Where is my sink? Reconstruction of landscape development in southwestern Africa since the Late Jurassic

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ABSTRACT

Quantifying the rates and timing of landscape denudation provides a means to constrain sediment flux through time to offshore sedimentary basins. The Late Mesozoic evolution of drainage basins in southern Africa is poorly constrained despite the presence of several onshore and offshore sedimentary basins. A novel approach has been developed to calculate the volume of material eroded since the Late Jurassic at different time steps by constructing structural cross-sections and extrapolating thicknesses of eroded material. Using different assumptions, the calculated volumes of material eroded from southwestern Africa range from 2.52 x10^6 km^3 (11.3 km of vertical thickness removed) to 8.87 x10^5 km^3 (4.0 km of vertical thickness removed). For the southward draining systems alone, the calculated removal of 7.81 x10^5 – 2.60 x10^5 km^3 of material is far greater than the volumes of sediment recorded in offshore sedimentary basins (268 500 km^3). Reconstruction of the drainage systems using geomorphic indicators and clast provenance of the Uitenhage Group, as well as extrapolated surface exposure ages, indicate the southern draining systems were active from the Late Jurassic with coeval activity in axial and transverse drainage systems. The calculated volumes are tied to published apatite fission track (AFT) dates to constrain the changes in exhumation rate through time (using multiple scenarios), which indicate a significant amount of Early Cretaceous exhumation (up to 1.26 x10^6 km^3, equivalent to 5.70km of vertical thickness). For the first time, this has permitted long-term landscape evolution to be used to support the interpretation that some of the ‘missing’ sediment was deposited in sedimentary basins on the Falkland Plateau as it moved past southern Africa during the Early Cretaceous. This implies that in this instance, the sinks are separated from their source areas by ~6000 km.

Key words: Drainage reconstruction, Mesozoic basins, Falklands Plateau basins, southern Africa, source-to-sink.

Highlights:

- The geomorphology of southern Africa is a record of Cretaceous drainage patterns
- The sink of eroded sediment is speculated to be the Falkland Plateau basins.
- The sink is separated by 6000km from its source.

1. Introduction

Reconstructing onshore routeing patterns and landscape development is an important stage in the analysis of ancient source-to-sink configurations (e.g., Clift et al., 2006, Romans et al., 2009; Covault et al., 2011; Macgregor, 2012; Sømme and Jackson, 2013; Helland-Hansen et al., 2016). This relationship can be challenging to constrain and quantify when assessing configurations in deep-time (i.e., Cretaceous and older) and close to active plate boundaries (Romans et al., 2009; Romans and Graham, 2013). Quantitative dating techniques such as in situ cosmogenic dating (e.g., Gosse and Phillips, 2001; von Blanckenburg and Willenbring, 2014),apatite fission track (AFT) (e.g., Gleadow et al., 1983, 1986; Gallagher et al., 1998), and (U-Th)/He thermochronology (Flowers and Schoene, 2010; Stanley et al., 2013) can place constraints on the timing and rate of erosion and exhumation. These approaches provide a means to understand onshore drainage basin configurations through time more accurately (e.g., Bierman, 1994; Gallagher and Brown, 1999; Cockburn et al., 2000) and when combined with remote sensing techniques, can aid offshore analysis by linking catchments areas to drainage evolution (McCauley et al., 1986; McHugh et al., 1988; Ramasamy et al., 1991; Blumberg et al., 2004; Gupta et al., 2004; Griffin, 2006; Youssef, 2009; Abdelkareem and El-Baz, 2015; Breeze et al., 2015).

South Africa is a passive margin (e.g., King, 1944; Fleming et al., 1999; Kounov et al., 2009), and comprises an interior plateau of low relief and high elevation, separated by the Great Escarpment from the coastal region of high relief and low average elevation. Large-scale river systems dominate the area to the north of the Great Escarpment such as the Orange River. Three large catchments control the area to the south of the escarpment: the Olifants, Breede and Gouritz catchments. The Great Escarpment forms the main drainage divide between the southward and westward draining systems.

Offshore southern South Africa there are several sedimentary basins (including the Bredasdorp, Pletmos (Infantaya Embayment), Gamtoos and Algoa basins) (McMillan et al., 1997). Despite the presence of these sedimentary basins, the onshore drainage development of river catchments south of the Great Escarpment has been under investigated (Rogers, 1903; Partridge and Maud, 1987). Landscape evolution research of South Africa has often focussed on the development and retreat of the Great Escarpment (e.g., King, 1953; Partridge and Maud, 1987; Fleming et al., 1999; Brown et al., 2002; Moore and Blenkinsop, 2006) and large-scale drainage systems such as the Orange River (e.g., Dingle and Hendry, 1984; Rust and Summerfield, 1990; de Wit et al., 2000).

During the Cretaceous, there was large-scale exhumation of southern South Africa, recorded by AFT data (Brown et al., 1990; Tinker et al., 2008a). At the same time, large rift basins developed onshore and offshore during the fragmentation of Gondwana and opening of the southern Atlantic Ocean (Macdonald et al., 2003). Tinker et al. (2008a) reported 6.0 - 7.5 km of exhumation using AFT data, if the whole Karoo Supergroup succession was present, and identified two pulses of exhumation in the Early- and Mid-Late-Cretaceous, respectively. The Uitenhage Group represents the only onshore depositional representation of the Jurassic-Cretaceous exhumation event (Shone, 2006), although the age is contentious due to poor chronostratigraphic control, as discussed below. Previously, however, drainage reconstructions have not fully integrated information on the geomorphic evolution of the region or sedimentology of the Uitenhage Group to constrain the timing, routeing, and volume of sediment flux from onshore drainage basins to offshore sedimentary basins.

This study aims to reconstruct the drainage history of two large drainage basins (the Gouritz and Breede catchments) in the Western Cape in order to: (1) calculate the maximum volume of material removed and compare relative timings with published AFT data; (2) compare the volume of material removed to the overall offshore sediment volumes during the Mesozoic; (3) examine the geomorphic indicators of river evolution and reconstruct the drainage evolution using geomorphological and sedimentological evidence, and (4) discuss where the ‘missing’ sediment was deposited during Mesozoic exhumation of southern South Africa.

2. Regional setting

2.1. Study area

The study area encompasses four onshore Mesozoic extensional basins in the Western Cape: the Oudtshoorn (study site - Kruisrivier Valley and N12), De Rust (study site - R341), Worcester (study site – Rooikrans) and Nuy (study site – Nuy Road) basins (Fig. 1). The onshore sedimentary basins are within two large discordant catchments in the Western Cape Province: the Gouritz (Richardson et al., 2016) and the Breede (Fig. 1), which have been developing since the Mesozoic break-up of Gondwana (Moore and Blenkinsop, 2002; Goudie, 2005; Hattingh, 2008).

The Mesozoic sedimentary basins have been deeply exhumed and dissected (Fig. 1; Green et al., 2016). The Oudtshoorn Basin is bounded by the Kango fault and is the largest onshore Mesozoic basin with a length of 80 km across the E-W strike and a width up to 21 km (Fig. 1). The Kango fault also bounds the De Rust Basin, which is 37 km in length (E-W strike) and has a maximum width of 8 km. The Worcester and Nuy basins are bounded by the Worcester fault. The Worcester Basin is highly dissected and is approximately 27 km in length and 3 km in width; the Nuy Basin is 15 km in length and 7 km in width. Hereafter, the Worcester and Nuy basins are referred to as the Worcester Basin.

2.2. Geology

The Cape and Karoo supergroups are extensively exposed in southern South Africa, with minor Pre-Cambrian metasediments (the Malmesbury, Kaaimans and Gamtoos groups) and granites (the Cape Granite suite) (Fig. 2). The Cape Supergroup is a siliciclastic succession composed of the Table Mountain, Bokkeveld and Witteberg groups (Broquet, 1992). The quartzitic Table Mountain Group represents shallow-marine sedimentation, with deposits including conglomerates, sandstones, mudstones, quartz arenites and mudstones. The argillaceous Bokkeveld Group represents deep-marine sedimentation. The Witteberg Group contains shallow marine quartzites and mudstones (Broquet, 1992). The Karoo Supergroup comprises the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg groups. The Dwyka Group represents glacial sedimentation and comprises tillites. The Ecca and Beaufort groups contain claystone, siltstone, and sandstone. The deposits represent an overall shallowing-upward succession from basin-floor and submarine slope, through shelf, to fluvial and lacustrine depositional environments (Johnson et al., 1996; Flint et al., 2011). The Stormberg Group contains mudstones and sandstones, and represents sub-aerial and fluvial deposition (Johnson et al., 1996). The Drakensberg Group contains flood basalts and dolerites associated with the initial rifting of

Gondwana (Visser, 1984). The Uitenhage Group comprises deposits associated with the large-scale exhumation of southern South Africa during uplift and extension (Durrheim, 1987; Shone; 2006; Bordy and America, 2016), and contains the Enon, Kirkwood and Sunday River formations. The Enon and Kirkwood formations crop out in the study areas, and are remnants of once thicker and more laterally extensive extensional basin-fill successions (Fig. 1) (Shone, 1978). The Enon Formation is conglomeratic with silty/sandy matrix (Shone, 2006), which are intercalated with sandstone layers (McLachlan and McMillan, 1976), and has been interpreted as an alluvial fan deposit (Rigassi and Dixon, 1972; Hill, 1972; Winter, 1973). Deposition of the Enon Formation was coeval with rapid denudation as shown by the high sediment concentrations and boulder beds (Dingle, 1973; Lock et al., 1975). The Kirkwood Formation is variegated silty mudstone and sandstone, and represents a meandering fluvial environment (Shone, 2006).

Dating control within the Uitenhage Group is sparse. An unpublished radiometric age of 162 +/- 7 Ma for the underlying Suurberg Group, based on K-Ar whole-rock dating of a single basalt sample, represents a maximum age constraint for the Uitenhage Group (McLachlan and McMillian, 1976). However, due to erosion (e.g., Tinker et al., 2008a) and/or sediment bypass the depositional age may be much younger. McLachlan and McMillan (1976) propose a Lower Valanginian to Berriasian age for the Enon and Kirkwood formations (~144-137 Ma); however, Green et al. (2016), assign a Tithonian to Valanginian age (151-136 Ma), based on data from Shone (2006) and Dingle et al. (1983). No onshore sediments of Jurassic age have been dated (McLachlan and McMillan, 1976). The Sunday River Formation, exposed in the Algoa Basin and onshore near the Coega River and Swartkops River Valley contains ammonites, dated as Upper Valanginian to Hauterivian (~140-130 Ma) (McLachlan and McMillan, 1976). Nonetheless, Partridge and Maud (1987) assign a Late Jurassic age to Uitenhage Group conglomerates.

The offshore sedimentary basins (Fig. 1) are interpreted as extensional pull apart systems that formed during rifting of East and West Gondwana and the subsequent opening of the southern Atlantic (Brown, 1995; McMillan et al., 1997; Paton, 2006; Tinker et al., 2008b; Sonibare et al., 2015). The change from net deposition to net erosion in the Western Cape area is related to Gondwana rifting and lowered base levels of the continent at this time. This caused intense exhumation of the Karoo Basin-fill and the Cape Fold Belt (CFB), and the development of southward draining rivers (Gilchrist et al., 1994). Offshore deposition of conglomerates in the Uitenhage Group have been recorded in the major sedimentary basins of the inner Outeniqua Basin. The timing of initial deposition is diachronous across the offshore sedimentary basins (Dingle and Scrutton, 1974), which could relate to the time taken for transport offshore into the sedimentary basins or uncertainties in dating the offshore deposits. The first appearance of conglomerate offshore is Late Jurassic in the Bredasdorp Basin (Sonibare et al., 2015), Early Cretaceous in the Pletmos Basin (Brink et al., 1993), and Late Jurassic to Early Cretaceous in the Gamtoos Basin (Thomson, 1999) and Algoa Basin (Dingle, 1973). The widespread presence of conglomerates offshore indicate that onshore erosion and sediment transport has been establish by the Late Jurassic and Early Cretaceous.

Tinker et al. (2008b) calculated an order of magnitude difference between the amount of sediment eroded onshore and the volume of sediment in the inner

Outeniqua Basin, the collective name for the Bredasdorp, Pletmos, Gamtoos and Algoa basins (Fig. 1), and outer (Southern) Outeniqua Basin. The volume of offshore sediment accumulation since ~136 Ma was estimated to account for 860 m of onshore exhumation, and a lag of 7 Ma was constrained from onshore denudation to offshore accumulation from 93 Ma to 67 Ma (Tinker et al., 2008b). Tinker et al. (2008b) calculated the variations in sediments volumes deposited in the offshore Outeniqua Basin, and reported episodes of increased sedimentation during ~136 – 130 Ma (48,800 x 10^4 km^3), 130 – 120 Ma (57,500 x $10^4 km^3$) and 93 - 67 Ma (83,700 x $10^4 km^3$). During ~120 – 93 Ma, a volume of 47,400 x $10^4 km^3$ was deposited, and decreased in the Cenozoic (67 – 0 Ma) to 31,200 x $10^4 km^3$.

2.3. Structure

Structurally, the Western Cape is dominated by the exhumed Cape Fold Belt (CFB), which is a compressional mountain range that formed in the late Permian and Triassic (e.g. Tankard et al., 2009; Flint et al., 2011). The CFB comprises resistant quartzite, as well as psammites and pelites, of the Cape Supergroup (Shone and Booth, 2005). Metamorphism within the Cape Supergroup reaches lowermost greenschist to anchizonal grade (Frimmel et al., 2001; Hansma et al., 2015). Greenschist facies form across a wide range of burial depth (8-50 km). However, considering the continental geothermal collision setting (between 25 and 20℃ km^{-1}; Frimmel et al., 2001), and assuming the density of overlying sediment of 2.6 g cm^{-3}, 12 – 15 km of overburden was estimated to reach 300℃ (Frimmel et al., 2001).

Southern South Africa can be split into two broad tectonic domains defined as thick- and thin-skinned for the southern and northern domain, respectively (Paton et al., 2006). Uitenhage Group sediments accumulated in the hanging-wall of WNW-ESE trending half-graben basins formed by extensional faults during rifting (Paton, 2006). The faults are reactivated thrust faults that originally formed during the Late Palaeozoic/Early Mesozoic orogeny (Paton et al., 2006; Stankiewicez et al., 2007). The reactivated faults originated as long planes rather than individual segments, resulting in uplift across the entire planar surface (Paton, 2006). The Kango and Worcester faults show displacements of 6-10 km (Dingle et al., 1983; Tankard et al., 2009). The onshore basins (e.g., Oudtshoorn, Worcester, Heidelberg, Swellendam; Robertson) have not been assessed in detail (e.g., Söhnge, 1934; De Villiers et al., 1964; Du Preez, 1994; Lock et al., 1975), but contain Mesozoic sediment accumulation of up to 3000 m thickness (e.g., Oudtshoorn Basin).

2.4. Geomorphology

Ancient landscapes (or ‘Gondwanan landscapes’; Fairbridge, 1968) are a record of long-term and large-scale exhumation. The present-day river courses can be used to infer drainage evolution through superimposition and antecedence (e.g., Oberlander, 1985; Summerfield, 1991; Stokes and Mathers, 2003; Stokes et al., 2008; Douglass et al., 2009). Certain landforms, such as deeply incised meanders in resistant lithologies or discordant drainage, are characteristic processes of superimposition or antecedence, as demonstrated in field and laboratory studies (e.g., Harvey and Wells, 1987; Douglass and Schmeeckle, 2007). Superimposition is the process by which ‘a river flowing over a young geological surface erodes the bedrock away and is lowered down onto an older more complex bedrock geology forming a drainage which is transverse to the structure' (Stokes and Mather, 2003, page 61). Examples of superimposed rivers are known from many parts of the world including parts of the Himalayas (Summerfield, 1991); southern Spain (Harvey and Wells, 1987) and parts of the Colorado Plateau, America (Hunt, 1969). This process requires large-scale removal of rock in order to imprint a drainage pattern discordant to the underlying strata, ignoring the tectonic grain (Oberlander, 1985; Summerfield, 1991).

The geomorphology of the Eastern Cape and Northern Cape rivers has been used to interpret ancient major drainage reversals via stream capture events (de Wit et al., 2000; Hattingh, 2008). Major drainage reorganisation has occurred in the Orange River catchment (de Wit et al., 2000) due to continental uplift, as well as denudation onto the underlying structured pre-Karoo topography, which would also have affected catchments towards the south. Linking the landform record to the sedimentary record of the region has been rarely attempted. Drainage reconstructions based on sediments from the Uitenhage Group have argued for a connection between downdip basins, with lows in the surface topography of the CFB acting as sediment corridors (Lock et al., 1975). However, Rigassi and Dixon (1972), argued that the similarity between the onshore Mesozoic basins (Fig. 1) is due to the same type of depositional environment prevailing across southern South Africa. Also, Paton (2006) argued that the downdip basins of the Oudtshoorn area were separated by pre-rift strata. Rogers (1903) invoked a complicated drainage history of the Gouritz catchment whereby the Groot River captured the Buffels and Touws rivers (Fig. 3). Rogers (1903) also incorporated the Uitenhage Group deposits into the reconstruction, and argued that because there are no Uitenhage Group deposits in the transverse river valleys (e.g. Gamka River) they were not active at the time of deposition. The reconstruction of the Gouritz drainage basin by Partridge and Maud (1987) has a planform similar to the present day, with extension of the tributaries to the north as the escarpment retreated. The lower portion of the catchment is also affected by changes in relative sea-level, with the river extending further onto the continental shelf in the mid-Cenozoic. Partridge and Maud (1987) integrated the presence of marine deposits and duricrusts into their reconstructions. Recently, Green et al. (2016) argued based on AFT data that the incision of the Gouritz Catchment into the Swartberg range is a Cenozoic event (30-20 Ma) that was driven by uplift.

Gilchrist et al. (1994) proposed that during Gondwana rifting, two drainage basin types developed in southern South Africa: internally draining catchments (e.g., Kalahari and Karoo rivers) separated by the Great Escarpment from externally draining catchments, which formed as Gondwana rifted. The distance of retreat and formation of the escarpment are contentious. King (1966) argued the escarpment formed at the coastline and has since retreated to its current position. However, chronometric data and numerical modelling have concluded that the escarpment formed near its present-day position, with much of the retreat occurring in the Cretaceous and limited retreat thereafter (e.g., Fleming et al., 1999; van der Beek et al., 2002; Brown et al., 2002; Kounov et al., 2007). Published retreat rates and distances using AFT and cosmogenic data (Table 1), show that the escarpment has retreated a maximum of 29 km to its current-day position (Brown et al., 2002). In contrast, Green et al. (2016) use AFT from 7 samples in the Beaufort West area to argue that the Escarpment is the remnant of Cenozoic denudation (20-30 Ma) (Fig. 3). There is variation in the retreat rate along the Great Escarpment, with higher rates in the Drakensberg range where the escarpment is formed by basalt, and lower rates in Namibia, where the escarpment is formed on quartzites. The Drakensberg area also receives higher rainfall, which could also account for the higher rates (Tinker, 2005). The Gouritz drainage basin has been affected by the retreat of the escarpment (Fig. 3). AFT data shows that large-scale exhumation has occurred in southern South Africa and that a large amount of sediment is missing from onshore Mesozoic basin-fills. Using cored boreholes, Tinker et al. (2008a) conclude that 3.3 - 2.5 km of exhumation took place in the Mid-Late Cretaceous of the eastern Southern Cape, diminishing to 2.5 – 2.0 km in the western Southern Cape and argued that a maximum of 7 km may have been eroded in the Early Cretaceous if erosion of the Karoo volcanics are taken into account. Wildman et al. (2015) argue for up to 6.3 km of exhumation in the Early Cretaceous, with an average of 4.3 km over the study area of the southwestern Cape of South Africa; up to 6.6 km during the Mid to Late Cretaceous (average of 4.5 km) and up to 2.4 km in the Late Cretaceous to Early Cenozoic. Wildman et al. (2016) argued for 1 - 2 km of material removed in the Early Cretaceous in the Western continental margin of southern South Africa, and one sample suggested up to 4 km of exhumation during this time period; up to 4 km in the Late Cretaceous and; up to 1 km in the Cenozoic, decreasing to 0.5 km from 30 Ma. Green et al. (2016) argued for three phases of exhumation and sediment accumulation during the Cretaceous, with a regional cooling event in the Late Cretaceous (85-75 Ma). However, these authors did not attempt to estimate the volumes of material removed and the resulting lithological thickness were not calculated.

The mechanisms of the large-scale exhumation remain contentious (e.g. Doucouré and de Wit, 2003; de Wit, 2007; Paton, 2011), with Tinker et al. (2008a) noting that Early and Late Cretaceous exhumation are related to mantle activity and the formation of large igneous provinces and kimberlites. Wildman et al. (2015) argued for increased regional exhumation in the Early Cretaceous due to the rifting of Gondwana. Furthermore, elevation gain of 2 km (Cox, 1989) associated with plume activity could have provided the energy to drive the change from deposition to erosion (Cox, 1989; Nyblade and Sleep, 2003).

3. Methodology

3.1. Volume of material removed

A grid of nine structural cross-sections (6 N-S and 3 E-W) were constructed across the Western Cape (study area of ~224, 200 km^2) using 1:250 000 geological map sheets (Fig. 4; sheet numbers: 3218 Clanwilliam; 3220 Sutherland; 3222 Beaufort West; 3319 Worcester; 3320 Ladismith; 3322 Oudtshoorn and; 3420 Riversdale). Key lithostratigraphic units were then extrapolated across the sections using maximum and minimum stratigraphic thickness data recorded within the literature (Table 2). The arc method (Busk, 1929) was used, where lithostratigraphic thickness is maintained (Table 2). A 3D model was constructed of the key intervals across the study area (Fig. 4) using Midland Valley's 3DMove software. The volume of material removed was calculated (Fig. 5) by using the difference between a base horizon and the top horizon interpolated from the top of individual cross-sections. The base horizon is a combination of the digital elevation model (DEM) of the present-day topography and the average height of the study area where cross-sections are extended at the coast. To establish **maximum** and **minimum** volumes of material removed a number of assumptions that relate to the original tectono-stratigraphic configuration of the area prior to exhumation are made:

1. The cross-sections were constructed with the Drakensberg volcanics, which currently do not crop out in the Western Cape, as either absent at the time (minimum) or extended into the study area at a similar thickness to their present-day occurrence in the east (maximum). Xenoliths in kimberlites have been used to reconstruct palaeo-geomorphological evolution in central South Africa, and it is argued that ~1500 m of the Drakensberg Group lithologies (mainly Lesotho Formation) were in the Kimberly area at the time of eruption (183 Ma) (Hanson et al., 2009). It is highly likely, therefore, that the Drakensberg volcanics extended across the entire Karoo Basin. Additionally, AFT work by Green et al. (2016) found a high chlorine content in the Uitenhage Group sandstones, indicative of volcanogenic sources, which could have been derived from the denudation of the Drakensberg volcanics.

2. Only lithologies older than Cretaceous are included in the cross-sections, as the main period of exhumation occurred during the Cretaceous (Tinker et al., 2008a). Although the Uitenhage Group deposits are locally thick, they are minor compared to the volume of material removed. For example, the volume of Cretaceous deposits in the Oudtshoorn Basin, assuming a maximum fill of 3000 m (McLachlan and McMillian, 1976), is 6900 km^3. Calculations did not take into account sills and dykes associated with Karoo volcanics (Encarnación et al., 1996) that may have been eroded. This would represent a minor additional volume given the mapped distribution of these features within the drainage basins (Fig. 2).

3. The cross-sections were constructed either with all post-Carboniferous deposits (the Karoo Supergroup) onlapping against the folds of the CFB (minimum) or with all

the eroded lithostratigraphic units conformable and maintaining a constant thickness across the CFB to the present-day coastline (maximum), which assumes that all folding is post-depositional. There is no evidence beyond the present shoreline to constrain the upper lithological bounding surface.

4. Although removal of this sediment would have had an impact on lithospheric loading the isostatic effect is non-trivial to calculate as it will be a function of crustal architecture, nature of the removed sediment, elastic thickness of the lithosphere and thermal regime of the lithosphere and asthenosphere. It is, therefore, beyond the scope of this study to consider the isostacy and we only consider the geometric response.

To minimise uncertainties in volume calculation, multiple scenarios were developed. The extension at the coast scenario extends the onshore geology a maximum of 100 km offshore, limited to the Falklands Agulhas transform fault and it is assumed that the lithostratigraphic groups extended farther at a similar elevation to that at the coast. This is because the variation in coastline extent is not fully constrained, although analysis of the offshore basins suggests that it was broadly similar to the current day coastline (e.g., Paton, 2002; MacDonald et al., 2003; Paton and Underhill, 2004). When the current coastline is used this varies the output by ~30% of the maximum assumption.

3.2. Sedimentary analyses

To assess provenance and sedimentary environments of the Oudtshoorn, De Rust and Worcester Basins, five representative sedimentary logs (cumulative thickness of

67.4m) and 950 clast measurements were collected to record clast lithology, size and roundness, and imbrication.

3.3. Drainage network analyses

River planform can be used to infer the evolutionary history of a catchment and provide important insights into the geological development of the region (Twidale, 2004). Aster 30m DEM from NASA Reverb (2015) for southern South Africa was analysed using ArcGIS. Present-day river patterns and catchment areas were extracted using the hydrological toolbox using a conditional (con) value of 3000 (representative of a contributing drainage area of 3.35 km^2) showing both perennial and ephemeral rivers (Abdelkareem et al., 2012; Ghosh et al., 2015). Evidence of stream capture was identified to constrain drainage evolution (Summerfield, 1991). Sharp changes in channel direction (~90°) indicate capture sites, where the previous river course of a beheaded stream leaves a dry upstream reach and fluvial deposits in an abandoned river valley (wind gaps) (Summerfield, 1991). Stream reversal can be shown by barbed confluences, whereby the tributary joins the main river at an anomalous angle (Haworth and Ollier, 1992). Misfit streams are valleys that have anomalous cross-sectional areas compared to the streams that currently occupy them (Dury, 1960). Misfit streams can form by variation in discharge (Dury, 1960) caused by extrinsic factors such as climate change and tectonic activity, or intrinsic factors such as stream capture (Summerfield, 1991). In alluvial settings, identification of misfit streams uses the degree of meandering and the underlying floodplain deposits (Dury, 1960), however due to the lack of accommodation in bedrock settings this is not possible. To assess stream misfit in bedrock settings the minimum bulk catchment erosion was calculated using ArcGIS, whereby a horizontal ‘cap’ is placed on the catchment to establish the volume of material removed from the catchment area. Catchment area correlates with rate of erosion established from cosmogenic nuclide concentrations (Bellin et al., 2014). Therefore minimum bulk catchment erosion is also expected to correlate with catchment area and provides a measure of stream misfit. If the catchment area is too small or large for the extracted volumes, the catchment may be misfit. Ten catchments from different tectonic and climatic settings from a range of locations (Table 3) were chosen and compared to catchments in the study location. The minimum bulk catchment erosion method represents an underestimate of material removed as the watershed and interfluve areas have also been lowered due to erosion (Brocklehurst and Whipple, 2002; Bellin et al., 2014).

3.4. Cosmogenic nuclide dating

Cosmogenic dating using in situ produced cosmogenic nuclides was used to constrain the exposure ages of surfaces including erosional strath terraces. The highest accessible erosion surface in Gamkaskloof (Fig. 6) was dated using in situ ^{10}Be. The sample was crushed and the 0.25 - 0.5 mm grain fraction extracted and treated using standard lab procedures (Von Blanckenburg et al., 1996, 2004). The ^{10}Be/^{9}Be ratios were measured in BeO targets with accelerator mass spectrometry at ETH Zürich (Kubik and Christl, 2010). The sample was normalised to the ETH in-house secondary standard S2007N, 0.162 g of ^{9}Be carrier was added to the sample, and uncertainties were propagated from AMS counting statistics and the 38% uncertainty on the blank sample. Incision rates were calculated using CRONUS (Balco et al., 2008), which uses the known decay rates of ^{10}Be, and integrates sample information such as elevation, latitude and longitude, shielding and sample density.

The age of the drainage systems in the Western Cape, including the deeply incised gorges, are poorly constrained (e.g., Rogers, 1903; Davis, 1906; Maske, 1957; Green et al., 2016), but can be used to improve understanding of temporal links between drainage basins and sedimentary basins. The sample used in this study was from the highest accessible surface within Gamkaskloof (Fig. 6), which is one of three breaches of the CFB within the Gouritz drainage basin, and marks where the Gamka River transverses the resistant quartzites of the Cape Supergroup (the confluence with the Dwyka River is 9 km upstream). The calculated incision rate was then used to extrapolate the time taken (exposure age) to incise from the highest elevation point of the Swartberg to the present day river. Cosmogenic dating can be used for the last 10^6 years when using ^{10}Be (Darvill, 2013), and southern South Africa has been shown to be in long-term steady state whereby the cosmogenic nuclide results are similar to results from AFT for the Cenozoic (e.g., Bierman and Caffee, 2001; Codilean et al., 2008).

3.5. Scenarios of exhumation: timing and thickness of material removed

To estimate the amount of material eroded from southern South Africa, during different periods of exhumation (e.g., Tinker et al., 2008a,b; Wildman et al., 2015; Wildman et al., 2016), different scenarios, based on AFT data and offshore accumulation rates (Tinker et al., 2008a,b; Wildman et al., 2015; Wildman et al., 2016) were developed with the thickness of sediment removed calculated for the Early Cretaceous; Mid Cretaceous; Late Cretaceous; Late Cretaceous to Early Cenozoic; Early Cenozoic to Mid Cenozoic; and Late Cenozoic were recorded.

These periods were established using the time periods of proposed exhumation using AFT and offshore accumulation; there is some overlap between time periods (Table 4). The relative change in exhumation is the change in thickness of material removed during each time period, using the minimum and maximum exhumation from each scenario. This was then applied to the data extracted using the 3D Move model, with an emphasis on the maximum and median exhumation for the entire study area, and the maximum exhumation constrained to the southern draining catchments. This allows the maximum thickness of material removed for each of the different scenarios, and the relative change in exhumation from the Late Jurassic to Cenozoic, to be constrained.

4. Results

4.1. Amount of exhumation

Table 5 shows the volumes of material removed and the corresponding average lithological thickness, over the study area of the cross-sections of ~224 200km^2 calculated from a range of different scenarios using the uncertainties outlined above (section 3.1). An absolute maximum of 2.52 x 10^6 km^3 of material was removed from the Late Jurassic-Late Cretaceous and modelled timing is discussed below (Section 5.3), which equates to an average of 11.3 km thickness of material removed across the study area. This is reasonable when considering the metamorphic grade of the Cape Supergroup (Frimmel et al., 2001). Using the minimum assumptions, a volume of 8.87 x10^5 km^3, which equates to 4.0 km thickness of material removed in the study area. When constraining this to the southern draining catchments only, the value is reduced to 2.60 x10^5 km^3, which equates to 1.2 km thickness of material removed. This is much lower than expected given the metamorphic grade of the Cape

Supergroup (Frimmel et al., 2001). The median (using the maximum and minimum scenario assumptions) value indicates up to 7.6 km thickness of material removed (equivalent volume of 1.71 x10^6 km^3) when including the Drakensberg Group. Limiting the data to the southerly draining catchments, 2.3 km thickness of material has been removed with the Drakensberg Group present, or 2.1 km thickness (4.66 x10^5 km^3) without the Drakensberg Group. The median value is reasonable when considering AFT data (e.g., Tinker et al., 2008a). The variation in lithological thickness removed is shown in Figure 5, with maximum thicknesses over the CFB and in western South Africa.

4.2. Sedimentology

4.2.1. Sedimentary facies

Sedimentary logs were collected from the Enon Conglomerate (Fig. 7), the oldest unit of the Uitenhage Group in the Oudtshoorn and De Rust basins adjacent to the Kango fault, and in the Worcester basin farther from the boundary fault (the Worcester fault). Facies one (F1) comprises poorly-sorted to rare normally-graded clast-supported conglomerate with coarse sand to gravel grade matrix in 1 - 5 m-thick beds with common erosional bases (Fig. 7). Individual clasts have deeply weathered crusts (Fig. 7). Clast imbrication in the Worcester Basin suggests a dominant southeastward palaeoflow (Fig. 8). Facies two (F2) comprises poorly–sorted lenticular conglomerate beds (up to 3 m) with a coarse sand matrix (Fig. 7). Facies three (F3) comprise structureless to weakly laminated lenticular coarse sand to gravel beds that range in thickness from 0.10 to 1.2 m. Locally, beds contain dispersed clasts (up to 10 cm; Fig. 7). Facies 4 (F4) comprises lenticular mediumand coarse-grained sandstones with pebble stringers (Fig. 7). There is no distinct difference in roundness or clast size between the different conglomeratic facies; however there are differences between basin-fills (Table 6). Clasts sizes from the Oudtshoorn Basin show a wide spread about the a, b and c axes (Table 6). Clasts are dominantly sub-rounded to sub-angular in the Oudtshoorn Basinm and dominantly sub-rounded and rounded in De Rust (Fig. 8). The Worcester Basin clasts are smaller than those in Oudtshoorn or De Rust. There is a larger spread of clast sizes within the Rooikrans study site compared to the Nuy Road study site as shown by the standard deviation values.

4.2.2. Clast provenance

The clasts in the Oudtshoorn and De Rust basins are dominated by quartzites of the Cape Supergroup (Fig. 8). The clasts within the Worcester Basin (Fig. 8) are primarily sandstones, mudstones and diamictite (Karoo Supergroup), but no quartzite clasts are found. No volcanic or dolerite clasts are observed.

4.2.3. Depositional environment

The bi-modal clast data (Fig. 8) at Oudtshoorn suggest deposition in alluvial fans with short transport distances from the source to the basin (Shone, 2006; Hattingh, 2008; Bordy and America, 2016). Additionally, well-rounded quartzites with weathered surfaces, which represent reworked sediment were also observed. The De Rust (Fig. 8) deposit is more rounded than at Oudtshoorn, which suggests greater transport distance from the source area. The Worcester deposit (Fig. 8) is more fluvial in character, as shown by the higher proportion of rounded and imbricated clasts and the dominance of graded and laminated sandstone/gravel beds and erosion surfaces (Rastall, 1911).

4.3. Geomorphological evidence

The Gouritz and Breede catchments are dominated by trunk rivers with courses that are discordant to the underlying tectonic fold structures and extensional faults (Rogers, 1903). The trunk rivers are ancient rivers (Cretaceous in origin and related to 'Gondwana landscapes'; Fairbridge, 1968; Rabassa, 2010), with their courses superimposed onto the underlying strata (Fig. 9), and meanders deeply incised into resistant quartzite of the Cape Supergroup. Furthermore, the rivers have anomalous bends (Fig. 9), with angles of up to 90°, and barbed confluences indicating flow reversal. Three large-scale misfit streams are identified in the Gouritz catchment (Fig. 9, 10). Two of the catchments (Figs. 9a, c) investigated here, have higher minimum bulk catchment eroded volumes than similar sized catchments, and some larger catchments (Table 3; Figs. 1, 10), from the global data set. The one exception is a catchment in Bolivia (Insel et al., 2010), where erosion rates are extremely high due to tectonic activity in the Andes. The catchment at Garcia Pass (Fig. 9, inset a) does not show an anomalous volume, however Rogers (1903) identified a wind gap at this location related to a previous Buffels River course. Our data indicate that the stream capture took place prior to the full exhumation of the Cape and Karoo Supergroups, and capture occurred before the underlying Table Mountain Group was exposed.

4.4. Cosmogenic dating

The strath terrace dated at Gamkaskloof (Swartberg Range), is at a height of 90 m above the current-day river, with incision rates based on cosmogenic nuclides of 1.22 +/- 0.02 $m.Ma^{-1}$ (Fig. 6). Assuming constant rates, incision from the strath height to the current river took ~70 Ma. Extrapolating cosmogenic data back to the start of the Cenozoic provides a crude constraint, but due to the steady state of southern South Africa since the start of the Cenozoic is deemed reasonable. Using the maximum Cretaceous exhumation rates of 175 mMa^{-1} (Tinker et al., 2008a) incision of ~6 km of material removed would have taken 35 Myr. However, Cenozoic rates of incision are lower (e.g., Fleming et al., 1999; Cockburn et al., 2000; Bierman and Caffee, 2001; van der Wateran and Dunai, 2001; Kounov et al., 2007; Codilean et al., 2008; Dirks et al., 2010; Decker et al., 2011; Erlanger et al., 2012; Chadwick et al., 2013; Decker et al., 2013; Scharf et al., 2013; Bierman et al., 2014; Kounov et al., 2015), up to 15 mMa^{-1}, which would have taken 66 Myr to incise the 1 km deep gorges in the Cape Fold Belt.

4.5. Scenarios of exhumation history

Table 7 shows four different scenarios related to the exhumation history of southern South Africa (Tinker et al., 2008a,b; Wildman et al., 2015, 2016). For the Early Cretaceous period, a minimum of 18% of the total exhumation could be represented in this time period (Scenario 1) to a maximum of 47% (Scenario 2); this relates to exhumation of 2.07 km and 5.30 km thickness of material removed for the maximum exhumation respectively (and between 1.39 km and 2.94 km for the median exhumation). During the Mid Cretaceous, 20% (Scenario 1) to 40% (Scenario 3) of the total exhumation is represented, relating to 2.47 and 5.47 km thickness of material removed, respectively for the maximum exhumation (and between 1.66 km and 3.08 km for the median exhumation). Total exhumation percentage increases during the Late Cretaceous, from 17% (Scenario 1) to 50% (Scenario 2), related to 1.95 km and 5.65 km thickness of material removed, respectively for the maximum scenario (and between 1.31 km and 3.13 km for the median exhumation). During the Late Cretaceous - Early Cenozoic, the maximum exhumation decreases, and 14 % (Scenario 3) to 31% (Scenario 1) of the exhumation is represented, relating to 1.66 km and 3.51 km thickness of material removed, respectively to the maximum exhumation (and between 1.12 km and 2.36 for the median exhumation).

Exhumation rates decrease further in the Cenozoic.

Exhumation rates decrease further during the Early to Mid Cenozoic. During this time, exhumation represents 60% (Scenario 4) to 6% (Scenario 3) of the total exhumation, equating to a maximum thickness of 2.50 km and 0.69 km material removed, or a thickness between 1.60 km and 0.8 km for the median exhumation. Scenario 4 indicates that in the Late Cenozoic, exhumation rates decrease further to 11% of the total, representing 1.26 km thickness of material removed (and 0.84 km for the median exhumation). Scenario 4 uses data from the western margin of southern Africa, and will not be used further in this study, but highlights that the exhumation discussed in this paper was of continental scale.

5. Discussion

5.1. Evolution of onshore sedimentary basins

The infill stratigraphy of onshore half-graben sedimentary basins were more than 2 km thick (Green et al., 2016, Fig. 11). The precise timing of different half-graben subsidence, and the number of infill and incision cycles, remains poorly constrained. The clast composition of the remnant fill can be used to place constraints on the different evolutionary histories in relation to exhumation of the Karoo and Cape supergroups, and potential source areas. Karoo Supergroup clasts dominate the Worcester Basin (Fig. 2). This suggests that at the time of deposition, the depth of exhumation of surrounding source areas had not reached the Witteberg Group quartzites, which would have produced larger and more resistant clasts than the Karoo Supergroup (Fig. 8). The present-day distribution of Karoo Supergroup outcrops supports the presence of a drainage basin further north (Fig. 2). Karoo Supergroup rocks are unconformably overlain by the Uitenhage Group conglomerates in the Worcester Basin, which indicates significant exhumation (upper Ecca and Beaufort formations) before accumulation during the formation of the Worcester Basin. The small clast size and clast roundness, and the large proportion of sand, suggests that the sediment was not locally derived, although the conglomerates unconformably overly the Karoo Supergroup indicating significant erosion prior to deposition. The absence of material in the Worcester Basin of local Cape Supergroup provenance could be due to non-exposure of the Cape Supergroup or erosion of the younger basin-fill (Green et al., 2016). No clasts of the Beaufort or Drakensburg groups are found within the conglomerate. This could be a function of shallow burial and weakly lithified material, which was easily broken down to sand grade material (Tinker, 2005; Hanson et al., 2009; Green et al., 2016). However, the absence of dolerite clasts may be used to place a northern limit on the source area (Fig. 2). The Oudtshoorn and De Rust basin clasts are primarily Table

Mountain Group quartzites, which crop out at the basin margins (Fig. 2), and indicate deeper exhumation at this location at the time of basin formation and filling compared to the Worcester Basin.

5.2. Drainage basin reconstruction

The rivers in southern South Africa have undergone significant re-organisation since the break-up of Gondwana (Partridge and Maud, 1987; De Wit et al., 2000; Goudie, 2005), and this is the case for the Gouritz catchment. As Gondwana started to rift, reactivation of thrust faults as long extensional faults (Paton et al., 2006) led to the development of half-graben basins with sedimentation and the initiation of net southward draining river systems on the rift margin (Gilchrist et al., 1994). The small coastal draining rivers would have eroded headward, due to the reduction of base level at the newly formed coastline capturing internal draining catchments (Gilchrist et al., 1994) that eroded the youngest unlithified shallowly buried deposits. Prior to deep exhumation of the Karoo Basin and the Cape Fold Belt, the large southerly drainage systems have already been in place as shown by their superimposed planform into resistant quartzites (Rogers, 1903), bedrock meanders with high gradients in the trunk rivers (Richardson et al., 2016), and the deeply incised confluence of the Olifants and Gouritz rivers. Furthermore, the large trunk rivers do not follow the tectonic grain of southern South Africa or follow geological lines of weakness (Richardson et al., 2016), which supports superimposition. Additional support for the ancient origin of the trunk rivers comes from estimates using cosmogenic dating of terraces in Gamkaskloof, in which the rivers had incised to 90 m above the present-day river by the end of the Cretaceous. Superimposition, supported by AFT analysis (e.g., Tinker et al., 2008a), requires a vertical component of incision (Maw, 1866; Gilbert, 1877; Rogers, 1903; Partridge et al., 2010), and is unlikely to have been formed solely by headward erosion from the coast (e.g., Gilchrist et al., 1994). The data in Section 4.4 are plausible especially when considering the missing Cape and Karoo sequence above the strath terrace is not included in the age estimate, further a sample located at the top of the CFB showed Cretaceous exhumation (Green et al., 2016). However, alternatively, it has been argued that the trunk rivers, such as the Gamka River, could have formed more recently (30 - 20 Ma) (Green et al., 2016), with ~1 km incision into the resistant Cape Supergroup (Swartberg Range). However, this rapid incision is not supported by the majority of published AFT and cosmogenic studies that show low denudation rates since the Cretaceous (e.g., Tinker et al., 2008a,b; Scharf et al., 2013; Kounov et al., 2015), or the timing of offshore sedimentation.

In the Late Jurassic – Early Cretaceous, the rivers meandered (as shown by the superimposed planform, Fig. 11) and incised into shallowly buried volcanic (westward equivalent of Drakensburg Group) and fluvial deposits of the upper Beaufort Group. During incision, and net southward drainage, the rivers encountered increasingly deeply buried and more resistant rocks (Tinker et al., 2008a). The precise relationship between incision, local uplift and subsidence patterns during fault reactivation, is largely speculative. Nonetheless, the superimposed river systems, the deposition of the Enon conglomerate, the published apatite fission track studies (Brown et al., 1990; Brown et al., 2002; Tinker et al., 2008a), and the offshore basin stratigraphy (Dingle, 1973; Brown, 1995; McMillan et al., 1997; Paton and Underhill, 2004; Tinker et al., 2008b; Sonibare et al., 2015) all indicate large volumes of material eroded and transported offshore in the Early and Late Cretaceous (Section 5.3). Exhumation was by efficient and well-established fluvial networks that were established by the Early Cretaceous (Tables 4 and 7) following the break-up of Gondwana (Fig. 11).

The deposition of the Mesozoic conglomerate in onshore half-graben basins was coeval with the exhumation and incision of the Cape Supergroup in the Outdshoorn Basin. In the case of the western Oudtshoorn Basin, this suggests that transverse and axial drainage systems, and large-scale erosion of the bedrock and sediment accumulation, was penecontemporaneous but <1 km apart. Coeval axial and transverse drainages are well documented in tectonically-active settings, with relief increasing due to tectonic activity related to the early stage of mountain growth and are features of many mountain ranges of the world (e.g., Davis, 1889; Oberlander, 1985; Hovius, 1996; Ramsey et al., 2008; Babault et al., 2012; Grosjean et al., 2015). The interplay between axial and transverse rivers is not well-documented using deposits alone (Szwarc et al., 2015). Many facies models related to basins in continental rift settings emphasise a major component of axial deposition with minor footwall-draining transverse systems (e.g., Leeder and Gawthorpe, 1987; Schlische, 1992). These models do not account for large cross-cutting transverse river systems (e.g., Gawthorpe and Leeder, 2000) that can be an important component of rift settings after headward erosion of transverse rivers and integration of the entire drainage net (axial and transverse systems) (e.g. Gilchrist et al., 1994). In the case of the Gouritz catchment, there was large-scale net deposition within the axial river system and net erosion within the large transverse river system during the Cretaceous due to the position of drainage networks with respect to areas of uplift (erosion) and subsidence (deposition). We speculate that the integration of the drainage net occurred rapidly at this location. The lack of deposits in the transverse rivers is due to the low preservation potential within bedrock channels due to high stream power and the net erosional setting (Hancock et al., 1998). This leads to efficient bypass of sediment to the offshore basins and does not necessarily indicate that the transverse systems were inactive during the deposition of the Uitenhage Group as postulated by Rogers (1903) and Green et al., (2016).

During the Early Cretaceous, there were drainage divides within the Olifants River due to pre-rift strata (Paton, 2006). Stream captures and a large-scale misfit stream indicate that part of the river system drained through the Oudtshoorn Basin to the confluence with the Gamka River, and another part drained eastward and discharged into the Indian Ocean at Jeffreys Bay (Figs. 9, 10). Drainage divides were located in the Touws River area, with westward stream flow to the Worcester Basin (Breede River), and partly to the east into the Buffels River, as supported by the provenance of the Mesozoic conglomerates in the Worcester Basin (Fig. 8). The Buffels River drained south, and influenced the onshore Heidelberg Basin as a conduit for sediment, as shown by the wind gap at Garcia Pass (Rogers, 1903).

Apatite fission track work by Green et al. (2016) concluded that at least 1.5 km of deposits overlay the remnant Enon conglomerate outcrops in the Oudtshoorn Basin in the Late Cretaceous (Fig. 11). The Enon conglomerate and the overlying deposits could represent one phase of net deposition. However, Green et al. (2016) speculate the material could be detritus from the Cango Inlier (north of the Oudtshoorn Basin) or be related to post-Drakensberg volcanism as the apatites from the Uitenhage

Group show high chlorine content, which is related to a volcanic source. The deposition of this material may have diverted the Olifants River within the floodplain, or formed epigenetic gorges (e.g. Ouimet et al., 2008). However, exhumation of the Cape Supergroup, and the CFB as a geomorphic feature towards the south, would have limited the space into which the river could have migrated. The Gamka River was powerful and able to incise the resistant Cape Supergroup and most likely continued as a conduit for sediment bypass during this period of sedimentation in the Outdshoorn Basin. Green et al. (2016) suggests episodic block uplift which would not have changed the overall regional gradient of the Western Cape and the rivers would still drain southward. A record of episodic uplift is no longer evident in the current river morphometric indices (Richardson et al., 2016). At the time of block uplift, however, propagating knickpoints will have formed during river adjustment to new regional base levels (e.g., Seidl et al., 1994, 1997; Wohl et al., 1994; Weissel and Seidl 1998; Stock and Montgomery, 1999), with faster response times to larger tectonic perturbations (Whittaker and Boulton, 2012). In addition, due to the high erosive power of the rivers during this time and the presence of transverse drainage systems, it is likely the rivers managed to keep pace with uplift rather than be deflected by it (e.g., Stokes et al., 2008; Douglass et al., 2009). This is due to the large catchment areas of the transverse trunk rivers, resulting in high stream power and knickpoint development (e.g., Burbank et al., 1996; Bishop et al., 2005). During uplift, large trunk rivers will try to maintain their gradients, which can result in aggradation upstream of the uplift (Burbank et al., 1996). If aggradation keeps pace with, or exceeds, uplift then the river will remain discordant to the structure due to the maintenance of the long profile gradient and resulting impacts on stream power (Burbank et al., 1996, Humphrey and Konrad, 2000). There is no evidence of upstream aggradation remaining within the catchment, due to the large-scale denudation of southern South Africa (Tinker et al., 2008a; Green et al., 2016). If uplift exceeds aggradation then the transverse rivers must erode the block. In this case, the resistance of the block becomes a dominant control on the development of discordant rivers (Burbank et al., 1996). The trunk rivers were capable of incising deeply into quartzite, which indicates the rivers were powerful and likely to have eroded more easily the younger less resistant stratigraphy above the Table Mountain Group (Fig. 2). The morphometric indices of the Gouritz catchment indicate that the smaller stream order catchments are structurally-controlled within the CFB with trellised stream patterns, whereas the trunk rivers simply dissect the fold belt, with straight long profiles sections seen within the CFB region (Richardson et al., 2016).

The Groot River is interpreted to have captured the Buffels and Touws rivers, as indicated by the right-angled confluence (Fig. 9) (Rogers, 1903). Stream captures may have also occurred within the Olifants River, most likely resulting in a large-scale misfit stream towards the east (Fig. 9). The climate of the Western Cape Province has not changed significantly since the Cretaceous (Bakker and Mercer, 1986) and the area is now relatively stable tectonically compared to the Cretaceous as shown by the lack of scarps and reduction in sediment production (e.g., Tinker et al., 2008b; Bierman et al., 2014). Therefore, stream capture is the preferred mechanism to explain the misfit streams. Further development towards the north of the Gouritz catchment due to the retreat of the escarpment extended the catchment and caused capture of the Orange River catchment area. Stream capture of the Hex River by the Touws River (Gouritz catchment) has reduced the size of the Breede catchment since the Cretaceous.

5.3. Implications for timing of exhumation and volumes of material transported offshore

Many researchers argue on the basis of AFT that large-scale exhumation had finished by the end of the Cretaceous (Gilchrist et al., 1994; Gallagher and Brown, 1999; Cockburn et al., 2000; Brown et al., 2002; Tinker et al., 2008a; Kounov et al., 2009; Flowers and Schoene, 2010), with minor changes to the present-day physiography (Partridge, 1998; Brown et al., 2000; Brown et al., 2002; Doucouré and de Wit 2003; de Wit 2007; Tinker et al., 2008a; Kounov et al., 2015). Additional evidence is shown by a reduction in offshore sediment volumes (Tinker et al., 2008b; Paton et al., 2008; Hirsch et al., 2010; Dalton et al., 2015; Sonibare et al., 2015), low Cenozoic cosmogenic erosion rates (e.g., Fleming et al., 1999; Cockburn et al., 2000; Bierman and Caffee, 2001; van der Wateran and Dunai, 2001; Kounov et al., 2007; Codilean et al., 2008; Dirks et al., 2010; Decker et al., 2011; Erlanger et al., 2012; Chadwick et al., 2013; Decker et al., 2013; Scharf et al., 2013; Bierman et al., 2014; Kounov et al., 2015) and differential erosion of kimberlite pipes (Hawthorne, 1975; Gilchrist et al., 1994; de Wit, 1999). Locally, offshore sedimentation in the Cenozoic is significant, but is minor compared to Mesozoic deposition (e.g., Tinker et al., 2008b; Hirsch et al., 2010; Dalton et al., 2015; Sonibare et al., 2015). Further, modelling by Gilchrist et al. (1994) argued that much of the denudation, and establishment of the drainage net of southern South Africa, occurred before the Cenozoic.

A range of scenarios were assessed using maximum and median exhumation. The data shown in Table 7, for the Early Cretaceous, is based on a limited number of samples, but does indicate a significant amount of exhumation in this period (up to 47%, Scenario 2), which is argued to be regional by Wildman et al. (2015). Up to 40% of the exhumation is accounted for in the Mid Cretaceous (Scenario 3), which increased to 50% (Scenario 2) in the Late Cretaceous. All scenarios show a decrease in exhumation during the Late Cretaceous to Early Cenozoic with up to 31% of exhumation represented (Scenario 1). This decreased further in the Early to Mid Cenozoic, when up to 20% of exhumation is represented (Scenario 2). As stated above, the majority of researchers have argued for periods of increased exhumation in the Early Cretaceous and Mid-Late Cretaceous, with limited exhumation in the Cenozoic. The majority of studies present clusters of data around the Mid-Late Cretaceous (e.g., Flowers and Schoene, 2010) and a few boreholes show Early Cretaceous cooling, particularly south of the escarpment (e.g., Tinker et al., 2008a). This is because there has been greater exhumation south of the escarpment, and the Early Cretaceous signature has been removed due to erosion and sediment bypass (e.g., Tinker et al., 2008a and Wildman et al., 2016) and explains the lack of boreholes with Early Cretaceous exhumation.

Despite the evidence above, such a scenario has been disputed by Burke (1996) and Green et al. (2016) who argue for a younger age of landscape development. Burke (1996) argued the topography and Great Escarpment was formed due to uplift around 30 Ma ago, and related to the establishment of the African superswell under the African lithosphere. Robert and White (2010), Roberts et al. (2012), and Rudge et al. (2015) have also argued for a Cenozoic age of the landscape with Cenozoic uplift and development of rivers within southern South Africa. However, their simple 1D inversion models do not preclude Late Mesozoic development of the discordant trunk rivers, and may represent a second phase of landscape development. Green et al. (2016) argued for younger active landscape development based on AFT data, and argued that the deep bedrock gorges within the CFB were formed during the Cenozoic, when there was differential denudation with higher erosion within the Swartberg Mountain range (CFB) as shown by Cenozoic cooling (30-20 Ma). However, Green et al. (2016) did not collect samples near the large cross-cutting transverse rivers of the Gouritz catchment (e.g., Gouritz River), and were from smaller subcatchments that dissect the CFB (with current catchment areas of 179 km^2 and 1060 km^2). The samples showing Cenozoic cooling were taken at the base of the Swartberg Mountain, near the current river bed, and do not indicate that the large trunk rivers were not already active, and eroding the ~1 km of material above the sample. Green et al.'s (2016) research indicates that there was additional uplift around 30-20 Ma ago, during which downcutting would have continues in gorges existing at the time. The CFB is an exhumed mountain belt that formed during the Permo-Triassic (Tankard et al., 2009). The uplift implied from the AFT data represents the latest stage of landscape development to affect the region after denudation leading to exhumation of the mountain chain. Therefore, successively younger fission track ages towards the base of a mountain are to be expected as exhumation continues. Based on the above considerations, it is therefore argued that by the end of the Cretaceous the current watershed of the Gouritz catchment was mostly in place with the main trunk rivers active and depositing material offshore southern South Africa (Fig. 11).

5.4 *Where is the 'missing' sediment?*

Using the maximum exhumation values, ~ 11 km of exhumation has occurred across southern South Africa, with significant exhumation in the Early and Late Cretaceous, and the largest amount of exhumation over the CFB (Fig. 11). This is reasonable when considering the metamorphic grade of the Cape Supergroup (Frimmel et al., 2001). AFT studies also show large-scale denudation in the Mid-Late Cretaceous (~ 7 km, Tinker et al., 2008a). The discrepancy between the higher rates of exhumation stated here is considered to be due to the removal of an Early Cretaceous signature in many boreholes dated using AFT (e.g., Tinker et al., 2008a). Given this, and the offshore accumulations (e.g., Tinker et al., 2008b), it is highly likely that the additional 4km of exhumation occurred in the Early Cretaceous.

The maximum estimated volume of 7.81 x 10^5 km^3 material eroded from the southern drainage basins is larger than the volume of major long-lived submarine fan systems, such as the Amazon Fan, and if point-sourced would result in a fan up to 400 km long (e.g. Sømme et al., 2009) and kilometres thick. However, there is a major mismatch between the estimated onshore erosion and offshore accumulation of sediment. In the Outeniqua Basin and southern Outeniqua Basin, there is 268 500 km^3 of material (Tinker et al., 2008b). Therefore, ~5.13x 10^5 km^3 (maximum) to ~2.53 x 10^5 km^3 (median) of sediment is unaccounted for (Table 5). If the southward draining catchments were active at least in the Early Cretaceous, the missing volume could have been transported deeper offshore via sediment gravity flows and hemipelagic processes (Tinker et al., 2008b).

During rifting, and the deposition of the Uitenhage Group, the Falkland Plateau was located offshore southern South Africa (Macdonald et al., 2003, Fig. 12). Adie (1952) first stated that the Falkland Plateau was in a rotated position east of South Africa, and formed part of the missing SE corner of the Karoo Basin. The amount and timing of Falkland Plateau rotation remains contentious (e.g., Richards et al., 1996; Macdonald et al., 2003; Stone et al., 2009; Richards et al., 2013) and is beyond the scope of this work. However, as the Falkland Plateau moved westward along the south side of the Falkland-Agulhus transform fault in the Late Jurassic to Early Cretaceous, the Falkland Plateau Basin developed (Macdonald et al., 2003; Fig. 12). The Falkland Plateau Basin formed the distal extension of the Pletmos and Bredasdorp basins in the early Aptian (Martin and Hartnady, 1986; Fouché et al., 1992; Ben-Avraham et al., 1993, 1997; Macdonald et al., 2003) or Albian (Ludwig, 1983). A second phase of rifting occurred in the Early Cretaceous resulting in the North Falkland Basin, and the drifting apart of the plateau and the African continental plate (Richards et al., 1996; Fish, 2005; Fig. 12). Ludwig (1983) argued that the large change in depositional environment on the Maurice Bank from black shales to oxygenated nannofossil claystone is due to the plateau moving past the tip of Africa.

Taking an average of the scenarios presented in Table 7, during the break-up and rotation of the Falkland Plateau in the Early and Mid Cretaceous, when the plateau passed the tip of South Africa, a maximum of ~50% and minimum of ~20% (using the Scenarios in Table 7) of the exhumed material could have reached the plateau area (Fig. 12). This represents an average lithological thickness of 5.70 – 2.28 km for the maximum exhumation, and 1.75 – 0.7 km when constrained to the southern draining systems, and between 3.8 – 1.52 km for the median exhumation and 1.15 -

0.46 km when constrained to the southern draining systems in the median scenario. Although drainage divides evolve over time, and all the scenarios show rates increased in the Late Cretaceous, a significant volume of sediment was available to be transported offshore and accreted to the Falkland Plateau (Fig. 12; 13).

Recent research on the Sea Lion Main Complex (SLMC) discovery in the North Falkland Basin has identified an Early Cretaceous fluvial prodeltaic and turbidite succession in a lacustrine syn-rift sequence (Farrimond et al., 2015; Griffiths, 2015). The basin has large amounts of sand deposits (Bunt, 2015; Williams, 2015) and comprise multiple basin-floor fans that offlap into a deep lake basin (Griffiths, 2015). U^{238}/Pb^{206} zircon ages suggest that the SLMC accumulated over <250 ka during the early Aptian. If the Falkland Plateau was offshore southern South Africa with erosion from the continent, and transverse and axial sediment routeing then this configuration could account for the large and rapid accumulations of sand in the syn-rift lake basins (Fig. 12). The SL 10 and 20 fans are ~87 m thick and extend over areas of 115 km^2 (Bunt, 2015). Extra-basinal material is predominantly coarse material of volcanic and metamorphic origin, with rivers draining the sub-aerial basement to the east (Williams, 2015). Williams (2015) states the Sea Lion Main Complex sands are derived largely from a co-existing shallow water system, which we postulate were supplied by the southerly draining river systems of southern South Africa (Fig. 12). Several authors have commented on the similarity between the stratigraphy of the Falkland Plateau Basin and the offshore Mesozoic basins of southern South Africa (Martin et al., 1981; McMillian et al., 1997). Martin et al. (1981) also argued that between the Late Jurassic and Early Cretaceous, during the rift to drift period, the Bredasdorp, Pletmos Gamtoos, and Algoa basins were the proximal tongues of the large Falkland Plateau Basin (Macdonald et al., 2003). In summary, we posit that the implication of this configuration is that a large proportion of the 'missing' sediment eroded during the Late Jurassic and Early Cretaceous is represented by deposits in rift basins of the North Falkland Basin and the Falkland Plateau Basin. Further support comes from global sediment thickness maps (Divins, 2003, Whittaker et al., 2013; Fig. 13). The Falkland Plateau is distinctive due to the thickness of sediment cover and lack of adjacent significant landmass, in contrast to southern South Africa (Fig. 13). This configuration means that the sedimentary basins are dislocated by ~6000 km from their drainage basins. This highlights the challenges of constraining and quantifying source-to-sink relationships in deep-time and close to active plate boundaries (Romans et al., 2009; Romans and Graham, 2013).

6. Conclusions

A mismatch in the volumes of material eroded onshore and the volume of sediment deposited in offshore basins in the Mesozoic has been calculated. Large-scale exhumation (up to 11 km, since the Late Jurassic), initiated by rifting, resulted in the deposition of the Uitenhage Group in extensional basins, the only onshore representation of major landscape denudation. Integrating sedimentology, geomorphology and cosmogenic dating, evolutionary histories of two large-scale discordant basins in the Western Cape have been deciphered for the first time. The catchments had a complicated history and underwent multiple reorganisations due to stream capture in the Cretaceous. However, the main transverse trunk rivers of the catchments are long-lived features (up to 145 million years), resulting in extensive offshore sediment deposition. By reconstructing sediment routeing patterns and developing a range of exhumation scenarios tied to published AFT data, we interpret that the location for much of the 'missing' sediment is on the Falkland Plateau Basin, deposited during the Early Cretaceous when up to 50% of the sediment was available to be transported offshore. This represents a sediment sink has been has been separated from its source by 6000 km. In order to verify this, further work is needed to petrographically analyse the deposits on the Falkland Plateau. In addition, cosmogenic dating on drainage routeing patterns will better constrain the onshore patterns of drainage evolution.

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Figures

Figure 1 – Location map of study sites and Mesozoic basins of southern South Africa, adapted from McMillan et al. (1997). The current day planforms of the Breede and Gouritz catchments are shown.

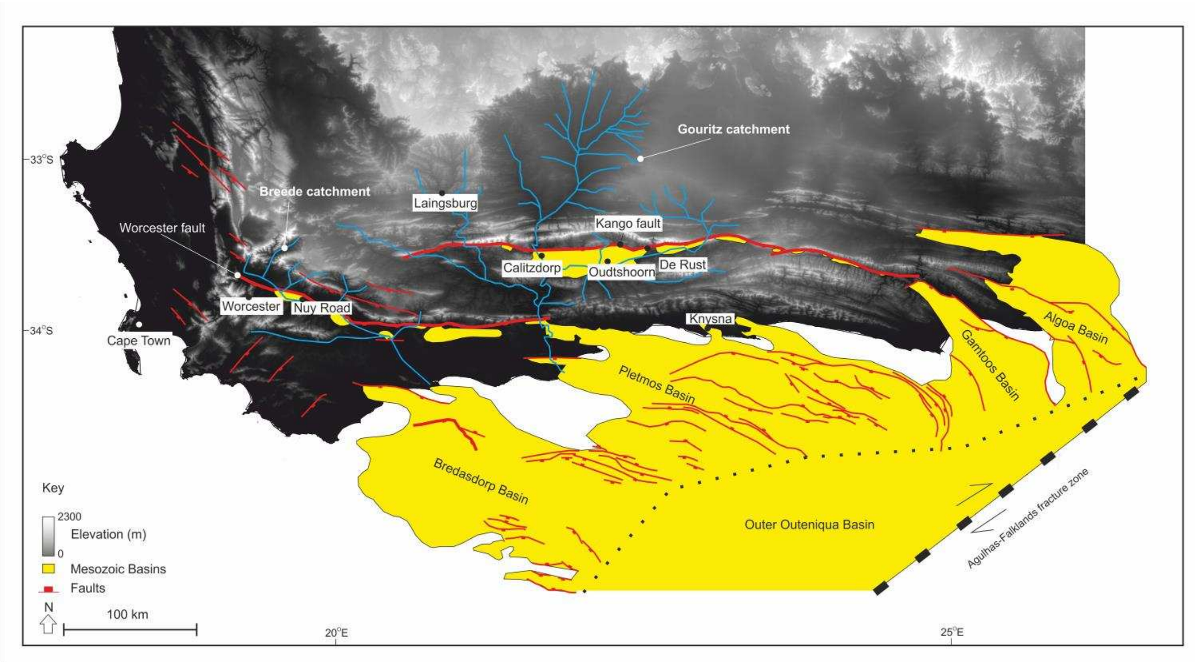

Figure 2 – Geological map of southern South Africa showing key stratigraphic units used in the cross section construction. The current day distribution of the Drakensberg volcanics are towards the north. The cross sectional locations A-J are also displayed.

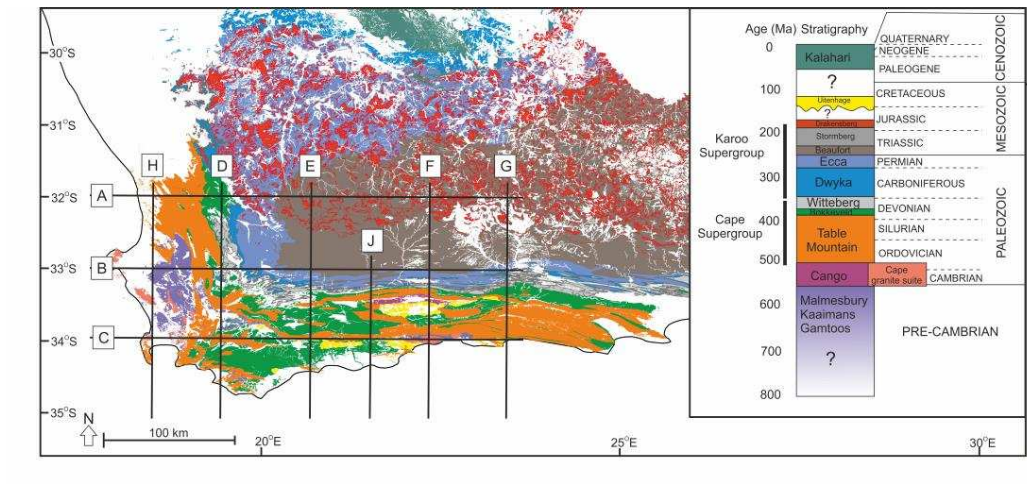

Figure 3 – The Gouritz River current catchment planform and trunk river location; the main trunk river transect the Cape Fold Belt, and do not exploit structural weaknesses. Many of the headwater streams within the catchment dissect the Great Escarpment, further stream capture in this location will increase the drainage area of the Gouritz catchment and reduce the catchment area of the Orange River. The sample location of the cosmogenic sample can be observed, which is also shown on Fig. 6.

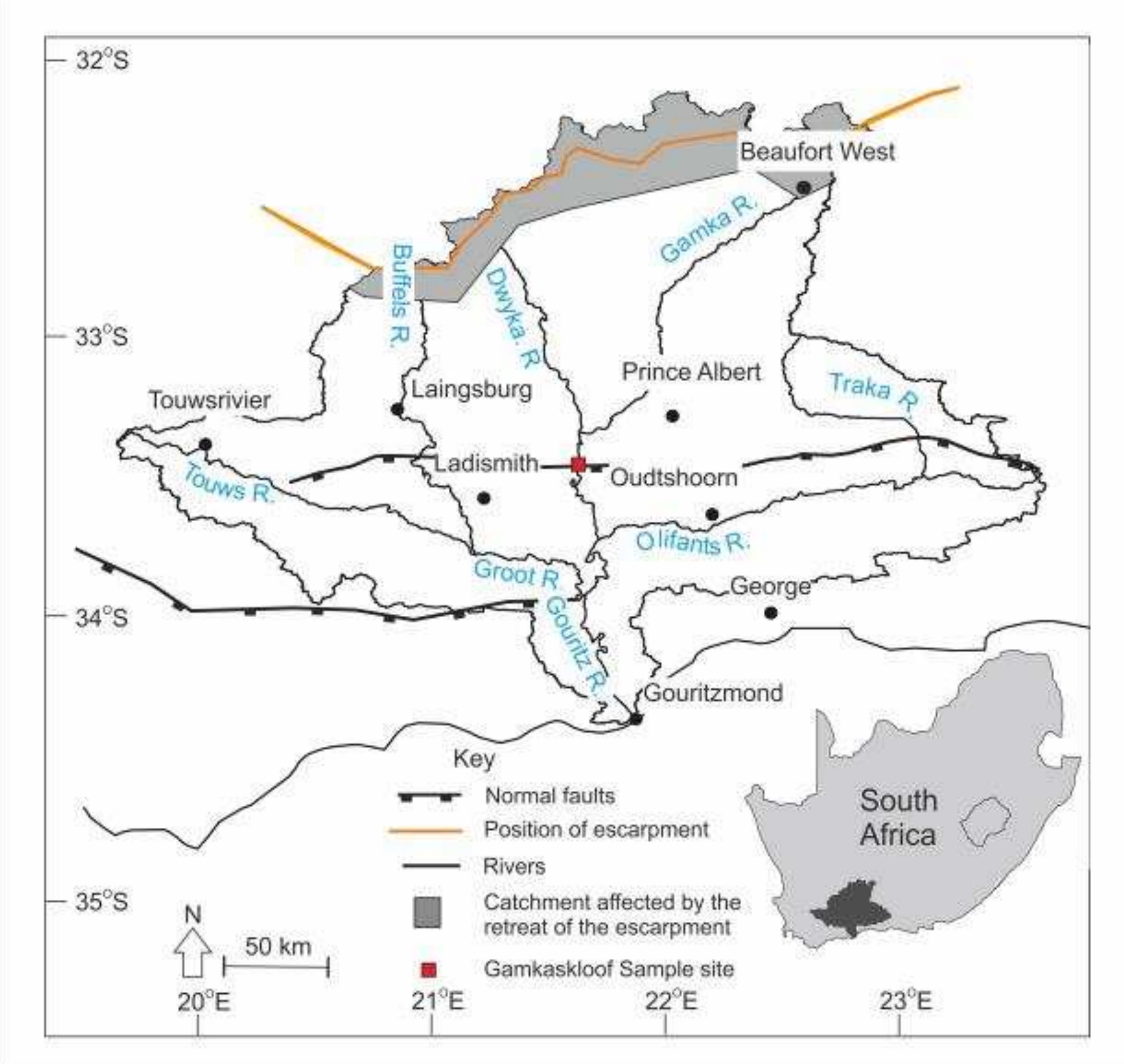

Figure 4 – 3D Move scenarios and example cross sections. Inset 1) a key showing the lines used to represent present day topography and scenarios of exhumation; 2) a location map of the 9 cross sections used in 3D Move to calculate exhumation volumes; 3), 4) and 5) show cross sections C, F and E, respectively, which show the maximum assumptions (with and without Drakensberg Group), median assumptions (with and without Drakensberg Group) and minimum assumptions and; 6) shows geological cross section F using the maximum assumptions where the top surface represents the maximum lithological extent prior to erosion. The key for the lithology can be found on Figure 2. Additional cross sections can be found in the online supplementary data.

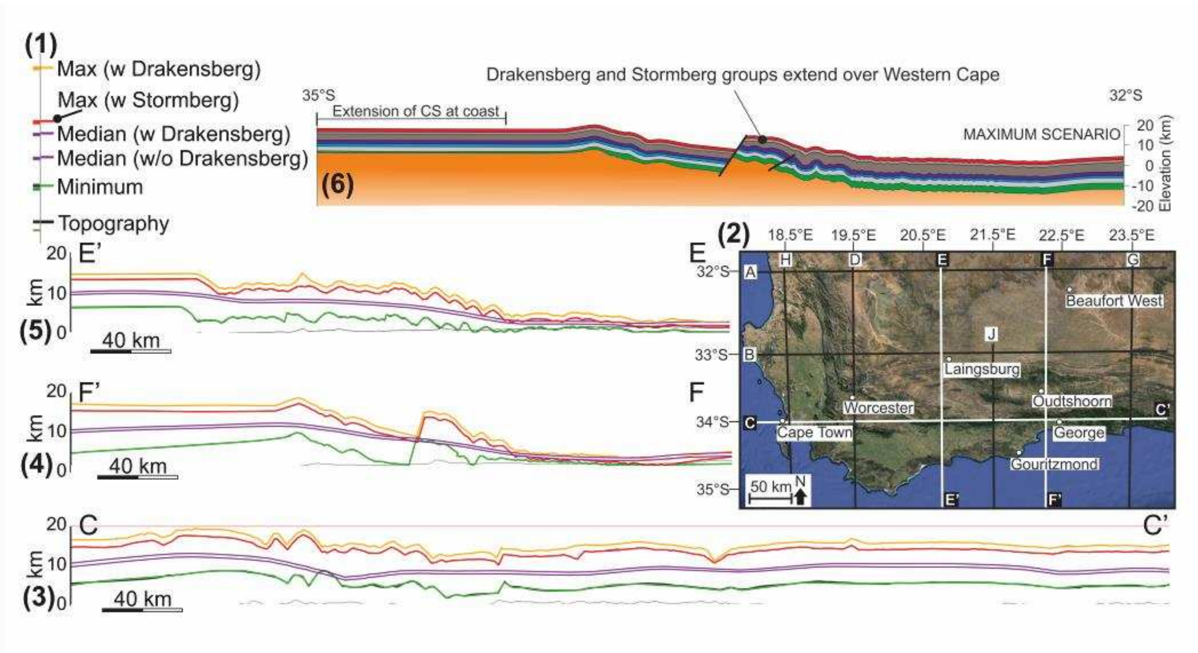

Figure 5 – Variation in the amount of sediment removed in southern South Africa. A) Maximum scenario with Drakensberg lithologies present, B) maximum scenario without Drakensberg lithologies present C) median scenario and D) minimum scenario.

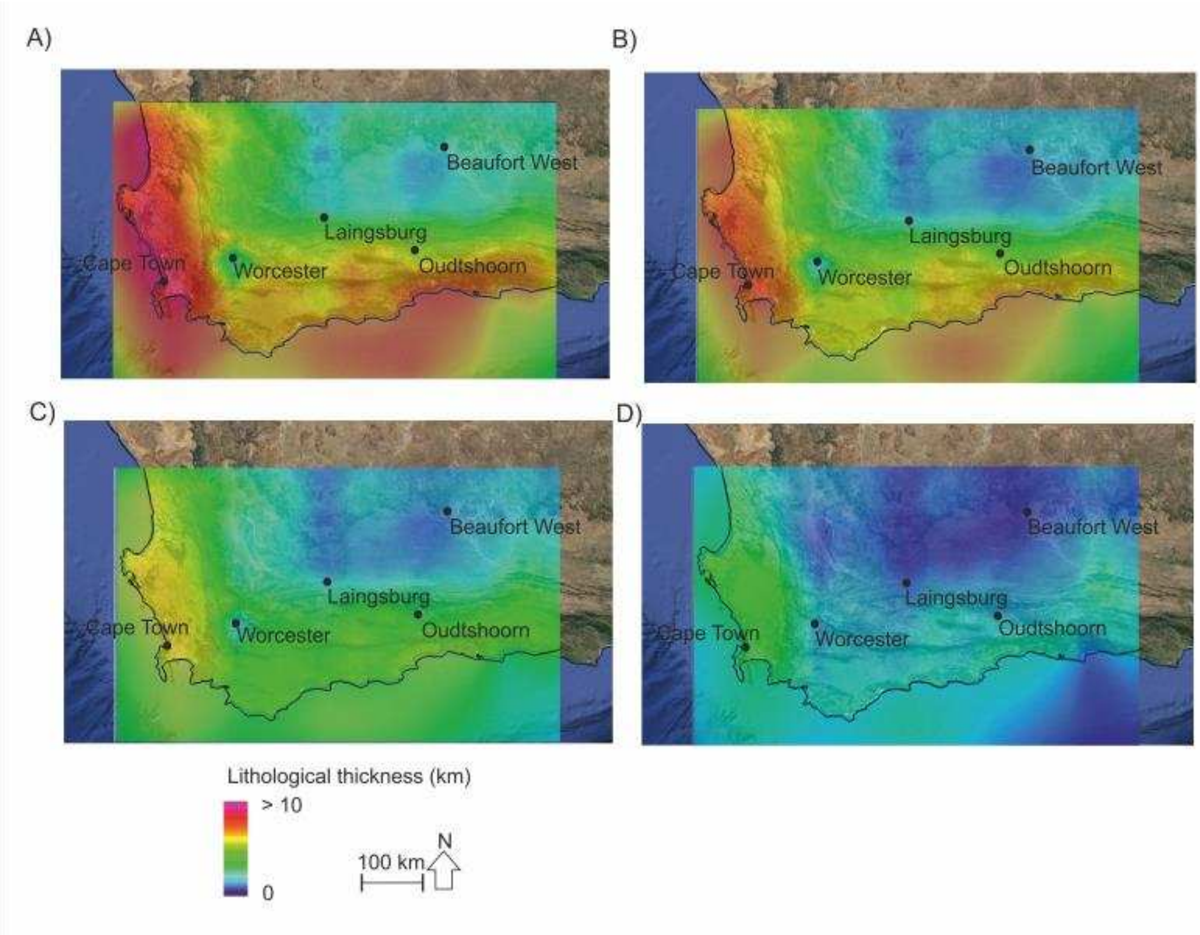

Figure 6 – Gamkaskloof erosion surfaces and sampling point for cosmogenic dating. The transverse Gamka River dissects the Cape Fold Belt. The red dashed line represents the erosion surface sampled.

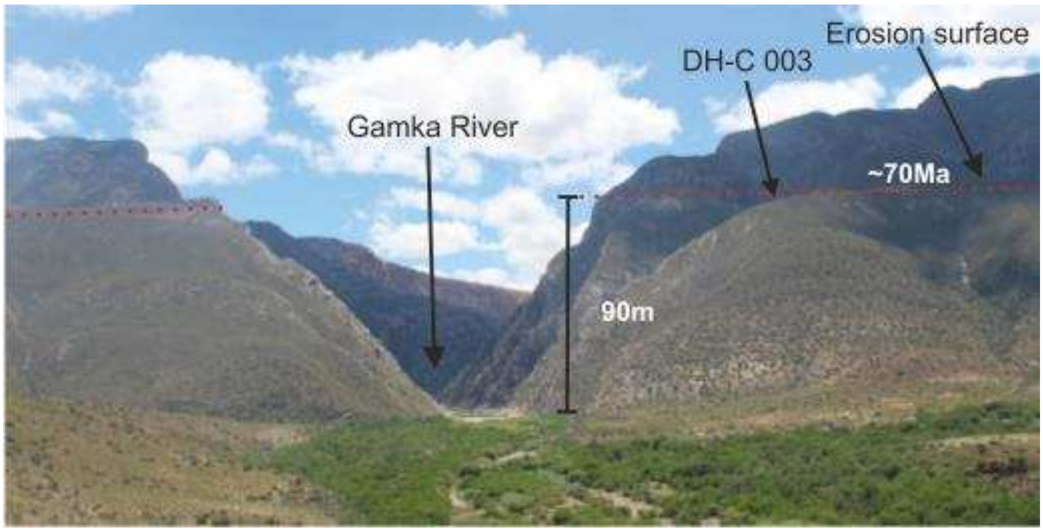

Figure 7 – Facies descriptions and sedimentary logs from the Mesozoic basins; A) sedimentary logs from the Mesozoic Basins within the study area and; B) facies observed within the Mesozoic Basin. Inset Bi) comprises poorly-sorted to rare normally-graded clast-supported conglomerate with coarse sand to gravel grade; Bii) comprises poorly–sorted lenticular conglomerate beds (up to 3 m) with a coarse sand matrix; Biii) structureless to weakly laminated lenticular coarse sand to gravel beds; and Biv) lenticular medium- and coarse-grained sandstones with pebble stringers (delineated by the dashed white line).

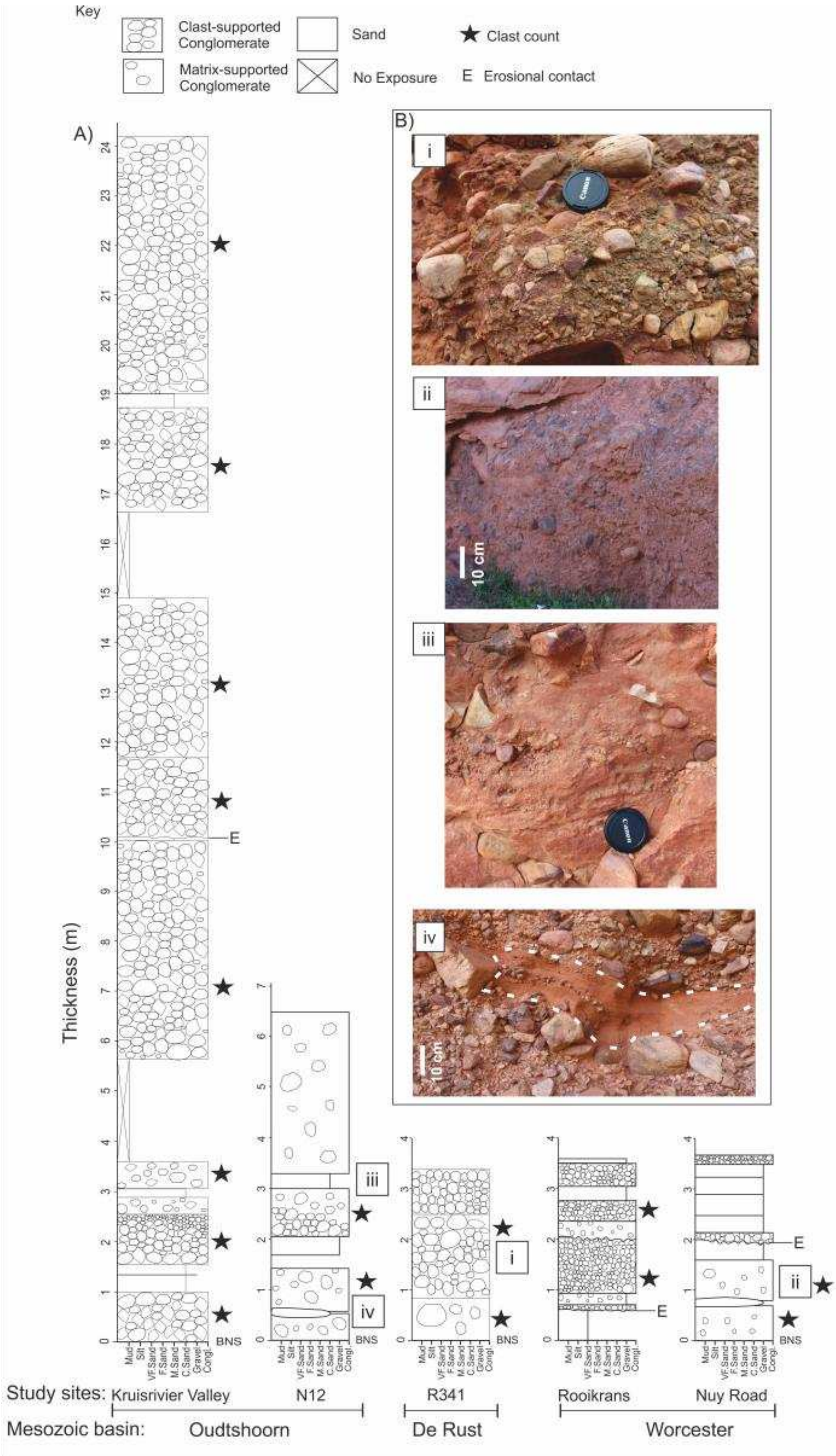
Key
Clast-supported Conglomerate
Matrix-supported Conglomerate
Sand
No Exposure
Clast count
E Erosional contact
A)
Thickness (m)
B)
i
ii
iii
iv
10 cm
10 cm
E
BNS
Mud
Silt
VF Sand
F Sand
M Sand
C Sand
Gravel
Congl.
Study sites: Kruisrivier Valley
N12
R341
Rooikrans
Nuy Road
Mesozoic basin:
Oudtshoorn
De Rust
Worcester

Figure 8 - Clast characteristics: A) clast lithology; B) clast roundness; and C) stereoplot from Rooikrans study site, with poles to strike and dip of clast imbrication indicating SE palaeoflow.

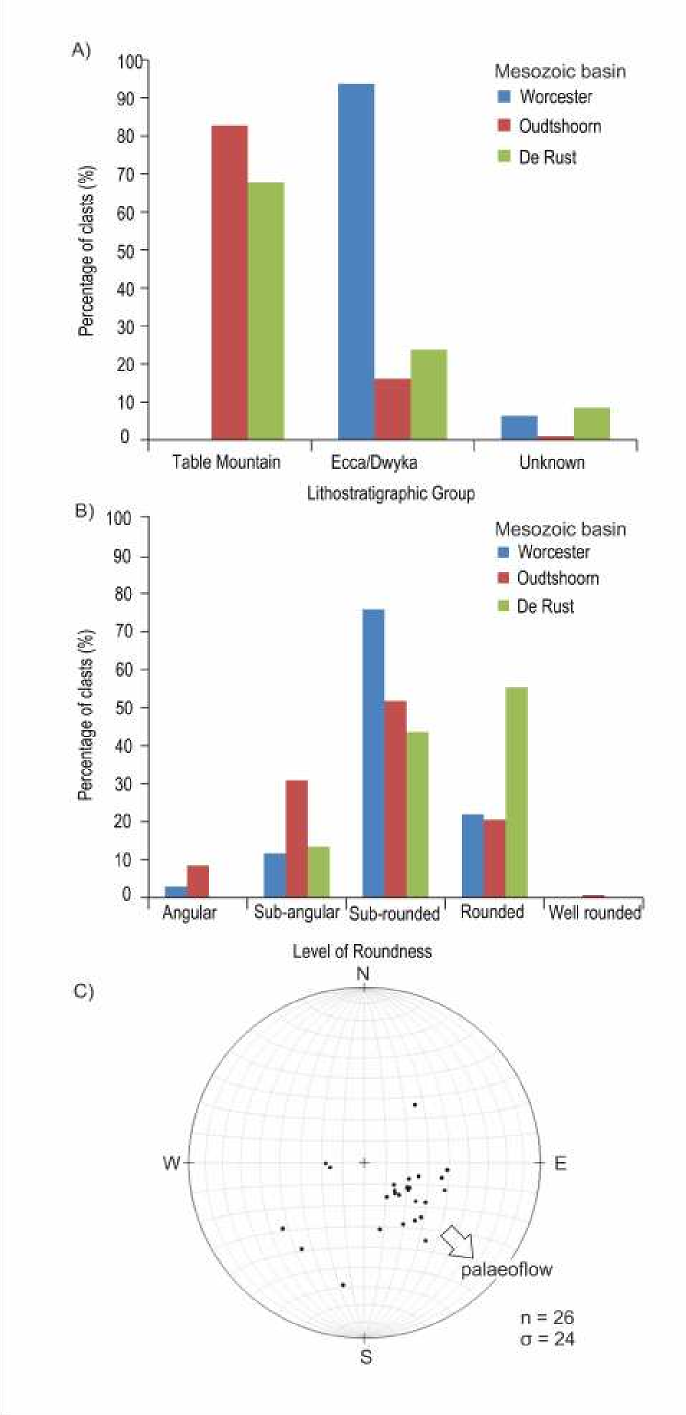

Figure 9 – Geomorphic evidence of drainage reorganisation. Main map shows the location of inset images. (1), (2) and (3) are satellite images showing stream capture points; (A), (B) and (C) are DEMs showing misfit streams; and (i) is a greyscale DEM showing barbed confluences.

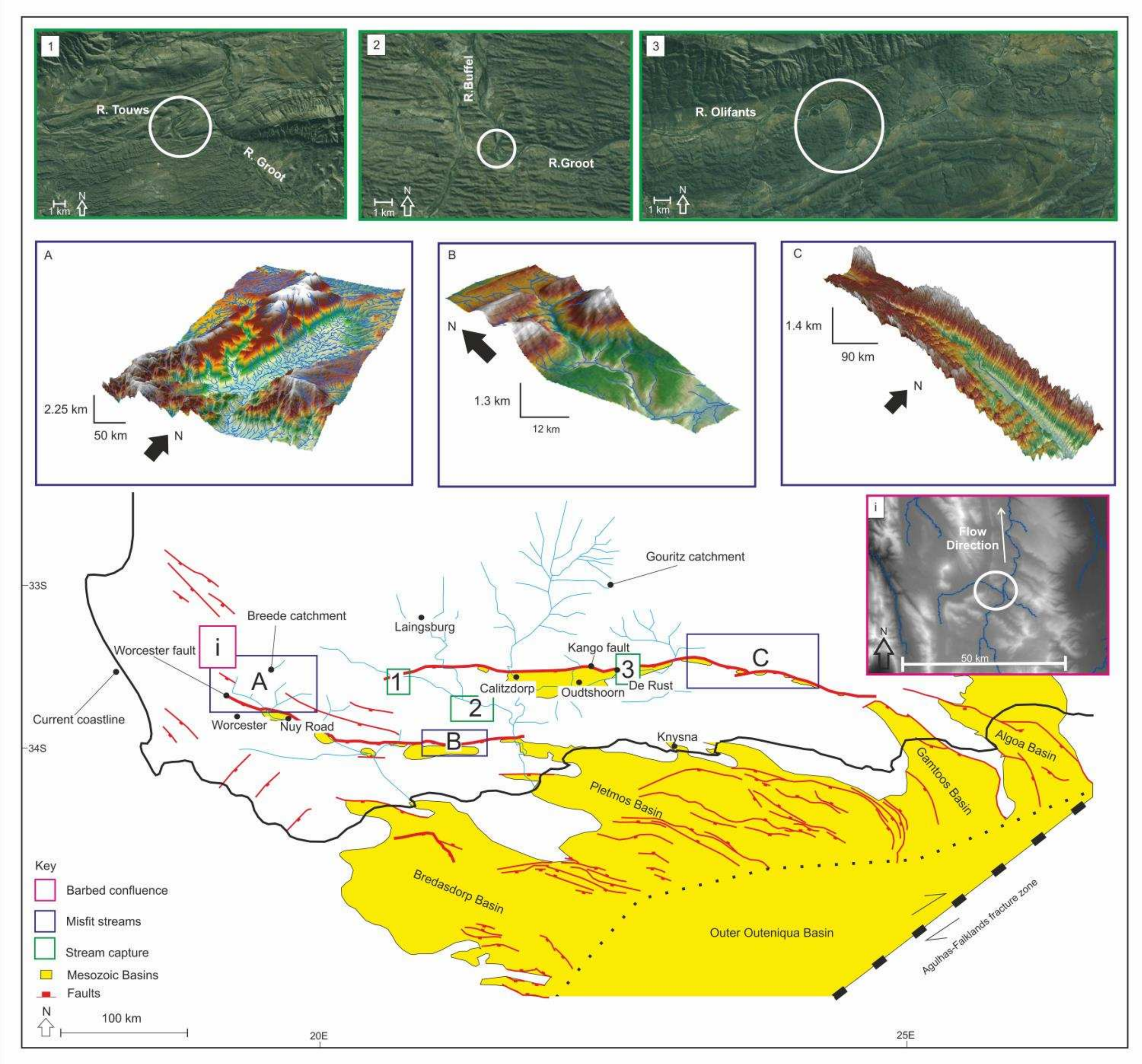

Figure 10 - Comparison of how misfit the valleys in South Africa are compared to worldwide examples. The worldwide sample data information can be found in Table 3.

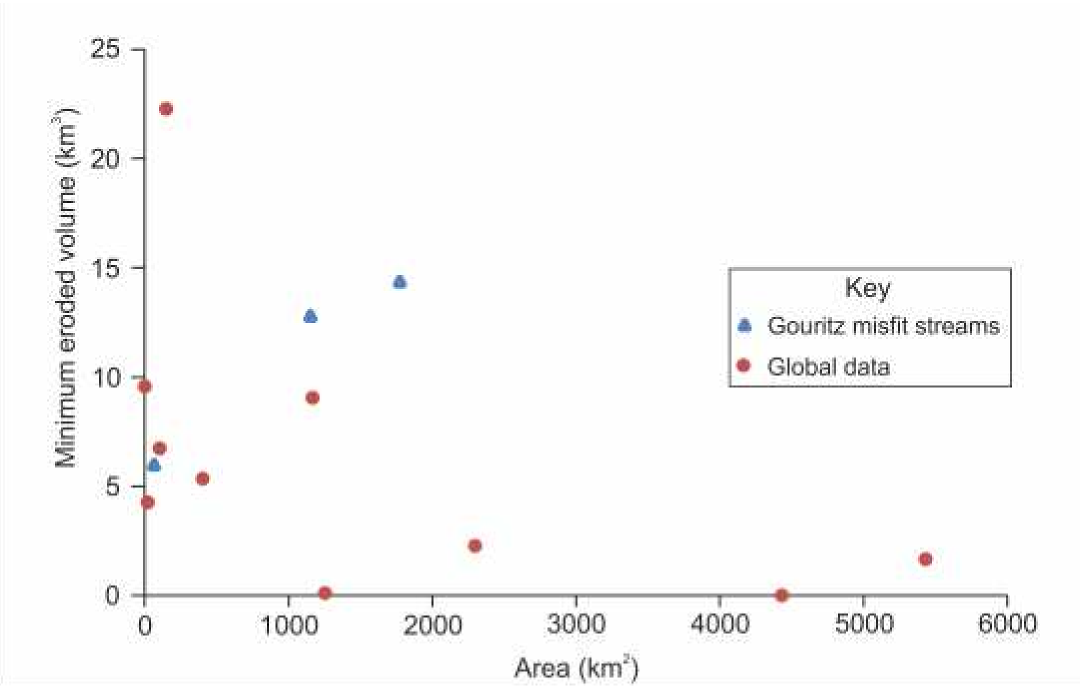

Figure 11 – Drainage evolution of southern South Africa from the pre-rifting of Gondwana to the Late Cretaceous. A) Drainage just after Gondwana fragmentation (Late Jurassic, ~150Myr); B) drainage during in Early-Mid Cretaceous (~100Myr); and C) drainage during the Late Cretaceous (~66Myr). The inset box shows the amount of exhumation during each time period (red) and the remaining lithological thickness (grey) using the mean value of the scenarios in Table 7.

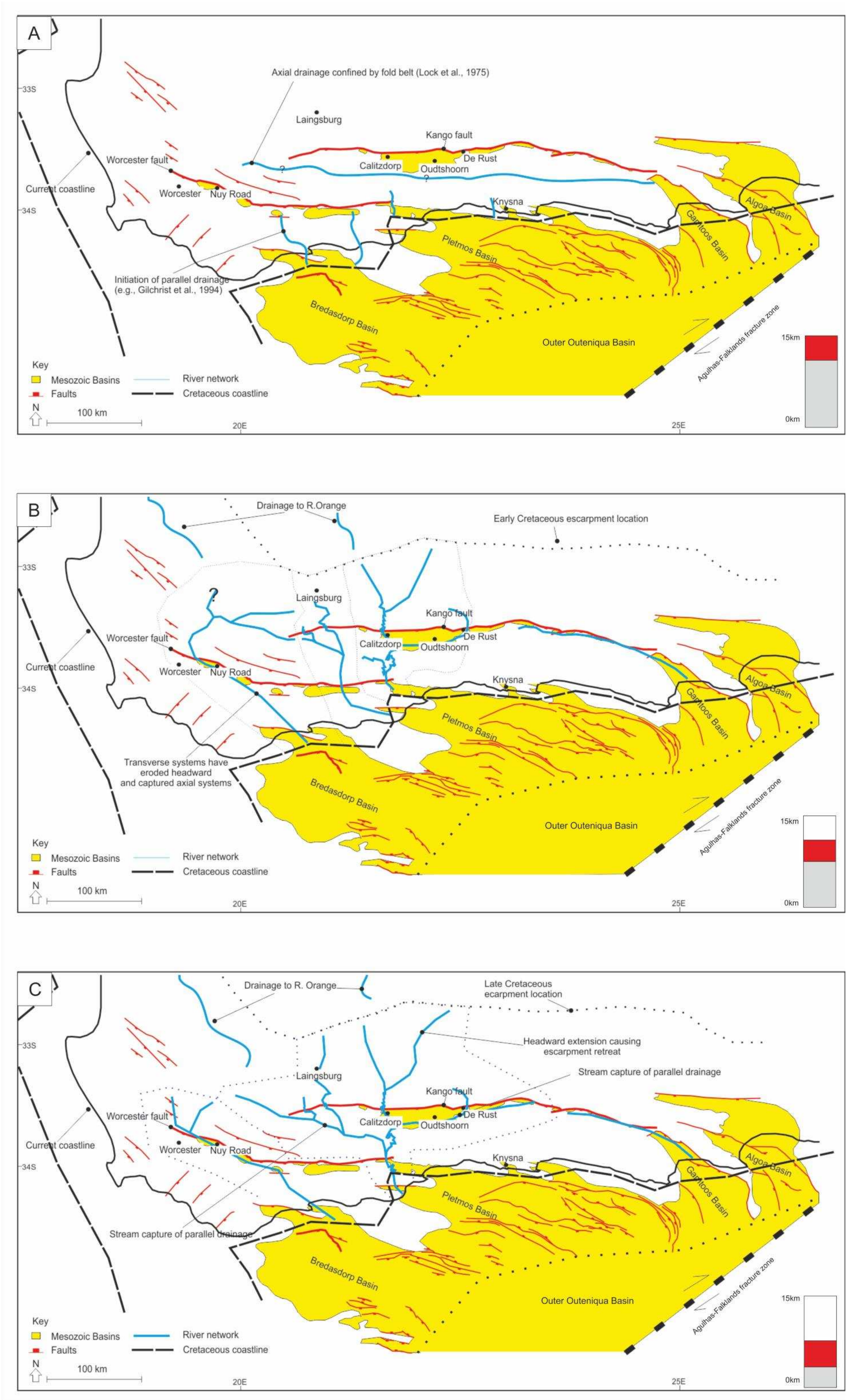
A
Axial drainage confined by fold belt (Lock et al., 1975)
Laingsburg
Kango fault
Calitzdorp
De Rust
Oudtshoorn
Worcester fault
Current coastline
Worcester
Nuy Road
Knysna
Algoa Basin
Gamtoos Basin
Pletmos Basin
Initiation of parallel drainage (e.g., Gilchrist et al., 1994)
Bredasdorp Basin
Outer Outeniqua Basin
Agulhas-Falklands fracture zone
33S
34S
20E
25E
15km
0km
Key
Mesozoic Basins
Faults
River network
Cretaceous coastline
N
100 km
B
Drainage to R.Orange
Early Cretaceous escarpment location
Transverse systems have eroded headward and captured axial systems
C
Drainage to R. Orange
Late Cretaceous ecarpment location
Headward extension causing escarpment retreat
Stream capture of parallel drainage

Figure 12 - Palaeogeographic reconstruction of the Late Jurassic to Early Cretaceous of the southern South Atlantic region based on Macdonald et al. (2003; their Figs. 11 and 13). Note that the Falkland Plateau Basin and the North Falkland Basin could both have formed downstream depocentres of the Outeniqua Basin.

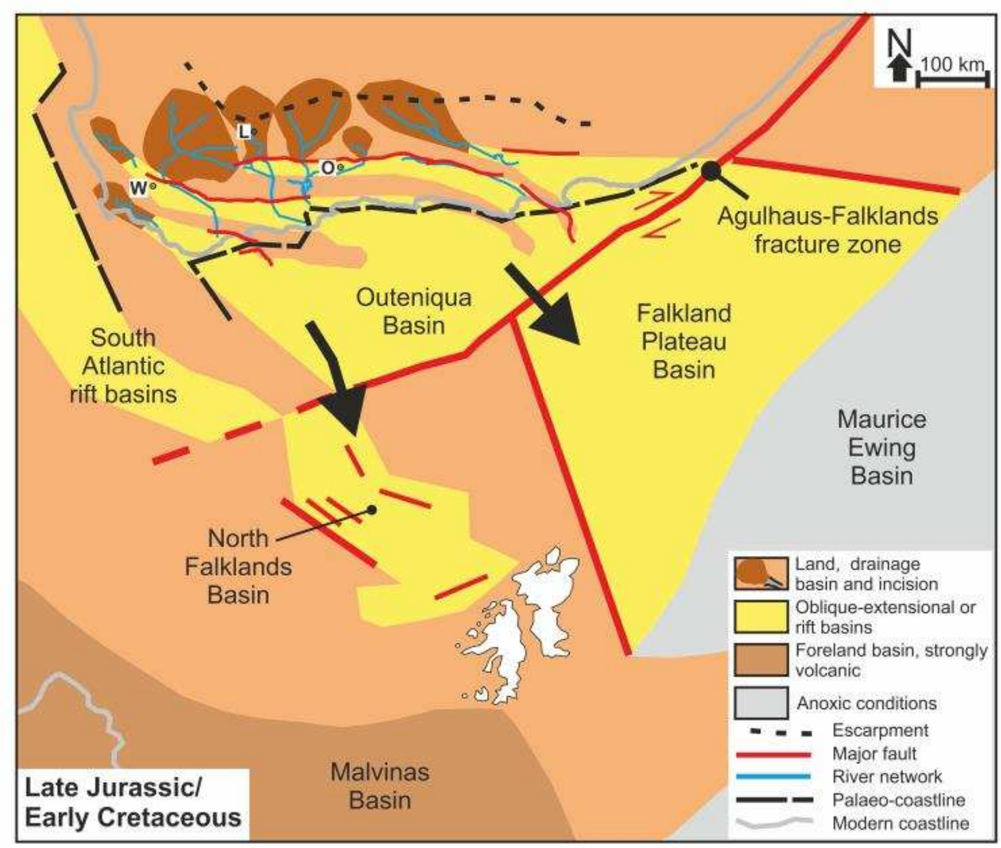

Figure 13 - Sediment thickness map for present-day southern South Atlantic from Divins (2003) and Whittaker et al. (2013). Note the marked disparity of sediment thickness and small land area on the Falkland Plateau. Thickness is in metres.

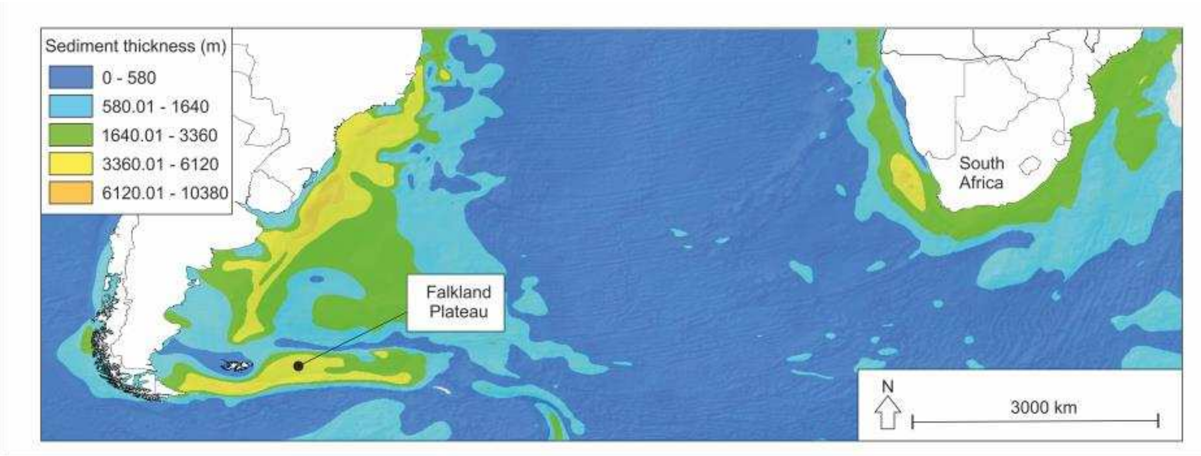
Sediment thickness (m)
0 - 580
580.01 - 1640
1640.01 - 3360
3360.01 - 6120
6120.01 - 10380
Falkland
Plateau
South
Africa
N
3000 km

Table 1 – Published data on the retreat of the Great Escarpment

Reference	Nuclides	Material	Region	Lithology	Landform	Denudation rate (m/Myr)	Integration time (Ma)
Fleming et al. 1999	36 Cl	Basalt	Drakensberg (se) escarpment	Basalt	Face	50 -95	0 – 1 Ma
Cockburn et al. 2000	10 Be, 26 Al	Quartz	Central Namibian (western) margin	granite-gneiss	escarpment faces and ridges	10	
Bierman and Caffee, 2001	10Be, 26Al	Quartz	Central Namibian (western) margin	granite, granite-gneiss, quartzite, pegmatite	outcrop, including inselbergs	3.2	0 – 1 Ma
				sediment	escarpment highlands coastal plain	16 5 8 6.4	
Kounov et al. 2007	3He, 21Ne	Quartz	Southwestern Karoo	Quartzite	Plateau surfaces	1.5-3	0 – 1 Ma
		Pyroxene	Southwestern Karoo	Dolerite	Plateau surfaces	1-2.1	
Decker et al. 2011	3He	Pyroxene	South-central Karoo and north east KwaZulu-Natal	Dolerite	Scarps, summits, plains and ridges	0.5-4	0 – 1 Ma
Brown et al. 2002	AFT, 36Cl	Apatites	Drakensberg Escarpment			100-200	Cretaceous

Table 2 – Thicknesses of key lithologies used in the geological cross sections.

Group	Max Thickness (m)	Min thickness (m)	Reference
Drakensberg	1,400		Catuneanu et al., 2005
Stormberg	1,400		Johnson, 1976
Beaufort	3,000	3,000	Adams et al 2001
Ecca	1,800	1,800	Adams et al., 2001
Dwyka	1,300	600	Rowsell and De Swardt, 1976
Witteberg	2,000	1,700	King, 2005; King et al., 2009
Bokkeveld	2,000	2,000	1:250,000 Map Data
Table Mountain	2,500	2,500	Shone and Booth, 2005

Table 3 – Global data extracted to see how misfit the valleys of the study area are.

Location	**Latitude**	**Longitude**	**Area (km^2)**	**Minimum bulk catchment erosion (km^3)**	**Reference**
Namibian desert and escarpment	-21.304	16.217	1251.873	0.106	Bierman et al. 2007
Queensland Escarpment, Australia	-16.852	145.648	2296.749	2.269	Bierman et al. 2009
Stanley, Virginia, US	38.532	-78.603	5430.284	1.659	Duxbury 2009
Tin Can Creek, Australia	-12.453	133.270	403.6931	5.348	Heimsath et al. 2009
Peradeniya, Sri Lanka	7.261	80.595	1165.496	9.059	Hewawasam et al. 2003
Nahal Yael, Isreal	29.580	34.930	0.447029	9.576	Clapp et al. 2000
Bredbo River, Australia	-36.000	149.500	20.97207	4.269	Heimsath et al. 2006
Rio Azero, Bolvia	-19.610	-64.080	4432.853	0.003	Insel et al. 2010
Little River, Tennessee US	35.664	-83.592	149.4539	22.268	Matmon et al. 2003
Northern Flinders Range, Australia	-30.187	139.428	103.945	6.740	Quigley et al. 2007

Table 4 – Scenarios of exhumation: recorded lithological thicknesses removed over key intervals

Scenario	Period 1 exhumation		Period 2 Exhumation		Period 3 exhumation		Period 4 exhumation		Period 5 exhumation		Total lithological thickness removed
	Timing	Thickness removed	Timing	Thickness removed	Timing	Thickness removed	Timing	Thickness removed	Timing	Thickness removed	
1 - Tinker et al., 2008b (using offshore accumulation rates)	136-130Ma	Equivalent to 160m onshore denudation	130 – 120 Ma	Equivalent to 190m onshore denudation	~120 – 93Ma	Equivalent to 150m onshore denudation	93 – 67 Ma	Equivalent to 270m onshore denudation	67 – 0 Ma	Equivalent to 100m onshore denudation	870m
2 - Tinker et al., 2008a (AFT)	140 – 120 Ma	1500 – 4000 m			100 – 80 Ma	2500 – 3500 m			<80 Ma	1000 m	5000 – 8500 m
3 - Wildman et al., 2015 (AFT)	Early Cretaceous	3500 – 6300 m	Mid-Late Cretaceous	3700 – 6600 m	Late Cretaceous – Early Cenozoic	1400 – 2400 m			Cenozoic	1000 m	9600 – 16300m
4 - Wildman et al., 2016 (AFT)	Early Cretaceous	1000 – 4000 m			110 – 70 Ma	2000 – 4000 m	70 – 30 Ma	1000 – 2000 m	<30 Ma	500m	4500 – 10500m

Table 5 – Volume of material removed from southern South Africa, data from 3D Move.

Scenarios	Volume (km^3)	Thickness (km)
	MAXIMUM	
	Extended at the coastline	
With Drakensberg	2.52×10^6	11.30
Without Drakensberg	2.18×10^6	9.70
	To current coastline	
With Drakensberg	1.40×10^6	6.30
Without Drakensberg	1.17×10^6	5.30
	Southerly draining catchments	
With Drakensberg	7.81×10^6	3.50
Without Drakensberg	6.72×10^6	3.00
	MEDIAN	
	Extended at the coastline	
With Drakensberg	1.71×10^6	7.60
Without Drakensberg	1.53×10^6	6.80
	To current coastline	
With Drakensberg	9.34×10^5	4.20
Without Drakensberg	8.18×10^5	3.60
	Southerly draining catchments	
With Drakensberg	5.21×10^5	2.30
Without Drakensberg	4.06×10^5	2.10
	MINIMUM	
Extended at the coastline	8.87×10^5	4.00
To current coastline	4.67×10^5	2.10
Southerly draining catchments	2.60×10^5	1.20

Table 6 – Clast size data and standard deviation (in brackets).

Study Site	A axis (cm)	B Axis (cm)	C Axis (cm)
Worcester – Rooikrans	34 (6.99)	33 (5.05)	24 (3.73)
Worcester – Nuy Road	10 (1.72)	6 (1.19)	5 (0.95)
Oudtshoorn – Kruisrivier	39 (6.19)	29 (4.11)	18 (2.96)
Oudtshoorn – N12	22 (5.34)	10 (3.11)	10 (2.28)
De Rust	52 (9.55)	33 (6.83)	28 (5.04)

Table 7 – Exhumation scenarios: variation in the amount of exhumed material based on scenarios within Table 4 applied to data from 3D Move (Table 5). The main number is the maximum exhumation and the number in brackets relates to the median exhumation.

	Scenario 1 – Tinker et al., 2008b		Scenario 2 – Tinker et al., 2008a		Scenario 3 – Wildman et al., 2015	
	Maximum	Maximum – southern draining	Maximum	Maximum– southern draining	Maximum	Maximum – southern draining
Late Jurassic - Early Cretaceous (~140-~120Ma)	18.39%		30 .00 – 47.06%		36.46 – 38.65%	
	2.07km (1.39km)	0.64km (0.42)	3.39 – 5.31 km (2.28 – 3.58km)	1.05 – 1.65km (0.69 – 1.08km)	4.11 – 4.37km (2.77 – 2.94km)	1.28 – 1.35km (0.84 – 0.88km)
Early - Mid Cretaceous (~130-120Ma)	21.84%				38.54 – 40.49%	
	2.47km (1.66km)	0.76km (0.50km)			4.35 – 4.57km (2.93 – 3.08km)	1.35 – 1.42km (0.89 – 0.93km)
Late Cretaceous (~120-~70Ma)	17.24%		41.18 – 50%			
	1.94km (1.31km)	0.60km (0.40km)	4.65 – 5.65km 3.13 – 3.8km)	1.44 – 1.75km (0.95 – 1.15km)		
Late Cretaceous – Early Cenozoic (~90-~70Ma)	31.03%				14.58 – 14.73%	
	3.5km (2.35km)	1.09km (0.71km)			1.66 – 1.65km (1.11 – 1.12km)	0.51 – 0.52km (0.33 – 0.34km)
Early Cenozoic to Late Cenozoic (~80Ma to 0Ma)	1.50%		11.76 – 20%		6.13 – 10.41%	
	1.30km (0.87km)	0.40km (0.26km)	1.33 – 2.26km (0.89 – 1.52km)	0.41 – 0.70 km (0.27 – 0.46km)	0.69 – 1.18 km (0.46 – 0.79km)	0.71 – 1.21km (0.14 – 0.24km)