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Investigating the distribution of magmatism at the onset of Gondwana breakup with novel strapdown gravity and aeromagnetic data

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ABSTRACT

Massive volumes of mafic magmatism forming the Karoo-Ferrar Large Igneous Province (LIP) in Southern Africa and Antarctica preceded Jurassic breakup of the Gondwana Supercontinent. This widespread LIP magmatism is attributed to a major mantle plume, or plumes, impacting an area thousands of kilometres across. Magmas in lava flows and shallow sills, which flowed laterally hundreds to thousands of kilometres, form most of the exposed LIP. Hence, the distribution of shallow level mafic rocks may not reflect the location of mantle melting. In contrast, large deep-seated mafic intrusions such as gabbros likely more directly overlie areas of mantle melting. Antarctic exposures of such intrusions are limited to the Dufek Intrusion and outcrops > 1000 km to the north, hence the true pattern of mantle melting is poorly constrained. Regional aeromagnetic and aerogravity data suggest other Jurassic mafic intrusions are present, but detailed analysis of these bodies is lacking. To define more precisely the distribution of mafic intrusions we use data from the first stand-alone strapdown gravity survey in Antarctica. This innovative technique allows collection of aerogravity data during draped flight, resolving anomalies with a wavelength of ~6 km and a root-mean-square error of 1.8 mGal. Combining this new gravity data with coincident aeromagnetic data we investigate a ~50 mGal gravity and associated > 1000 nT magnetic high in Coats Land, East Antarctica. Our interpretation is that the so called 'Halley High' reflects a large gabbroic body ~80 km long, 30 km wide and ~6 km thick, equivalent to the inferred total size to the better known Stillwater layered mafic intrusion in the US. Our interpretation of a large mafic intrusion supports the suggestion from reconnaissance aeromagnetic data that this and other similar anomalies are Jurassic mafic intrusions. These large mafic intrusions, and hence underlying mantle melting, appear restricted to a linear band parallel to the continental margin. This structured pattern of mantle melting is consistent with shallow mantle convection and lithospheric extension playing a significant role in the later stages of the Karoo-Ferrar magmatism. An apparent 650 km gap in mafic intrusions adjacent to the continental Weddell Sea Rift System suggests different mantle processes were occurring here. Future joint magnetic and strapdown gravity surveying presents a key opportunity to fully constrain the location and extent of mantle melting during Gondwana breakup.

1. Introduction

Breakup of Gondwana was associated with massive volumes of magmatism. The exposed magmas are dominated by shallow level Karoo Continental Flood Basalts (CFB) in South Africa and Dronning Maud Land, and the Ferrar sill complex elsewhere in Antarctica (Elliot and Fleming, 2000). Given their approximate coincident age, these two provinces are often amalgamated into the Karoo-Ferrar Large Igneous Province (LIP), which extends from southern Africa around the Dronning Maud Land, Coats Land and Transantarctic Mountain margins of East Antarctica, a distance of > 3000 km (Fig. 1) (Elliot, 1992; Elliot and Fleming, 2000; Ferraccioli et al., 2005; Jourdan et al., 2005; Riley et al., 2005). This major magmatic event is widely attributed to the impact of a significant mantle plume at the base of the Gondwanan lithosphere, which was associated with magmatism and subsequent continental rifting (Storey, 1995; Storey et al., 2013; White and McKenzie, 1989). The extent of the mantle plume, super plume, or multiple plume heads is difficult to constrain given the proposed 100 s to 1000 s km of lateral transport of surficial flood basalts and sills (Elliot et al., 1999; Leat, 2008; Luttinen et al., 2010). Deep-seated large mafic intrusions, which reflect igneous centres, may be better indicators of the areas of mantle melting, as suggested in the North Atlantic LIP

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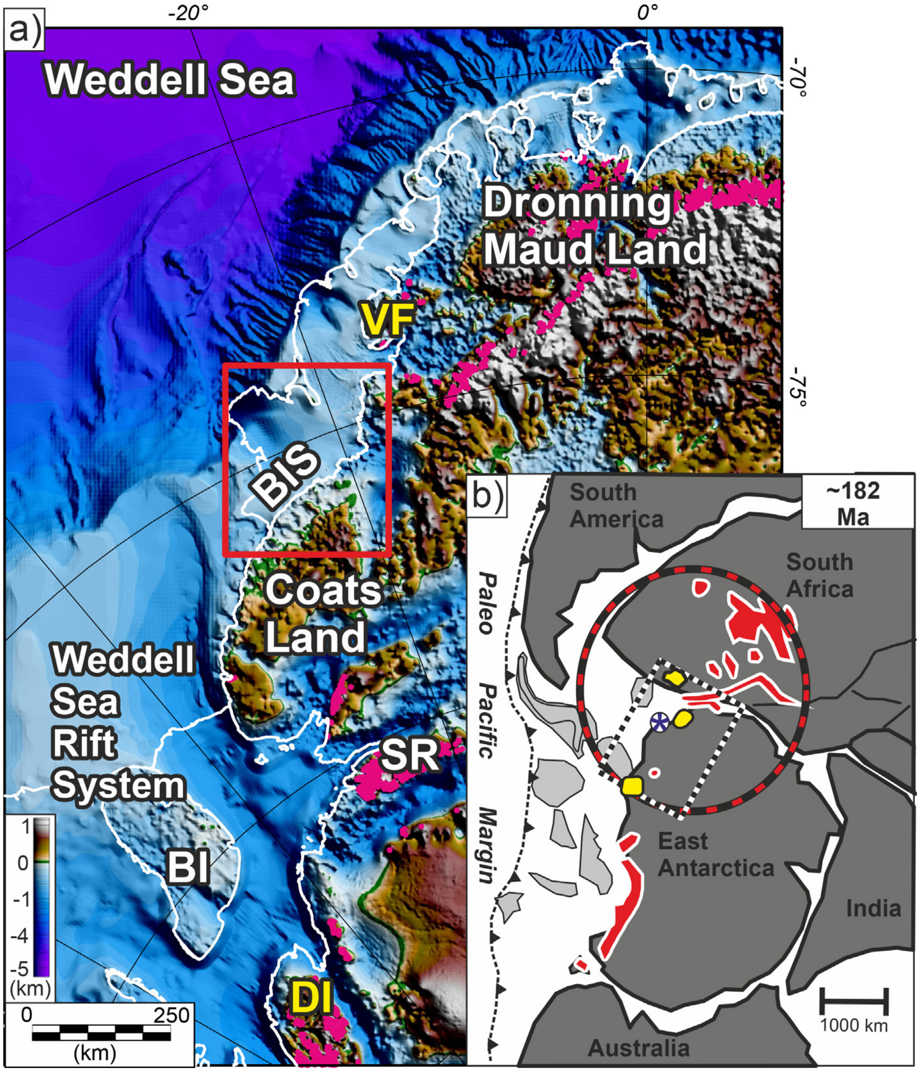

Fig. 1. Geographic and tectonic setting. a) Bathymetry and onshore sub-ice topography from BEDMAP2 (Fretwell et al., 2013). Red box over the Brunt Ice Shelf (BIS) locates Fig. 2. White lines show coast and ice shelf margins. Pink lines locate rock outcrops. Yellow letters mark gabbroic layered intrusions (Dufek Intrusion (DI) and in the Vestfjella area (VF)). SR and BI mark the Shackleton Range and Berkner Island respectively. b) Tectonic reconstruction of Gondwana (Dalziel et al., 2013; Jordan et al., 2017). Red areas mark Karoo-Ferrar magmas. Yellow areas locate exposed large gabbroic intrusions. Circle marks inferred plume head (White and McKenzie, 1989). Black and white dotted box locates (a). Blue star locates study area. Light and dark grey areas mark microcontinental fragments and continental blocks respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Geoffroy et al., 2007). Unfortunately, deeper level mafic intrusions associated with the Karoo-Ferrar LIP in Antarctica are only exposed in two areas (Fig. 1) (Semenov et al., 2014). Firstly Vestfjella in Dronning Maud land where two separate layered Gabbro intrusions up to 25 km^2 and 3 km thick are seen cross cutting the CFB sequences (Vuori and Luttinen, 2003). Secondly the Dufek Intrusion ~1000 km further south, suggested from geological observations to cover an area of 24,000–34,000 km^2 with an estimated thickness of 8–9 km (Ford and Himmelberg, 1991), although aeromagnetic data suggests an area of closer to 6600 km^2 (Ferris et al., 1998). Gabbroic intrusions such as the Mount Ayliff/Insizwa complex and the New Amalfi intrusion are also seen in Southern Africa (Lightfoot and Naldrett, 1983) where geological and geophysical considerations suggest such bodies are sill-like structures ~1 km thick, with an original area of ~2000 km^2 (Lightfoot and Naldrett, 1983; Sander and Cawthorn, 1996).

The sub-ice extent of individual Antarctic intrusions has been investigated using aerogeophysical data, although precise determination of intrusion size has been controversial (Behrendt et al., 1981; Ferris et al., 1998; Semenov et al., 2014). A number of additional magnetic anomalies of high to moderate amplitudes associated with magmatism during Gondwana break up are inferred within the continental crust from regional aeromagnetic compilations (Corner, 1994; Golynsky and Aleshkova, 1997; Leitchenkov et al., 1996), regional aerogravity data (Aleshkova et al., 1997) and ground based surveys (Ruotoistenmäki and Lehtimäki, 1997). However, the details of these features have remained scarce due to the reconnaissance nature of the geophysical data coverage. Here we use new 5 km line spacing aeromagnetic data and innovative new strapdown aerogravity data collected over the Brunt Ice Shelf in 2017, to investigate in detail the structure and origin of one of these key anomalies. Using a range of digital enhancements, depth to source calculation and modelling we propose that a significant, likely Jurassic, mafic body is present beneath the northern margin of the Brunt Ice Shelf. Confirmation of this anomaly as a large mafic intrusion supports previous interpretations of numerous mafic bodies lying along the Antarctic rifted margin e.g. (Golynsky and Aleshkova, 1997), and hence the concept of regionally extensive mantle melting feeding the Karoo-Ferrar LIP. The implications of this interpretation for the distribution, timing, mechanism and possible analogues for magma generation at the onset of Gondwana breakup are discussed.

1.1. *Geographical and geological setting*

The study area lies beneath the Brunt Ice Shelf, ~80 km south from the continental shelf break and the deep ocean floor of the Weddell Sea (Fig. 1a). West of the study area is the Weddell Sea Rift System, a Jurassic continental rift overlain by a broad sediment-filled marine basin (Jordan et al., 2017; Leitchenkov and Kudryavtzev, 1997; Studinger and Miller, 1999). To the south and east of the study area is the East Antarctic continent, which is typically blanketed by the 2–4 km thick East Antarctic Ice Sheet, although sparse outcrops along the coast and in some inland mountain chains allow assessment of the underlying geology (Fig. 1a). The overarching geological structure of this part of