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Aeromagnetic signatures over western Marie Byrd Land provide insight into magmatic arc basement, mafic magmatism and structure of the Eastern Ross Sea Rift flank

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Abstract

Aeromagnetic signatures over the Edward VII Peninsula (E7) provide new insight into the largely ice-covered and unexplored eastern flank of the Ross Sea Rift (RSR). Positive anomalies, 10–40 km in wavelength and with amplitudes ranging from 50 to 500 nT could reveal buried Late Devonian(?)–Early Carboniferous Ford Granodiorite plutons. This is suggested by similar magnetic signature over exposed, coeval Admiralty Intrusives of the Transantarctic Mountains (TAM). Geochemical data from mid-Cretaceous Byrd Coast Granite, contact metamorphic effects on Swanson Formation and hornblende-bearing granitoid dredge samples strengthen this magnetic interpretation, making alternative explanations less probable. These magnetic anomalies over formerly adjacent TAM and western Marie Byrd Land (wMBL) terranes resemble signatures typically observed over magnetite-rich magmatic arc plutons. Shorter wavelength (5 km) 150 nT anomalies could speculatively mark mid-Cretaceous mafic dikes of the E7, similar to those exposed over the adjacent Ford Ranges. Anomalies with amplitudes of 100–360 nT over the Sulzberger Bay and at the margin of the Sulzberger Ice Shelf likely reveal mafic Late Cenozoic(?) volcanic rocks emplaced along linear rift fabric trends. Buried volcanic rock at the margin of the interpreted half-graben-like "Sulzberger Ice Shelf Block" is modelled in the Kizer Island area. The volcanic rock is marked by a coincident positive Bouguer gravity anomaly. Late Cenozoic volcanic rocks over the TAM, in the RSR, and beneath the West Antarctic Ice Sheet exhibit comparable magnetic anomaly signature reflecting regional West Antarctic Rift fabric. Interpreted mafic magmatism of the E7 is likely related to mid-Cretaceous and Late Cenozoic regional crustal extension and possible mantle plume activity over wMBL. Magnetic lineaments of the E7 are enhanced in maximum horizontal gradient of pseudo-gravity, vertical derivative and 3D Euler Deconvolution maps. Apparent vertical offsets in magnetic basement at the location of the lineaments and spatially associated mafic dikes and volcanic rocks result from 2.5D magnetic modelling. A rift-related fault origin for the magnetic lineaments, segmenting the E7 region into horst and graben blocks, is proposed by comparison with offshore seismic reflection, marine gravity, on-land gravity, radio-echo sounding, apatite fission track data and structural geology. The NNW magnetic lineament, which we interpret to mark the eastern RSR shoulder, forms the western margin of the "Alexandra Mountains horst". This fundamental aeromagnetic feature lies on strike with the Colbeck Trough, a prominent NNW half-graben linked to Late Cretaceous(?) and Cenozoic(?) faulting in the eastern RSR. East–west and north–north–east to NE magnetic trends are also imaged. Magnetic trends, if interpreted as reflecting the signature of rift-related normal faults, would imply N–S to NE crustal extension followed by later northwest–southeast directed extension. NW–SE extension would be compatible with

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Cenozoic(?) oblique RSR rifting. Previous structural data from the Ford Ranges have, however, been interpreted to indicate that both Cretaceous and Cenozoic extensions were N–S to NE–SW directed.

Keywords: Aeromagnetic anomalies; Magmatic arc; Mafic rock; Rifting; West Antarctica

1. Introduction

Previous studies of magnetic anomaly patterns combined with seismic and gravity investigations have revealed major faults, magmatism and crustal structure within the Ross Sea Rift (RSR) (inset in Figs. 1 and 2). The Ross Sea Rift forms a relatively well-studied component of the modern, continental scale, West Antarctic Rift System (Tessensohn and Wörner, 1991; Behrendt et al., 1994, 1996, 1997; Behrendt, 1999).

Magnetic data over the western Ross Sea Rift shoulder forming the Transantarctic Mountains (TAM) have been used to study the inherited pre-rift features of the Paleozoic basement and the later crustal blocks affected by Jurassic and Cenozoic rift-related volcano–tectonic activity (Ferraccioli and Bozzo, 1999). Along the Eastern Ross Sea Rift flank, western Marie Byrd Land forms a much more subdued topographic high within the subsided and extended crust of West Antarctica, highlighting the likely asymmetric structure of the rift. Western Marie Byrd Land is relatively unexplored from the geophysical point of view. This is, however, a key region to: (a) reconstruct multistage Cretaceous to Cenozoic Eastern Ross Sea rifting; (b) New Zealand–Marie Byrd Land rifting (Late Cretaceous) and (c) for establishing pre-rift ties between East and West Antarctica terranes (Weaver et al., 1994; Davey and Brancolini, 1995; Bradshaw et al., 1997). The lack of magnetic anomaly studies for western Marie Byrd Land also contrasts with the formerly adjacent New Zealand region for which magnetic data provide new constraints upon basement geology and later tectonic evolution (Sutherland, 1999).

A regional aeromagnetic survey was performed over the Edward VII Peninsula (Fig. 1) in an area, which is almost entirely ice-covered in order to augment crustal information concerning this key sector of West Antarctica (Damaske et al., in press). In this study, we interpret magnetic anomaly maps and models over the Eastern Ross Sea Rift flank over the Edward VII Peninsula. The aim of our study is to place new constraints upon crustal structure and tectonics of western Marie Byrd Land. We focus upon possible buried Late Devonian(?)–Early Carboniferous magmatic arc plutons and upon later Cretaceous and Cenozoic rift-related magmatic and tectonic features of the West Antarctic Rift System, both interpreted from the observed aeromagnetic signatures over the Edward VII Peninsula region.

2. Geology of the Edward VII Peninsula and adjacent Ford Ranges

Edward VII Peninsula (E7) is adjacent to the Eastern Ross Sea. It forms the westernmost tip of Marie Byrd Land (West Antarctica). Thick snow and ice cover buries most of the Peninsula leaving only isolated outcrops to reveal the geology of the region (Fig. 1). An NZ Antarctic Research Programme expedition (1987/1988) made additions to the previous 1:250,000 geologic maps of the Alexandra Mountains Quadrangle, which include the Alexandra Mountains and the Rockefeller Mountains (Wade et al., 1977; Adams et al., 1989). Further geological fieldwork was performed during the 1992/1993 GANOVEX VII expedition (Smith, 1996; Van der Wateren et al., 1996; Kleinschmidt and Brommer, 1997).

Low-grade Ordovician metasedimentary rocks of the Swanson Formation are the oldest outcropping unit. Rb–Sr ages of 421–431 Ma are interpreted to reflect regional metamorphism (Adams et al., 1995). Later thermal metamorphism could reflect the emplacement of anorogenic mid-Cretaceous (95–100 Ma) Byrd Coast Granite, which dominates the Rockefeller Mountains (Weaver et al., 1992). High-grade metamorphic rocks of the Alexandra Mountains are migmatites interpreted as having developed through contact metamorphism adjacent to the Cretaceous Byrd Coast Granite (Smith, 1996). Little is known about the structural geology due to poor exposure, but kink band axes, folds and thrusts within Swanson Formation rocks over the "Central Plateau" (Fig. 1) region have

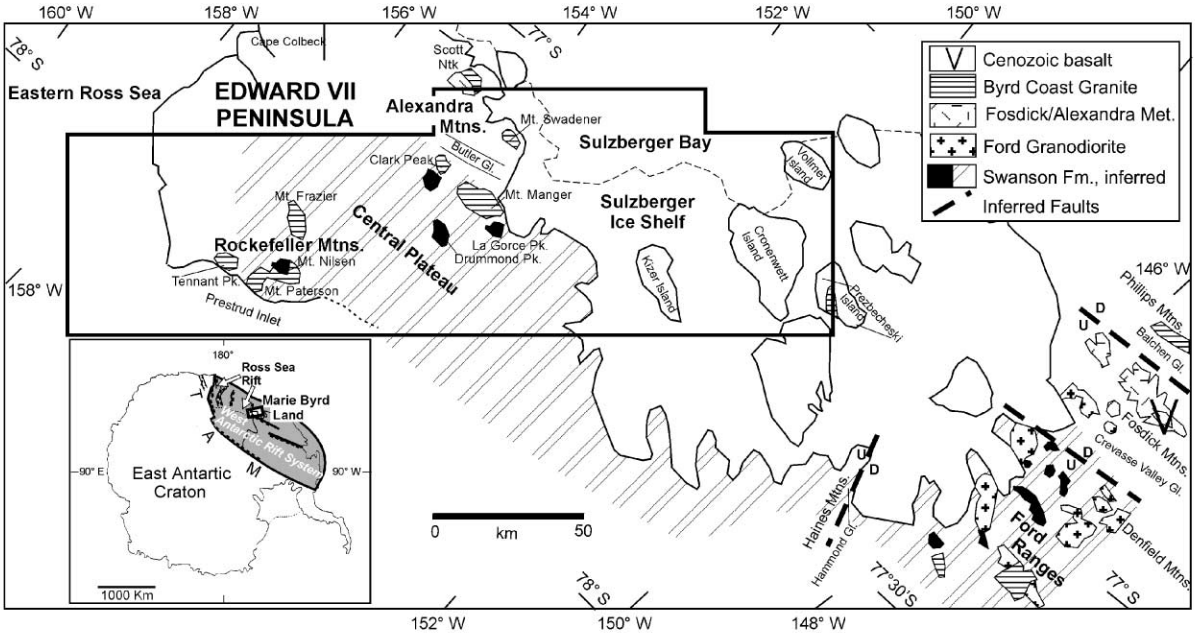


Fig. 1. Geologic sketch map of the Edward VII Peninsula and adjacent Ford Ranges (modified from Kleinschmidt and Brommer, 1997). Inferred faults over the Ford Ranges from Luyendyk (1993). The bold rectangle indicates the aeromagnetic survey outline. The inset shows that the study area is part of western Marie Byrd Land and is placed along the eastern flank of the Ross Sea Rift (RSR), a component of the continental scale West Antarctic Rift System.

an approximately NW–SE trend (Kleinschmidt and Brommer, 1997). The three main rock units predominate in distinct areas (Fig. 1), which have been inferred to be bounded by major faults possibly along the NW–SE axis of the peninsula (Adams et al., 1989).

In the better-exposed Ford Ranges, 350–380 Ma Ford Granodiorite intrudes Swanson Formation rocks. This I-type granitoid suite is calc-alkaline and has low initial $^{87}Sr/^{86}Sr$ ratio (Weaver et al., 1991). A Permian granite has also been detected in the Chester Mountains (Richard et al., 1994). Byrd Coast Granite in the Ford Ranges has older (140–110 Ma) Rb–Sr ages and lower $^{87}Sr/^{86}Sr$ ratios compared to the E7 granites (Weaver et al., 1992). The Fosdick Metamorphic Complex, which has been compared to the Alexandra Mountains high-grade complex, represents a mid-crustal section interpreted to have uplifted rapidly in Late Cretaceous time (Richard et al., 1994; Smith, 1997). Cretaceous mafic dikes intrude all these rocks (Luyendyk, 1993). Flat tops in the Fosdick and Phillips Mountains may represent remnants of the 75 Ma(?), regionally extensive, West Antarctic erosion surface (LeMasurier and Landis, 1997). In the Fosdick Mountains, the westernmost outcrops of the Late Cenozoic volcanic province of Marie Byrd Land (LeMasurier and Wade, 1990) overlie the erosion surface. Individual ranges within the Ford Ranges trend E–W and NW–SE and have been interpreted to be fault controlled (Luyendyk, 1993; Richard et al., 1994). A major E–W-trending, N-dipping, normal fault along the Balchen Glacier is interpreted to separate the Phillips Mountains from the Fosdick Mountains (Fig. 1). Faulting is thought to be mid-Cretaceous in age, although subparallel outcrops of Pleistocene volcanics are interpreted to suggest reactivation in Late Cenozoic times (Luyendyk, 1993; Richard et al., 1994).

3. Tectonic evolution and regional structure

Prior to rifting in the Ross Sea, western Marie Byrd Land (wMBL) shared a history of Cambrian deep-water sedimentation (Swanson Formation) and Devonian–Carboniferous plutonism (Ford Granodiorite) with the Robertson Bay Terrane (Robertson Bay Group and Admiralty Intrusives) of northern Victorian Land (NVL) (Fig. 2). Although metamorphism and deformation is younger over wMBL compared to NVL (Adams, 1986), both areas have been regarded as part of the Ross Orogen (Kleinschmidt and Brommer, 1997). Similarities between these NVL–wMBL basement rocks and the Buller Terrane of the Western Province in New Zealand have also been discussed (Bradshaw et al., 1997). Collectively, these Lower Paleozoic rocks may record a similar tectonic history associated with subduction and possible terrane accretion along the Paleo-Pacific margin of Gondwana (Weaver et al., 1991; Ricci et al., 1997; Finn et al., 1999a). Rocks of the Bowers Terrane and Wilson Terrane of NVL do not crop out in wMBL.

During Mesozoic times, the Phoenix Plate was subducting beneath the East Gondwana continental margin including Marie Byrd Land and Zealandia (New Zealand, Chatham Rise, Campbell Plateau and Lord Howe Rise) (Bradshaw, 1989; Sutherland, 1999). A sudden change from a convergent to an extensional tectonic regime at about 105 Ma has been interpreted as resulting from oblique subduction of the Pacific-Phoenix spreading centre (PAC-PHO, see inset in Fig. 2) at the trench (Bradshaw, 1989) or, more recently, by slab capture (Luyendyk, 1995, 1997). Mid-Cretaceous Byrd Coast Granite of central Marie Byrd Land (124–95 Ma) records a rapid change from subduction-related I-type magmatism to rift-related A-type magmatism (Weaver et al., 1994). The later E7 anorogenic granites (95–100 Ma) were emplaced during the initiation of continental rifting along the Marie Byrd Land–New Zealand margin (Weaver et al., 1992). Strain indicators in the Fosdick Metamorphic Complex of the Ford Ranges indicate N–S to NNE–SSW extension (Richard et al., 1994), which is interpreted as compatible with transtensional and dextral rifting of the Campbell Plateau from Marie Byrd Land (see inset in Fig. 2). Sea floor spreading between Marie Byrd Land and the Campbell Plateau began at about 84 Ma (Mayes et al., 1990).

Plate tectonic reconstructions indicate that the main phase of extension within the Ross Sea Rift was between 105 and 85 Ma (Lawver and Gahagan, 1994). The remarkable fit between the Eastern Basin, Marie Byrd Land and the Campbell Plateau prior to 85 Ma could be an evidence for limited latest Cretaceous or Cenozoic extension in the Ross Sea, though this linkage is equivocal (Davey and Brancolini, 1995). New wide-angle seismic data have confirmed that the Ross Sea Rift grabens are underlain by highly extended crust and shallow mantle (Trey et al., 1999). In the western Ross Sea Rift, reactivation of Ross Orogen faults in a right-lateral strike-slip regime generated renewed Cenozoic extension and favoured N–S clustering of volcanic activity (Salvini et al., 1997). Cenozoic transtension may have induced NW–SE extension oblique to the Transantarctic Mountains rift margin (Bosum et al., 1989; Wilson, 1995; Bozzo et al., 1997; Ferraccioli and Bozzo, 1999). In MBL, Late Cenozoic block faulting linked to uplift and extension across the MBL dome may have disrupted the original continuity of the West Antarctic Erosion surface (LeMasurier and Landis, 1997). Post-Eocene vertical tectonics giving rise to basin-and-range structure in wMBL have been estimated to involve 1.5 km of vertical movement (Luyendyk et al., 1992). The magnitude of wMBL uplift is significantly less than inferred for parts of the TAM (Davey and Brancolini, 1995 and references therein; Van der Wateren et al., 1996). At 48 Ma, rift-related plutonism began over NVL (Tonarini et al., 1997). These alkaline plutons are unrecognized over MBL, but rift-related volcanic activity of the Marie Byrd Land volcanic province (LeMasurier and Thompson, 1990) is roughly coeval (30–0 Ma) with alkali basaltic volcanism of the McMurdo Volcanic Group (25–0 Ma). The entire alkaline magmatic province has been proposed to be genetically linked to a continental scale mantle plume head underlying the West Antarctic Rift System and centred beneath MBL (Hole and LeMasurier, 1994; Rocholl et al., 1995).

4. Magnetic anomalies of the Edward VII Peninsula

The regional aeromagnetic survey performed over the E7 area was set up with a 4.4-km profile line spacing, WSW–ENE profile line orientation, 22-km tie line interval, and was flown at a constant altitude of 2000 m (Damaske et al., in press). Standard processing techniques were implemented by application of microlevelling in the frequency domain (Ferraccioli et al., 1998). The resulting shaded relief total field magnetic

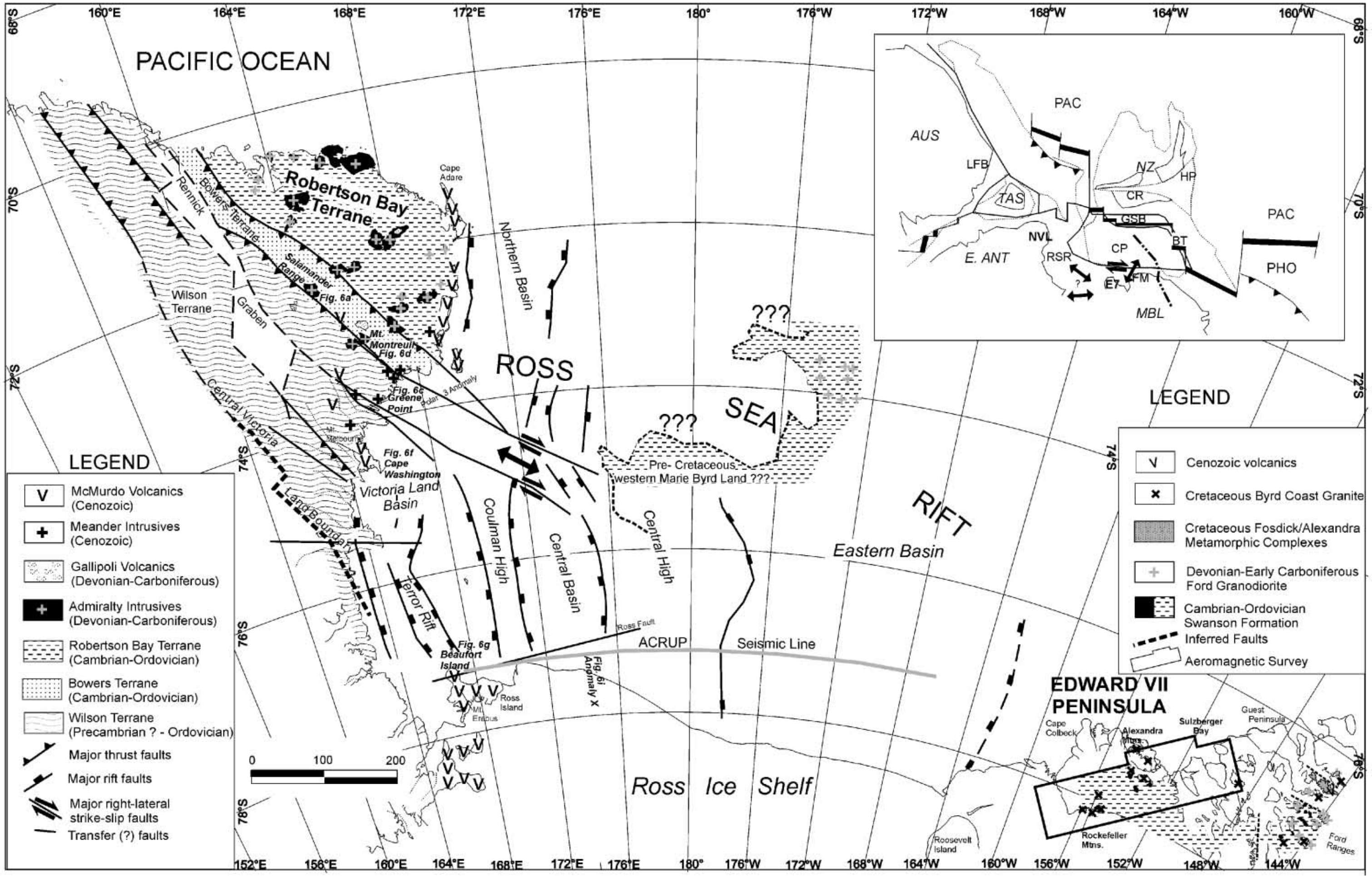


Fig. 2. Regional tectonic map of the Ross Sea Rift (RSR) region. A speculative pre-rift, pre-Cretaceous montage linking between western Marie Byrd Land and Northern Victoria Land is shown (modified from Kleinschmidt and Brommer, 1997). Location of magnetic anomalies displayed in Fig. 6a,c,d,f,g, and i is reported. The inset shows the plate tectonic configuration at approximately 100 Ma (modified from Bradshaw et al., 1997) when subduction of PAC-PHO spreading centre ceased and crustal extension in the RSR and Campbell Plateau (CP) preceded continental break-up. The double arrow in the Fosdick Mountains (FM) indicates the interpreted extension direction consistent with later transtensional dextral rifting of the CP from Marie Byrd Land (Richard et al., 1994). Double arrows in the RSR indicate that NE directed Jurassic(?) extension may have been followed by NW–SE directed Cenozoic extension (Bosum et al., 1989; Wilson, 1995; Ferraccioli and Bozzo, 1999). Other abbreviations: E7: Edward VII Peninsula; NVL: Northern Victoria Land; NZ: New Zealand; HP: Hikurangi Plateau, CR: Chatham Rise; GSB: Great South Basin; BT: Bounty Trough; AUS: Australia; LFB: Lachlan Fold Belt; TAS: Tasmania; E.ANT: East Antarctica. Dashed line marks inferred western boundary in MBL of the Western Province and of the Median Tectonic Zone of the New Zealand region (Sutherland, 1999).

anomaly image over this part of wMBL is superimposed upon a simplified geologic map to correlate magnetic anomaly patterns and sparse rock outcrops (Fig. 3). A discrete positive anomaly (labelled A) occurs over the Alexandra Mountains in the Mt. Swadener region and a similar feature (B) extends to an entirely ice-covered area further to the west. Amplitudes are above 400 nT with individual peaks of 500 nT. The wavelength of anomalies (a) and (b) is about 40 km. Outcropping rock is Byrd Coast Granite. Higher frequency anomalies with a wavelength of about 5 km and amplitudes around 150–170 nT are placed in between the two subcircular anomalies (Y). Over the Central Plateau, a peak (C) with an amplitude of 170 nT is distinct from a broader and lower amplitude anomaly (70 nT) close to Drummond Peak (G), where Swanson Formation outcrops. A subcircular 350 nT anomaly is also imaged at the edge of the survey (D). These anomalies contrast with the quiet negative magnetic field (− 100 nT) over Byrd Coast Granite of the Rockefeller Mountains. Offshore, the Sulzberger Bay features positive anomaly chains with different orientations (S, S′ , S″), amplitudes between 100 and 360 nT, and wavelengths of about 10 km. A single circular 200-nT anomaly (V) is detected in the Vollmer Island area (Fig. 1). In contrast, the Sulzberger Ice Shelf is a broad minimum reaching amplitudes of − 250 nT. The Eastern Ross Sea is a − 200 to − 100 nT minimum with NNE lineations and a 25-nT positive anomaly (M) in the Prestrud Inlet region.

Anomalies (A), (B) and (M) are still prominent in an upward continued map imaging the calculated magnetic anomaly field at 10 km, i.e. 8 km above the original flight level (Fig. 4a). These anomalies are therefore likely deep-seated in origin. The upward continued map enhances the long-wavelength positive magnetic anomaly field beneath the Alexandra Mountains, Central Plateau and Sulzberger Bay highlighting the presence of magnetic basement extending at depth throughout these regions. The map also enhances regional anomaly breaks across some magnetic lineaments (e.g., L1, L2 and L3?). Conversely, the higher-frequency anomalies (e.g., Y, R, C, S, S′, S″) disappear or are significantly smoothen out at the calculated 10-km level. The high-frequency components of the anomaly field, likely due to shallower sources, are however enhanced in the first vertical derivative magnetic anomaly map (Fig. 4b). Individual peaks are recognized as being superimposed upon magnetic anomalies (A) and (B) as was evident in profile magnetic anomaly data. High-frequency linear anomalies are clearly recognizable in the Eastern Ross Sea, in the Sulzberger Bay, and at margin of the Sulzberger Ice Shelf, along inferred magnetic lineament L5.

4.1. Magnetic lineaments and anomaly edges

Magnetic lineaments can be inferred from the original total field magnetic anomaly map (Fig. 3). However, recognition of these lineaments may be subjective since it can depend upon the direction of illumination selected for shading. To define the edges of the anomalies and the magnetic lineaments more objectively and accurately, we display in Fig. 4c a map of the local maxima of the horizontal gradient of pseudo-gravity (Cordell and Graunch, 1985; Blakely and Simpson, 1986). A pseudo-gravity map is obtained by applying a transformation to the original total field anomaly data involving reduction to the pole and vertical integration (Baranov, 1957). The term pseudo-gravity does not imply that the magnetic distribution is necessarily related to a density distribution. This approach simplifies magnetic interpretation, since the reduction to the pole centres the anomaly over the induced sources in the case of vertical source bodies and when remanent magnetization is parallel to the present earth field. Vertical integration acts as a low-pass filter, which enhances longer wavelength components of the anomalies. The horizontal derivatives then act as a high-pass filter, which enhances shallower sources. Edges of anomalies (A), (B), (M) and (S) are now clearly imaged. North–north–east trends of the Eastern Ross Sea intersecting the Shirase Coast are confirmed. These trends may be truncated along a linear boundary (L1) marking the sharp western margin of anomaly (B). A NE trend (L2) separates anomalies (B) and (Y) and (A), from anomalies (C) and (G) of the Central Plateau.

Three-dimensional Euler Deconvolution techniques were also applied. This method (Reid et al., 1990) makes use of the Euler's homogeneity equation relating the magnetic field and its gradient components to the location of the anomaly source and to the degree of homogeneity, which may be interpreted as a structural index (SI). The method is fairly effective for

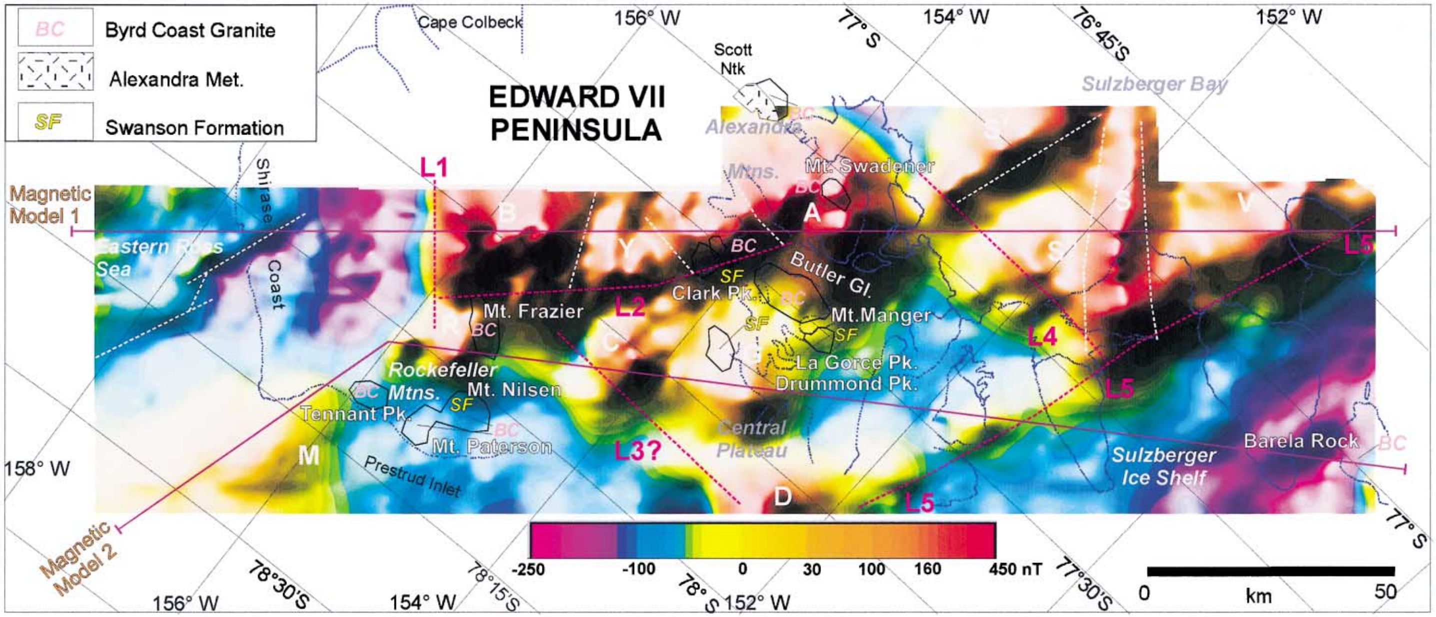


Fig. 3. Edward VII Peninsula aeromagnetic anomaly map superimposed upon geology. A Hue, Saturation, Value non-linear colour scale is adopted. Shading parameters are: inclination 330°, declination 30°. Dashed red lines and corresponding L1–L5 labels are inferred magnetic lineaments, where regional anomaly breaks can be identified. White lines are higher frequency magnetic linears. Anomalies are labelled for recognition and later interpretation. Outcrops with susceptibility measurements reported in Table 2 are displayed. The location of modelled magnetic profiles is also shown.

the delineation of magnetic boundaries and for the estimation of depth to their upper edges if aliasing, levelling and location noise level is not too high. An advantage of the method is that it is considered to be insensitive to magnetic inclination, declination and remanence since these are incorporated in the constant of the anomaly function for a given geologic source model. The most appropriate SI, which is essentially a measure of anomaly fall-off rate with distance, can be interactively selected by picking Euler Deconvolution solutions, which exhibit the tightest spatial clustering. An SI that is too low yields depths, which are too shallow, while one that is too high leads to depth over estimation. Depth estimates are known to be more precise for high-index sources. In Fig. 4d, we display 3D Euler Deconvolution solutions for SI 1.0, which is appropriate for imaging linear geologic sources of magnetic anomalies such as faults, dikes or edges of sills and is commonly used in regional interpretation. Table 1 reports statistical parameters, window size and

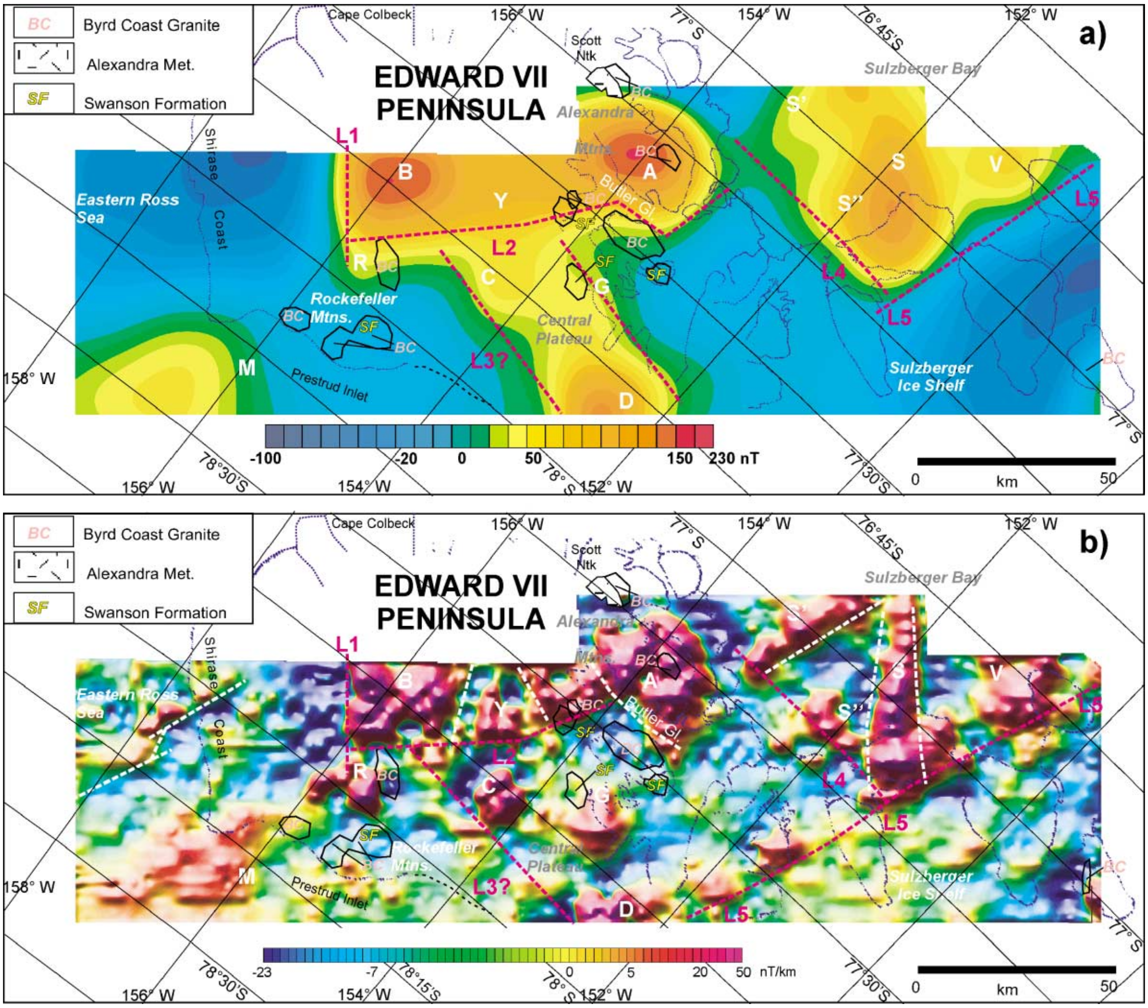


Fig. 4. Advanced processing aeromagnetic anomaly images for the Edward VII Peninsula region. (a) Upward continued map at the 10-km above sea calculated level; (b) first vertical derivative map; (c) horizontal gradient map of pseudo-gravity; (d) 3D Euler Deconvoultion solution map for structural index 1.0.

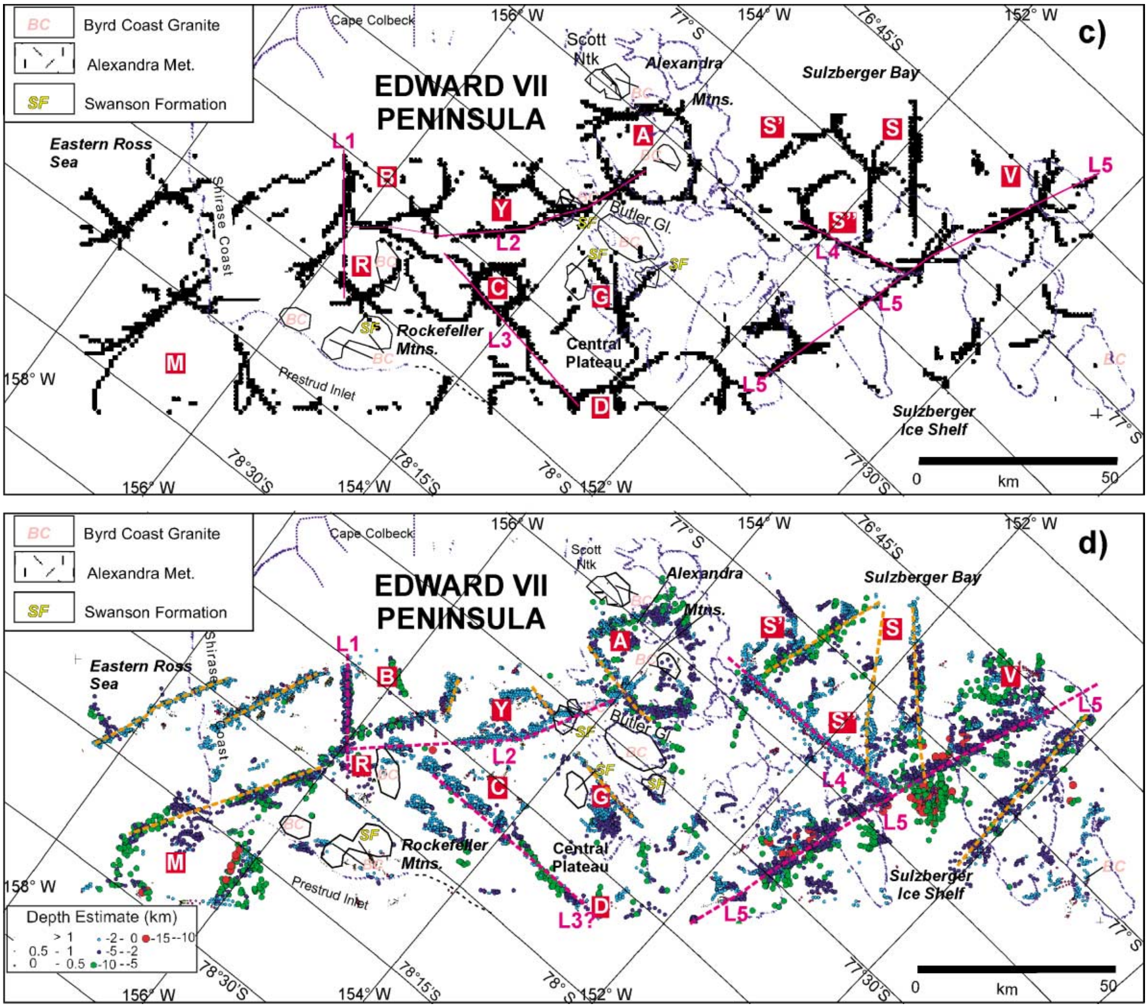


Fig. 4 (*continued*).

depth tolerance values of our Euler Deconvolution depth estimate for SI 1.0. The method was applied also for lower and higher structural indexes corresponding to contacts (SI 0), thick steps, i.e. large throw faults (SI 0.5), pipes (SI 2.0) and spheres, i.e. plutons with three finite dimensions (SI 3.0). Solutions for anomalies (A), (B) and (M) exhibit good clustering also at higher structural index indicating that two- to three-dimensional geologic sources are probable. North–north–east trending lineations in the Eastern Ross Sea are enhanced in the 3D Euler Deconvolution map for SI 1.0. A NNE trending lineament (L5) clearly divides the Sulzberger Bay from the Sulzberger Ice Shelf area. The Sulzberger Bay features NNW–SSE (S), E–W (S″, L4) and NNE (S′) trends. The two subcircular anomalies of the Alexandra Mountains region are separated by L2 from the Central Plateau and by L4 from the Sulzberger Bay. The subtle E–W boundary between the Central Plateau and the Rockfeller Mountains (L3?) is also evident, as imaged in the upward continued map (Fig. 4a). The sharp magnetic boundary flanking anomaly (B) of the Alexandra Mountains region and separating this area from the Eastern Ross Sea (L1) is confirmed. Deeper solutions with respect to

Table 1
3D Euler Deconvolution parameters and statistical results over the Edward VII Peninsula region for structural index 1.0

3D Euler Deconvolution	
Depth tolerance	3%
Window size	6×6 (2640×2640 m)
Structural index	SI = 1.0
Minimum value	− 13,000 m
Maximum value	2800 m (noise)
Mean value	− 1600 m
Standard deviation	2300 m

the Alexandra Mountains and Central Plateau regions were found for high structural indexes over the Sulzberger Ice Shelf (10 km), Sulzberger Bay (3–4 km) and for anomaly (M) (6 km).

4.2. Magnetic susceptibility and anomaly sources

Evaluation of magnetic properties of outcrops generally facilitates interpretation of the geologic sources of aeromagnetic anomalies. Results from sparse magnetic susceptibility measurements both within the aeromagnetic survey area and over the adjacent Ford Ranges are reported in Table 2. Low susceptibilities characterize both Byrd Coast Granite (mean $K = 0.0000825$ SI) and Swanson Formation metasedimentary rocks (mean $K = 0.000151$ SI) of the E7, which are therefore both highly unlikely to cause the high-amplitude anomalies we observe. Outcropping monzogranites and syenogranites belonging to the Byrd Coast Granite of the E7 have ilmenite not magnetite as the opaque phase, suggesting relatively reducing magmatic conditions for these rocks (Weaver et al., 1992). Byrd Coast Granite of the Ford Ranges could however be fairly magnetic ($K = 0.0033$ SI). This granitoid suite however differs in age and geochemistry from the Peninsula suite (Weaver et al., 1992, 1994). The high-grade metamorphic rocks of the Alexandra Complex at the north-western edge of the survey are highly magnetic ($K = 0.0093$ SI) but apparently anomaly (A) does not extend over these rocks. Late Cenozoic Olivine Basalt sampled in the Ford Ranges is even more magnetic ($K = 0.045$ SI). Cenozoic basalt or related rock types are therefore potential sources of magnetic anomalies, even if rocks of this age do not crop out over the Peninsula.

4.3. Magnetic models

Two profiles (Fig. 5a,b) were selected from our 2.5D magnetic modelling efforts performed to assess geometry and depth to the sources of the observed magnetic anomalies. Locations of the profiles are

Table 2
Susceptibility measurements along the Eastern Ross Sea Rift shoulder

Location	$\langle K \rangle$ (SI)	Rock type (number of samples)
Alexandra Mountains		
Scott Ntk.	0.009354	Alexandra Met. (6)
Mt. Swadener	0.000028	Byrd Coast Granite (1)
Mt. Manger	0.000080	Byrd Coast Granite (1)
Central Edward VII Peninsula		
LaGorce Pk.	0.000146	Swanson Formation (1)
Drummond Peak	0.000207	Swanson Formation (1)
Clark Pk.	0.000152	Byrd Coast dike (1)
Rockefeller Mountains		
Mt. Nilsen, Mt. Franklin	0.000099	Swanson Formation (5)
Mt. Frazier, Mt. Fitzsimmons	0.000090	Byrd Coast Granite (2)
Mt. Paterson, Mt. Schlossbach Washington R.	0.000100	Byrd Coast Granite (1)
Tennant Pk.	0.000045	Byrd Coast Granite (2)
Sulzberger Ice Shelf		
Barela Rock	0.007535	Byrd Coast Granite(?) (2)
Ford Ranges		
Mt. Kinley	0.003308	Byrd Coast Granite(?) (1)
Radford Island, Chester Mountains	0.000066	Ford Granodiorite (2)
Mt. Avers	0.45680	Cenozoic Olivine Basalt (3)

High-grade rocks of the Alexandra Mountains and Cenozoic mafic volcanic rocks of the Ford Ranges are highly magnetic. Swanson Formation and Byrd Coast Granite are only weakly magnetic.

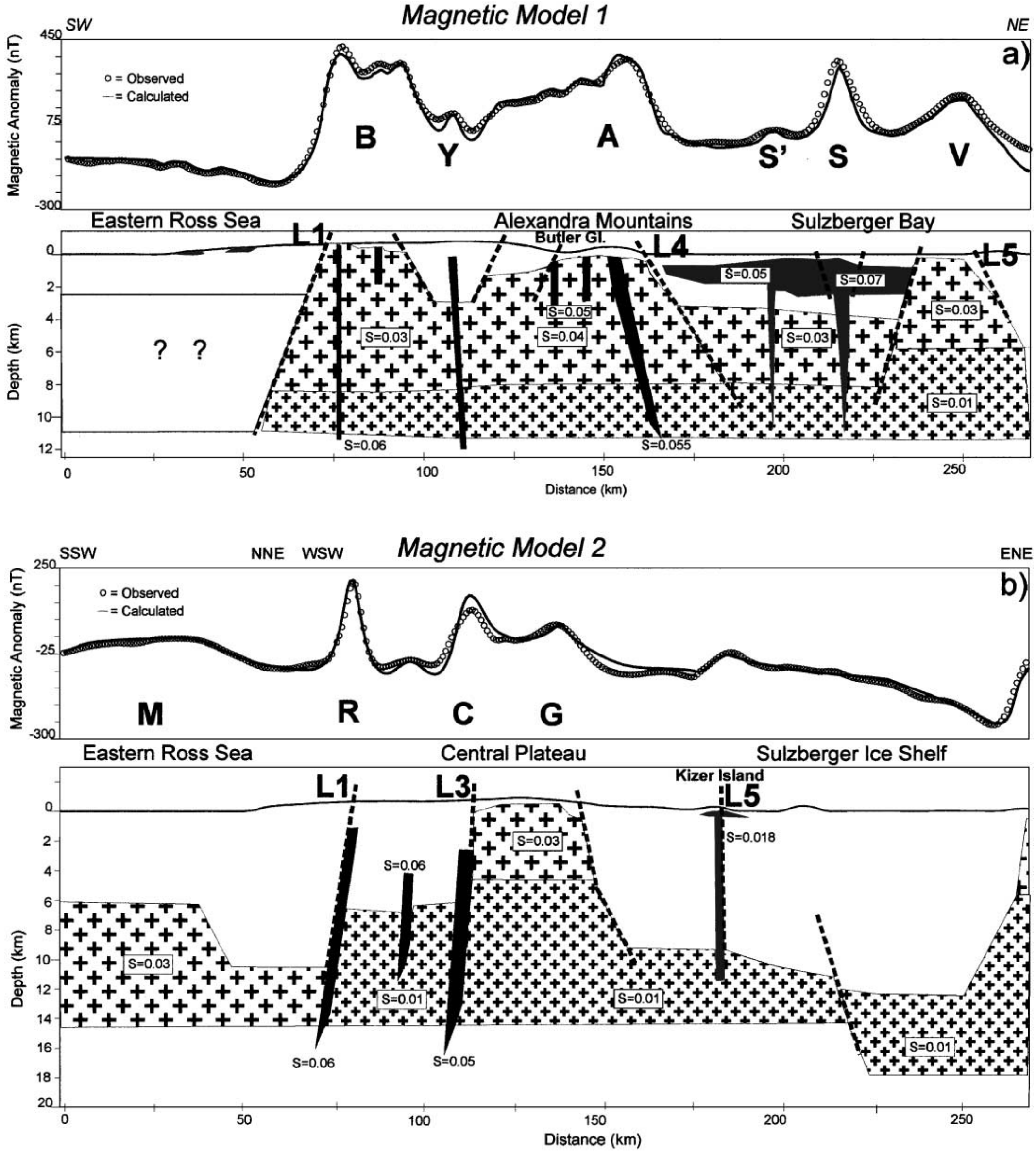


Fig. 5. Crustal structure and horst and graben-like architecture of the Edward VII Peninsula region as inferred from 2.5D forward magnetic modelling. Boxed numbers are apparent susceptibility values (SI units) adopted for pluton-sized (crosses), dike-like (black) and volcanic (grey) model bodies. Width of pluton-sized source bodies was assumed in the 2.5D approximation as + 15 and − 15 km for anomalies (a) and (b). Note anomaly labels and magnetic lineaments. White fill is non-magnetic background corresponding to indistinguishable Byrd Coast Granite, Swanson Formation and possible sedimentary infill within asymmetric graben-like crustal structures.

reported in Fig. 3. Magnetic Model 1 (Fig. 5a) crosses the Eastern Ross Sea, the Alexandra Mountains and Sulzberger Bay. Forward modelling indicates that 8- to 10-km thick, highly magnetic ($K = 0.03 - 0.04$ SI) bodies, with considerable horizontal dimensions (30–50 km), can explain the longer-wavelength components of anomalies (A) and (B). If comparable susceptibility is adopted for a magnetic body beneath the

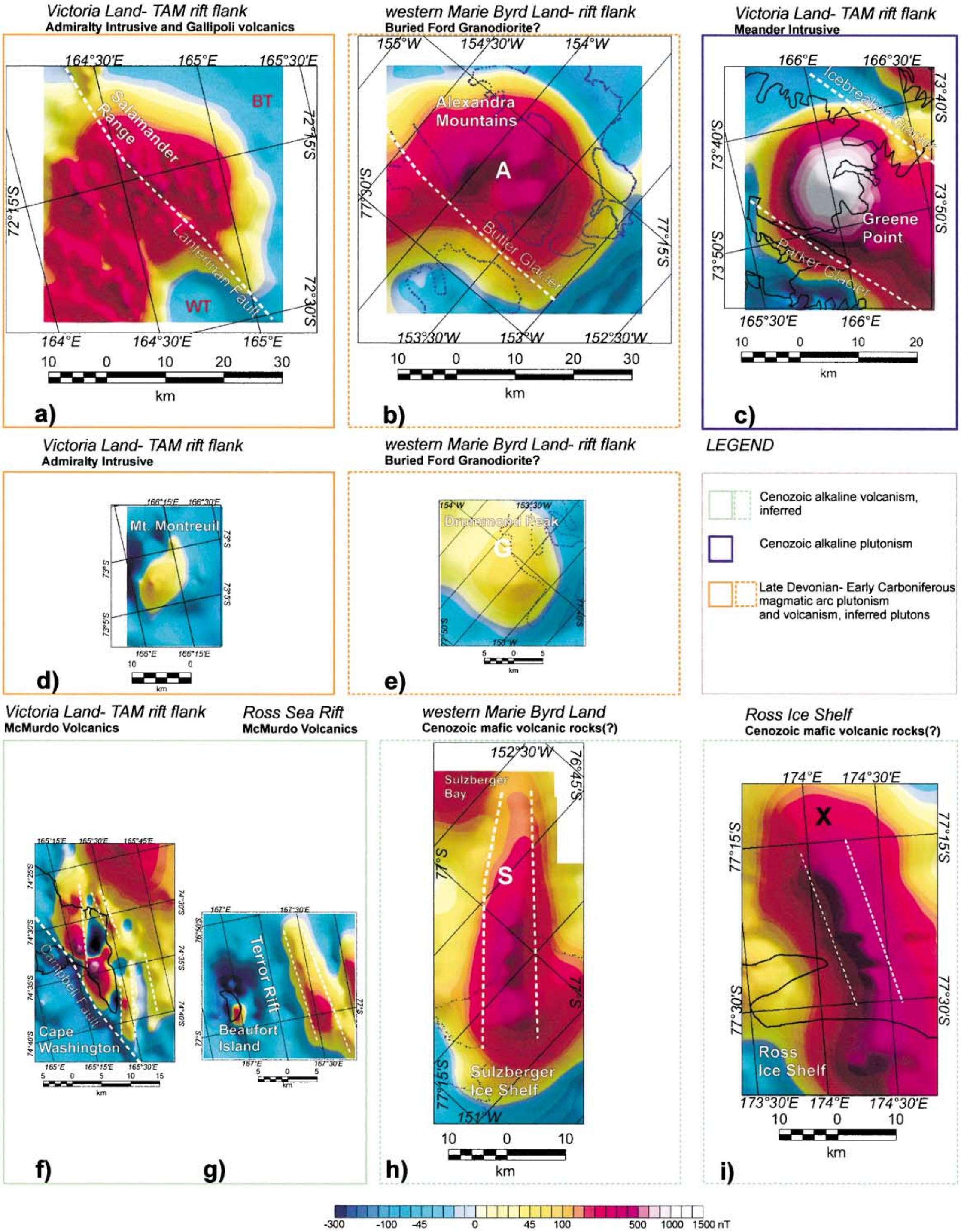
Sulzberger Bay, its top could drop down at depths of 3–4 km across a steep, north-dipping boundary, coinciding with the position of magnetic lineament L4. Deepening of magnetic basement in a downthrown graben-like structure would also be consistent with the results of Euler Deconvolution analysis. If no deep-seated magnetic bodies were introduced beneath Sulzberger Bay, calculated anomaly values would drop down too sharply to fit the observed long-wavelength minima. The much sharper magnetic break across lineament L1, flanking anomaly (B), can however be modelled without introducing magnetic basement at depth beneath the Eastern Ross Sea margin. If high susceptibility magnetic basement is modelled there anyway, then, it clearly must be deeper than over the adjacent Alexandra Mountains. Further, magnetic basement at depth beneath the Alexandra Mountains and the Sulzberger Bay ($K = 0.01$ SI) is introduced in Fig. 5a in analogy to magnetic model 2 (Fig. 5b). However, for model 1, one can fit the data also by simply assuming slightly lower susceptibility ($K = 0.02–0.03$ SI) bodies at upper crustal levels. The high-frequency components of the Alexandra Mountains area can be modelled either by an irregular upper surface of the pluton-sized bodies or by assuming a smoother upper surface and introducing highly magnetic ($K = 0.055–0.06$ SI) sub-vertical dike-like bodies as we display (black bodies in Fig. 5a). The higher amplitude, high-frequency, elongated anomalies over Sulzberger Bay, are modelled by introducing sub-horizontal magnetic bodies with $K = 0.05–0.07$ SI, probably representing volcanic rock reaching sea floor (grey bodies in Fig. 5a).

Magnetic Model 2 (Fig. 5b) crosses the Eastern Ross Sea margin from the Prestrud Inlet area, the Central Plateau and the Sulzberger Ice Shelf region. Anomaly (M) over the Eastern Ross Sea is modelled by introducing a pluton-sized body with similar susceptibility to the Alexandra Mountains bodies, but placed at greater depth (top at 6–10 km), in general agreement with Euler Deconvolution depth estimates. Higher-frequency anomalies (R) and (C) can be modelled by sub-vertical magnetic dikes (black bodies in Fig. 5b). These dike-like model bodies are spatially associated to magnetic lineaments L1 and L3(?). The lower amplitude anomaly (G) is explained by a magnetic pluton. Magnetic basement may drop down to 10 km beneath the Sulzberger Ice Shelf beneath a graben-like structure. A high-frequency anomaly at the location of lineament L5 is close to Kizer Island. This anomaly at the edge of the half-graben-like feature can be modelled in terms of volcanic rock ($K = 0.018$ SI) essentially extending to sea floor level (grey in Fig. 5b).

5. wMBL anomalies vs. magnetic anomaly signatures over the Transantarctic Mountains and the Ross Sea Rift

Sparse susceptibility data over the E7 indicate that most outcropping rocks have susceptibilities two to three orders of magnitude lower than apparent modelled susceptibilities at depth in the region (Fig. 5a,b). Therefore, the question is, what are the geological sources for the modelled pluton-sized, dike-like and volcanic-like bodies within this part of wMBL crust? This fundamental question could ideally be addressed by comparing the enigmatic magnetic anomalies over the E7 with magnetic signatures over the better-exposed Ford Ranges and by analysing a systematic wMBL rock magnetic property database. Previous aeromagnetic profiles (inset in Fig. 8) in that area (Beitzel, 1972) are, however, much too widely spaced

Fig. 6. Comparative analysis between western Marie Byrd Land, Victoria Land and Ross Sea Rift aeromagnetic anomalies. (a) Pseudo-circular anomaly over a large, partially exposed, Admiralty Intrusive with associated Gallipoli Volcanics crosscutting the Wilson Terrane (WT)–Bowers Terrane (BT) suture zone (Pertusati and Tessensohn, 1995; Fioretti et al., 1997a); (b) pseudo-circular anomaly over inferred buried Ford Granodiorite of the Alexandra Mountains north of Butler Glacier; (c) higher amplitude circular anomaly over an exposed Cenozoic Meander Intrusive (Tonarini et al., 1997); (d) pseudo-circular anomaly over a smaller Admiralty pluton; (e) pseudo-circular anomaly over a small inferred Ford Granodiorite pluton at Drummond Peak; (f) elongated high-frequency anomalies over fault-controlled Late Cenozoic basalt of the Mount Melbourne Volcanic Field (Ferraccioli et al., 2000); (g) elongated high-frequency anomalies over inferred Late Cenozoic basalts of the Terror Rift; (h) elongated high-frequency anomalies over inferred rift-related Late Cenozoic basalts in the Sulzberger Bay at the margin of the Sulzberger Ice Shelf; (i) elongated high-frequency anomalies over inferred Late Cenozoic Central Basin basalts at the margin of the Ross Ice Shelf (Behrendt et al., 1996). Dashed white lines are inferred faults.


Victoria Land- TAM rift flank
Admiralty Intrusive and Gallipoli volcanics
164°30'E
165°E
165°30'E
BT
Salamander Range
72°15'S
72°15'S
Lanterman Fault
WT
72°30'S
164°E
164°30'E
165°E
10 0 10 20 30
km
a)
western Marie Byrd Land- rift flank
Buried Ford Granodiorite?
155°W
154°30'W
154°W
Alexandra Mountains
A
77°30'S
77°15'S
Butler Glacier
153°30'W
153°W
152°30'W
10 0 10 20 30
km
b)
Victoria Land- TAM rift flank
Meander Intrusive
166°E
166°30'E
Icebreaker Glacier
73°40'S
73°40'S
73°50'S
Greene Point
73°50'S
Parker Glacier
165°30'E
166°E
10 0 10 20
km
c)
Victoria Land- TAM rift flank
Admiralty Intrusive
Mt. Montreuil
d)
western Marie Byrd Land- rift flank
Buried Ford Granodiorite?
Drummond Peak
G
e)
LEGEND
Cenozoic alkaline volcanism, inferred
Cenozoic alkaline plutonism
Late Devonian- Early Carboniferous magmatic arc plutonism and volcanism, inferred plutons
Victoria Land- TAM rift flank
McMurdo Volcanics
Campbell Fault
Cape Washington
f)
Ross Sea Rift
McMurdo Volcanics
Terror Rift
Beaufort Island
g)
western Marie Byrd Land
Cenozoic mafic volcanic rocks(?)
152°30'W
76°45'S
Sulzberger Bay
77°S
S
77°S
77°15'S
Sulzberger Ice Shelf
151°W
10 0 10
km
h)
Ross Ice Shelf
Cenozoic mafic volcanic rocks(?)
174°E
174°30'E
X
77°15'S
77°15'S
77°30'S
77°30'S
Ross Ice Shelf
173°30'E
174°E
174°30'E
10 0 10
km
i)
-300 -100 -45 0 45 100 500 1000 1500 nT

(about 50 km) and too poorly located to make this comparison significant for source interpretation of our higher resolution data over E7. To our knowledge, there is no published systematic wMBL rock magnetic property database either. Therefore, our approach to interpret buried magnetic sources of the wMBL crust involves comparison with known magnetic signatures over the better-exposed Transantarctic Mountains (TAM) rift shoulder and over the western and central Ross Sea Rift (Fig. 6a–i), where some magnetic anomalies are also constrained by coincident seismic reflection interpretation (see Davey and Brancolini, 1995 for review). The locations of examined anomalies outside wMBL are reported in Fig. 2. There are variety of reasons that justify this comparative analysis: (1) similar magnetic anomalies might be expected since rift-related Cenozoic wMBL rock types have equivalents over the TAM (e.g., LeMasurier and Thompson, 1990; Hole and LeMasurier, 1994; Rocholl et al., 1995) and these presently widely apart regions may have been adjacent or at least much closer prior to Ross Sea rifting (e.g., Weaver et al., 1991; DiVenere et al., 1994; Luyendyk et al., 1996; Kleinschmidt and Brommer, 1997); (2) aeromagnetic line spacing over the TAM and Ross Sea is 4.4 km as over the E7, but coverage is much more extensive (Chiappini et al., this volume); (3) a systematic database of magnetic properties of outcropping rocks is available for the TAM region (Bosum et al., 1989; Bozzo and Meloni, 1992; Bozzo et al., 1995).

Anomaly (A) of the Alexandra Mountains (Fig. 6b) is comparable in terms of shape and wavelength to the Salamander Range anomaly (Fig. 6a) over a large, partially exposed, 350 Ma Admiralty Intrusive with associated Gallipoli Volcanics (Fioretti et al., 1997a), and to the Greene Point anomaly (Fig. 6c) over a partially outcropping (48–38 Ma) Meander Intrusive (Tonarini et al., 1997). The Greene Point anomaly is, however, considerably more intense. The peak value is 1700 nT at the barometric flight level of 3660 m (Bosum et al., 1989), i.e. a higher than flight level over E7 (2000 m). Distance to source, estimated from three-dimensional magnetic modelling, is 3.5–4 km. A vertical pipe-like magnetic body, with upper surface at 250 m above sea level, 12 km in diameter, extending to depths of 20 km and with apparent susceptibility of 0.12 SI fits the observed anomaly (Bosum et al., 1989). This high apparent susceptibility requires substantial magnetite content in the middle Eocene Greene Point alkaline gabbro (Tonarini et al., 1997). Rock samples indicate susceptibilities of 0.06 SI and higher over gabbroic portions of the Meander Intrusives (Bosum et al., 1989). Other circular anomalies belonging to the Polar 3 Anomaly (Bosum et al., 1989) and along exposures of Meander Intrusives of the TAM (Fig. 2) have been modelled by using susceptibilities of this magnitude. Such high susceptibility is not required in 2.5D modelling of the Alexandra Mountains anomaly (A), but dike-like bodies (1–2 km wide), apparently intruding the pluton-sized body, are modelled by adopting comparable values (Fig. 5a). If one assumed that the upper surface of the Alexandra body is much deeper than the one depicted in our E7 magnetic model, then higher apparent susceptibilities could be introduced, but this appears to be inconsistent with independent Euler Deconvolution depth estimates.

The Salamander Range anomaly (Fig. 6a) exhibits peaks of 360 nT at the barometric flight level of 2700 m (Bozzo et al., 1999). Exposed topography lies between 2500 and 2000 m providing a minimum depth to the source in the range of 500 m. Outcropping Gallipoli volcanics have mean susceptibility values of 0.013, while Admiralty Intrusives exhibit bi-modal distribution of K values with the higher susceptibility suite in the 0.01–0.04 K range (Bozzo et al., 1995). These measured K values are compatible to apparent susceptibility values used to model anomaly (A) over the E7 (Fig. 5a). Circular anomaly (G) close to Drummond Peak over the E7 (Fig. 6e) is remarkably similar to the one observed over Mt. Montreuil (Fig. 6d), where a small Admiralty Intrusive outcrops (Pertusati and Tessensohn, 1995). This pluton is magnetic (Bozzo et al., 1995).

The high-amplitude, linear and short-wavelength anomaly chain (S) in the Sulzberger Bay (Fig. 6h) is similar to typical shallow-source magnetic anomalies observed over Late Cenozoic rocks of the McMurdo Volcanic Group (LeMasurier and Thompson, 1990). These volcanic rocks are commonly emplaced along linear trends interpreted as West Antarctic rift fabric (Behrendt et al., 1996). In the Cape Washington area (Fig. 6f), close to the quiescent Mount Melbourne volcano (Fig. 2), linear N–S anomalies, with peak values of 750 nT overlie highly susceptible ($0.01 < K < 0.05$ SI), 3 Ma basalt lava flows with subordinate hyaloclastites linked to fissural volcanic activity (Armienti et al., 1991; Bozzo and Meloni, 1992). These N–S magnetic trends have been interpreted as being leaky faults of the Mount Melbourne Volcanic field favouring upwelling of basaltic magmas and accommodating deformation along the NW–SE strike-slip Campbell Fault (Ferraccioli et al., 2000). In the western Ross Sea Rift, similar linear magnetic trends near Beaufort Island (Fig. 6g), part of the Erebus volcanic province (Fig. 2), flank the Cenozoic Terror Rift (LeMasurier and Thompson, 1990; Salvini et al., 1997). Anomaly (S) of the Sulzberger Bay region is also remarkably similar to the 825 nT anomaly (X) (Fig. 6i) located at the northern margin of the Ross Ice Shelf (Fig. 2). Anomaly (X) marks the southern continuation of the Central Basin south of the Ross Fault (Behrendt et al., 1996). Amplitudes of anomaly (X) are higher compared to anomaly (S) but flight elevation is lower (610 m) compared to the E7 (2000 m). Anomaly (X) can be modelled by thick, high apparent susceptibility ($K = 0.07–0.09$) rift–basin infill, likely representing Late Cenozoic volcanic rock reaching sea floor (Behrendt et al., 1996). Apparent susceptibilities and geometry of these previous magnetic models for the Ross Ice Shelf anomaly (X) match those adopted in our magnetic model for anomaly (S) in the Sulzberger Bay over the E7 region (Fig. 5a).

6. Discussion

6.1. Buried Ford Granodiorite: a fundamental component of the Edward VII Peninsula crust

We propose that pluton-sized magnetic bodies modelled as forming a significant component of the E7 upper crust (Fig. 5a–b), are buried Late Devonian?–Early Carboniferous Ford Granodiorite intrusions (Fig. 7). This interpretation is based upon the following elements.

(1) Magnetic anomalies of similar amplitude and wavelength to those of the E7 over the TAM overlie the Admiralty Intrusives (Fig. 6b–e vs. a–d), i.e. age equivalent rocks with closely matching geochemistry and mineralogy to the Ford Granodiorite of wMBL (Weaver et al., 1991). In the granodiorites of the Ford Ranges, magnetite has been reported (Weaver et al., 1991). This is compatible with high susceptibility values as seen for similar Admiralty Intrusives of northern Victoria Land.

(2) Magnetic anomaly (G) (Fig. 6e) lies close to Drummond Peak, where a low-grade thermal metamorphic overprint with a Rb–Sr age of 360 Ma in Swanson Formation rocks suggests that a Ford Granodiorite intrusive had contact effects (Adams et al., 1989). Furthermore, Kizaki (1958) described hornblende-bearing granitoids resembling Ford Granodiorite in dredge samples collected in the Prestrud Inlet region, also suggesting the presence of these rocks in the crust.

(3) Geochemical and isotopic characteristics of the Byrd Coast Granite of the Edward VII Peninsula suggests derivation from an older infracrustal I-type magmatic source (Weaver et al., 1992). Partial melting of Swanson Formation metasediments cannot explain the chemistry or isotope composition of the Byrd Coast Granite but Ford Granodiorite sources can. Weaver et al. (1992) argued that the subduction-related geochemical signatures of the mid-Cretaceous granite may have been inherited from an I-type granodiorite–tonalite source of Late Devonian–Early Carboniferous age, which would therefore have to be a component of the crust.

(4) Alternative, or maybe additional explanations, though possible, are not entirely as satisfying with presently available constraints. We have shown how magnetic anomalies with wavelengths comparable to the Alexandra Mountains anomaly, but generally much higher in amplitude, mark rift-related Cenozoic Meander Intrusives of the TAM (Fig. 6c). Cenozoic subvolcanic feeder bodies with lower apparent susceptibilities than over the TAM could therefore be possible. Cenozoic rifting over central and eastern Marie Byrd Land was accompanied by voluminous mafic volcanic activity (LeMasurier and Thompson, 1990). Furthermore, high susceptibility was measured over Late Cenozoic volcanics of the Fosdick Mountains (Table 2). However, anomaly (A) overlies exposed non-magnetic mid-Cretaceous Byrd Coast Granite of Mount Swadener (Weaver et al., 1992; Adams et al., 1995). A Cenozoic pluton would intrude the Cretaceous granite itself, but this has not been recognized in the field. Contact metamorphic effects of Cenozoic age are not reported either. Typically, Meander Intrusive-type rocks are emplaced at shallow level in the crust and at times

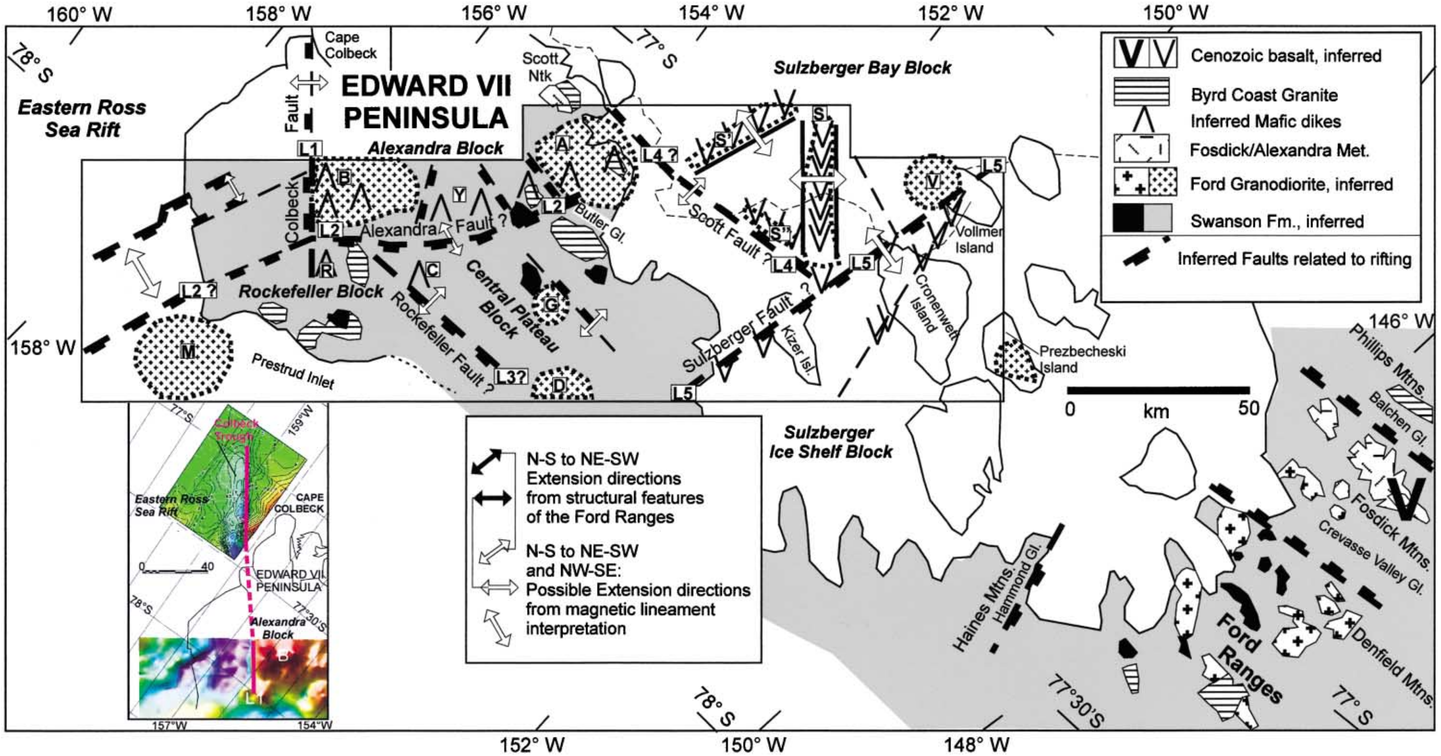


Fig. 7. Aeromagnetic interpretation map over the Edward VII Peninsula. Buried Ford Granodiorite, speculative mid-Cretaceous dikes and likely Cenozoic basalt have been inferred. Interpreted horst and graben crustal architecture is probably linked to multi-stage crustal extension as recognized over the adjacent Ford Ranges and in the Eastern Ross Sea Rift. Note from the inset exact co-linearity between the western margin of the Alexandra block onshore and the Colbeck Trough offshore (Luyendyk et al., in press).

show transitions to volcanic rocks (Tonarini et al., 1997). Cenozoic volcanic rocks do not outcrop at the surface over the Alexandra Mountains. One might argue that the formerly associated Late Cenozoic volcanic edifices may have been glacially eroded, as proposed by Behrendt et al. (1997) to explain the lack of edifices for many similar subcircular West Antarctic magnetic anomalies. Alternatively, tectonically induced erosion of Late Cenozoic volcanoes in a recently uplifted, horst-like Alexandra Mountains block along the Eastern Ross Sea Rift margin (Fig. 7) could be used to argue in favour of a buried Cenozoic feeder body. A pluton-sized mafic–ultramafic feeder body would however be expected to cause a significant gravity anomaly. For example, a positive Bouguer gravity anomaly with an amplitude of 40 mGal overlies a partially exposed Cenozoic Meander Intrusive over the TAM, requiring a high-density (2.9 g/cm^3) pluton extending down to depths of about 10 km to fit the observed gravity data (Reitmayr, 1997). A comparable Bouguer gravity anomaly (Luyendyk and Smith, in press) was not detected over the Alexandra Mountains in the area of magnetic anomaly (A). Present gravity coverage over the E7 is however very limited (30 stations). The apparent lack of prominent gravity signature might nevertheless be significant since it might match the lack of evident gravity signature over exposed Early Carboniferous Salamander Range granite (Fioretti et al., 1997a) over the TAM (Caneva, personal communication, 1999).

Another alternative is that the pluton-sized magnetic bodies are regionally extensive mid-Cretaceous mafic intrusives presently at upper crustal level. There are no geologic arguments against this hypothesis since mid-Cretaceous thermal and metamorphic effects are recognized over the E7 (Adams et al., 1995). Ponding of mantle-derived mafic magmas in the crust together with high geothermal gradients have been inferred to cause partial melting of buried Ford Granodiorite to produce the isotopically enriched Byrd Coast Granite of the Peninsula (Weaver et al., 1992; Weaver et al., 1994). Cretaceous mafic rocks do not crop out in the survey area but in central Marie Byrd Land, A-type granitoids are associated to mafic rocks including dikes, sills and layered gabbro complexes (Weaver et al., 1994). These mafic rocks are mostly olivine tholeiites. A layered alkali gabbro has an $^{40}Ar/^{39}Ar$ age of 99 Ma (Weaver et al., 1994). This age would be within the range of the Byrd Coast Granite of the Edward VII Peninsula. Magnetic properties for these rocks are unknown and there is no extensive aeromagnetic survey over central Marie Byrd Land to make comparisons with, neither to rule out nor to support this alternative hypothesis. We would however expect a pluton-sized mid-Cretaceous layered gabbro of the E7 to exhibit a prominent gravity signature, as argued for a Cenozoic mafic intrusive which, as previously noted, is not evident (Luyendyk and Smith, in press). Smaller scale dikes would not show up in reconnaissance gravity mapping. One might therefore infer that the high-frequency magnetic anomalies modelled in terms of mafic dikes (black bodies in Fig. 5a,b) could be mid-Cretaceous in age. This speculation is possible considering that mafic dikes of this age are well exposed over the Ford Ranges (Luyendyk, 1993; Richard et al., 1994).

A further alternative for anomalies (A) and (B) is that they represent the magnetic signature of a high-grade metamorphic complex, which could form a major, 100 km long, at least 25 km wide, horst along the Eastern Ross Sea Rift flank (Figs. 4a and 6). This hypothesis is attractive because the high-grade crustal block could well exhibit very high apparent susceptibility at depth as evident also from our sparse susceptibility measurements at the surface (Table 2). In addition, the comparable 90×30-km dimensions (Figs. 1 and 7) of the Fosdick Mountains, where high-grade rocks are well exposed (Smith, 1997) make this alternative appealing. The NE trend of the magnetic "Alexandra Mountains block" (Fig. 7) is however highly oblique to the E–W trend of the Fosdick Mountains. Furthermore, the 100-mGal gravity high associated to the Fosdick Mountains block, linked to asymmetric crustal extension and mantle upwarp, appears to be lacking over the E7 (Figs. 3 and 8 in Luyendyk, 1993; Luyendyk and Smith, in press). Furthermore, aeromagnetic anomaly (A) does not appear to extend to Scott Nunataks where the magnetic high-grade rocks outcrop (Smith, 1996). If this holds true, it might indicate that a crustal scale, their volume is negligible over the E7 compared to the Ford Ranges. Further, aeromagnetic surveying over the Scott Nunataks area is however needed to verify if the Alexandra Mountains anomaly (A) does not extend there, as it presently appears, or if this is a mere magnetic edge effect. Extensive aeromagnetic surveying over the Fosdick Mountains metamorphic complex would also furnish an important comparative basis to validate or reject the high-grade Alexandra Mountains crustal block alternative.

6.2. Interpreted horst and graben structure of the Edward VII Peninsula region and associated mafic magmatism

We interpret the observed long-wavelength, high-amplitude, anomaly breaks across magnetic lineaments L1, L2, L3, L4 and L5 as magnetic evidence for the segmentation of the E7 region into horst and graben fault blocks along the Eastern Ross Sea Rift flank (Fig. 7). Apparent vertical offsets in magnetic Ford Granodiorite(?) basement at the location of the lineaments is one argument we put forward to propose this hypothesis (Fig. 5a–b). One might, however, argue that the sharp depth variations in magnetic basement across the lineaments could simply reflect original pre-rift differences in the level of emplacement of the inferred Ford Granodiorite(?) plutons. If, however, these buried E7 plutons are similar to subvolcanic Early Carboniferous bodies exposed over the part of the TAM (Fioretti et al., 1997a,b), as suggested by similarity in magnetic anomaly signature, then these E7 plutons were originally all likely to have been emplaced at very shallow crustal level. We therefore argue that abrupt depth variations in magnetic basement could be linked to post-emplacement faulting associated to much later regional rifting and uplift of the E7.

A fault correspondence for magnetic lineaments would also agree with the observation that the modelled, mafic volcanic rocks and dikes are spatially associated to the magnetic lineaments (Figs. 5a,b and 7). Our magnetic comparative analysis (Fig. 6h vs. f,g,i) speaks in favour of a probable Late Cenozoic age for shallow volcanic rock in the Sulzberger Bay (anomalies S, S′, S″) emplaced along inferred Cenozoic(?) rift-related faults as previously observed over the TAM (Bosum et al., 1989; Ferraccioli et al., 2000) and in the Ross Sea Rift (Behrendt et al., 1996). Highly magnetic, dike-like magnetic sources associated to the inferred rift-related faults could be Cenozoic in age or older, e.g., mid-Cretaceous in age, as previously discussed.

A further magnetic argument we put forward to support the horst and graben working hypothesis is first order similarity between our calculated magnetic crustal models for the E7 region and those computed by Bosum et al. (1989) for better established horst and graben structures of the Ross Sea Rift (Fig. 2). One must consider that our E7 magnetic models are non-unique evidence for horst and graben-like crustal structure. This is due to: (1) the lack of coincident and robust geophysical and geologic constraints along the modelled profiles; (2) to inherent potential field modelling ambiguities; and (3) to the large number of unknown magnetic variables (e.g., geometry of interfaces, vertical and horizontal magnetic susceptibility contrasts, remnant vs. induced magnetization ratios, 3D effects). We therefore contrast our aeromagnetic horst and graben perspective for the E7 region (Fig. 7) with: (a) offshore bathymetric, seismic reflection and marine gravity constraints; (b) on-land radio-echo sounding, gravity, apatite fission track and geologic data. We also include relevant observations from the adjacent Ford Ranges to support our aeromagnetic structural interpretation for the E7.

We interpret the magnetic Alexandra Block to be a horst-like crustal feature forming the Eastern Ross Sea Rift flank (Fig. 7). The NE–SW trending magnetic lineament (L2), displayed in Fig. 7 as the inferred Alexandra Fault(?), separates the Alexandra Block from the less magnetic, likely relatively downthrown, Central Plateau Block. The NNW–SSE magnetic lineament (L1), which marks the abrupt change from the high-amplitude Alexandra Block anomalies to the non-magnetic Eastern Ross Sea Rift basement, is referred to as the inferred Colbeck Fault. This fundamental aeromagnetic feature, likely imaging the Eastern Ross Sea Rift shoulder, is co-linear (inset in Fig. 7) with the prominent 100-km long Colbeck Trough, imaged offshore with bathymetric, multichannel seismic and marine gravity data (Luyendyk et al., 1999; Luyendyk et al., in press). The 800-m high fault scarp mapped on the east side of the Colbeck Trough defines the probable offshore prosecution of the inferred Colbeck Fault. Stratigraphic correlations with seismic sequences of the western and central Ross Sea Rift have been interpreted to indicate that the majority of faulting was prior to Late Oligocene time (Luyendyk et al., 1999). Tilting of younger sedimentary units may be linked to Late Tertiary subsidence of the Eastern Ross Sea Rift margin, possibly coeval with uplift and volcanic activity of the Marie Byrd Land dome (Luyendyk et al., 1999).

A 40-mGal residual Bouguer gravity high (rock density = 2.7 g/cm^3) marks the Colbeck Trough (Luyendyk and Siddoway, written communication, 2001). This gravity feature along the Eastern Ross Sea Rift margin is comparable to the one observed in the Terra Nova Bay region along the western Ross Sea Rift margin (Fig. 2). The latter gravity anomaly has been interpreted as reflecting mantle upwarp along the western part of the Victoria Land Basin (Ferraccioli et al., 2000). Possible mantle upwarp beneath the Eastern Ross Sea Rift might also induce upwarp of the Curie isotherm as has been discussed for the Terror Rift in the western Ross Sea Rift (Bosum et al., 1989). This could furnish a viable explanation for possible demagnetization of the Eastern Ross Sea Rift magnetic basement compared to the highly magnetic Alexandra Block basement.

The continental shelf in the Eastern Ross Sea, west of Cape Colbeck, features NNE trending grabens, where seismic sequence RSS1, inferred to be middle Eocene? to Early Oligocene?, is recognized (Luyendyk et al., 1999). These NNE grabens are parallel to the mapped NNE magnetic trends of the Eastern Ross Sea Rift block (Figs. 3, 4a– and 7).

The eastern margin of the Alexandra basement horst is less evident from aeromagnetic data compared to the western margin. However, we interpret magnetic lineament L4 as marking a possible crustal discontinuity, termed the inferred Scott Fault along the eastern E7 mainland (Fig. 7). Magnetic basement beneath the half-graben-like Sulzberger Bay Block may be downthrown across this inferred fault (Fig. 5a). About 3 km thick, sedimentary and shallow volcanic rock is likely to be present within the Sulzberger Bay Block. Marine gravity compiled with on-land gravity also suggests a possible structural discontinuity between the Sulzberger Bay Block, where the crust is relatively thinner, and the E7 mainland, which features relatively thicker crust (Luyendyk and Smith, in press). The horst and graben-like crustal structure inferred from magnetics over the E7 area is likely to produce regional crustal thinning, as observed over the Ross Sea Rift (Davey and Brancolini, 1995). However, relative crustal thickening modelled from sparse gravity data (Luyendyk and Smith, in press) beneath the Alexandra and Central Plateau basement highs, is comparable with wide-angle seismic evidence for relative (5–8 km) crustal thickening beneath basement highs of the Ross Sea Rift (Trey et al., 1999).

The aeromagnetic perspective for horst and graben structure of the E7 area is also in general agreement with the regional interpretation of Davey and Brancolini (1995) of mostly ice-covered, basin-and-range-style of bedrock morphology, revealed by old, reconnaissance, radio-echo sounding data (Drewry, 1983). Our magnetic interpretation for a horst-like Alexandra Block also matches Adams et al. (1995) observations indicating that the lower grade metasedimentary rocks at Drummond Peak and the sharp contacts with the Rockefeller Mountains granites testify to a shallower structural level compared to the deeper level of the Alexandra Metamorphic Complex. Apatite fission track data has been interpreted to show that the E7 Alexandra and Rockefeller blocks were separated by a major fault active in the mid-Cretaceous, and later reactivated in the Late Cretaceous–Early Tertiary (Adams et al., 1995). Lisker and Olesch (1997) interpreted apatite fission track data over the E7 to reveal horst and graben tectonics at 75–65 Ma, involving 1000 m of denudation, followed by 2500 m of tectonically induced denudation at 25 Ma.

More local graben or half-graben-like structures are superimposed upon the magnetic Alexandra horst block (Fig. 7). The approximately E–W trending sharp edge of magnetic anomaly (A) can be modelled as a fault (Figs. 5a and 6b) along Butler Glacier, dipping to the south. This aeromagnetically inferred fault matches a proposed fault running beneath Butler Glacier based upon contrasting mineral and textural character testifying to differing crustal levels across the inferred fault (Smith, 1996). The residual 50–60 mGal Bouguer gravity low over the Butler Glacier region could be due to low density sediments under the glacier (Luyendyk and Smith, in press), maybe representing sedimentary infill of the inferred half-graben. The Butler Glacier likely exploits the inferred fault. This would be comparable with extensive magnetic imaging of faults (e.g., Fig. 6c,f) typically concealed beneath glaciers of the TAM rift flank (Bosum et al., 1989; Bozzo and Meloni, 1992; Salvini et al., 1997; Ferraccioli and Bozzo, 1999; Ferraccioli et al., 2000). Detailed radio-echo sounding data over the Alexandra Block could be used to verify if inferred faults flanking anomaly (Y) also exhibit a bedrock signature.

We interpret NNE trending magnetic lineament L5 as marking a major crustal discontinuity, termed the inferred Sulzberger Fault (Fig. 7). Across the inferred, fault magnetic basement appears to drop down in the half-graben-like Sulzberger Ice Shelf Block to considerable (up to 10 km) depths (Fig. 5b). A N–S linear magnetic feature could represent a fault splay intersecting L5 at Vollmer Island. Volcanic rock punctuates these inferred faults. Shallow volcanic rock at the margin of the Sulzberger Ice Shelf Block has been modelled in the Kizer Island area (Fig. 5b). The volcanic rock is marked by a coincident positive Bouguer gravity high (Luyendyk and Smith, in press). Byrd Coast Granite and Swanson Formation basement is virtually non-magnetic. Therefore, independent seismic and gravity constraints would be needed to assess thickness of possible sedimentary infill within the inferred Sulzberger Ice Shelf asymmetric graben. The free-air gravity low over the southern Sulzberger Ice Shelf has been interpreted as marking a prosecution of the sedimentary Sulzberger Basin imaged in echo soundings (Luyendyk and Smith, in press).

The approximately E–W trend of the inferred Rockefeller Fault, Scott Fault and Butler Glacier Fault over the E7 is parallel to previously inferred major normal faults of the Ford Ranges, namely to the inferred Balchen Glacier and Crevasse Valley Glacier faults (Fig. 7). The Ford Ranges faults and strain indicators in the Fosdick Metamorphic Complex fit N–S to NNE crustal extension (Luyendyk et al., 1992; Luyendyk, 1993; Richard et al., 1994). This extension direction was coeval with rapid uplift of the Fosdick Metamorphic Complex between 100 and 94 Ma and was active again from 80 to 70 Ma during rapid cooling of the complex (Richard et al., 1994). Further reactivation of the faults occurred in post-Oligocene times, channelling present-day ice flow along the regional E–W valleys of the Ford Ranges (Siddoway, 1999). Late Cenozoic volcanic centres along E–W trends of the Fosdick Mountains (bold V in Fig. 7) confirm Cenozoic reactivation of these faults (Luyendyk et al., 1992). Over the E7 region, volcanic rock inferred to be Late Cenozoic in age is imaged by anomaly (S″) which trends E–W along the inferred Scott Fault. However, volcanic rock in the Sulzberger Bay Block is imaged also along different NNW (S) and NE (S′) trends. The NNW (Late Cenozoic?) volcanic lineament (S) is parallel to the inferred Colbeck Fault marking the Eastern Ross Sea Rift margin. Assuming that these are both normal faults, a NNE extension direction can be inferred over the E7, i.e. sub-parallel to the NE–SW Cenozoic extension direction inferred from brittle fault analysis over the Ford Ranges (Siddoway, 1999).

The inferred Alexandra Fault and the Sulzberger Fault are regional scale E7 features with a NE to NNE orientation, which does not have a counterpart over the Ford Ranges and which lies highly oblique to exposed topography in both regions (Fig. 7). These magnetic features are however sub-parallel to graben-like structures imaged at the margin of the Eastern Ross Sea Rift. The inferred Alexandra Fault appears to truncate the inferred Rockefeller Fault. The inferred Sulzberger Fault also seems to truncate the inferred E–W Scott Fault. The inferred Sulzberger Fault truncates NNW–SSE trending anomaly (S). Assuming that the inferred Alexandra and Sulzberger faults are normal faults, as would be compatible with magnetic modelling, a simple interpretation might be that multi-stage N–S to NE–SW extension was followed by later NW–SE extension. Inferred northwest–southeast extension for the E7 would parallel NW–SE extension interpreted from marine magnetic lineaments in the Eastern Basin within the Ross Sea Rift (Fig. 4 in Davey and Brancolini, 1995). This magnetic speculation for the E7 would however conflict with the structural interpretations for the Ford Ranges indicating Cenozoic N–S to NW–SE shortening across the previously faulted and thinned region rather than NW–SE extension (Siddoway, 1999). If this kinematic scenario holds for the E7 also, then one possibility is that the NE–SW magnetic trends are not the signature of normal faults related to regional NW–SE extension, but the magnetic expression of strike-slip or transfer faults. There is, however, no evident horizontal offset imaged in the E7 aeromagnetic data to prove this, contrary to the TAM-western Ross Sea Rift region where transfer systems are delineated in magnetic anomaly data (Bosum et al., 1989; Behrendt et al., 1996). Alternatively, wMBL may be segmented into two different structural domains namely the E7 and the Ford Ranges (Whitehead et al., 1999), and therefore, kinematic interpretations over one domain may not apply entirely to the other. Extensive aerogeophysical work over the Sulzberger Bay–Sulzberger Ice Shelf and Ford Ranges and higher resolution magnetic data over the E7 could be used to test regional kinematic interpretations. From a general point of view, however, the better known basin-and-range structure of the Ford Ranges (Siddoway, 1999) is comparable to our aeromagnetic interpretation for horst and graben structure of the E7 region.

6.3. Magnetic imprints of regional tectonic evolution

Recently complied magnetic anomaly data for the Eastern Ross Sea, Ross Ice Shelf, West Antarctic Ice Sheet and wMBL regions, as part of the Antarctic Digital Magnetic Anomaly Project (Johnson et al., 1996; Chiappini et al., 1998, 1999), portray at a more regional scale the tectono-magmatic setting of the E7 Ross Sea Rift shoulder (Fig. 8). High-amplitude (over 400 nT) positive anomalies are imaged from marine magnetic data over the Eastern Basin, likely due to substantial volumes of rift-related Cenozoic(?) magmatic rock associated to this Ross Sea Rift basin (Davey and Brancolini, 1995; Trey et al., 1999). Aeromagnetic data highlights linear West Antarctic Rift fabric and subcircular, high-amplitude (up to 1100 nT) anomalies due to rift-related Cenozoic(?) volcanic edifices and associated plutonic roots concealed beneath the West Antarctic Ice Sheet (Finn et al., 1999b). The hinge zone between the West Antarctic Rift and the wMBL rift shoulder is largely unknown. Widely spaced (over 50 km), old and poorly located aeromagnetic data (Beitzel, 1972) suggests that the Rockefeller Plateau region features subcircular, high-amplitude, magnetic anomalies, which may also relate to Cenozoic magmatism (Fig. 8). These anomalies differ from lower amplitude anomalies over the Ford Ranges, possibly associated to exposed Ford Granodiorite. A single profile over the Fosdick Mountains images relatively higher amplitude anomalies likely due to exposed Late Cenozoic volcanics (LeMasurier and Wade, 1990). A single profile also suggests that the E7 Alexandra and Sulzberger Bay magnetic high continues further to the east until Guest Peninsula. The magnetic Alexandra Block appears from a single profile to continue further to the north towards Cape Colbeck, likely confirming the previously proposed prosecution of the inferred Colbeck Fault along the Eastern Ross Sea Rift margin (inset in Fig. 7).

Overall, we propose that the aeromagnetic signatures over the E7 area may represent local magnetic imprints of much more regional tectonic evolution (Fig. 9A–C). Magnetic anomalies have been delineated over the Early Carboniferous Admiralty Intrusives of the TAM and over coeval but buried Ford Granodiorite of the E7. These anomalies are comparable in amplitude and wavelength to those typically observed over magmatic arc plutons, e.g. over the Carboniferous–Cretaceous Median Tectonic Zone of New Zealand (Sutherland, 1999), or over the Cretaceous(?) Antarctic Peninsula arc (Johnson, 1999). Apparent susceptibilities and dimensions of the inferred plutons resulting from the E7 magnetic models are similar to those marking the arc-back-arc transition region over the Antarctic Peninsula (Fig. 4 in Johnson, 1999). Gastil et al. (1990) suggested that a trench-distal province of magnetite-rich plutons might have generated above a deep dehydrated subducting slab beneath Baja California. On the basis of these analogues and following the tectonic model of Ricci et al. (1997), we propose that both the westernmost Admiralty Intrusives of the TAM and the inferred Ford Granodiorite of the E7 may have formed trench-distal magmatic arc plutons related to subduction of oceanic lithosphere outboard of the Robertson Bay and wMBL (Fig. 9A).

High-frequency magnetic anomalies over the E7 have been modelled in terms of highly magnetic dikes intruding buried Ford Granodiorite basement (Fig. 5a,b). The dikes could speculatively be mid-Cretaceous mafic dikes as indicated by the geology of the adjacent Ford Ranges and of central Marie Byrd Land (Luyendyk, 1993; Weaver et al., 1994). These inferred dikes could be related to regional scale processes (Fig. 9B?) involving, at upper crustal level, the generation of anorogenic Byrd Coast Granite by partial melting of Ford Granodiorite, inferred mid-crustal flow of the Fosdick/Alexandra Metamorphic Complex accommodating upper crustal extension, lower crustal mafic underplating and possible mantle plume activity (Smith, 1997; Bradshaw and Weaver, 1999). These magmatic processes may be genetically linked with early rift stages within the Ross Sea Rift and with extension between wMBL and the Campbell Plateau (Smith, 1997).

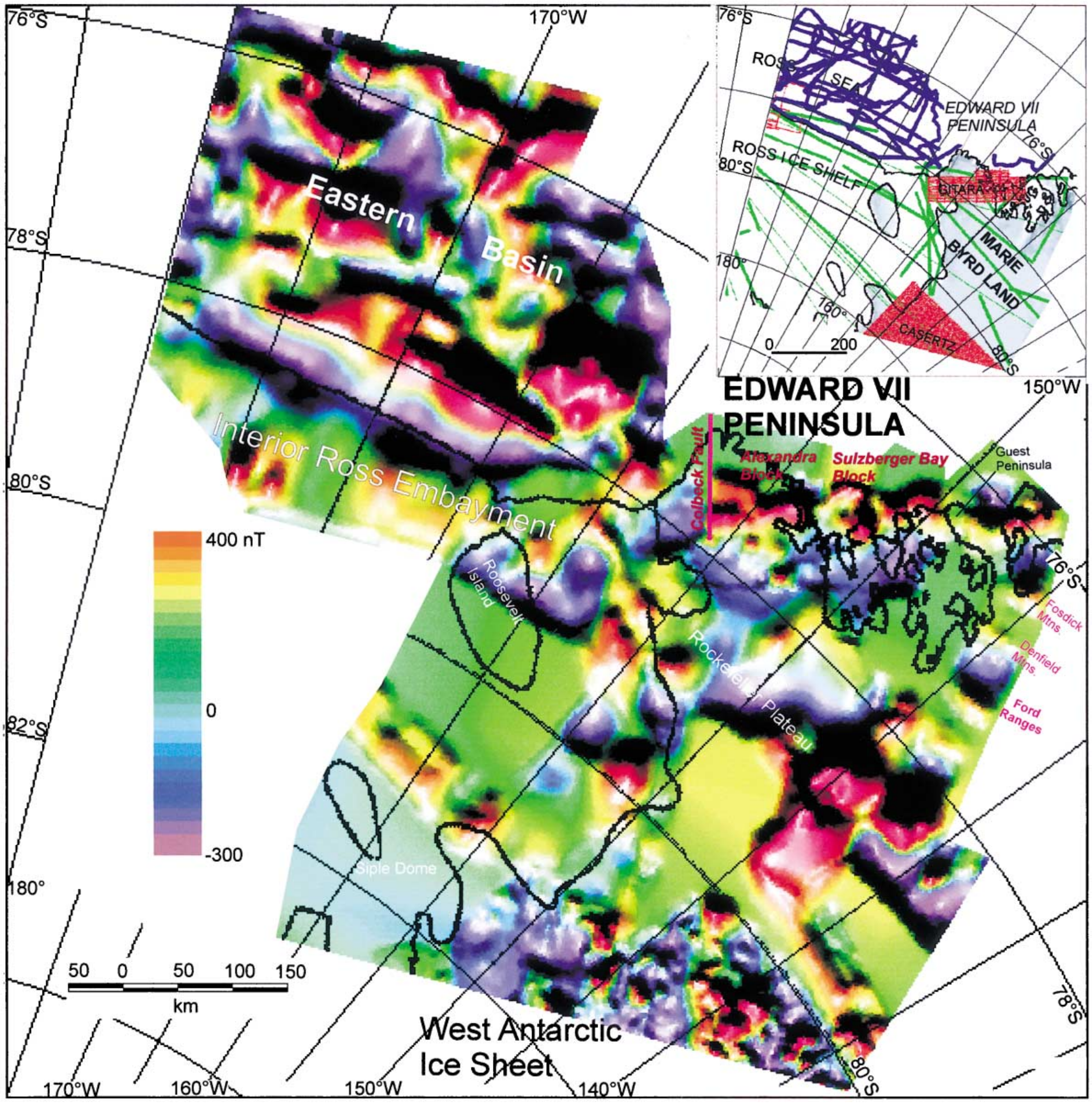


Fig. 8. ADMAP magnetic anomaly map imaging at a broader scale the tectonic setting of the Edward VII Peninsula placed at the Eastern Ross Sea Rift margin and north of rift structures identified beneath the West Antarctic Ice Sheet (Finn et al., 1999b). Inset shows the location of aeromagnetic flight lines (red indicates line spacing <5 km), marine magnetic tracks (blue) and old aeromagnetic profiles (green for mean line spacing of 50 km). Satellite magnetic anomaly data was used to fill in areas with no near-surface data.

The elongated magnetic anomalies of the Sulzberger Bay Block and along the flank of the Sulzberger Ice Shelf Block of the E7 resemble those typically observed over rift-related Cenozoic volcanics of the West Antarctic Rift System (Bosum et al., 1989; Behrendt et al., 1994, 1996; Behrendt, 1999; Finn et al., 1999b). These E7 Cenozoic volcanic rocks may be related to renewed regional crustal extension and possible mantle plume activity (Fig. 9C) centred beneath MBL (LeMasurier and Landis, 1997).

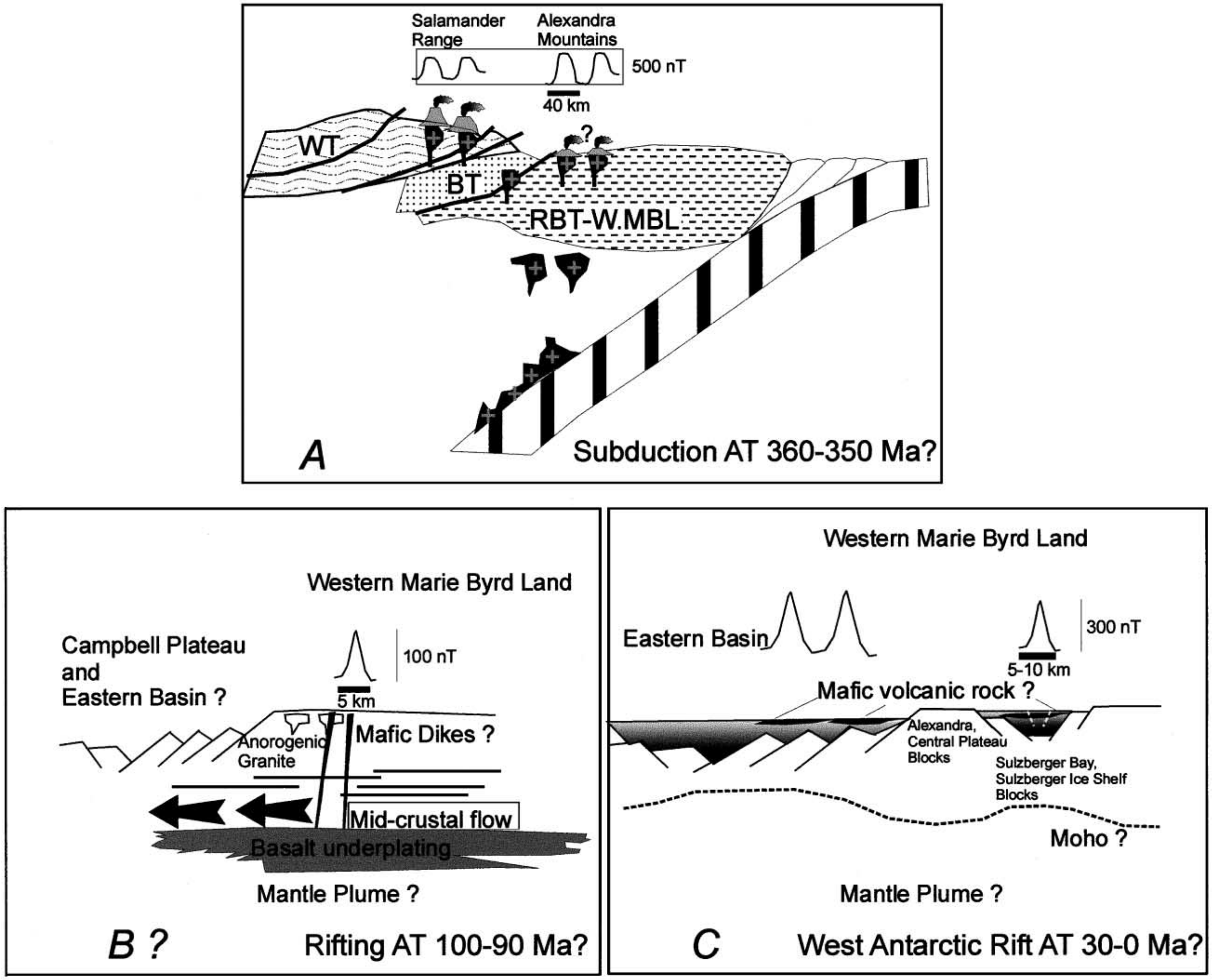


Fig. 9. Magnetic imprints as possible tracers of regional tectonic evolution. Inset (A) (modified from Ricci et al., 1997) depicts typical magmatic arc magnetic signature over Admiralty Intrusives and over inferred buried Ford Granodiorite as possible evidence for a subduction-related tectonic scenario at about 350 Ma outboard of the Robertson Bay Terrane (RBT) and of western Marie Byrd Land (wMBL). Inset (B)? (modified from Smith, 1997) depicts magnetic mafic dikes modelled over the Edward VII Peninsula as speculatively related to an early 100–90 Ma stage of Ross Sea rifting and/or with extension between wMBL and the Campbell Plateau. Inset (C) depicts mafic volcanic rock emplaced along linear trends offshore the Edward VII Peninsula as rift-related Cenozoic volcanics of the continental scale West Antarctic Rift System (Behrendt, 1999).

7. Conclusions

Interpretation of magnetic anomalies over the E7 along the Eastern Ross Sea Rift flank is challenging because of limited rock outcrop and because of the lack of clear magnetic markers at the surface to correlate with geology. However, an integrated approach involving: (1) comparison with better known magnetic signatures over the TAM and Ross Sea Rift; (2) analysis of independent E7 geochemical constraints; (3) results from independent geological and geophysical studies both over the E7 and over the adjacent Ford Ranges; (4) similarity between local E7 magnetic anomalies and more regional and better established magnetic signatures, has been used to conclude the following.

(1) Buried Ford Granodiorite intruding Swanson Formation rocks is a component of the E7 crust as it is in the adjacent Ford Ranges. Together with the Admiralty Intrusives of northern Victoria Land, it may mark a phase of crustal development at about 350 Ma linked to subduction of oceanic crust outboard of the Robertson Bay Terrane and likely formerly adjacent wMBL.

(2) Mid-Cretaceous mafic dikes, could speculatively be a component of the E7 crust, linked to regional crustal extension in the Ross Sea Rift and between wMBL and the Campbell Plateau of New Zealand.

(3) Volcanic rock, likely Late Cenozoic age in age, is spatially associated to linear trends interpreted as local rift fabric of the E7. The E7 volcanic rocks may reflect regional reactivation of the West Antarctic Rift System in the Cenozoic.

(4) The eastern flank of the Ross Sea Rift features a horst and graben crustal structure, likely resulting from multi-stage Cretaceous and Cenozoic extension. N–S to NE–SW extension directions, speculatively interpreted from E7 magnetic lineaments, are consistent with those previously interpreted from geologic indicators of the Ford Ranges, but the inferred later NW–SE extension is not. This possible extension direction for the E7 would however be consistent with NW–SE Ross Sea Rift extension.

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