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The missing piece of the South Atlantic jigsaw and its role in crustal reactivation an undiscovered triple junction and continental break-up.

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Abstract

Although the South Atlantic has been extensively studied, two questions remain unanswered. Firstly, the location of the regionally extensive Gondwanian Orogeny remains enigmatic in the Orange Basin, offshore South Africa. Secondly, why does the Argentinian Colorado rift basin have an east-west trend that is perpendicular to the conjugate Orange Basin and Atlantic spreading? Here we present a new structural model for the southern South Atlantic by recognising the South African foldbelt offshore for the first time. The foldebelt trend changes from north-south to east-west offshore and correlates directly with the restored Colorado Basin. The Colorado-Orange rifts form a triparte system with with the Namibian Gariep belt, that we name the Garies triple junction. All three rift branches were active during Gondwana break-up rifting, but during the Atlantic rift phase the Colorado Basin became a failed rift while the other two branches defined the present day location of the South Atlantic.

Not only do our results address these two outstanding questions of South Atlantic configuration, they raise a cautionary note regarding the use of gravity anomalies to define continent-ocean boundaries. Furthermore, we highlight the importance of differentiating between early rift evolution and subsequent rifting that occurs immediately prior to seafloor spreading.

Introduction

The evolution of both sides of the southern South Atlantic has received renewed interest over the last few years, as have their influence on plate configuration and reconstructions (Koopmann et al., 2014; Pangaro and Ramos, 2012, Heine et al., 2013; Blaich et al., 2011; Franke et al., 2010; Moulin and Aslanian, 2010; Paton et al., 2008). The region is considered to be the quintessential passive continental margin providing type localities for investigating the processes involved in lithospheric stretching and margin evolution including: the role of volcanism; rift margin development; and passive margin petroleum systems (Hirsch et al., 2007; Heine, et al., 2013; Peron-Pinvidic et al., 2013; Sibuet and Tucholke, 2013).

Common to all these studies, and their precursors, is the premise that much of the rift geometry that controls the subsequent Atlantic spreading was inherited from pre-Jurassic crustal heterogeneity, and that these structures were reactivated during Mesozoic rifting (Light et al 1993; Clemson et al., 1997). In the southern portion in particular, the onshore Cape Foldbelt (CFB) of South Africa, which was reactivated during the Mesozoic, is laterally continuous with the Ventana Foldbelt of Argentina (Hälbich et al., 1983; De Wit and Ransome, 1992; Macdonald et al., 1996; Paton et al., 2006; Tankard et al., 2009; Stankiewicz et al., 2009; Pangaro and Ramos., 2012). Despite the substantial evidence for this continuity both onshore South Africa and onshore and offshore Argentina, the position offshore South Africa remains enigmatic.

In this study by integrating deep-seismic reflection data with gravity and magnetic data we are, for the first time, able to constrain the basin configuration of the deeper portion of the South Africa Orange Basin (Figure 1). This enables us to differentiate between structures associated with Mesozoic rifting and the reactivation of the underlying basement. In doing so, we are able to identify the position of the CFB offshore South Africa, and hence provide the missing piece of the jigsaw for South Atlantic reconstructions. Although our results specifically relate to the southern South Atlantic, they also provide insights into the processes of early continental break-up, more specifically the influence of crustal architecture in reactivation and lithospheric stretching.

Regional Setting

Throughout the last 1200 Myrs, southern South Africa has experienced repeated episodes of compressional and extensional deformation that have been demonstrably superimposed onto the same existing structural heterogeneity (Figure 2; Tankard et al., 1982; Dingle et al., 1983; Hälbich, 1993; Thomas et al., 1993). Of significance is the Gondwana suture, evident from a large positive magnetic anomaly (Beattie Anomaly) and electrically conductive zone (Southern Cape Conductive Belt; SCCB) in the lower crust or upper mantle (De Beer, 1983; Pitts et al., 1992). This suture developed 950-900 Ma during the Namaqua-Natal orogeny (Thomas et al., 1993) when compression inverted the passive margin that existed along the southern margin of the Kapvaal craton. Following this compression, between 900-600 Ma, a series of east-west trending extensional basins evolved into which the Pre-Cape Group sediments were deposited. A subsequent period of compression (the Pan African Orogeny; 600-450 Ma), led to the inversion of these extensional basins (Tankard et al., 1982; Gresse, 1983; Krynauw, 1983; Shone et al., 1990). A proposed south dipping mega-décollement and northward verging thrust system may also be attributed to this episode of compression, although this remains speculative (Hälbich, 1993).

Following the Pan African Orogeny, clastic sediments of the Ordovician to Early Carboniferous Cape Supergroup were deposited along an intra-continental margin. This deposition ceased due to renewed compression in the Gondwanian orogeny, The onset of which is identified by the regionally correlatable PermianDwyka tillite. This Gondwanan compression led to the deformation of the Cape Supergroup which, in South Africa is manifested within the Cape Fold Belt (CFB) and the Karoo foreland basin to the north (Figure 3; Hälbich et al., 1983; Hälbich, 1993; Veevers et al., 1994). This Gondwanan foldbelt is traceable from the Sierra de la Ventana in western Argentina to the Pensacola Mountains of the Trans-Antarctic Mountains (Du Toit, 1937; Pargaro and Ramos, 2012).

The final stage in the tectonic evolution of the southern South Atlantic margins occurred with the break-up of the Gondwanan continent. Continental rifting, which initiated in the Middle Jurassic with depositional of terrestrial and shallow marine sediments (Dingle et al., 1983; McMillan et al., 1997), resulted in the superimposition of Mesozoic extensional structures onto the CFB (De Wit and Ransome, 1992; Hälbich, 1993). Rifting continued with the deposition of shallow or non-marine sediments onshore, while in the offshore portions, the rate of extension rapidly increased resulting in an abrupt transition to a deepwater setting (McLachlan and McMillan, 1976; Shone, 1978; Dingle et al., 1983; Paton & Underhill, 2004). The rift-drift transition is considered to have occurred during the Valanginian, and is marked by the onset of deposition of shallow marine post-rift sediments (McMillan et al., 1997).

Central Cape regional section

The geometry of the pre-rift sequence (pre-Jurassic) is generally poorly imaged in seismic reflection data even in more recent vintages; therefore, to understand the geometry of CFB, we use the onshore exposure of the central Cape (Figures 3-5). These exposures allow us to characterise the style of CFB deformation, and through the integration of the onshore geometry with offshore seismic data, to consider how the structural configuration of the fold belt influences subsequent Mesozoic extensional structures.

The CFB is controlled by a regional south dipping crustal detachment onto which both the Permo-Trias compression and the Mesozoic extensional structures decolle (Stankiewicz et al., 2009). Structural sections and restorations of the onshore portion demonstrate that despite this common detachment horizon there is a significant variation in deformation style from north to south (Figure 4; Paton et al., 2006). In the north, deformation is dominated by thin-skinned, north verging shallow angle thrusts. Structural modelling of these suggest a common detachment at approximately 10km depth, in agreement with the detachment derived from deep reflection and refraction studies through the Central Cape (Stankiewicz et al., 2009). This strongly contrasts to the style of deformation further south (Figure 3) that comprises a series of box-folds with wavelengths of approximately 8 km and amplitudes of 5 km. Internally, these folds comprise steeply dipping northern and southern limbs with significant shortening accommodated in both fold limbs and the intervening flat, by multi-layer chevron folding (Figure 4). As the regional cross-section reveals (Figure 3b), the CFB is dominated by these box folds, in particular to the south of the Karoo deformation front.

The position of the subsequent Mesozoic extensional faulting is controlled by this pre-Mesozoic fold belt architecture (Figure 3). The extensional faults are consistently positioned immediately to the south of the northern limb of the box folds, which Paton et al. (2006) suggest is a consequence of two stages of structural inversion. They postulate that much earlier normal faults influenced the deposition of the Cape Supergroup during the Cambro-Ordovician intra-continental margin; these faults were then inverted in compression (positive inversion) during the Permian Gondwanian Orogeny; and that these same faults were reactivated once more in extension (negative inversion) during Mesozoic rifting.

Orange Basin Regional Transect

The seismic reflection data provide imaging of the entire continental margin from the relatively un-thinned present-day continental crust, across the attenuated continental crust/volcanic terrains and into the oceanic crust (Figure 5). The ages of seismic packages are constrained in the nearshore areas by a number of wells penetrating post-rift, syn-rift and basement units, thereby providing a framework to the mega-sequence interpretation Muntingh, 1993; Paton et al., 2008).

A mega-sequence approach to the seismic interpretation is taken, and although it is based upon the existing seismic stratigraphic framework some modification has been required to account for the additional imaging at depth (Figure 5; Muntingh, 1993, Brown et al., 1995). In total nine packages are identified (from youngest to oldest): Tertiary; Late Cretaceous; Early Cretaceous; oceanic crust; seaward dipping reflections; syn-rift; pre-rift; and mid to lower continental crust.

The Tertiary package is very similar to that observed elsewhere along the Orange Basin in both the Republic of South Africa and Namibia (Paton et al, 2008; Mohammed et al. this issue) and comprises a very thin, or absent, package in the inner part of the margin but rapidly thickens across the break in slope forming a break-of-slope fan system in the deepwater portion of the basin. In the section presented here (Figure 5) the stratigraphy is relatively undeformed, although it should be noted that there are localised gravity collapse features evident throughout the Orange Basin (Dalton et al., this issue; Butler and Paton, 2010).

In contrast to the aerially restricted Tertiary package, the Late Cretaceous (Cenomanian-Maastrichtian) package is widespread along the margin and dominates the post-rift stratigraphy. The upper sequence was deposited across the majority of the margin, has concordant reflections in the inner part and an aggradational geometry at the break in slope. Significant erosional truncation is also evident at the top of the sequence immediately below the Tertiary package. The middle Cretaceous sequence (Mid-Aptian to Cenomanian), which comprises fluvio-deltaic sediments, forms a westward prograding shelf margin sequence associated with distributed deposition prior to the establishment of the Orange River basin as a single point source of sediment entry.

The Lower Cretaceous sequence (Barremian to Mid-Aptian) exhibits significant thickness variation across the margin forming a broad, shallow basin with onlap onto both the present day margin in the east but also pre-rift stratigraphy in the outboard portion.

The horizon that defines the base of the Barremian (Middle Cretaceous) sequence is correlateable across the entire margin, however, the sub-crop to that horizon is highly variable and it is difficult to determine whether packages are time-equivalent. At the westernmost extent of the data coverage the subcrop to the Barremian sequence is characterised by chaotic/transparent reflectivity with a high amplitude, rubbly top, characteristic of oceanic crust. The oceanic crust transitions eastwards into continuous, high amplitude reflections that show a consistent oceanward dip; these are Seaward Dipping Reflectors (SDRs) that are commonplace along volcanic passive margins (Franke, 2013). Towards the east, the package beneath the Barremian sequence is dominated by continuous, high amplitude reflections, which are penetrated in the nearshore position by well A-J1, and comprises interbedded fluvial and volcanic sequences (Figure 6). Geometrically, the sequence in the inner part of the margin is defined by diverging reflections indicating a syn-rift sequence. This is likely to be of Upper Jurassic to lowest Cretaceous age.

The basement/pre-rift mega-sequence has a highly variable seismic character that changes significantly with depth. At relatively shallow levels, immediately beneath the Barremian sequence, there is significant concordant reflectivity. In places this has a consistent dip although occasionally there is short-wavelength folding present. At a mid-crust level (~ 10 Km) the seismic character is dominated by a series of highly reflective, continuous, shallow dipping reflections that are mappable across the data set in 3-dimensions. Given their depth and character these are interpreted to be mid-crustal shear zones and are likely to be structurally below the regional decollement surface (Figure 4). Immediately above the high angle reflectivity is a relatively transparent signature at a depth of approximately 8 km that is traceable across much of the section up until the ocean crust. At shallower levels (~ 6 km), and up to the Top Basement unconformity, increasing reflectivity is observed within this transparent package

Variations in structure along the margin

There is considerable variation in fault geometry and pre-rift seismic character both along and across the margin. In the northern part of the Orange Basin (northern South Africa and Namibia) is a series of north-south trending half grabens separated by the Kudu Basement High. The faults to the east of the basement high are west dipping and appear to have reactivated the west dipping pre-rift reflectivity that is most likely to be the Proterozoic Gariep Belt (Mohmmad, this volume; Gray et al., 2008) while the faults to the west of the high are associated with Atlantic rifting.

In contrast, in the southern Orange Basin the pre-rift, as described in the previous section, is divided into two very different packages. The package that is dominated by concordant reflectivity is penetrated in near shore wells and is either Cambrian quartzites consistent with the Cape Supergroup or Devonian meta-sediments of the Bokkeveld Group (Figure 2). There are two important points to note. First, the continuity of the seismic character across the section (Figure 5) suggests the presence of continental lithosphere significantly further to the west than has previously been considered. Secondly, this upper pre-rift package broadly defines high amplitude box folds with significant internal folding in the anticlines, relatively undeformed southern limbs and commonly normal faulted north limbs. These structures are considered to be the equivalent of the box-folds that characterise the onshore CFB (Figure 7).

Mapping of the structures reveals a significant variation in trend and geometry: in the south-east the basin is dominated by a small population of very large faults (throws of 10 km) with little evidence of small, distributed faulting. These are very similar to the faults in a comparable position along trend in the CFB, e.g., Gamtoos and Plettenberg Faults (Paton and Underhill, 2006). This structural grain trends east-west in the Central cape (underpinning the Gamtoos and Plettenburg faults) and then abruptly becomes north-south trending at the Cape Syntaxis (Figure 9). This north-south trend continues offshore and is mappable in the sub-surface (Figure 7). Further to the north, the north-south trending faults do not continue along the margin, and instead their orientation changes to east-west trending. North-south orientated sections reveal that both the CFB structures and subsequent Mesozoic rift faults have this east-west orientation (Figure 8a and b). These structures are mappable towards the west until they are deeper than is seismically imaged (Figure 9).

Gravity and magnetic mapping

The gravity high along the margin has long been used to define the continental ocean boundary, with continental crust being taken to be on the landward side and oceanic crust on the outboard side (Rabinowitz and La Brecque, 1979). This has often been used as a constraint for the extensive nature of the break-up volcanic distribution and as a pin-point for plate reconstructions (Moulin and Aslanian, 2009; Franke et al., 2010; Blaich et al., 2011; Heine et al., 2013).

When our interpretation of the deep seismic reflection data is compared with this gravity signature it reveals that the gravity high corresponds to a position significantly inboard of not only the position of the principle SDRs but also much of the late stage rift- basin (Figure 9). The diffuse outboard gravity anomaly corresponds with the transition between attenuated continental crust and oceanic crust, as identified by the seismic reflection data. The variability of the crustal architecture that we observe illustrates that a sharp transition between oceanic and continental crust is not appropriate for this margin. However, we do note that the transition between the volcanic province and definitive ocean crust is not only a very narrow zone identifiable on seismic reflection data but that it corresponds with a discrete step in magnetic anomaly intensity, and this step can be used with significant certainty to trace this boundary.

Based upon these observations we superimpose our structural modelling onto both the gravity and magnetic intensity maps (Figure 10a and b). The magnetic maps reflect the north-south orientation of the eastern ocean crust, and also illustrates the variation in magmatic bodies. The inboard magnetic highs do not correspond to identifiable magmatic bodies (based upon the observed seismic reflection character), but rather reflect basement highs and are recording the high degree of magnetic susceptibility of pre-Cambrian basement.

The gravity maps exhibit more variability, although both the gravity high anomaly and the diffuse outer high that is coincident with oceanic crust are north-south trending.. Further gravity modelling is required to further constrain this signature, however, existing modelling along the margin suggests a lower crustal origin rather than a shallow crustal cause (Hirsch et al.2007), We propose that the variation in gravity signature, especially the shorter wavelength component (therefore shallower) is a reflection of the upper crustal architecture. When the fault map is superimposed upon the gravity anomaly it reveals that the earlier north-south trending faults that become east-west trending are evident as are the later north-south trending structures.

Continuity of the structures within Western Gondwana

The Phanerozoic structures and stratigraphy of eastern Argentina and its adjacent offshore shelf are dominated by Upper Palaeozoic and Mesozoic sequences. The Palaeozoic consists of Patagonian foreland basin deposits (Ramos, 2008; Rapalini, 2005; Milani and De Wit, 2008; López de Lucchi et al., 2010; see refs in Pangaro) and the Ventanian Fold Belt (VFB; Pangaro and Ramos, 2012; Ramos, 2008; Tomezzoli and Vilas, 1999; López Gamundi et al., 1995). It is the latter that is the focus of this study. The VFB is a NW trending structural feature that extends at least 800 km across both onshore and offshore areas.

The onshore stratigraphy are Cambrian to Devonian aged quartz-rich platform deposits that overlie the Rio de la Plata Craton and are therefore both the lateral and time equivalent depositional sequence to the Cape Supergroup, as first postulated by Keidel (1916) and du Toit (1927). The Permian sequence, that overlies the Devonian, is a 3.5 km thick sequence of turbidites and interbeded volcanic rocks that also contains the direct equivalent to the Permian Dwyka formation of South Africa that represents the onset of the Gondwanian Orogeny.

The offshore continuity of the VFB has been previously proposed, although required further substantiation (Fryklund et al., 1996). The oldest sequence penetrated offshore was a syn-Gondwanian Orogeny, Upper Carboniferous sequence below the base of the rift half grabens which is correlated to the Sauce Grande Formation, which is the South African Dwyka equivalent. The overlying half grabens have been recognised in the sub-surface but an absence of clearly imaged seismic reflection data had prevented the correlation of structural trends into the offshore region. Franke (2006) proposed that VFB equivalent structures were present offshore, but it has only been recently that definitive evidence has been produced. Pangaro et al. (2012) integrated seismic reflection and gravity data, and proposed that the nature of folding within the seismic data correlated to structures offshore and demonstrated a north verging geometry that is consistent with the east-west trending VFB. Furthermore, they proposed that a seismic stratigraphic package characterised by small scale folding was the Lower Palaeozoic sequence. t

The missing link of the CFB in South Africa.

When current plate reconstructions of western Gondwana are considered there is a significant dichotomy. The CFB is east-west trending in southern South Africa (Halbich et al., 1983; De Wit and Ransome, 1992; Paton et al., 2006; Tankard et al., 2009) and abruptly changes to a north-south orientation at the Cape Syntaxis; but because of limited exposure its continuity towards the north and offshore remains unconstrained. Despite extensive analysis of offshore data (Muntingh, 1993, Brown et al., 1995; Paton et al., 2008; Koopmann et al., 2014) the relatively limited imaging at depth of these reflection data has previously prevented mapping of basement involved structures with any degree of certainty (Figure 11). This has resulted in existing structural models being dominated by the shallower north-south trending normal faults of Early Cretaceous rifting. Existing studies of the Argentinian crustal architecture have also speculated the geometry of the foldbelt from the VFB into the CFB and the presence of both a Cape and Colorado Syntaxis (Pangaro and Ramos,2012).

For the first time, our interpretation of new seismic reflection profiles provides evidence of the continuity of the western Gondwanian Foldbelt. Our new structural model identifies that the CFB does indeed continue to trend northward for approximately 100 km but that as continues into the Orange Basin a further syntaxis is identifiable within the seismic reflection and gravity data, that results in an abrupt change in foldbelt orientation to one that is trending east-west.. This trend then continues towards the west and is directly equivalent to the Colorado Basin of Argentina and the onshore Sierra de le Ventana.

Further evidence for this correlation of the western Gondwanian Foldbelt is provided when the structural styles of the Permian compression are compared. Not only are the structures similarly manifested as small-scale north verging asymmetric folding but the style and location of the subsequent negative inversion, identified by the normal faults, are comparable.

A tale of two rifts

Although our new structural model provides evidence for the location of the CFB and, therefore constrain the missing link for all of the plate reconstruction of the South Atlantic, in doing so it creates a conundrum that is fundamental to our understanding of continental break-up.

The present day depocentres on both margins of the southern South Atlantic are north-south trending, parallel to the present day rift orientation. Yet, this is at odds with the common consensus that the location of continental rifting is determined constrained by heterogeneities within the crust, that subsequently controls the position of continental break-up. Our revised structural model of the southern South Atlantic reveals a more complex development.

The initial rifting along western Gondwana was a consequence of the reactivation of the western Gondwanian Foldbelt with broadly south-west orientated extension, hence east-west trending faults. This led to the development of the main rift basins of the Orange Basin and the Colorado Basin in Argentina (Muntingh, 1993, Brown et al., 1995; Franke et al., 2010; Pangaro and Ramos 2012). As these rift basins formed through the negative inversion of the fold belts, rift basin geometry was controlled by the underlying fold belt geometry, including the Cape and Colorado syntaxes whose northern extent was likely to have been controlled by the presence of the Kalahari and Rio del Plata cratons. The timing of this rifting was likely to have been Mid Jurassic to early Cretaceous.

During the Mid Cretaceous, the rift configuration changes significantly and is much more dominated by the South Atlantic rifting that superimposes a north-south trend. As Mohammed et al., (this volume) demonstrate the Namibian rift system utilised the North-South trending Gariep Belt. At some locations this north-south trend must have intersected with the east-west trending Gondwanian Foldbelt. Given the resultant geometry we speculate that this formed a triple junction with three active rift arms, which we call the Garies Triple Junction. As the South Atlantic rifting became established, the Gariep Belt, and the north-south trending portion of the western Gondwanian Foldelt ultimately controlled the position of the Atlantic rift system.

A number of study suggest that rift geometry controls the location of subsequent continental break-up and seafloor spreading (e.g. Vauchez et al., 1997). In many margins although it is invoked, it is difficult to demonstrate with confidence. The example of the South Atlantic highlights that the pre-break up configuration can be complex and is likely to overprinted by the latter stages of rifting making it difficult to determine the early structural configuration.

Our study also highlights that caution must be used when using gravity anomalies to constrain plate reconstructions. It is commonly assumed that the gravity high along passive continental margins correspond to the transition from continental to oceanic crust, and are used as the pin point for restorations yet our study demonstrates that the gravity anomaly is located within the continental crust domain and is likely to correspond to a lower crustal body (Hirsch et al., 2007), rather than an ocean-continent transition. The consequence of this is that plate-reconstructions in the South Atlantic, and indeed any other margin where this is applicable, would underestimate the amount of continental crust that should be accounted for.

Conclusions

The use of newly acquired deep, seismic reflection data allows us to re-evaluate the structural configuration of the Orange Basin, South Africa. This has allowed us to determine the location of the Cape Foldbelt in the offshore area for the first time and correlate its continuity across into the Ventana Foldbelt of Argentina. This new 'structural model, therefore, provides the missing link in the South Atlantic of the location of the western Gondwanian Foldelt.

In addition, our new structural model proposes that prior to break-up there was a triple junction rift system comprising the rifts of South Africa, Gariep and Colorado. During South Atlantic rifting the Colorado system become inactive and the former two became the location of ultimate continental break-up.

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Figure 1 – Location of study area, including the distribution of the data and location of key lines. The colours denote the sediment thickness of the Orange Basin, with numbers represent thickness in Km.

Figure 2 – Chronostratigraphy of the Orange Basin (after Brown et al., 1995; Paton et al., 2008)

Figure 3 – Regional geology of southern South Africa. A) Summary geological map of South Africa showing the location of the main stratigraphic units in the area, including the Pre-Cambrian inliers, the Cape Supergroup, the Karoo foreland basin and the Meszoic rift basins. This also shows the location of the broadly east-west trending Cape Foldbelt. B) North-south cross-section through the foldbelt that illustrates the southern dipping decollement onto which the Mesozoic faults decolle, the thin-skinned nature of the deformation at the north of the foldbelt and the internal deformation of the Cape Supergroup (after Hälbich, 1993; Veevers et al., 1994, Paton et al., 2006, Tankard et al., 2009).

Figure 4a – Detailed structural section through the ??? box-fold within the Central Cape Foldbelt that shows the broad geometry is dominated by consistent, very steep dip panels forming the box fold limbs and relatively flat fold top. The inset photos show internal geometry, including: a) the relatively undeformed northern limb of a fold from ?????; b) internal chevron folding of the quartzite dominated Cape Supergroup; and c) the relatively undeformed southern limb at ?????. This style of deformation is representative across the foldbelt (Paton et al., 2006).

Figure 5 – Regional seismic section across the South African Orange Basin (Figure 1 for location). This section shows the entire margin geometry from the relatively unstretched continental crust, across the rift basins and break-up volcanics into ocean crust. The main mega-sequences used in this study are identified.

Figure 6 – East-west trending seismic section that shows the geometry of the main rift sequence within the Orange Basin. This sequence is penetrated by wells (Figure 1) and the basin comprises inter-bedded fluvial sandstones and volcanics.

Figure 7 – A comparison of the pre-rift mega-sequence in the regional seismic sections and the onshore Cape Foldbelt structures. Folding of concordant reflectivity is imaged in the seismic data and overall forms anticline geometry with a wavelength of ~ 10 km (a) that are very similar in geometry to the Cape Supergroup box-folds observed in the Central Cape (b). This section is orientated east-west and provides evidence of the continuity of the Cape Foldbelt to the north-west of the Cape Syntaxis.

Figure 8 – North-south trending sections in the central area of the Orange Basin to show the change in trend of the foldbelt (Figure 1 for location). a) This section shows the presence of east-west trending Mesozoic normal faults. These faults are the lateral equivalent to the north-south trending faults in Figure 6. b) This corresponds

to the northern end of the Cape Foldbelt and show that the folding present within the pre-rift stratigraphy are geometrically identical to those in Figure 7.

Figure 9 – Structural map of the study area superimposed upon offshore Bouger Gravity data. The structural map shows the continuity of the CFB to the north of the Cape Syntaxis with a North-West orientation. There is an abrupt change to an east-west orientation that defines a second syntaxis. The east-west trend in the west, which also corresponds to a gravity low, is overprinted by later north-south trending faults. As discussed in the text, although the gravity anomaly is dominated by the G Anomaly this is more likely to be associated with lower crustal bodies rather than shallower crustal structure.

Figure 10 – This 3D perspective from the south of the basin shows the relationship between the basin architecture and a) gravity anomaly and b) magnetic intensity. It shows that there is no correspondance between the G Anomaly and the position of the continent-ocean boundary. In contrast the largest gradient magnetic intensity reflects the transition from SDRs to oceanic crust.

Figure 11 – Reconstruction of the southern South Atlantic at 140 Ma. The Cape Foldbelt structures and Mesozoic rift faults, as interpreted in this study, have been plotted as have the structures from Namibia (Mohammed et al, this volume) and the Colorado Basin (Pangaro and Ramos, 2012). This configuration implies that there was a rift triple junction at the intersection of the three rift systems. b) During the principle phase of South Atlantic rifting the Colorado Basin became inactive and rifting was focussed on the Orange and Gariep rift systems.

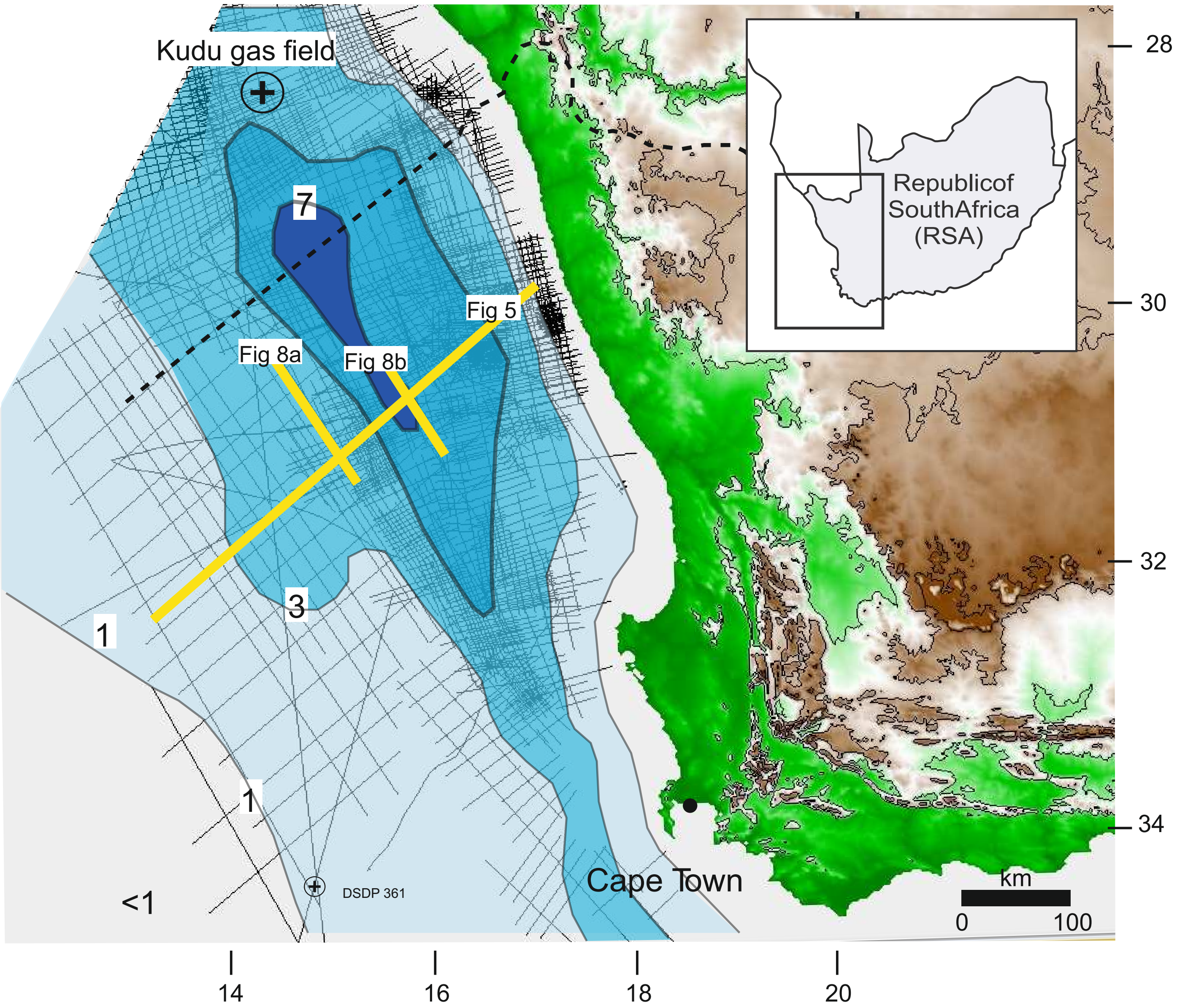
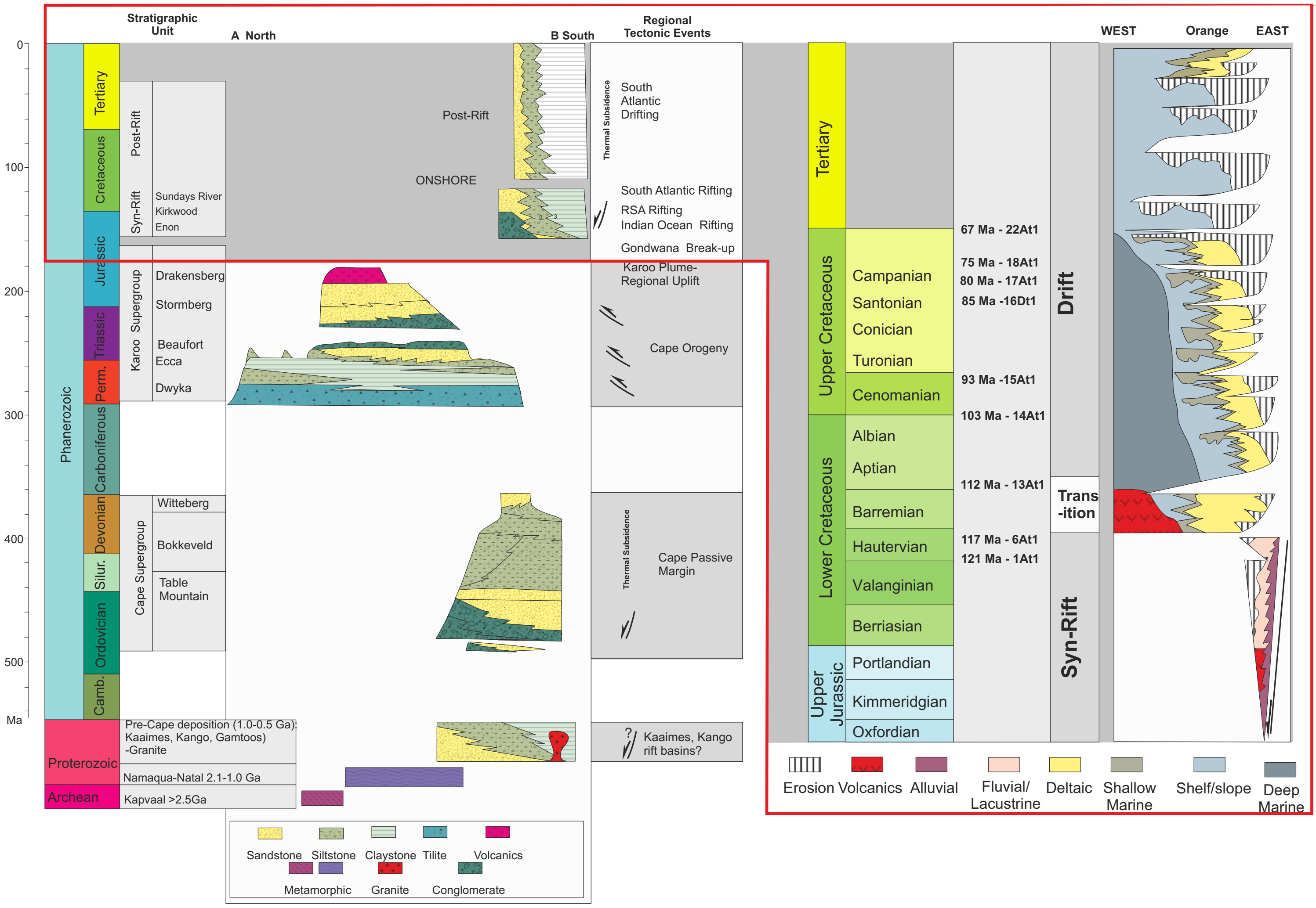
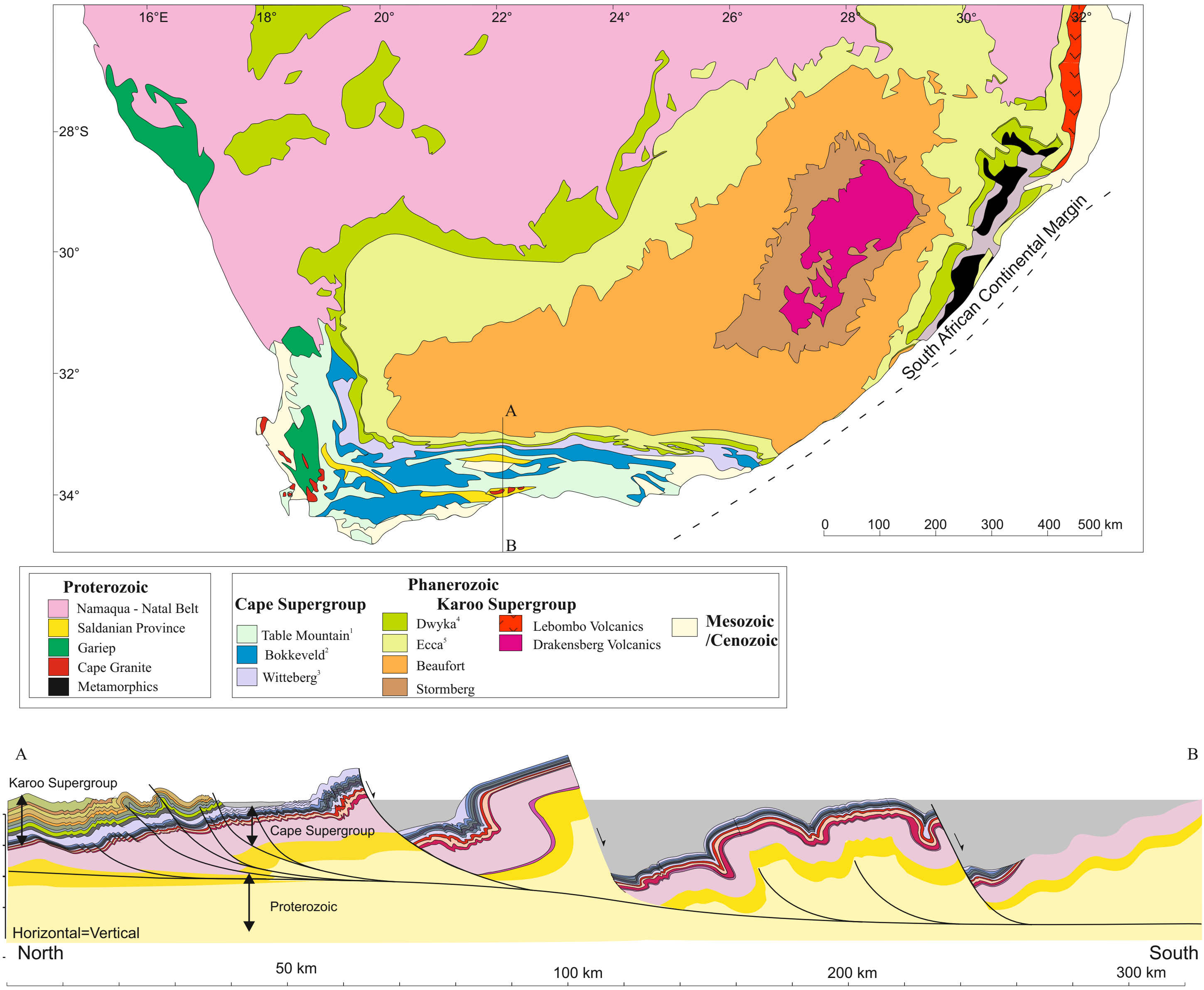


Figure 1 - Regional setting and data



Stratigraphic Unit
A North
B South
Regional Tectonic Events
Ma
0
100
200
300
400
500
Phanerozoic
Tertiary
Cretaceous
Jurassic
Triassic
Perm.
Carboniferous
Devonian
Silur.
Ordovician
Camb.
Proterozoic
Archean
Post-Rift
Syn-Rift
Sundays River
Kirkwood
Enon
Karoo Supergroup
Drakensberg
Stormberg
Beaufort
Ecca
Dwyka
Cape Supergroup
Witteberg
Bokkeveld
Table Mountain
Pre-Cape deposition (1.0-0.5 Ga): Kaaimes, Kango, Gamtoos) -Granite
Namaqua-Natal 2.1-1.0 Ga
Kapvaal >2.5Ga
Post-Rift
ONSHORE
Thermal Subsidence
South Atlantic Drifting
South Atlantic Rifting
RSA Rifting
Indian Ocean Rifting
Gondwana Break-up
Karoo Plume-Regional Uplift
Cape Orogeny
Cape Passive Margin
Kaaimes, Kango rift basins?
Sandstone
Siltstone
Claystone
Tilite
Volcanics
Metamorphic
Granite
Conglomerate
WEST
Orange
EAST
Tertiary
Upper Cretaceous
Campanian
Santonian
Conician
Turonian
Cenomanian
Lower Cretaceous
Albian
Aptian
Barremian
Hautervian
Valanginian
Berriasian
Upper Jurassic
Portlandian
Kimmeridgian
Oxfordian
67 Ma - 22At1
75 Ma - 18At1
80 Ma - 17At1
85 Ma -16Dt1
93 Ma -15At1
103 Ma - 14At1
112 Ma - 13At1
117 Ma - 6At1
121 Ma - 1At1
Drift
Trans -ition
Syn-Rift
Erosion
Volcanics
Alluvial
Fluvial/ Lacustrine
Deltaic
Shallow Marine
Shelf/slope
Deep Marine

Figure 2 -



16°E
18°
20°
22°
24°
26°
28°
30°
32°
28°S
30°
32°
34°
A
B
South African Continental Margin
0
100
200
300
400
500 km
Proterozoic
Namaqua - Natal Belt
Saldanian Province
Gariep
Cape Granite
Metamorphics
Phanerozoic
Cape Supergroup
Table Mountain[1]
Bokkeveld[2]
Witteberg[3]
Karoo Supergroup
Dwyka[4]
Ecca[5]
Beaufort
Stormberg
Lebombo Volcanics
Drakensberg Volcanics
Mesozoic
/Cenozoic
A
B
Karoo Supergroup
0 km
Cape Supergroup
10 km
Proterozoic
20 km
Horizontal=Vertical
North
South
50 km
100 km
200 km
300 km

Figure 3

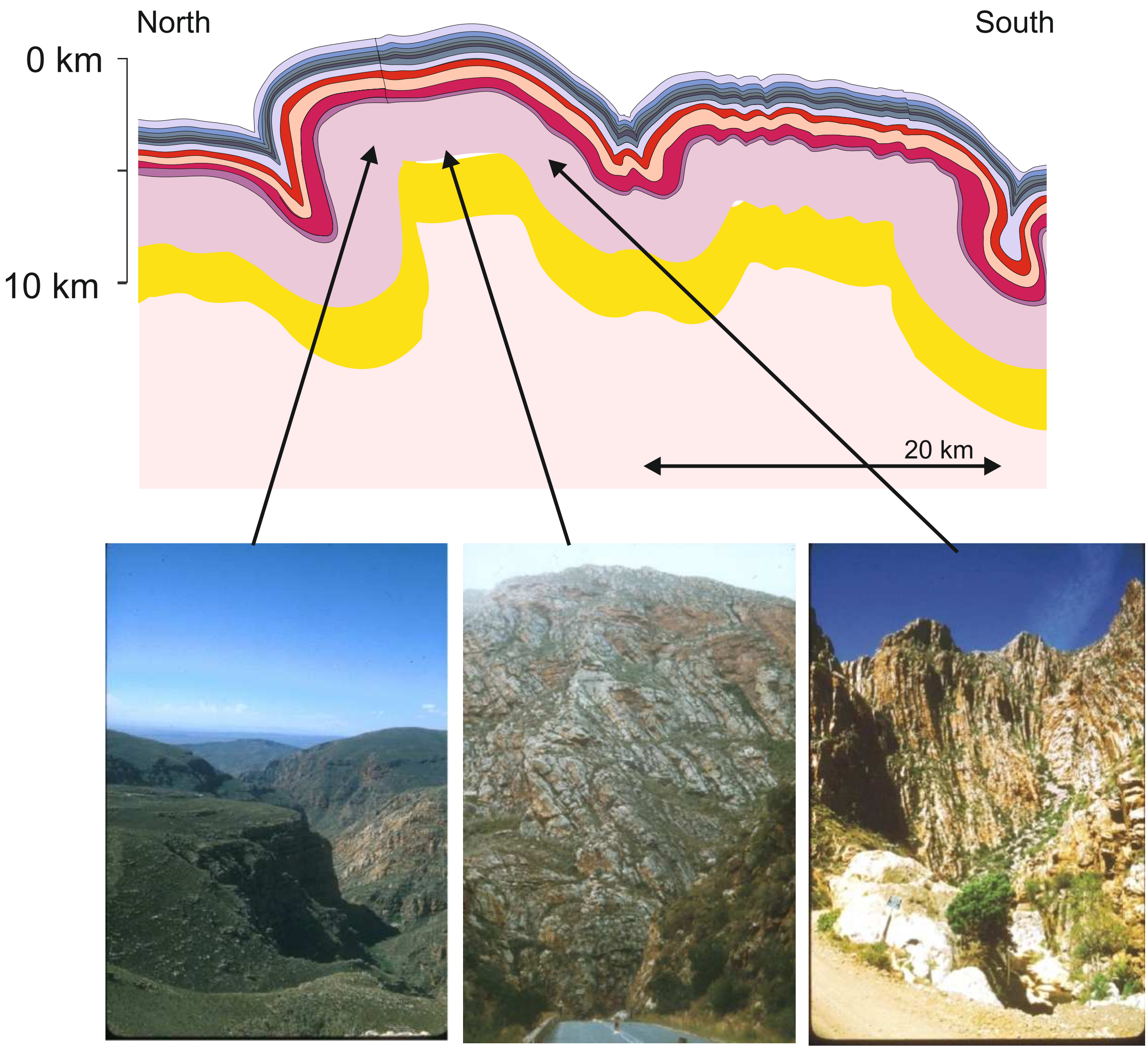


Figure 4

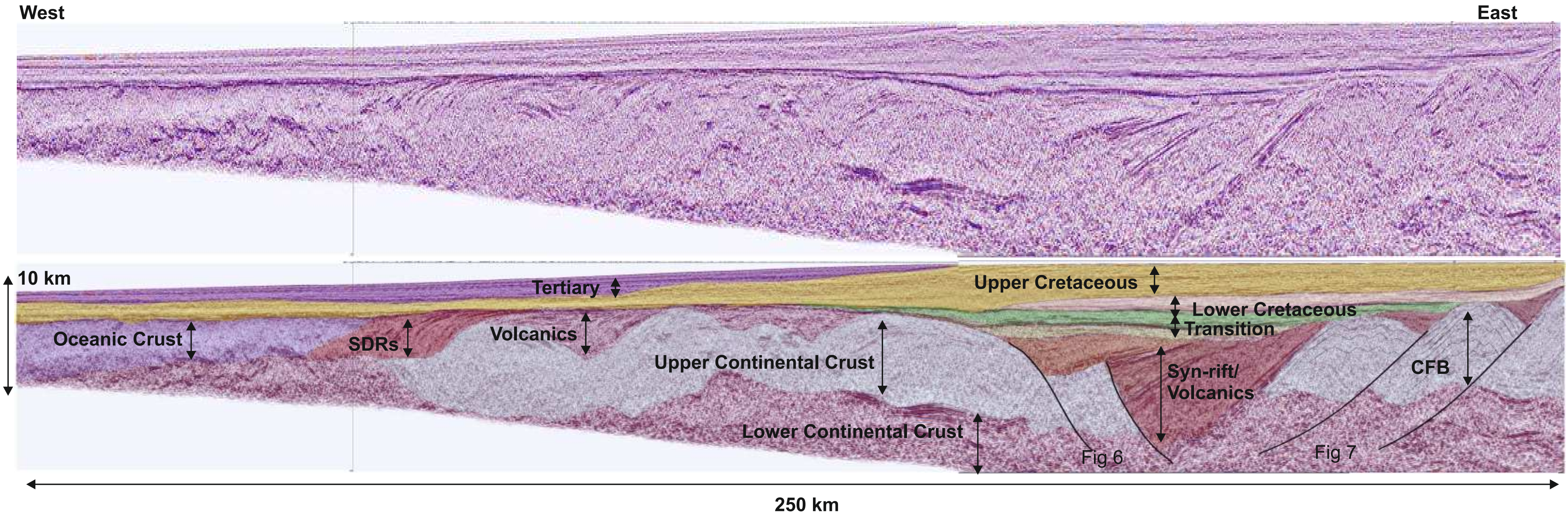

West
East
10 km
Tertiary
Upper Cretaceous
Lower Cretaceous
Transition
Oceanic Crust
SDRs
Volcanics
Upper Continental Crust
Syn-rift/
Volcanics
CFB
Lower Continental Crust
Fig 6
Fig 7
250 km

Figure 5

Figure 8

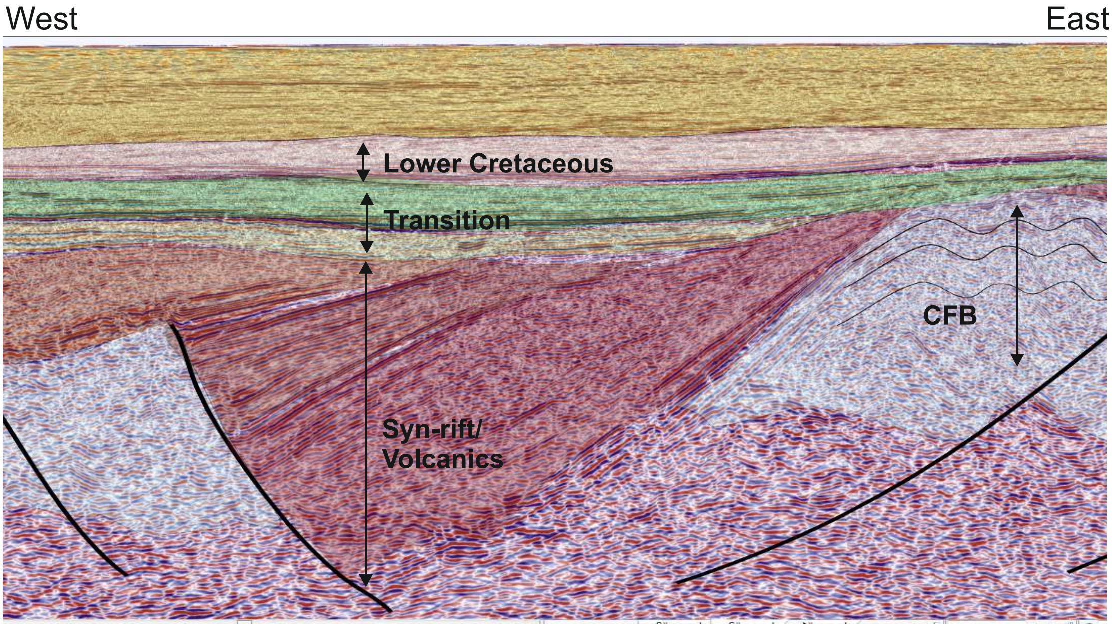
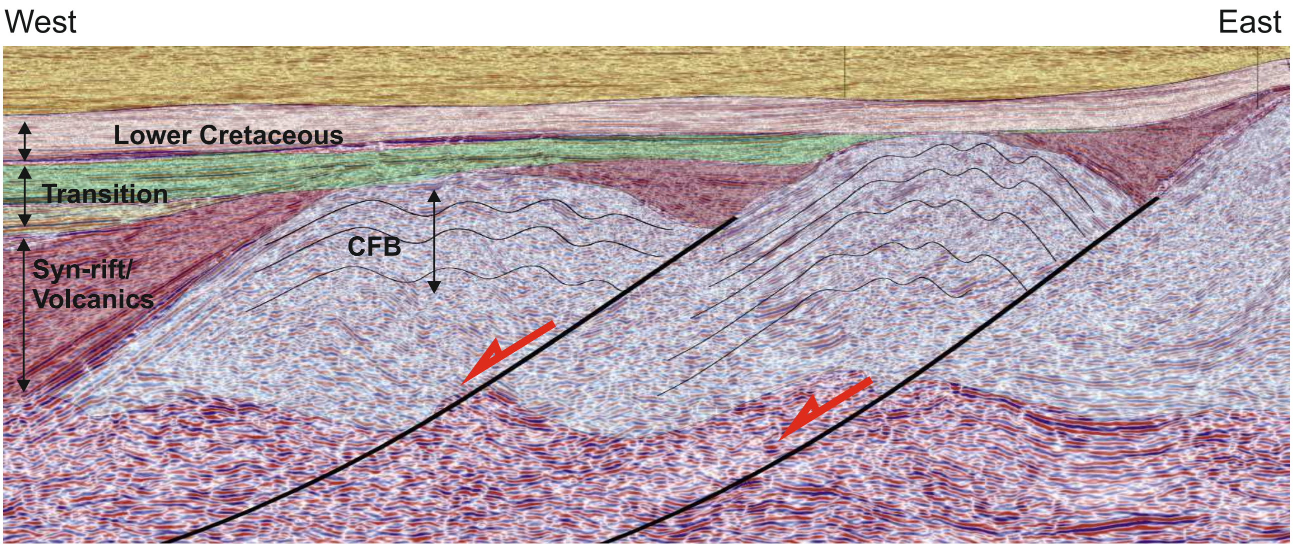
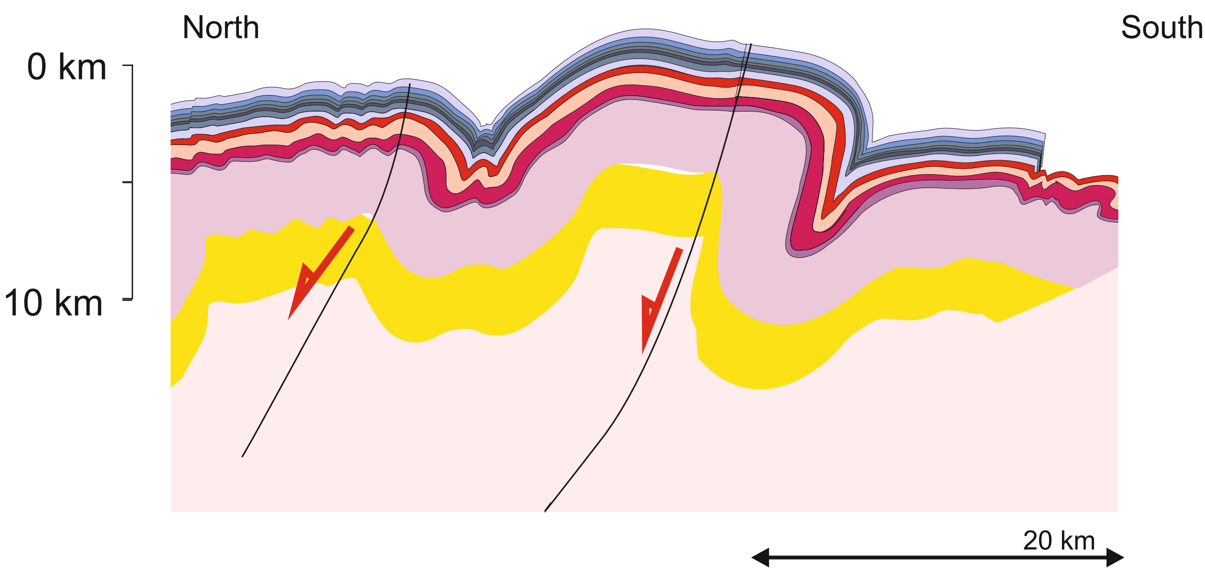


Figure 7



a)



b)

Figure 8a

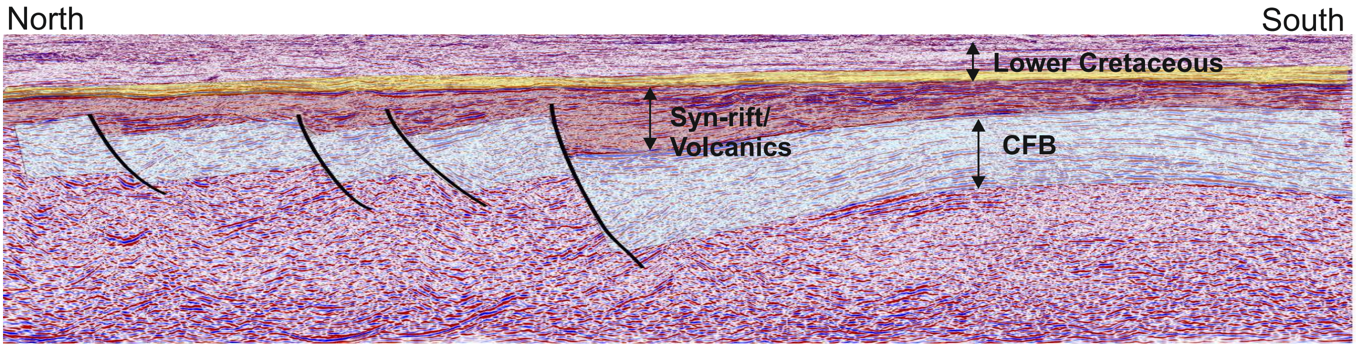


Figure 8b

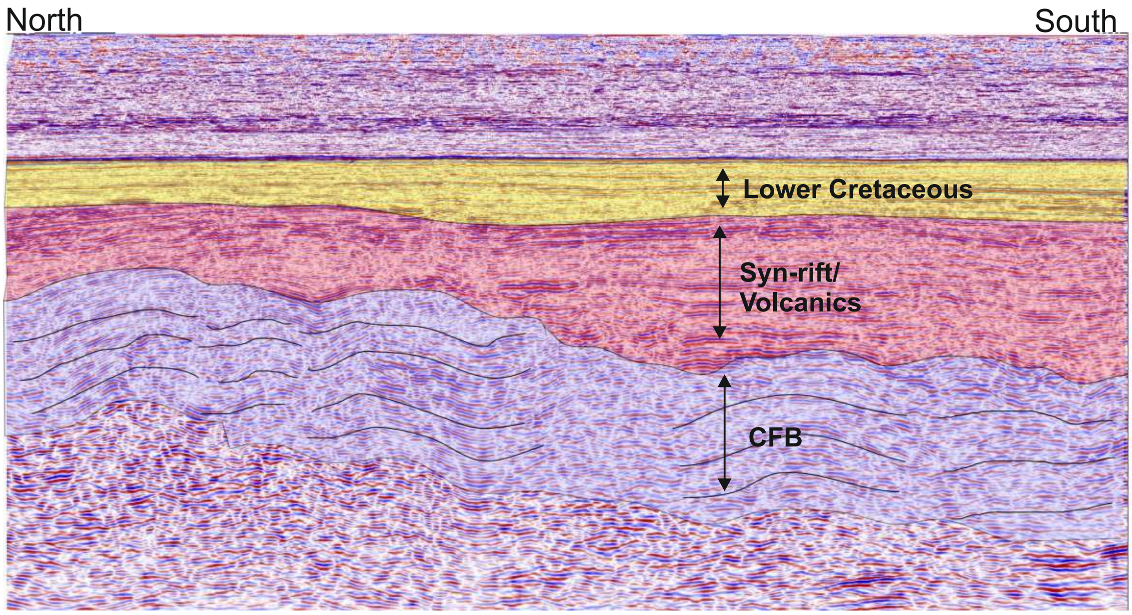
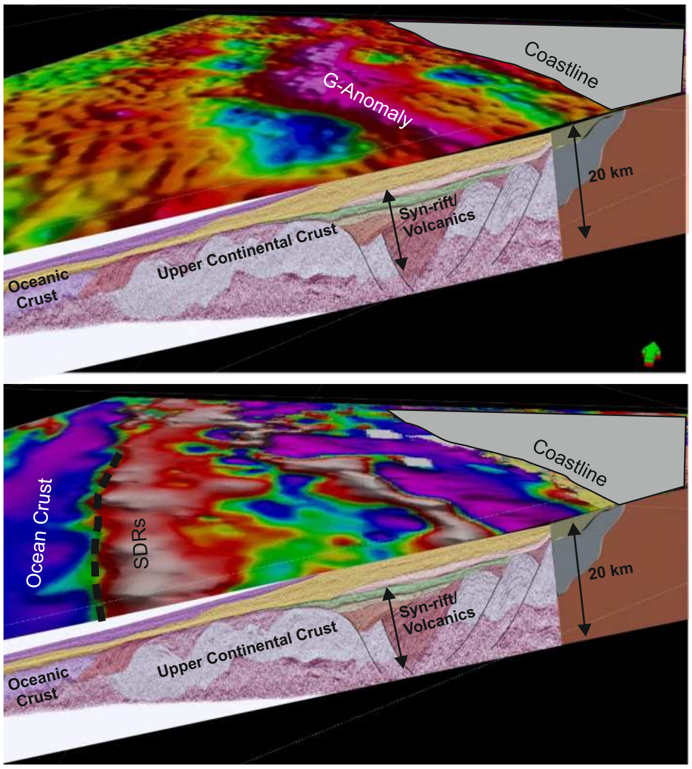
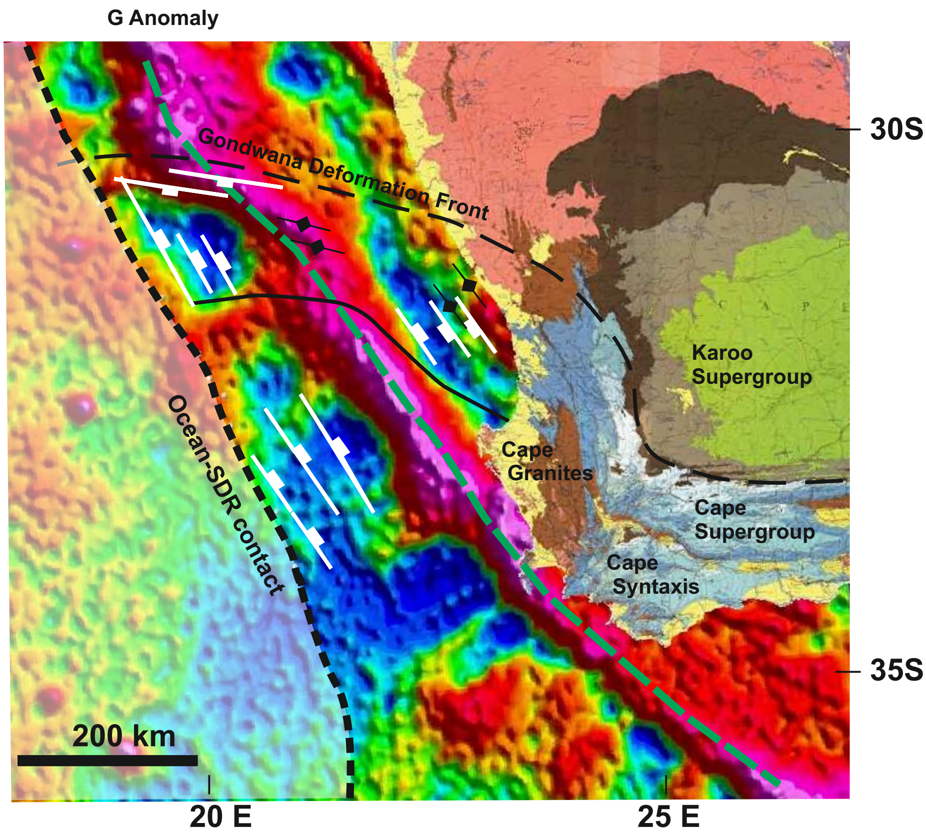


Figure 9



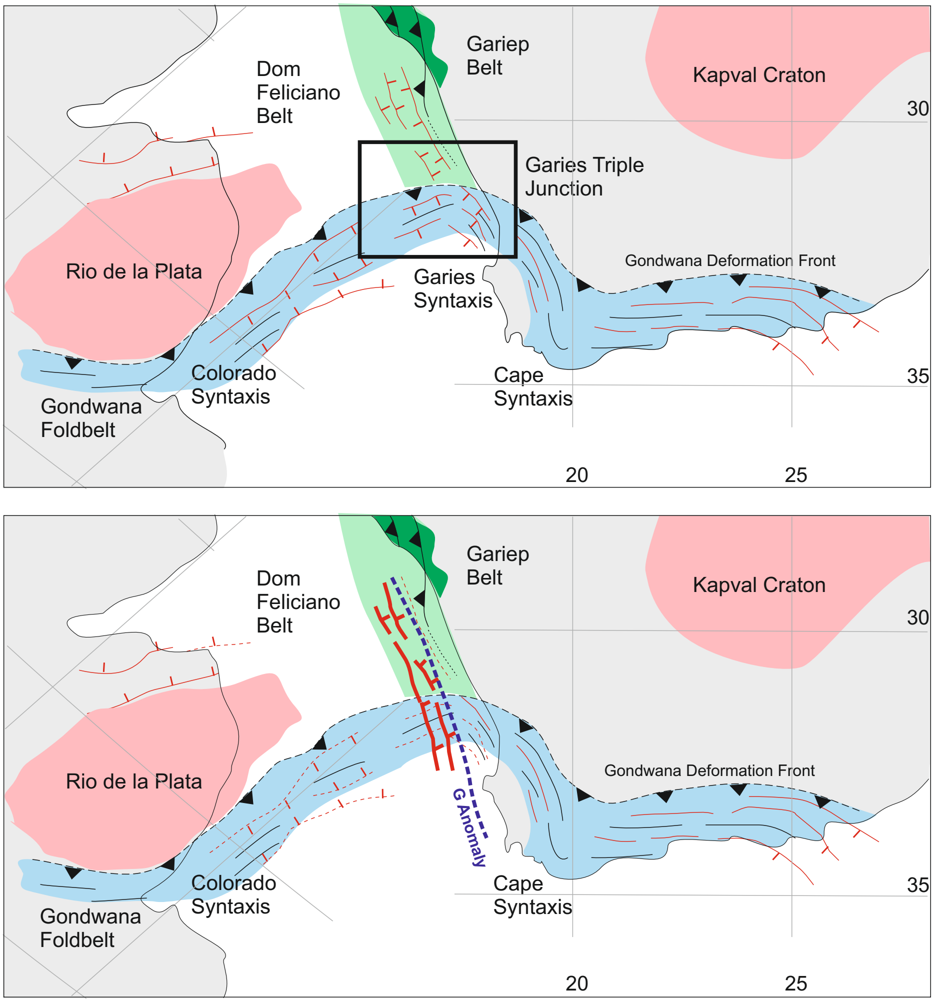
Coastline
G-Anomaly
20 km
Syn-rift/
Volcanics
Upper Continental Crust
Oceanic
Crust
Coastline
Ocean Crust
SDRs
20 km
Syn-rift/
Volcanics
Upper Continental Crust
Oceanic
Crust

Figure 10



G Anomaly
Gondwana Deformation Front
Karoo Supergroup
Cape Granites
Cape Supergroup
Cape Syntaxis
Ocean-SDR contact
200 km
30S
35S
20 E
25 E

Figure 11


Gariep
Belt
Dom
Feliciano
Belt
Kapval Craton
30
Garies Triple
Junction
Rio de la Plata
Garies
Syntaxis
Gondwana Deformation Front
Colorado
Syntaxis
Gondwana
Foldbelt
Cape
Syntaxis
35
20
25
Gariep
Belt
Dom
Feliciano
Belt
Kapval Craton
30
Rio de la Plata
Gondwana Deformation Front
G Anomaly
Colorado
Syntaxis
Gondwana
Foldbelt
Cape
Syntaxis
35
20
25