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High-resolution airborne gravity imaging over James Ross Island (West Antarctica)

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Abstract James Ross Island (JRI) exposes a Miocene-Recent alkaline basaltic volcanic complex that developed in a back-arc, east of the northern Antarctic Peninsula. JRI has been the focus of several geological studies because it provides a window on Neogene magmatic processes and paleoenvironments. However, little is known about its internal structure. New airborne gravity data were collected as part of the first high-resolution aerogeophysical survey flown over the island and reveal a prominent negative Bouguer gravity anomaly over Mt Haddington. This is intriguing as basaltic volcanoes are typically associated with positive Bouguer anomalies, linked to underlying mafic intrusions. The negative Bouguer anomaly may be associated with a hitherto unrecognised low-density sub-surface body, such as a breccia-filled caldera, or a partially molten magma chamber.

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Introduction

Aeromagnetic data are often utilised to image volcanoes. Recent examples include aeromagnetics over Yellowstone (Finn and Morgan, 2002) and Mt Rainier (Finn et al., 2001). Extensive aeromagnetic investigations over the West Antarctic Ice Sheet have identified subglacial volcanic caldera complexes (Behrendt et al., 1998) and a possible active subglacial volcano (Blankenship et al., 1993). Other examples include aeromagnetic and land-based gravity surveys over Mt Melbourne, along the Ross Sea coast (Ferraccioli et al., 2000) and Deception Island (Muñoz-Martín et al., 2005).

Considerable improvements in GPS accuracy have made airborne gravity an increasingly utilised tool for Antarctic geological research (Bell et al., 1999). However, to our knowledge airborne gravity has not been used so far to investigate Antarctic volcanoes (LeMasurier and Thomson, 1990). We show the potential of airborne gravity for volcano studies, by presenting a high-resolution airborne gravity survey flown over the James Ross Island (JRI) region, close to the eastern tip of the Antarctic Peninsula (Fig. 1).

JRI is dominated by the long-lived (>6Ma to 80 ka) James Ross Island Volcanic Group (Smellie et al., 2006). JRI is currently undergoing intense study as the volcanogenic deposits contain a detailed record of Neogene paleoclimates and paleoenvironments (Smellie, 1999; Smellie et al., 2006). The offshore sedimentary sequences are also under investigation by the SHALDRIL project (SHALDRIL, 2006). Although JRI stratigraphy can be investigated directly, where there is exposed rock, its interior is covered by a permanent ice cap. Hence the sub-surface structure of JRI is poorly understood. Regional studies comprise land-based gravity and aeromagnetic studies (Garrett 1990, LaBrecque and Ghidella, 1997).

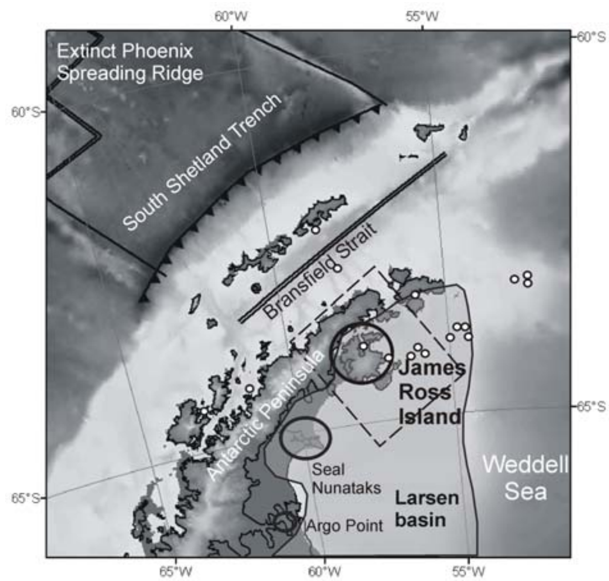

Figure 1. Tectonic setting of James Ross Island (Robertson Maurice et al., 2003). Oval regions mark alkali volcanic fields (Smellie, 1999). Shaded region marks the Larsen basin (Del Valle et al., 1992). White dots are locations of SHALDRIL drill sites. Dashed box marks location of Figure 2.

Geological framework

JRI developed on the western edge of the Larsen Basin (Del Valle et al., 1992; Elliot, 1998), a locus of Late Mesozoic to Cenozoic subsidence and deposition in a back-arc associated with subduction west of the Antarctic Peninsula. The Antarctic Peninsula was the site of coeval magmatic arc activity (Elliot, 1998; Hathway, 2000). However, the Cenozoic alkaline volcanic outcrops at Argo Point, Seal Nunataks and JRI have a geochemical signature akin to ocean-island basalts (OIB) (Hole and Larter, 1993; Hole et al., 1991; Smellie, 1999).

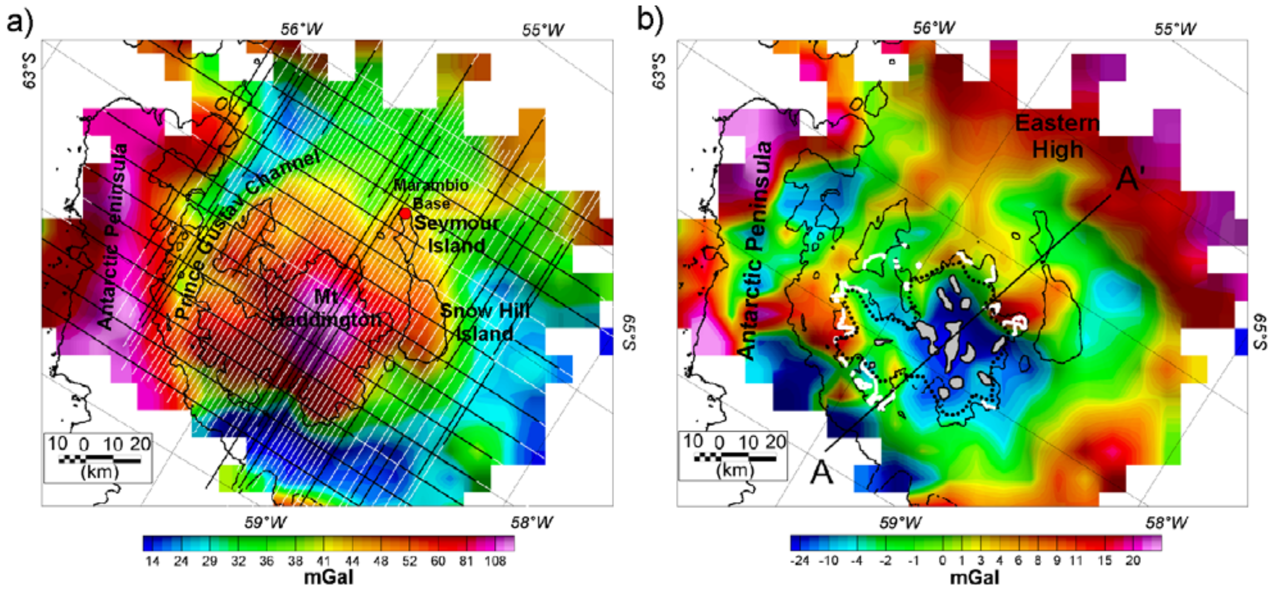

Figure 2. a) Free Air gravity anomalies and aerogravity (black) and aeromagnetic lines (white) b) Bouguer anomalies. Note the location of cross section A-A'. White lines: Cretaceous outcrop. Dotted line: short wavelength aeromagnetic anomalies on JRI. Grey region: prominent aeromagnetic highs.

The volcanism has been linked with the cessation of subduction due to collision of the Phoenix spreading centre with the continental margin, leading to slab windows beneath the back-arc and associated mantle melting (Hole et al., 1991). However, this hypothesis cannot explain the volcanism associated with JRI as subduction continues along the South Shetland Trench (Hole et al., 1995; Larter and Barker, 1991; Robertson Maurice et al., 2003). Instead slab roll-back drew asthenospheric mantle beneath previously thinned crust, leading to decompression melting in the mantle and production of OIB-like basalts (Hole et al., 1995). An alternative view is that JRI volcanism relates to a mantle plume (Smellie, 1999).

Survey layout and aerogravity processing

An aerogeophysical survey was flown over the JRI region during the 1998/99 campaign using a British Antarctic Survey Twin Otter, with logistical support was at Marambio Base (Fig. 2a) by the Argentinian Antarctic Programme. Over 3000 line km of airborne gravity data were acquired and 10,000 line km of aeromagnetics. Line-spacing was 2 km, with orthogonal tie lines 10 km apart. Large vertical accelerations were associated with changing altitudes during draped aeromagnetic flights. Hence not all flights yielded gravity data. Flight line altitudes were constrained by the local topography and were 1050, 1500, 1950, 2050 and 2500 m.

Airborne gravity data were acquired using a LaCoste and Romberg model S-83 air-sea gravimeter modified by ZLS (LaCoste, 1967; Valliant, 1992). Dual frequency GPS data were recorded on the aircraft and at a fixed base station allowing for differential kinematic, GPS methods to be applied (Mader, 1992). Accurate positional information is essential for airborne gravity data reduction. Still readings monitored drift, and land-gravity ties to Rothera (Jones and Ferris, 1999) were made to determine absolute gravity values.

Standard processing steps included the vertical acceleration, latitude, Eotvos, horizontal acceleration, and free-air corrections (Harlan, 1968; Jones and Johnson, 1995; Jones et al., 2002; Woollard, 1979). The data were low-pass filtered for wavelengths <9 km to reduce the effect of noise on the geological signal (Childers et al., 1999; Holt et al., 2006). All airborne gravity data were continued to a common altitude of 2050 m and levelled (Bell et al., 1999). Residual crossover errors after levelling have a standard deviation of 2.9 mGal, which is comparable to the accuracy of more recent high-resolution aerogravity collected over East Antarctica (Ferraccioli et al., 2005). Comparison with previous land based gravity data (Garret, 1990), gives a RMS difference of ~4.5mGal.

The complete 3D Bouguer correction was calculated to estimate the gravity effect of the topography and ice and was based on a digital elevation model (DEM) of JRI (BAS, 1995), in addition to BEDMAP (Lythe et al., 2000). The correction was calculated for an elevation of 2050 m, to least squares accuracy, using a Gauss–Legendre quadrature (GLQ) integration method (von Frese et al., 1981; von Frese and Mateskon, 1985). An ice density of 915 kgm^{-3} and a water density of 1028 kgm^{-1} were used. The rock density varied (Fig. 3), as the volcanic edifice consists of lower density rocks than the standard Bouguer correction value of 2670 kgm^{-3} (Smellie and Gudmundsson pers. comm., 2007). Finally the EGM 96 satellite-derived gravity field for the region (Lemoine et al., 1998) was subtracted (Fig. 2b).

Gravity anomaly patterns

The Bouguer gravity anomaly map reveals three distinct regions (Fig. 2b). The western flank of the Antarctic Peninsula features Bouguer anomalies of 20 to 40 mGal, in contrast to the eastern part (–5 to –20 mGal) This pattern is also observed over Palmer Land, 700 km further south, where it reflects a more mafic arc batholith over the western Antarctic Peninsula and a more felsic arc batholith in the east (Ferraccioli et al., 2006). The Eastern High is associated with a long-wavelength positive Bouguer anomaly of 10-20 mGal, likely associated with isostatic compensation of the continental margin (Watts and Stewart, 1998). A regional gradient of ~0.175 mGal/km results from Airy compensation, which is less than the observed gradient of 0.35 to 0.5 mGal/km (Fig 3). The proximity to the continental margin therefore explains part of the long wavelength positive anomaly, but the sharp inflection east of Seymour Island (Fig. 3), likely reflects a major strike-slip fault zone (Sloan et al., 1995), bringing denser basement rocks closer to the surface.

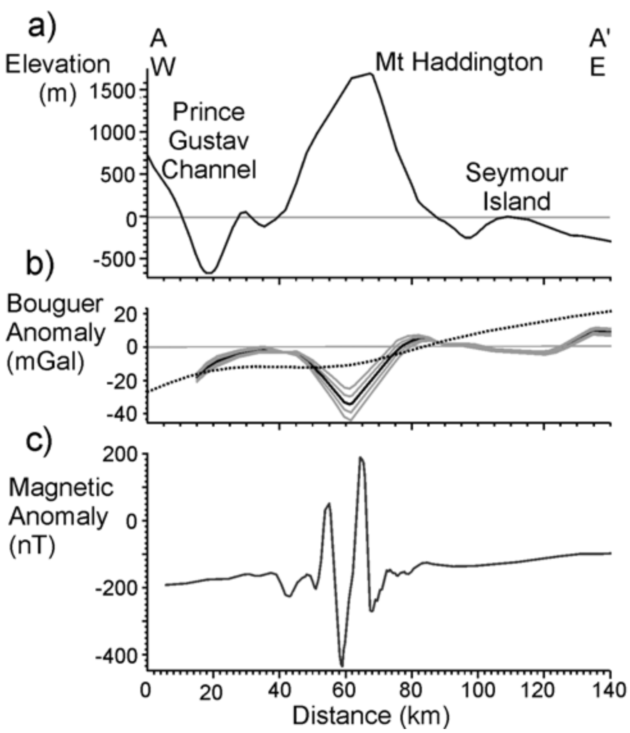

Figure 3. Cross section A-A’ across JRI. a) Topography. b) Bouguer gravity anomalies with correction densities of 2270 to 2670 kgm^{-3}. Solid line: anomaly for the preferred correction density of 2467 kgm^{-3}. Dotted line: anomaly due to Airy isostatic compensation at the Moho. c) Aeromagnetic anomalies along the same profile.

A negative Bouguer gravity anomaly of over -40 mGal is associated with Mt Haddington over JRI. Decreasing the standard Bouguer correction value from 2670 kgm^{-3} to 2270 kgm^{-3} decreases the amplitude of the negative anomaly (Fig. 3b). Density measurements over JRI and a consideration of the lithological variations based upon the distribution of rock types, indicates that a density of 2467 kgm^{-3} should be used for the Bouguer correction (Smellie and Gudmundsson pers. comm., 2007), leaving a residual Bouguer gravity anomaly of -35 mGal. The negative anomaly cannot be accounted for by simple Airy isostatic compensation of the surface topography, as shown by the dotted line in Fig 3.

The negative Bouguer anomaly peak correlates well with high- amplitude aeromagnetic anomalies. The short wavelength aeromagnetic anomalies on JRI delineate subglacial volcanic rocks at, or close to, the surface. Spectral analysis (Spector and Grant, 1970) suggests the source bodies are at ~-10 km (basement source?) and ~-800 m (volcanic source). Similar analysis of the Bouguer gravity data suggests source depths of ~ 12 and 5 km.

The origin of the negative Bouguer anomaly is enigmatic, as mafic volcanoes are typically associated with positive Bouguer anomalies resulting from dense gabbroic material within now-solidified magma chambers (Walker, 1989; Williams and Finn, 1985). Where comparable negative Bouguer gravity anomalies have been observed beneath volcanoes such as Clear Lake California (Chapman, 1975; Stanley and Blakely, 1995), Yellowstone (Finn and Morgan, 2002; Lehman et al., 1982) and Mt Melbourne (Ferraccioli et al., 2000) two hypotheses are typically proposed: a low-density breccia-filled caldera, or a hot body such as a magma chamber beneath the volcano. However, in the case of JRI there is no geological evidence for a caldera, or for recent eruptions associated with a hot magma chamber.

Conclusion

Airborne gravity data reveal a prominent negative Bouguer gravity anomaly over Mt Haddington, which dominates JRI. The negative gravity anomaly correlates with high-amplitude aeromagnetic anomalies, suggesting a genetic link between volcanic processes and the inferred low-density body beneath JRI. Explanations for the body include (1) low-density infill of a caldera, or (2) a partially molten magma chamber beneath the island. If a hot magma chamber does indeed underlie JRI, it would indicate the volcano is merely dormant, rather than extinct. This could be consistent with the long, but sporadic, eruption history suggested by Smellie, et al. (2006). Seismic and electromagnetic arrays, such as those over Mt Melbourne (Armadillo et al., 2002) could test our provocative hypothesis.

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