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An integrated geophysical study of the Beattie Magnetic Anomaly, South Africa

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ABSTRACT

The source of the Beattie Magnetic Anomaly (BMA) still remains unclear, with several competing hypotheses. Here we add a piece to the puzzle by investigating available potential field data over the anomaly. Filtered magnetic data show the BMA as part of a group of linear magnetic anomalies. As the linear anomaly north of the BMA is associated with exposed supracrustals, migmatites and shear zones within the Natal thrust terranes we assume a similar source for the BMA. This source geometry, constrained by seismic and MT data, fits potential field data over the BMA and other magnetic linear anomalies in the south-central and south-western Karoo. In these models the bodies deepen from ~5 km towards the south, with horizontal extents of ~20–60 km and vertical extents of ~10–15 km. Densities range from 2800 to 2940 kg/m^3 and magnetic susceptibilities from 10 to 100 × 10^{-3} SI. These magnetic susceptibilities are higher than field values from supracrustal rocks (10–60 × 10^{-3} SI) but could be due to the fact that no remanent magnetisation was included in the model. The lithologies associated with the different linear anomalies vary as is evident from varying anomaly amplitudes. The strong signal of the BMA is linked to high magnetic susceptibility granulite facies supracrustals (~10–50 × 10^{-3} SI) as seen in the Antarctic, where the mobile belt continued during Gondwana times.

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1. Introduction

The Beattie Magnetic Anomaly (BMA) that runs along almost the entire southern portion of South Africa (Fig. 1) was first recognised in the early 1900s (Beattie, 1909) but even today its source is the matter of an ongoing debate. On the east coast, where the BMA source is at its shallowest, it is truncated by the Agulhas fracture zone, implying that the body causing the anomaly formed prior to Gondwana breakup (Pitts et al., 1992).

Several geophysical studies have been conducted to better understand the source of the magnetic anomaly. One of these include a large-scale magnetic survey carried out in southern South Africa in the early 1970s (and later extended), which led to the identification of the Southern Cape Conductive Belt (SCCB, Fig. 1) (de Beer and Gough, 1980; de Beer et al., 1982; Gough et al., 1973). This 140 km broad and 1000 km long conductive zone that runs east-to-west across southern South Africa was suggested to be linked to a lower crustal or upper mantle source. The rough coincidence of the SCCB and BMA led to the proposal of a common source, namely a dipping slab of serpentinised oceanic crust representing a Pan African suture zone (~500 Ma) (de Beer and Meyer, 1983; de Beer et al., 1974, 1982; Hälbich, 1993). A receiver function study recognised discontinuities at ~8–11 km and ~18 km depth at four seismic stations in this region that were attributed to this slab (Harvey et al., 2001). The BMA and SCCB show no special correlation with younger (≤180 Ma) large-scale geological features such as the edge of the inland plateau (Fig. 1).

Studies by Corner (1989) correlating geological and magnetic data led to the hypothesis that the BMA forms part of the NNMB basement rocks. Corner (1989) proposed water movement and mineralisation along low-angle thrust zones within the basement as the source, as well as the extension of the BMA into Antarctica. Thomas et al. (1992b) in turn suggested that the BMA is one of several magnetic linear anomalies visible along the east coast of South Africa, which are associated with shear zones within the Natal basement. The magnetic linear anomaly north of the BMA close to Amanzimtoti was labelled the Williston anomaly, and the Mbashe anomaly was identified to the south of the BMA (Thomas et al., 1992b).

Several geophysical studies have been conducted in recent years in the south-western Karoo linked to the Inkaba yeAfrica project, which have explored deeper basement structures including the BMA. These include magnetotelluric (MT) studies (Weckmann et al., 2007a, 2007b), as well as a near-vertical reflection study (Lindeque et al., 2007, 2011) and wide-angle refraction studies (Stankiewicz et al., 2007, 2008). These

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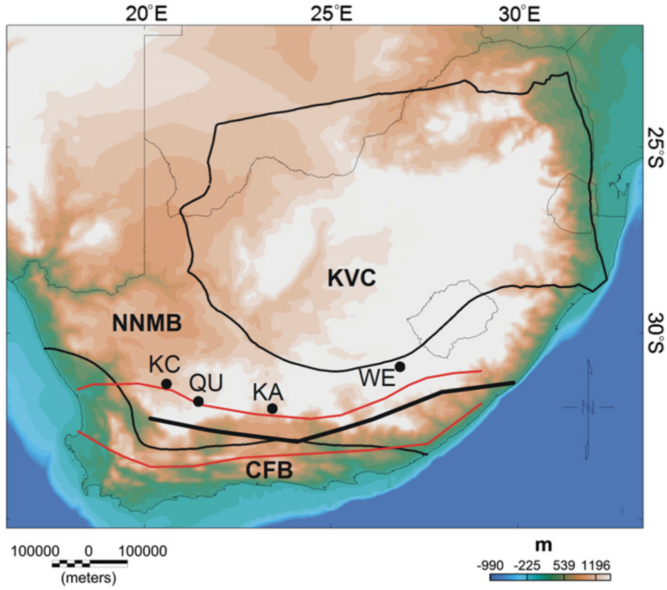

Fig. 1. Topographic map of South Africa (Amante and Eakins, 2009) with the major tectonic provinces outlined (thin black lines). These include the Archean Kaapvaal Craton (KVC), surrounded by the Namaqua–Natal mobile belt (NNMB), and the deformed Cape Fold Belt (CFB) in the south. The outline of the Southern Cape Conductive Belt (red lines), and the maximum axis of the Beattie Magnetic Anomaly are shown (thick black line). The location of deep SOEKOR boreholes that intersect basement is labelled (black circles, KA1/66, KC1/70, QU1/65 and WE1/66, Eglington and Armstrong (2003)).

studies placed the source of the anomaly in the south-western Karoo at a depth of between 5 and 15 km within the mid-crust.

A comprehensive magnetic modelling study by Quesnel et al. (2009) showed that two wide, highly-magnetised sheet-like prisms (~80 km, >5 $A.m^{-1}$) provide the best-fit for the BMA. Tankard et al. (2009) used geological and geophysical data to attribute the BMA to volcanic rift fill, while the SCCB is linked to upthrust mantle using teleseismic Moho depths.

Despite these comprehensive studies of the BMA, a more detailed investigation of existing magnetic and gravity data over the anomaly is needed. In this study we present an integrated analysis using these and other geophysical data to identify the source of the anomaly. We also investigate similar linear magnetic anomalies within the Natal belt, one of which partly outcrops north of the Beattie on the east coast of South Africa. Newly investigated links between geology and magnetic anomalies in this region are extended to the source of the Beattie.

2. Geology of the Namaqua–Natal Metamorphic Belt and Cape Fold Belt

The source of the BMA is covered across its entire extent by younger sediments. To the north of the anomaly Namaqua–Natal mobile belt (NNMB) basement rocks are exposed, while to the south deformed Cape Supergroup rocks are exposed in the Cape Fold Belt (CFB). As several previous geophysical studies have linked the anomaly to this mobile belt (Corner, 1989; Thomas et al., 1992b; Weckmann et al., 2007b), we investigate the exposed Natal portion of the belt on the east coast of South Africa.

The NNMB abuts the KVC and dates to the formation of Rodinia around 1 Ga (Jacobs et al., 1993). This belt can be traced through the Falkland Plateau to Western Dronning Maud Land in east Antarctica as these regions were joined during Gondwana times (Frimmel, 2004; Grantham et al., 2001; Jacobs et al., 1997).

While commonly thought of as one continuous belt, several studies have highlighted differences between the Natal and Namaqua belts. The Natal crust in the east has been identified as entirely juvenile with isotope model ages younger than ~1.5 Ga (using Rb–Sr, Sm–Nd and U–Pb dating; Eglington et al., 1989; Thomas and Eglington, 1990); while the Namaqua crust in the northwest contains older fragments of crust (2.0–1.7 Ga, using U–Pb and Sm–Nd dating; Raith et al., 2003; Robb et al., 1999) as well as juvenile fragments identified using isotope dating (Cornell et al., 1986; Geringer et al., 1994). Isotopic analysis of basement rocks from deep SOEKOR boreholes (KA1/66, KC1/70, QU1/65 and WE1/66 in Fig. 1) was used to define a boundary between the Namaqua and Natal belts in the south-western Karoo (Eglington, 2006; Eglington and Armstrong, 2003). Most importantly, borehole QU1/65 contains basement rocks from both terranes and is therefore on the boundary between the two belts. These data confirm the boundary previously suggested using geophysical data (de Beer and Meyer, 1984; Thomas et al., 1992b).

The Natal belt developed as a result of oceanic-arc tectonics, with arc complexes forming in a basin to the south and accreting onto the KVC to the north during basin closure (Cornell et al., 2006) (Fig. 2). The oceanic/island-arc of the Tugela terrane was emplaced onto the craton boundary between 1155 and 1140 Ma, followed by the accretion of the Mzumbe–Margate terranes between ~1091 and ~1070 Ma (age estimates vary slightly from study to study) (McCourt et al., 2006). Subsequent crustal thickening resulted in regional deformation fabrics and metamorphism. During the intrusion of the Oribi Gorge Suite (pulses at 1070 and 1030 Ma), the regime of deformation changed from northward-vergent fold and thrust tectonics, to ENE-trending sinistral shear (Eglington and Armstrong, 2003; Jacobs et al., 1993), resulting in the formation of large shear zones. This change in the tectonic regime was most likely due to continued northeast–southwest convergence along the approximately east–west craton margin (Jacobs and Thomas, 1994).

These large-scale shear zones commonly define terrane boundaries. The Tugela terrane at amphibolite and greenschist facies is separated by the ENE-trending Lilani–Mabigulu shear zone from the upper amphibolite (and locally granulite) facies Mzumbe terrane. The Melville thrust and associated shear zone (Lovat shear zone) in turn forms the boundary to the Margate terrane in the south, which has been metamorphosed to granulite facies (Jacobs et al., 1993; Thomas, 1989). An additional shear zone, the Vungu shear zone, has most recently been mapped by Voordouw (2010) further south of the Melville thrust.

Lithostratigraphic units making up the Mzumbe and Margate terranes include the supracrustal gneisses of the Mapumulo and Mzimkulu groups respectively, as well as S-type orthogneisses that are the oldest intrusives (SACS, 1980). Younger rocks within the Mzumbe terrane include S-type granitoids and mafic intrusions (Equeefa Suite), and the more recent A-type plutons of the Oribi Gorge Suite (McCourt et al., 2006).

The Mapumulo metamorphic rocks of the Mzumbe terrane are subdivided into the Quha and Ndonyane Formations in the south, while rocks in the northern part of the terrane are yet unclassified. There formations comprise heterogeneous layered gneisses (supracrustals) and migmatites with a wide range of compositions (Thomas, 1992). These deformed units originate mainly from sedimentary and volcanic/volcaniclastic rocks, and to a less extent extruded and/or eroded products from juvenile volcanic arcs (Thomas and Eglington, 1990; Thomas et al., 1992a). Several rocks within this terrane would be expected to be highlight magnetic, such as prominent layers (~1 m) of fine-grained banded magnetite quartzite, grunerite and garnet in the north of the Mzumbe terrane (Scogings et al., 1984). Serpentinite and amphibolite are found closely associated with these supracrustals.

A study by Maré and Thomas (1998) on one of these Oribi plutons led to the proposal that the strong magnetic signal associated with these plutons is due to the plutons themselves, as well as remnants of the supracrustal Mapumulo suite gneisses beneath the pluton. More

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