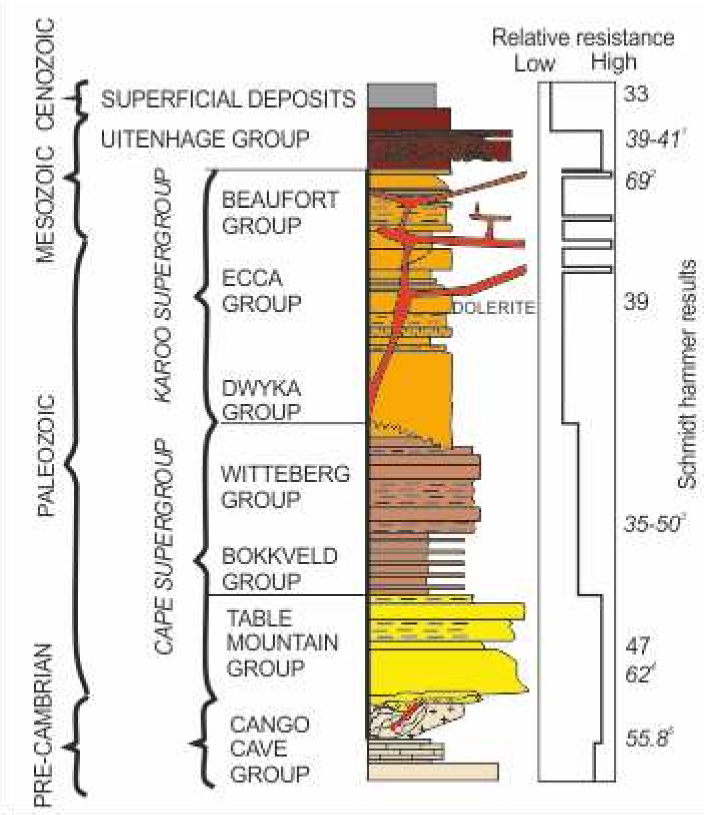
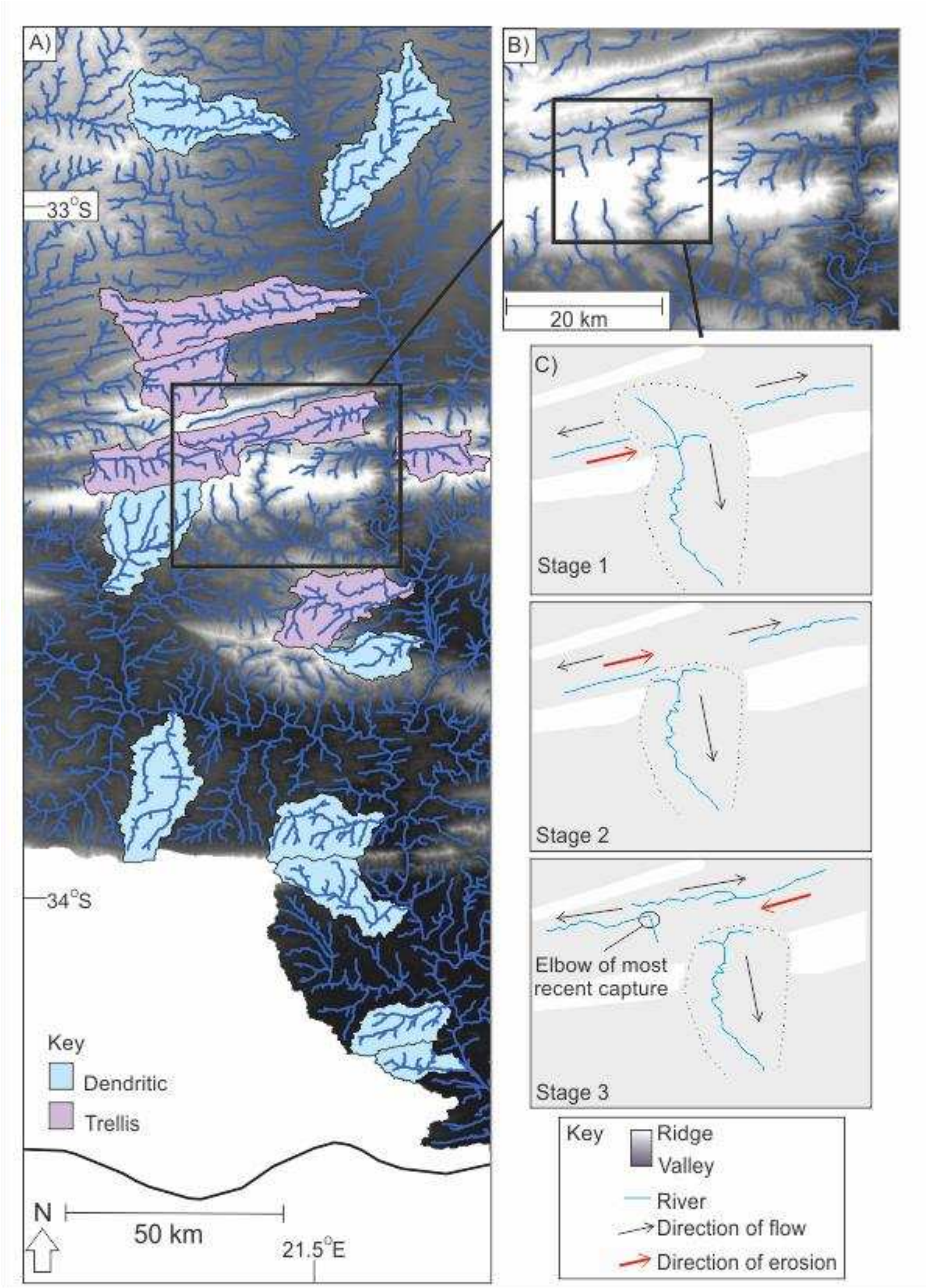
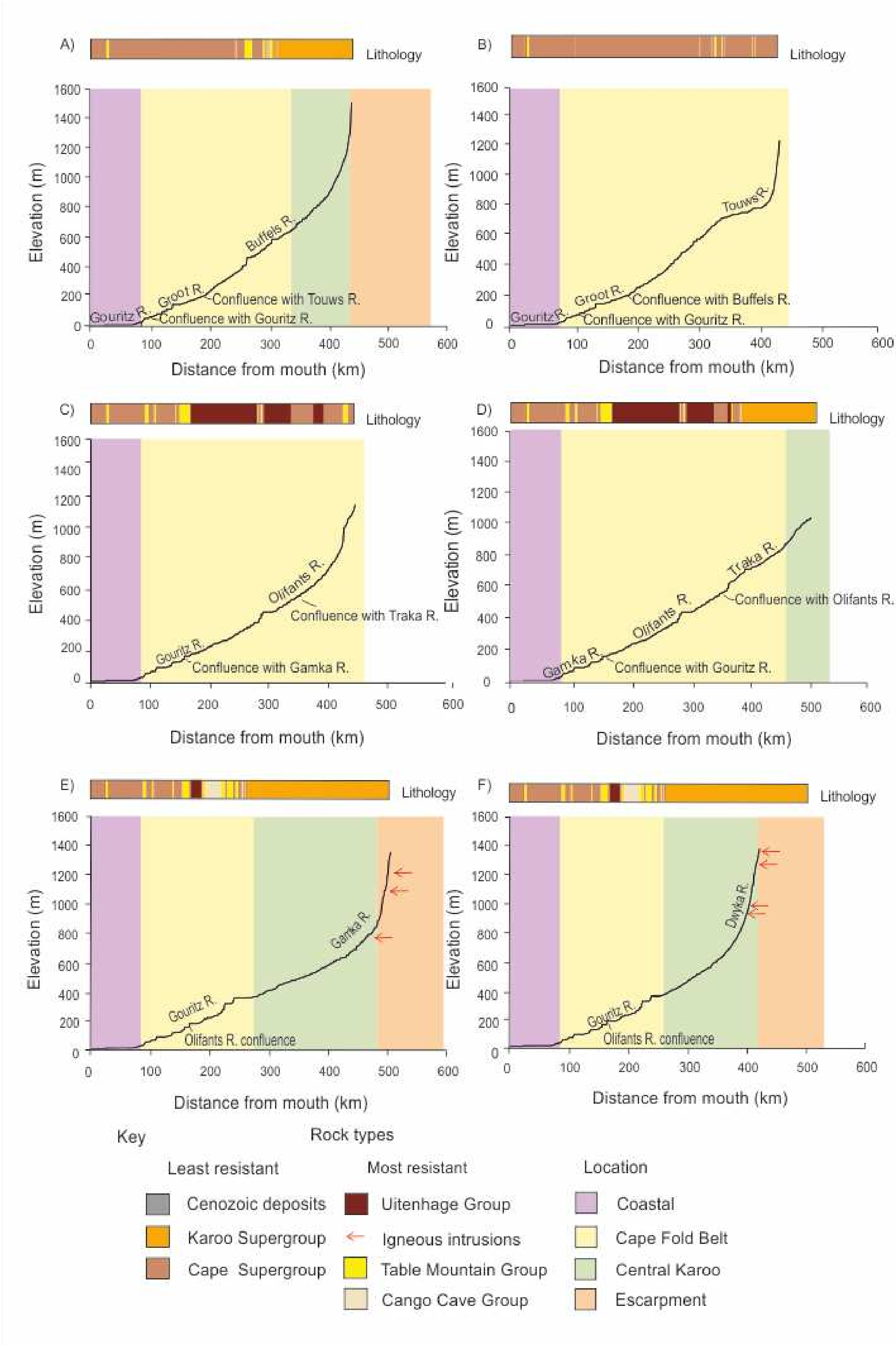

Relative resistance
Low High
CENOZOIC
MESOZOIC
PALEOZOIC
PRE-CAMBRIAN
SUPERFICIAL DEPOSITS
UITENHAGE GROUP
KAROO SUPERGROUP
CAPE SUPERGROUP
BEAUFORT GROUP
ECCA GROUP
DWYKA GROUP
WITTEBERG GROUP
BOKKVELD GROUP
TABLE MOUNTAIN GROUP
CANGO CAVE GROUP
DOLERITE
33
39-41
69
39
35-50
47
62
55.8
Schmidt hammer results

Figure 4


A)
33°S
34°S
Key
Dendritic
Trellis
N
50 km
21.5°E
B)
20 km
C)
Stage 1
Stage 2
Elbow of most recent capture
Stage 3
Key
Ridge
Valley
River
Direction of flow
Direction of erosion

1028 Figure 5



1029

1030

Figure 6

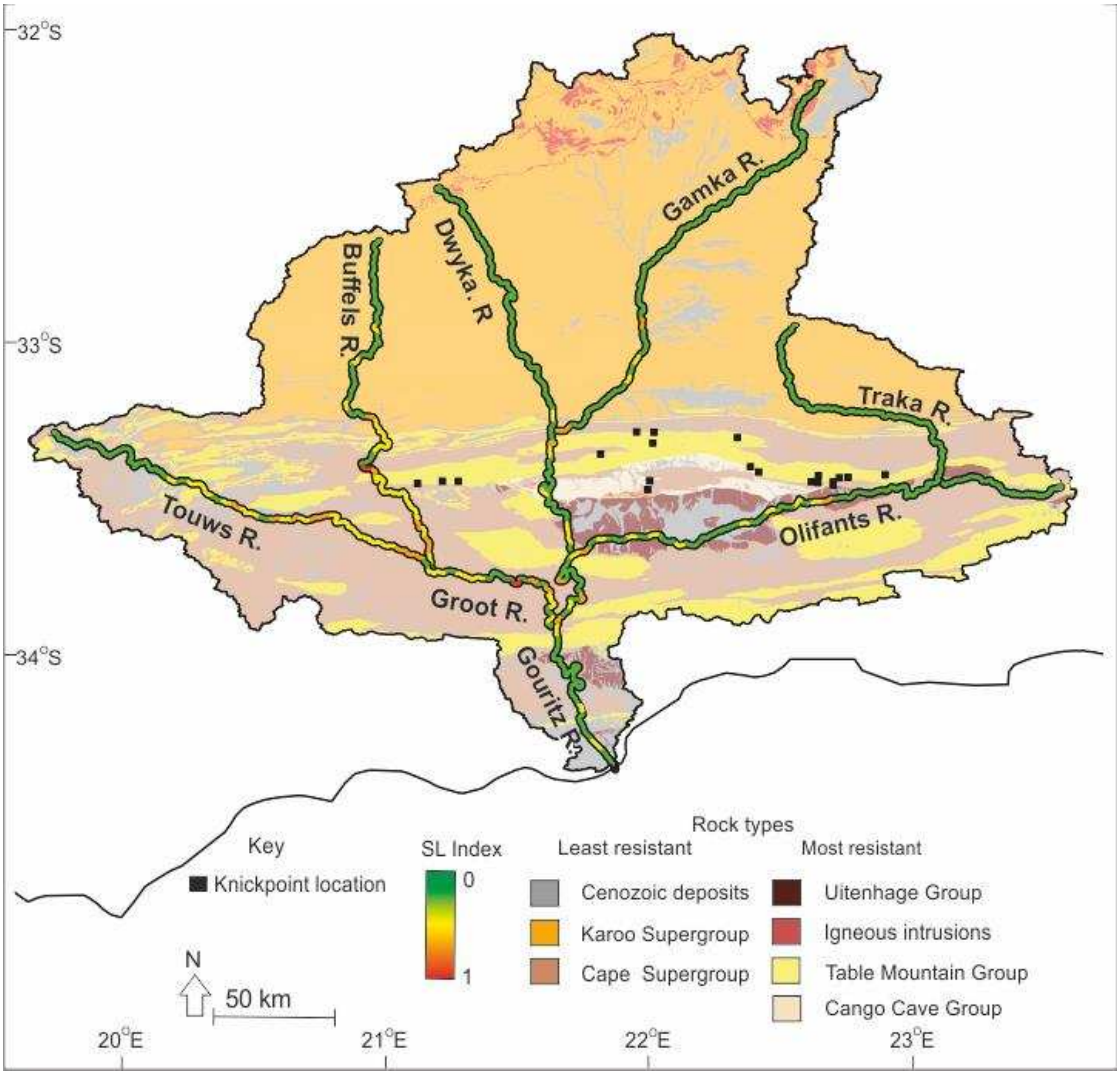

32°S
33°S
34°S
Gamka R.
Dwyka. R
Buffels R.
Traka R.
Touws R.
Olifants R.
Groot R.
Gouritz R.
Key
Knickpoint location
SL Index
0
1
Rock types
Least resistant
Most resistant
Cenozoic deposits
Karoo Supergroup
Cape Supergroup
Uitenhage Group
Igneous intrusions
Table Mountain Group
Cango Cave Group
N
50 km
20°E
21°E
22°E
23°E

Figure 7

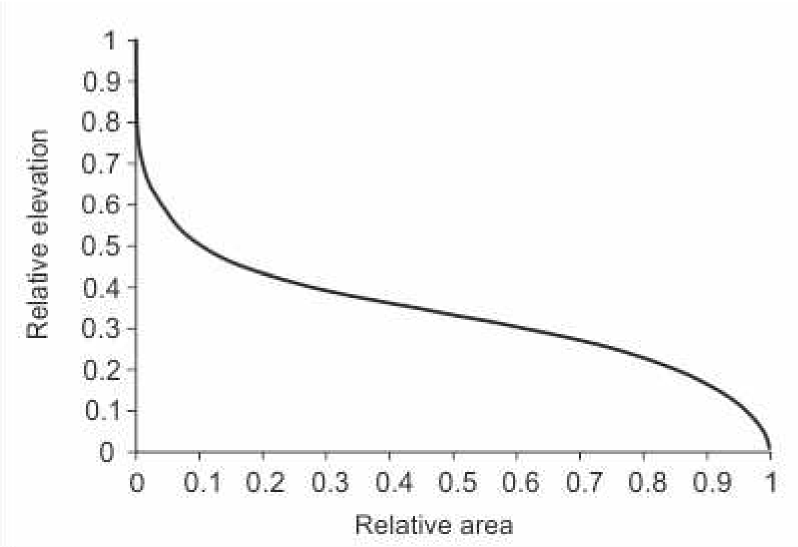


Figure 8

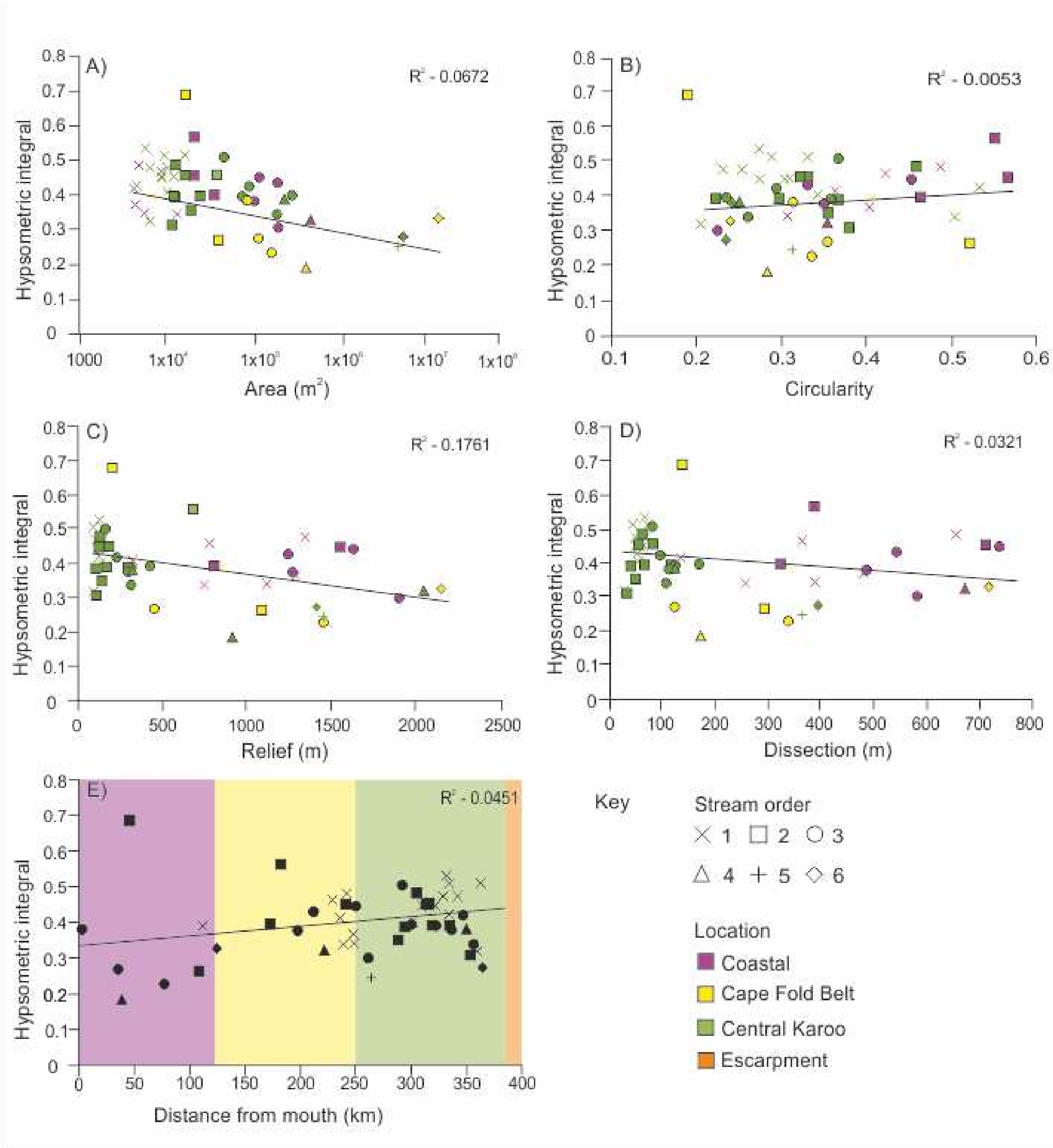

A)
R^2 - 0.0672
Hypsometric integral
Area (m^2)
B)
R^2 - 0.0053
Circularity
C)
R^2 - 0.1761
Relief (m)
D)
R^2 - 0.0321
Dissection (m)
E)
R^2 - 0.0451
Distance from mouth (km)
Key
Stream order
1 2 3
4 5 6
Location
Coastal
Cape Fold Belt
Central Karoo
Escarpment

Figure 9

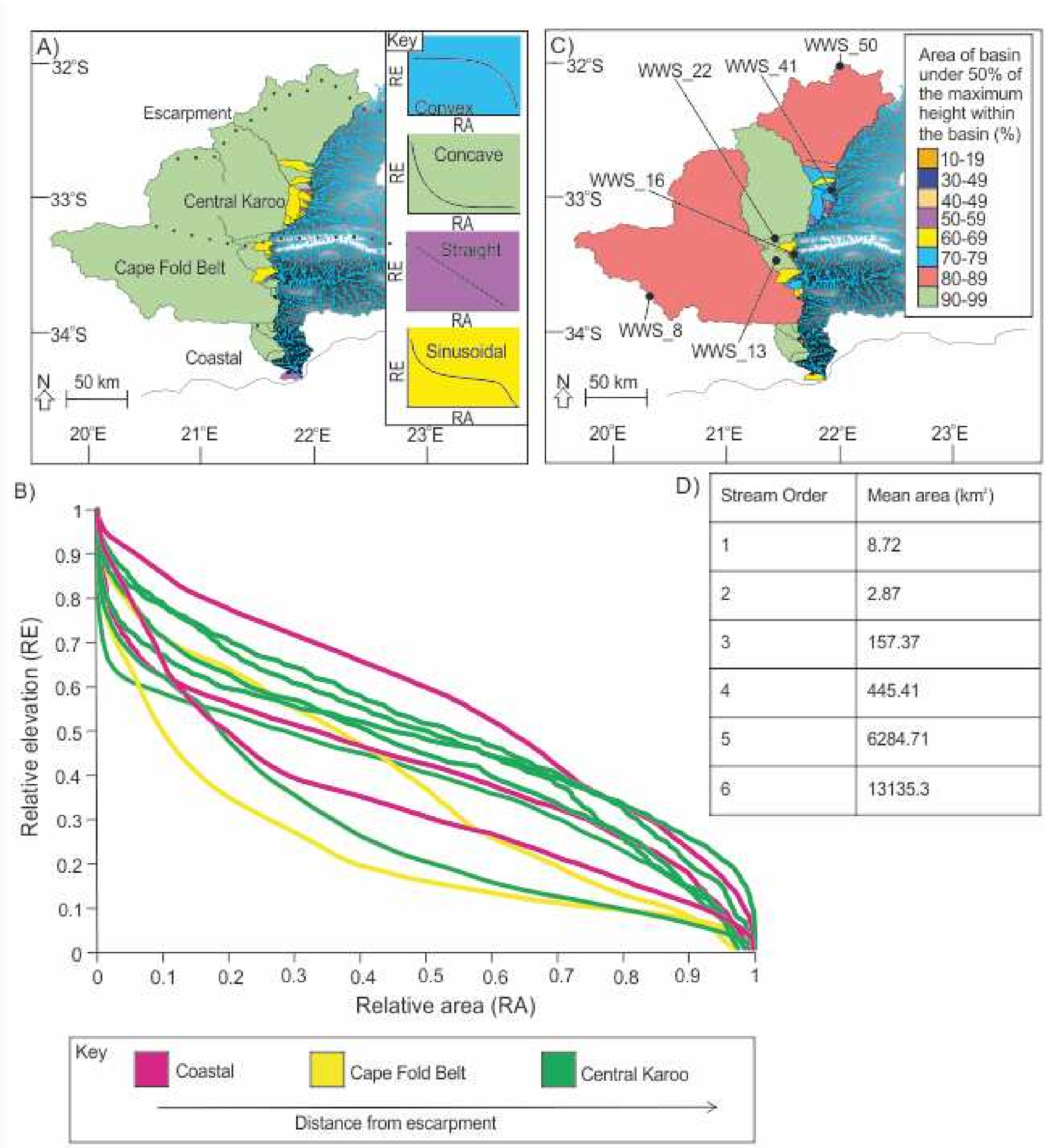
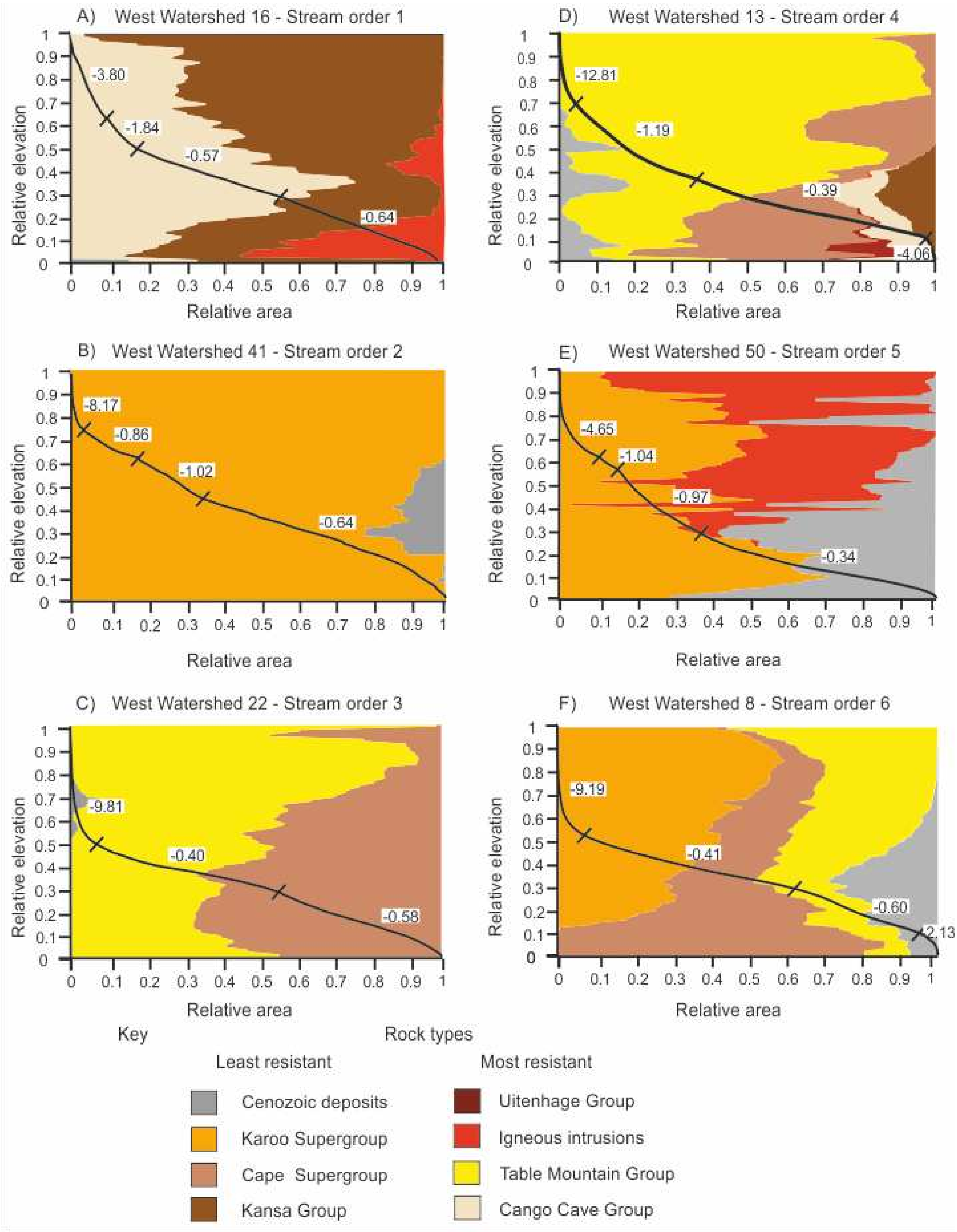
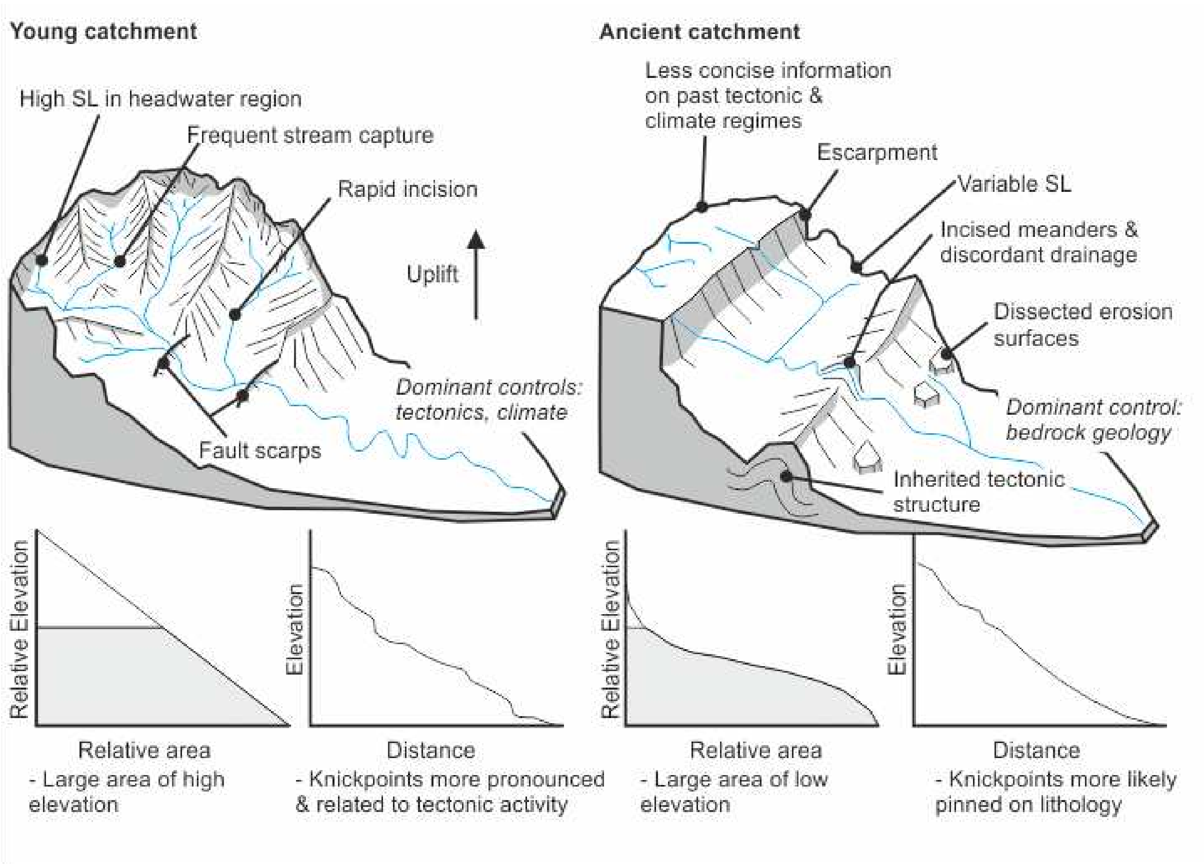

A)
32°S
33°S
34°S
Escarpment
Central Karoo
Cape Fold Belt
Coastal
N
50 km
20°E
21°E
22°E
23°E
Key
RE
RA
Convex
Concave
Straight
Sinusoidal
C)
WWS_50
WWS_22
WWS_41
WWS_16
WWS_8
WWS_13
Area of basin under 50% of the maximum height within the basin (%)
10-19
30-49
40-49
50-59
60-69
70-79
80-89
90-99
B)
Relative elevation (RE)
Relative area (RA)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Key
Coastal
Cape Fold Belt
Central Karoo
Distance from escarpment
D)
Stream Order
Mean area (km²)
1 8.72
2 2.87
3 157.37
4 445.41
5 6284.71
6 13135.3

Figure 10


A) West Watershed 16 - Stream order 1
-3.80
-1.84
-0.57
-0.64
D) West Watershed 13 - Stream order 4
-12.81
-1.19
-0.39
-4.06
B) West Watershed 41 - Stream order 2
-8.17
-0.86
-1.02
-0.64
E) West Watershed 50 - Stream order 5
-4.65
-1.04
-0.97
-0.34
C) West Watershed 22 - Stream order 3
-9.81
-0.40
-0.58
F) West Watershed 8 - Stream order 6
-9.19
-0.41
-0.60
-2.13
Relative elevation
Relative area
Key
Rock types
Least resistant
Most resistant
Cenozoic deposits
Karoo Supergroup
Cape Supergroup
Kansa Group
Uitenhage Group
Igneous intrusions
Table Mountain Group
Cango Cave Group

1085 Figure 11



1086