

Revealing the Beattie Magnetic Anomaly and the anatomy of the crust of southernmost Africa: Geophysics and deep sub-surface geology where the Cape Fold Belt and Karroo Basin meet

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ABSTRACT

The deep crust of the southernmost margin of Africa contains unresolved tectonic features such as the Paleozoic Cape Fold Belt (CFB), the Paleozoic-Mesozoic Karroo Basin and the largest terrestrial magnetic anomaly, the Beattie Magnetic Anomaly (BMA). Without resolving these structures, our understanding of the evolution of the southern margin will be incomplete and limited. Under the auspices of the Inkaba yeAfrica framework, several geophysical datasets were acquired from 2004 to 2007, along two transects across the margin and its unique tectonic features. This research presents a tectonic model and crustal geometry, at the centre 100 km of the western transect. The model is derived from the joint interpretation of: surface geology, aeromagnetic data, nearby deep boreholes, teleseismic receiver functions, impedance spectroscopy measurements on borehole samples, near vertical reflection seismic data (NVR), shallow P- and S-wave velocity data, wide angle refraction data and magnetotelluric data. The model differentiates a four component ~ 42 to 45 km thick crust and constrains the two part BMA to a ~10 to 12 km wide northern zone, and a ~5 to 7 km wide southern zone, both at ~7 to 8 km below surface, continuing for a depth of ~5 km, and, contained in the Mesoproterozoic Namaqua-Natal mid-crust. The BMA source is interpreted to be a Namaqua-like massive to disseminated, deformed/metamorphosed strataform sulphide ore body. The model presents evidence in support of a thin-skinned tectonic thrust model for the evolution of the flat-based CFB and shows no significant fore-deep stratigraphic thickening in the Karroo Basin towards the CFB front. The tectonic model suggests a Meso-Proterozoic collision orogen setting, overprinted by a mid-Phanerozoic thin-skinned fold and thrust belt coupled to the far-field accretion/subduction margin to the south.

Key words: Beattie Magnetic Anomaly, Karroo Basin, Cape Fold Belt, Seismic reflection, Namaqua Natal Metamorphic Belt.

INTRODUCTION

Tectonically, southernmost Africa is dominated by the Paleozoic Cape Fold Belt (CFB) and the Paleozoic-Mesozoic Karroo Basin, underlain by a Precambrian basement that hosts the world's largest terrestrial magnetic anomaly, the E-W Beattie Magnetic Anomaly (BMA) (Figures 1 and 2). These features were first observed almost a century ago, but remain enigmatic, and resolving them will have implications for our understanding of the anatomy and evolution of the southern margin of Africa. This research presents

further interpretation of the first ~100 km northeast-southwest near vertical reflection (NVR) seismic profile across the southernmost Karroo Basin (from Prince Albert in the south, to Slingersfontein farm in the north), the BMA and the tectonic front of the CFB (Figure 2). The NVR seismic profile forms part of the western branch of the longer onshore/offshore Inkaba yeAfrica geophysical Agulhas-Karoo Transect across the southern margin of Africa (www.inkaba.org). Inkaba yeAfrica is a German/South African research initiative that observes earth systems in a natural core-to-space laboratory over southern Africa (de Wit and Horsfield, 2006).

METHOD AND RESULTS

The NVR seismic data acquisition, -processing and preliminary interpretation of the profile are described in Lindeque *et al.* (2006; 2007). The final migrated seismic image is shown in Figure 3, the integrated line drawing interpretation is illustrated in Figure 4 and the new tectonic model depicted in Figure 5. The interpretation and revised tectonic model presented here, integrates coincident data from deep boreholes (Eglington and Armstrong, 2003), surface geology (Albat, 1984; CGS; Joubert 1971; 1986a,b; Macey 2000; 2001; in press; Stowe, 1980), impedance spectroscopy measurements on borehole samples (Branch *et al.* 2007), teleseismic receiver function data (Harvey *et al.* 2001), wide angle refraction data (Stankiewicz *et al.* 2007; 2008; Parsieglia *et al.* 2007; 2009), magnetotelluric data (Weckmann *et al.* 2007a,b), and shallow P- and S- wave velocity models (Bräuer *et al.* 2007). The NVR seismic profile reveals a complex circa 42 to 45 km thick crust, consistent with previous teleseismic receiver function analyses (Harvey *et al.* 2001) and wide angle refraction onshore/offshore modelling (Stankiewicz *et al.* 2007; 2008, Parsieglia *et al.* 2007; 2009). The resulting tectonic model differentiates four components:

1. THE UPPER CRUST

In the upper crust (<13 km), surface geology and two deep boreholes link a seismic stratigraphic package of variably dipping reflectors above a section of sub-horizontal reflectors to the Karoo- and Cape Supergroups, respectively. Folds and faults previously mapped at surface correlate downwards with distinct features in the upper 1 to 1.5 km of the seismic image, and with lateral velocity variation in shallow P- and S-wave velocity models (Bräuer *et al.* 2007). High S-wave velocities (2.82 - 3.30 km/s) correspond to major anticlinal hinges and low velocities to synclinal hinges. The seismic profile also images low-angle thrust faults rooted in a zone of local décollements at 2 to 3 km depth. This zone corresponds to velocity changes in the coincident refraction data, and a ~150 meter thick high conductivity/low resistivity ($< 2 \Omega\text{m}$) band in the coincident magnetotelluric (MT) data (Weckmann *et al.* 2007a,b). Impedance spectroscopy measurements on borehole samples of the graphitic and pyritiferous shales of the Whitehill- and Prince Albert Formations (the lower Ecca Group near the base of the Karoo Basin) suggest both formations may contribute to the high conductivity band (Branch *et al.* 2007). The ~2 to 5 km thick folded Karoo Supergroup rests paraconformably on the non-folded sandstone / shale Cape Supergroup. The latter corresponds to a prominent, sub-horizontal, highly reflective package along the entire profile, thickening N-S from ~2 to 10 km. The base of the Cape Supergroup is flat, even beneath the CFB front. The base is defined by a strong seismic discontinuity (unconformity) at ~5 to 10 km depth against the

underlying crystalline basement (see upper 10 km in Figures 4 and 5). The CSG is in parts, tectonically detached from the overlying Karoo Supergroup and underlying mid-crust (see CSG in Figure 5). There is no significant fore-deep stratigraphic thickening in the Karoo Basin, toward the CFB tectonic front (Figures 4 and 5, southern end).

2. THE MID-CRUST

This mid-crust wedge is ~21 km thick (from ~12 to ~33 km depth) in the south and ~13 km thick in the north and, consistent with rock retrieved from deep boreholes (Eglington and Armstrong, 2003), interpreted as an extension of the ~1.2 Ga Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB). Based on variation in reflectivity, the wedge is divided into three components and the fabric is interpreted as stacked wedges of the NNMB Bushmanland terrane (1.0 to 1.2 Ga amphibolite-granulite gneisses). The mid-crust contains a distinct north dipping seismic fabric, consistent with the D2 fabric mapped in the field (Albat, 1984; CGS; Joubert 1971; 1986a,b; Macey 2000; 2001; in press), but in contrast to previous models that postulated a dip to the south (*e.g.* Hälbig, 1983a,b,c; 1993). Previous models also propose NNMB up to the northern edge of the Cape Fold Belt Front (*e.g.* Cornell *et al.* 2006; de Beer and Meyer, 1983;1984) but the NVR seismic image presents evidence to suggest the NNMB continues below the CFB tectonic front and possibly farther south to the continental margin. A mid-crustal detachment, interpreted as a shear or thrust plane, separates the mid- and lower crust (red line and arrow in Figure 4, and red line between the mid-crust (shades of orange) and lower crust (shades of green and grey) in Figure 5).

3. THE BMA

Collectively the geophysical datasets constrain the two-part BMA, which is a new contribution to our understanding of this regional anomaly. The axes of the BMA maximum delineated from aeromagnetic data (Figure 1), correspond to two complex zones of higher reflectivity in the mid-crust, imaged ~5 to 7 km apart near the centre of the NVR seismic profile (Figures 3 to 5). A northern zone is ~10 to 12 km wide and a southern zone ~5 to 7 km wide. The combined width is ~24 km, with a maximum depth ~5 km and a depth to the top of the anomaly ~7 to 8 km. The northern zone corresponds to a high velocity ($> 6.4 \text{ km/s}$) region in the tomography model (Stankiewicz *et al.* 2007; 2008) and a ~5 to 10 km wide “bean shape” high conductivity anomaly (derived from the MT data, (Weckmann *et al.* 2007a,b)) with a bounding surface that is largely discordant to the seismic reflectors (Figure 5). The latter is interpreted as a metasomatic or metamorphic overprint effect. Some researchers previously related the source of the BMA to graphite bearing shear zones (Weckmann *et al.* 2007a,b) - but the mid-crust should then have displayed multiple

north dipping high conductivity anomalies to fit the seismic image, and others proposed a deep crustal suture zone and serpentinised ophiolite wedge (*e.g.* Burke, 1977; Corner, 1989; de Beer and Meyer, 1983;1984; Hälbich, 1993; Pitts *et al.* 1992). Here, it is postulated that the BMA source may also be interpreted as Namaqua-like massive to disseminated deformed / metamorphosed strataform sulphide ore body, flanked by smaller strataform ore bodies (Figure 5). This is similar to large base metal deposits found in the NNMB outcrops ~450 km to the northwest (Baillie, 2005; 2007; Colliston, 2002; 2003).

4. THE LOWER CRUST

The highly reflective lower crust wedge thins N-S from ~24 km to ~10 km thick and based on reflectivity variations, four sub-components are identified. From top to bottom these are: 1) a complex of north and south dipping reflectors (~5 to 20 km thick), interpreted as two interleaving slivers of Kheisian NNMB basement; 2) a ~10 km thick transparent layer, interpreted as older Palaeo-Proterozoic NNMB basement; and 3) a ~2 to 5 km thick layer of strong horizontal reflectivity, sub-parallel to a clearly imaged continuous Moho, interpreted as mafic underplating. The Moho shows complex structures at ~30 and 60 km along the profile. The NVR data suggest that the NNMB continues below the CFB front and possibly to the continental margin (Lindeque *et al.* 2007, Parsieglä *et al.* 2007; 2009).

THE TECTONIC SETTING

The upper crustal data supports a relatively thin skinned north verging end-Phanerozoic tectonic setting for the CFB most probably linked to far-field south-directed subduction processes (*e.g.* Lock 1980), without significant fore-deep stratigraphic thickening in the Karoo Basin, as suggested in previous models (*e.g.* Johnson *et al.* 2006). The middle- and lower crustal data supports Mesoproterozoic accretionary tectonics in a southward subducting regime during earlier NNMB basement evolution. The seismic discontinuity between the mid-and lower crust is interpreted as a south dipping thrust plane (thrusting to the north), related to Meso-Proterozoic tectonic accretion during final Rodinia assembly. The depth of the mid-crust discontinuity is consistent with teleseismic receiver function data (Harvey *et al.* 2003), and the interpreted thrusting to the north, is consistent with seismic profiles across the Kaapvaal craton that imaged the NNMB basement thrust against and onto the craton (*e.g.* Tinker *et al.* 2002). The tectonic model also suggests that the Meso-Proterozoic collision orogen was overprinted by a mid-Phanerozoic thin-skinned fold and thrust belt coupled to the far-field subduction/accretion margin to the south, during formation of Rodinia and Pangea respectively. This model stands in contrast to more widely accepted far-field subduction to the north models.

THE PROFILE IN A GLOBAL CONTEXT

Current Rodinia (Dalziel, 1991; Hoffman 1991) supercontinent reconstruction models link the NNMB to the Grenville Province of North America across the Grenville-Kibaran orogen (*e.g.* Li *et al.* 2008). The data presented allow the first direct comparison of seismic profiles across opposite flanks of this orogen. In this brief first order comparison of seismic profiles on neighbouring Rodinia remnants, the NVR seismic image may not be exactly the same as the LITHOPROBE Abitibi-Grenville line 32-33 that cross a coeval Mesoproterozoic terrane (Clowes *et al.* 1996; Ludden and Hynes, 2000; White *et al.* 2000), but structurally, it fits into the greater Rodinia reconstruction context. This first direct comparison of such NVR seismic profiles on adjacent remnants show that seismic profiles may be a useful tool to compliment or test palaeomagnetic pole data in supercontinent reconstructions.

CONCLUSIONS

Based on these datasets and seismic reflectivity variation, the complex 2 to 45 km thick crust is divided into four components: (1) the 2-5 km thick Karoo Supergroup and the 2.5-12 km thick Cape Supergroup (CSG) in the upper crust. The flat CSG base is defined by a strong seismic discontinuity. (2) The 13-21 km underlying mid-crust with a distinct north dipping seismic fabric, interpreted as ~1.2 Ga Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB) that contains the BMA (3). The highly reflective 10-24 km thick lower crust (4), interpreted as Kheisian NNMB basement and older Palaeo-Proterozoic NNMB basement. A 2-5 km thick highly reflective layer, sub-parallel to a clear Moho, interpreted as mafic underplating. In contrast to previous models, the NVR data and tectonic model presented here, support a thin-skinned north verging end-Phanerozoic tectonic setting for the CFB without significant fore-deep thickening in the Karoo Basin. The NVR data and joint interpretation of the other datasets also suggests the NNMB continues below the CFB tectonic front and possibly to the continental margin. In contrast to previous models it is postulated that the BMA source could be a large massive or disseminated metamorphosed strataform sulphide ore body similar to large base metal deposits in NNMB outcrops ~450 km to the northwest. The NVR profile fits in well with the recent global Rodinia reconstruction model.

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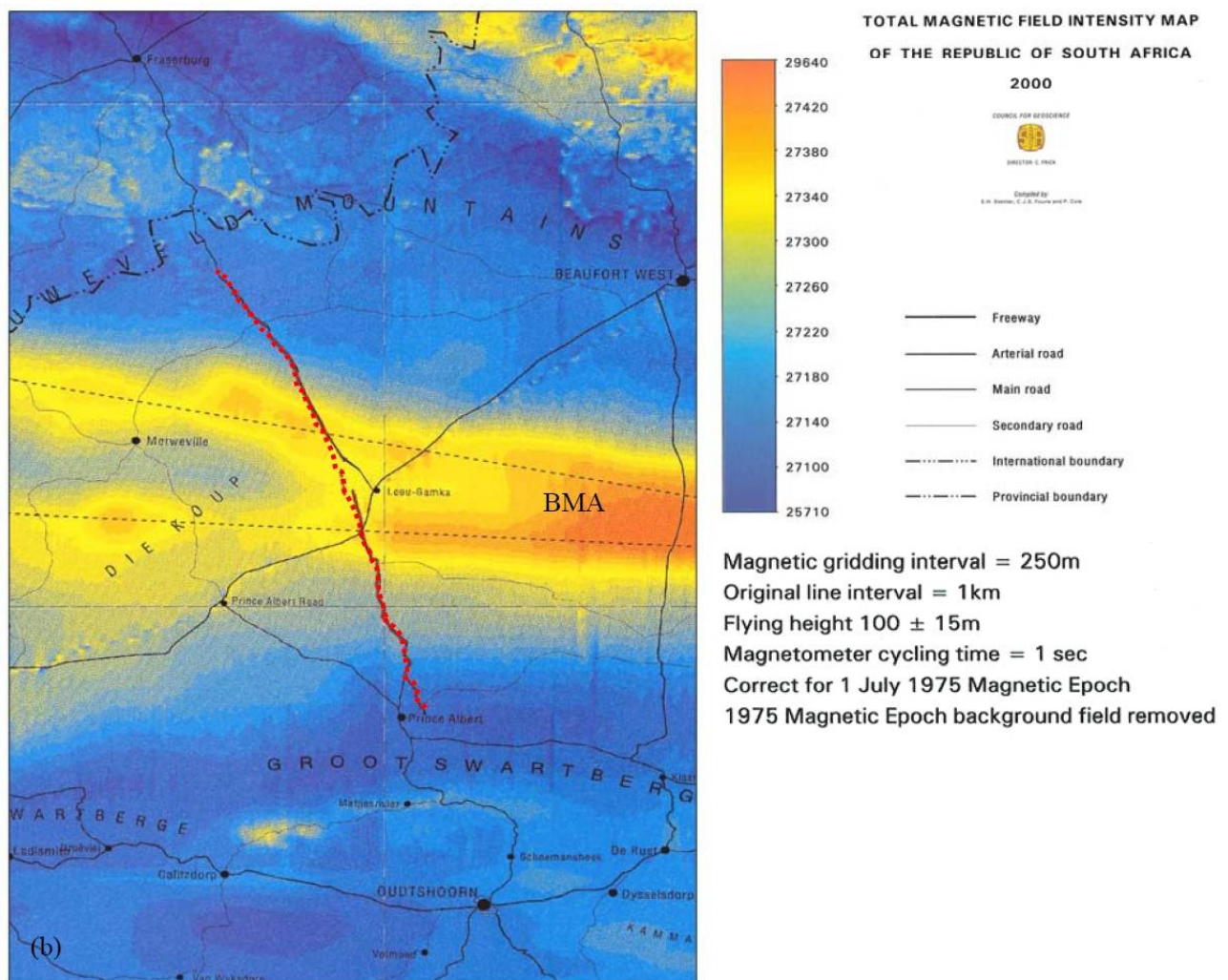
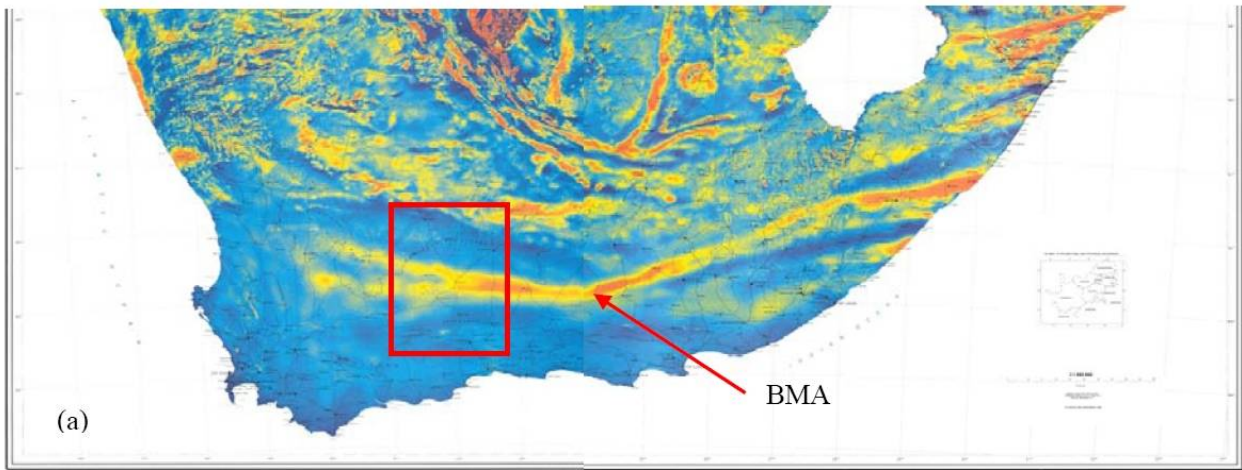


Figure 1. (a) Total field aeromagnetic map of southern Africa showing the regional east-west striking Beattie Magnetic Anomaly (BMA) and area of interest (red block). (b) Aeromagnetic map in area of interest: NVR1 profile shotpoints = red dots (~100 km); BMA maximum axes = black dashed lines; BMA extent (~ 30 km) = shades of yellow to red.

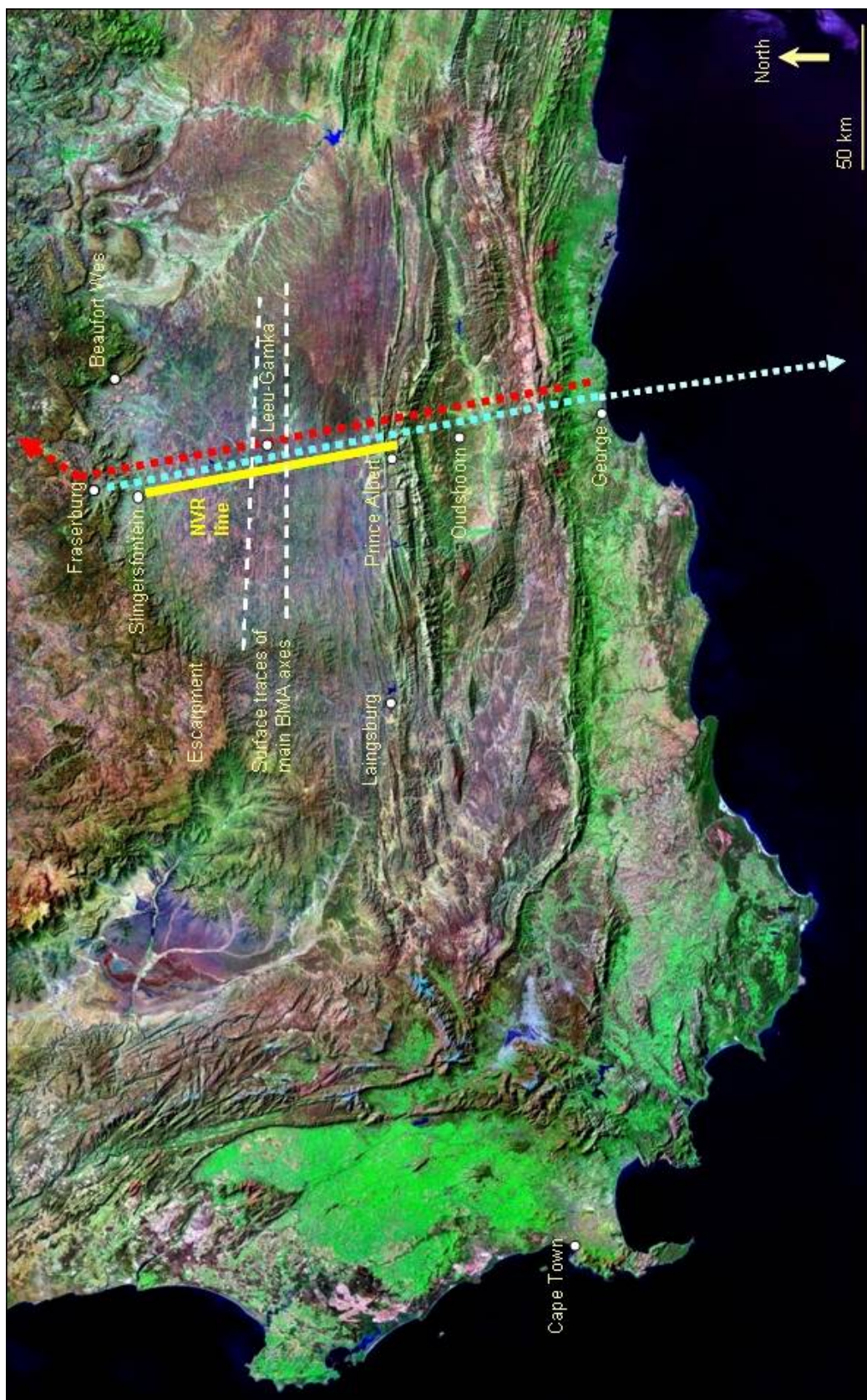


Figure 2. Satellite image of southwest South Africa showing the location map of the Agulhas-Karoo Geoscience Transect and surrounding towns. The different onshore-offshore experiments of the Agulhas-Karoo Transect are: yellow = Near Vertical Reflection (NVR) seismic line; light blue = Wide Angle Reflection Seismic (WRR) onshore-offshore line; red = Magnetotellurics profile. Surface traces of the main axes of the Beattie Magnetic Anomaly are indicated by the white dashed lines. (Source: <https://zulu.ssc.nasa.gov/>).

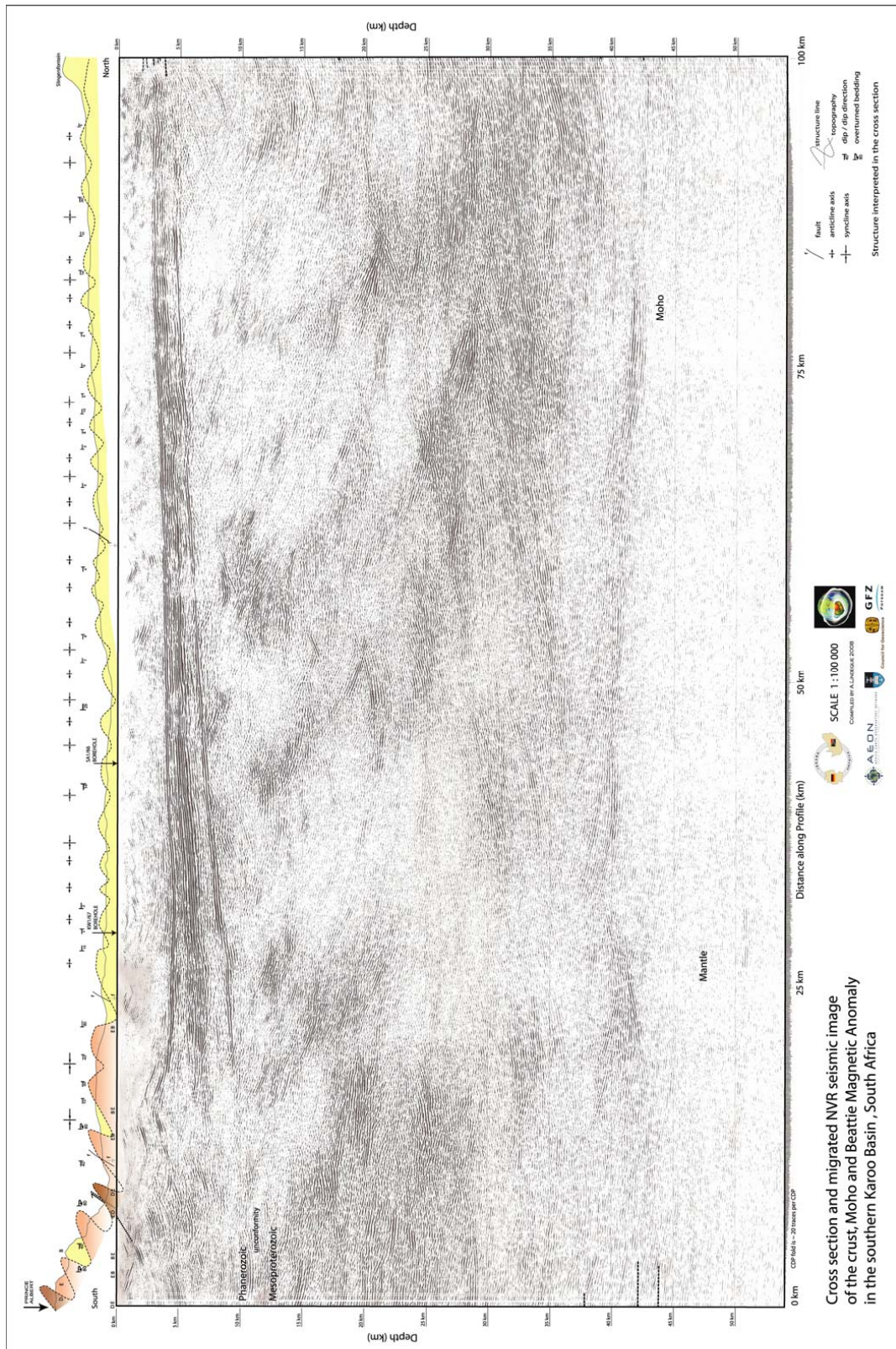


Figure 3. Geological cross section from the CGS 1:250000 mapsheets (5x vertical exaggeration) and the migrated CMP seismic profile in depth domain with coherency (dip- scan filter) applied before migration. Regions with complex distinct reflectivity are imaged in the upper, middle and lower crust. A series of shallow, continuous, slightly south dipping reflectors occur along most of the profile at approximately 1.5 to 3.5 s TWT. This package is very different from the deeper reflections. A region of strong reflectivity outlines the expected region of the BMA, at 5 s TWT and 55 to 65 km along the profile. Highly reflective lower crust is imaged from 12 to 15 s TWT, and the Moho is clearly imaged at 42 to 45 km or ~15 s TWT. CMP interval 50 m.

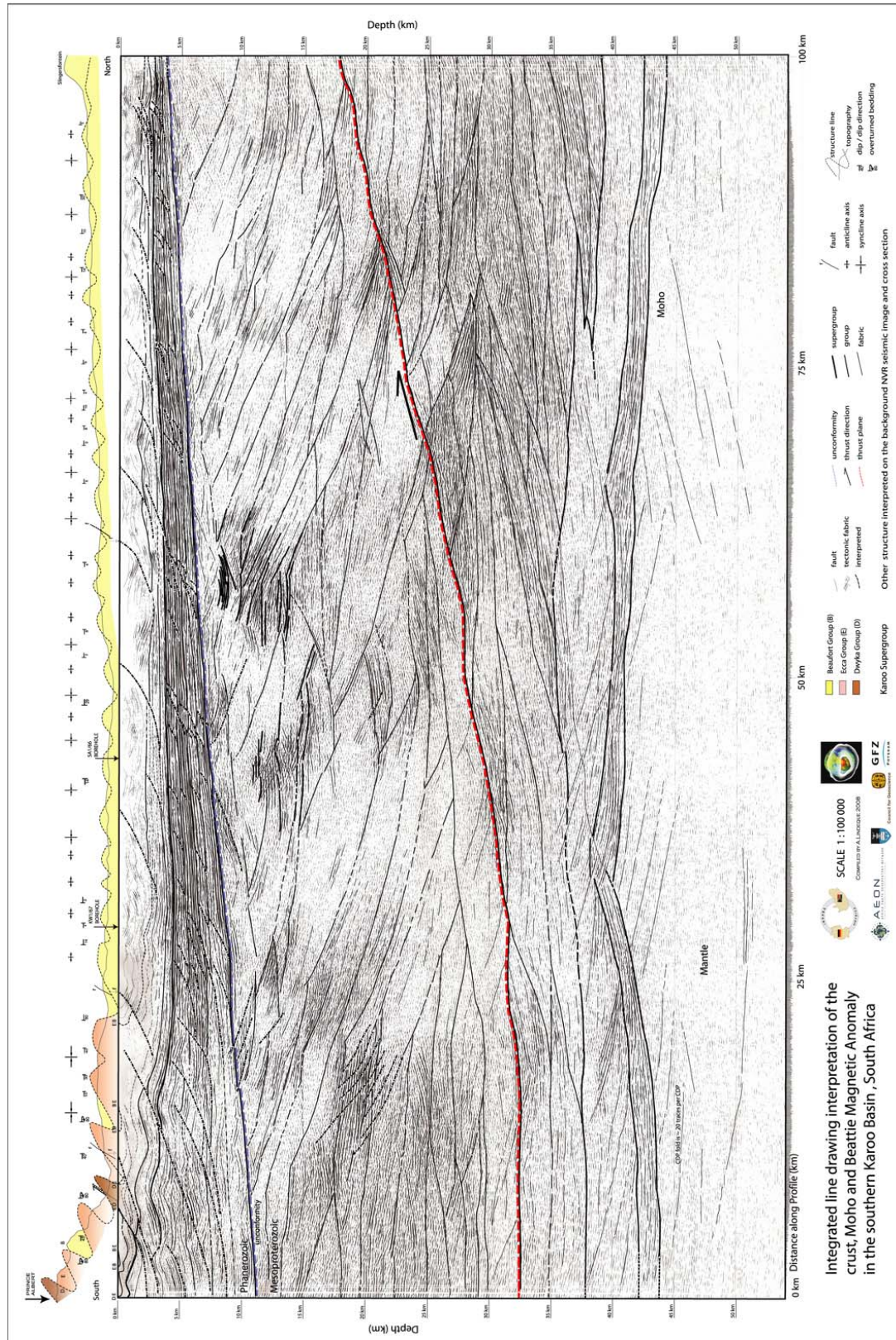


Figure 4. Interpretive line drawing superimposed on the migrated section and geological cross section at the top. Note the difference in tectonic fabric between the upper-, middle and lower crust. The upper crust fabric = mostly sub-horizontal with series of low angle listric faults; Mid-crust fabric dips dominantly north; Lower crust fabric is complex and dips both to the north and south, with an underlying less reflective layer. A highly reflective layer with dominantly horizontal fabric are imaged above the clearly defined Moho. The upper-/ mid-crust unconformity is marked in the blue dashed line and the mid-crustal detachment (interpreted as a thrust/shear plane) delineated by the red dashed line.

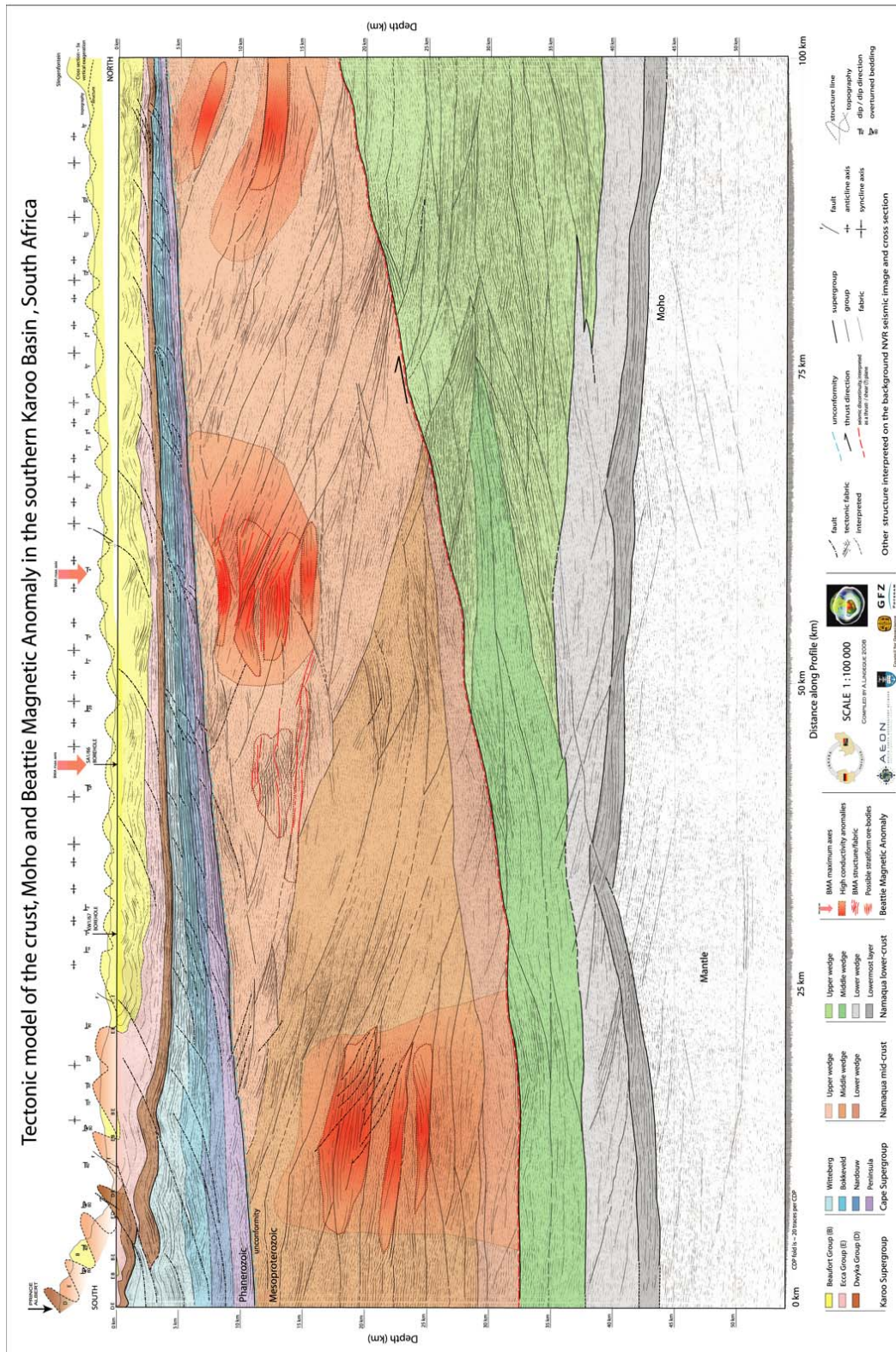


Figure 5. Newly proposed tectonic model and geological cross section from 1:250000 map sheets. The upper crust = Karoo Supergroup (yellow = Beaufort Group; pink = Ecca Group; brown = Dwyka Group) and Cape Supergroup (light blue = Witteberg Group; blue = Bokkeveld Group, light purple = Nardouw Formation and dark purple Peninsula Formation). Low angle thrusts (dashed lines) are rooted in a décollement, interpreted between the Ecca and Dwyka Groups, along the Whitehill Formation. The Phanerozoic Cape Supergroup is detached from the basement by a clearly imaged angular unconformity (blue dashed line). Mid-crust = shades of orange, interpreted as Mesoproterozoic Namaqua-Natal Metamorphic Belt wedges of the Bushmanland Group. The northerly dip contrasts with previous models. The two part Beattie Magnetic Anomaly (BMA) at depths of 7 - 15 km (red polygons in the middle). Mid-crustal detachment = red/black line in the middle; Lower crust = shades of green, interpreted as older Palaeo-Proterozoic slivers, bounded by a above, and older material below (light grey). A 1 to 2 km thick layer of mafic underplating material straddles the Moho (dark grey).