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Assessment of deep electrical conductivity features of Northern Victoria Land (Antarctica) under other geophysical constraints

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Abstract
The lithospheric and crustal structure of the Victoria Land continental block (Antarctica) has been studied by geological and geophysical surveys. Among them magnetovariational investigations (MV) have been addressed to highlight the deep electrical conductivity patterns which contribute to the understanding of continental rifting and tectonic setting of the region. The hypothetical event map for H linearly polarized perpendicular to the coast indicates a possible broad coast parallel conductivity anomaly zone. Despite the coast effect, this feature could be related to the deep upper mantle thermal anomaly leading to Cenozoic uplift of the Transantarctic Mountains rift flank. However, both the hypothetic event map polarized parallel to the coast and the induction arrows suggest that the area of enhanced conductivity may be confined to the Deep Freeze Range crustal block along the western flank of the Mesozoic Rennick Graben. We also discuss the possible association between increased conductivity over the Southern Cross block and extensive Cenozoic alkaline plutonism.

Key words *magnetovariation – electrical conductivity – lithosphere*

1. Introduction

Within the last decade international efforts have been initiated to investigate the lithospheric and crustal setting over Victoria Land in Antarctica by means of gravity, magnetics and seismics. This continental block is adjacent to the Ross Sea rift, which in turn is a fundamental component of the Mesozoic to present day West Antarctic Rift System (WARS). The Transantarctic Mountains (TAM) are the main morphological and structural element of Victoria Land. This range forms one rift shoulder of the continental scale WARS (fig. 1). The study of the TAM rift flank is of considerable interest also outside the Antarctic scientific community since it leads to addressing fundamental questions about tectonics, magmatic features and driving mechanisms of continental rifting.

From a general point of view, deep electrical conductivity patterns may considerably contribute to an understanding of continental rifting. In other rift systems worldwide zones of enhanced conductivity have infact been detected at many different levels within the extended crust (Jiracek *et al.*, 1995 and references therein).

Five magnetovariational (MV) campaigns were carried out during 1986/1987, 1987/1988,

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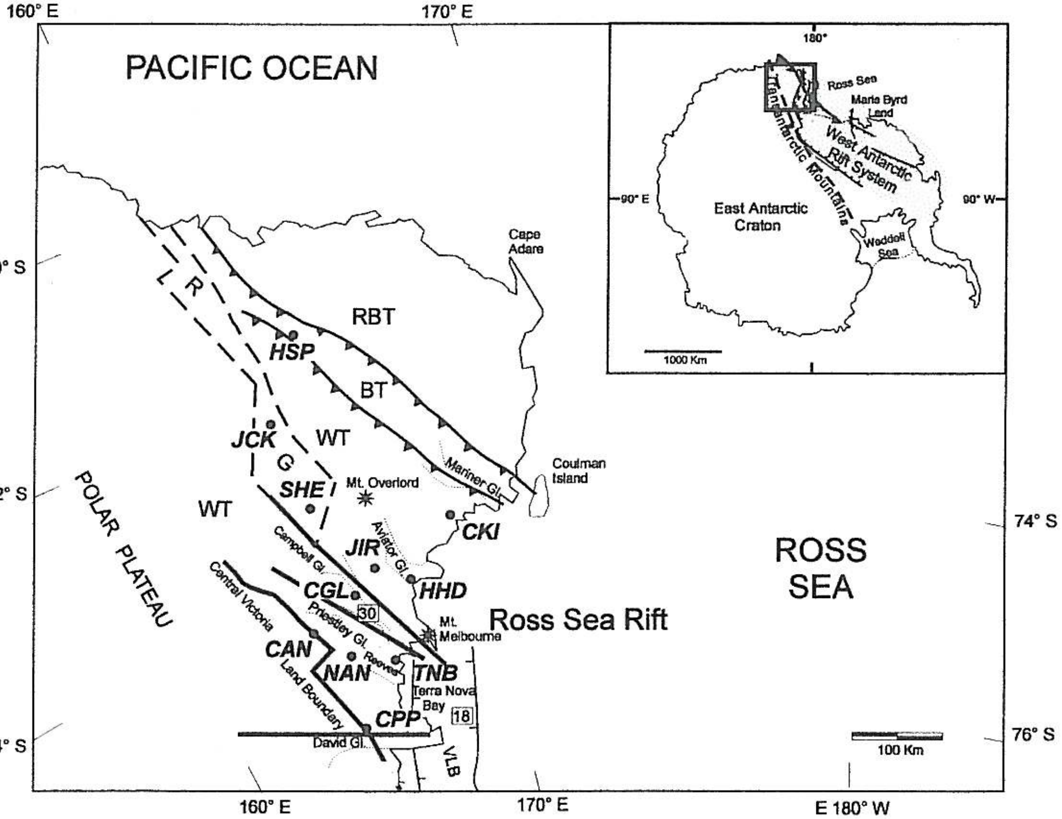

Fig. 1. Tectonic sketch of the area and locations of magnetovariational stations. Numbers in the square boxes indicate crustal thickness estimates derived from seismics and gravity. RG = Rennick Graben; VLT = Victoria Land Basin; RBT = Robertson Bay Terrane; BT = Bowers Terrane; WT = Wilson Terrane.

1988/1989, 1994/1995, 1996/1997 Italian Expeditions in Northern Victoria Land (NVL) in order to furnish new constraints on the deep crustal structure and tectonic setting of the region. MV data acquisition systems simultaneously recording three magnetic field components were installed in NVL for a period of about one month during each campaign, providing a total of eleven stations including the Terra Nova Bay geomagnetic observatory. The area under investigation is located between latitude 71°30′-75°30′S and longitude 161°30′-167°E (fig. 1). The stations were approximately 50 km spaced in the southern sector of the array while they are more sparse in the northern one.

Some preliminary observations and results from the first four campaigns were reported by Armadillo *et al.* (1997). During the Antarctic summer 1996/1997 the magnetovariational network was extended to fill the gap between Lanterman Range (HSP) and Sheehan Mesa (SHE). The new station was installed at Mt. Jackman (JKM) and operated for twenty days (Caneva and Bozzo, 1998).

In this paper we integrate the whole data set to obtain an estimate of the electromagnetic response of the lithosphere to crustal structure and tectonic evolution of Victoria Land as interpreted independently from a variety of geophysical data.

2. Geological and geophysical setting

The TAM are generally accepted to be linked to Cenozoic and Mesozoic extensional tectonics of the Ross Sea embayment though several contrasting models have been proposed to explain uplift phases of the range (Stern and ten Brink, 1989; Bott and Stern, 1992; Fitzgerald and Baldwin, 1997).

The present day TAM expose and are underlain by a dominantly contractional mountain belt referred to as the Ross Orogen that formed in earliest Paleozoic time (Goodge, 1995). In Northern Victoria Land (NVL) three tectonometamorphic terranes are interpreted to belong to the Ross Orogen: the Robertson Bay Terrane (RBT), the Bowers Terrane (BT) and the Wilson Terrane (WT). The RBT and BT are metasedimentary and metavolcanic terranes considered to be allochtonous with respect to the East Antarctic Craton. The WT has been described as an autochthonous magmatic arc linked to westward dipping subduction beneath the craton (Tessensohn, 1997; Ricci *et al.*, 1997). The structural architecture of the three terranes is dominated by NW-SE trending thrusts and/or strike slip faults (Flöttmann and Kleinschmidt, 1993).

A major erosional unconformity surface, the Kukri peneplain, separates the basement complexes from the overlying sedimentary rocks of the Devonian-Jurassic Beacon Supergroup (Woolfe and Barrett, 1995). In the Jurassic, widespread extrusion and intrusion of tholeiitic rocks reveal volcano-tectonic activity at the present site of the TAM (Elliot, 1992).

A Cretaceous thermal and tectonic events have been interpreted to have occurred within the Rennick Graben (RG), a major pull-apart basin possibly representing an extension within Victoria Land of the Mesozoic Ross Sea rift basins (Tessensohn, 1994).

During the Cenozoic an extensional to transtensional tectonic setting characterized the TAM and the Ross Sea. Renewed extension within the N-S to NNW Victoria Land Basin has recently been interpreted from offshore seismic data to be linked to reactivation of NW-SE basement faults as major right-lateral strike-slip faults (Salvini *et al.*, 1997). Structural geology data in Southern Victoria Land has also been interpreted to reveal NW-SE directed extension oblique to rift basins (Wilson, 1995). Rift-related alkaline igneous rocks are exposed along the TAM (LeMasurier and Thompson, 1990). In particular two main volcanoes are present within our study area: Mt. Melbourne (MM) and Mt. Overlord (MO). Alkaline intrusives up to 48 Ma have also been recognized within the Southern Cross Mountains (Tonarini *et al.*, 1997 and references therein). The presence of rift-related volcanic rocks within the Victoria Land rift Basin has been interpreted from magnetics, seismics and gravity (Behrendt *et al.*, 1996, and references therein).

A variety of geophysical investigations have been carried out mainly within the Ross Sea itself to study the crustal structure and tectonics of the West Antarctic Rift system (Behrendt *et al.*, 1993), while the crustal blocks of the Cenozoic and Mesozoic TAM are much less well known.

A seismic model of the Deep Freeze Range (DFR) area indicates that the crust thickens from 19 km adjacent to the Ross Sea rift to 30 km at 60 km inland beneath the TAM (O' Connell and Stepp, 1993). Preliminary results along the ACRUP seismic line to the south of the study area indicate that the crust thickens from about 18 km within the Victoria Land Basin to 25 km at the coast and 38 km at the edge of the Polar Plateau, over 100 km inland (Della Vedova *et al.*, 1997).

Gravity data have been interpreted (Kienle *et al.*, 1989) to indicate that the DFR itself is located in a transition area between thinner NVL crust (30 km) and thicker crust to the southwest (> 30 km). Thinning of the NVL crust may speculatively be linked to the extensional tectonic setting forming the Rennick Graben. Reitmayr (1997) however does not interpret the newly compiled gravity data over Victoria Land to show systematic differences in crustal thickness or in regional gravity anomaly pattern over Northern and Southern Victoria Land.

Aeromagnetic interpretations strongly support the idea that the TAM rift shoulder of Northern and Southern Victoria Land is segmented into discrete crustal blocks. Ferraccioli and Bozzo (1999) propose the existence of four main crustal blocks (see fig. 5a,b): the Southern Cross Mountains Block (SCB), the Rennick Graben

(RG), the Deep Freeze Range block (DFR), and the Prince Albert Mountains Block (PAB).

The SCB features prominent circular magnetic anomalies related to Cenozoic alkaline intrusives and recently active volcanoes such as Mt. Melbourne and Mt. Overlord. Offshore the SCB a high-amplitude anomaly chain trending ENE has been interpreted to reflect a Cenozoic leaky transfer fault zone linking offset segments of the Ross Sea rift (Behrendt *et al.*, 1996).

The southernmost RG is characterized by high-amplitude anomalies related to Jurassic Kirkpatrick Basalt within the graben itself. The DFR lacks such high-amplitude anomalies suggesting that this block should be regarded as the graben shoulder.

A regional magnetic lineament just west of Terra Nova Bay named the «Central Victoria Land Boundary» separates the PAB from the above NVL blocks. It is interpreted as being part of a major Lower Paleozoic (?) fault zone at the craton margin. Over the PAB much more widespread high frequency anomalies are related to Jurassic volcanics suggesting substantial differential uplift or preferential focussing of Jurassic tholeiitic magmatism along the cratonal margin (Ferraccioli and Bozzo, 1999).

3. Data processing

The MV method consists in the analysis and interpretation of the three components of the time-varying magnetic field at a number of stations which form a two-dimensional array. Data from the array are used to identify anomalous magnetic fields induced in the Earth by time varying external iono-magnetospheric sources and can provide inferences about deep conductivity structures (Berdichewsky and Zhdanov, 1984).

Each MV station consisted of a three-component fluxgate magnetometer connected to a digital datalogger and solar cell panels (fig. 2). Data were recorded on magnetic tapes with an accuracy of 0.5 nT at a sampling rate between 0.067 and 0.017 Hz after anti-aliasing filtering. An example of data record is shown in fig. 3, where the three components of the JCK station are reported.

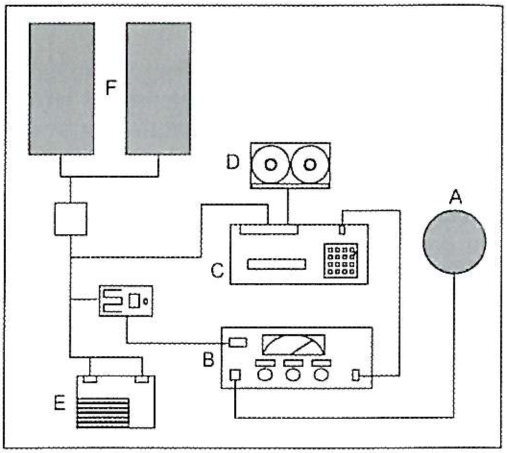

Fig. 2. Magnetovariational station scheme. A = fluxgate sensor; B = electronic console; C = micrologger (analog to digital converter); D = tape recorder; E = battery; F = solar panels.

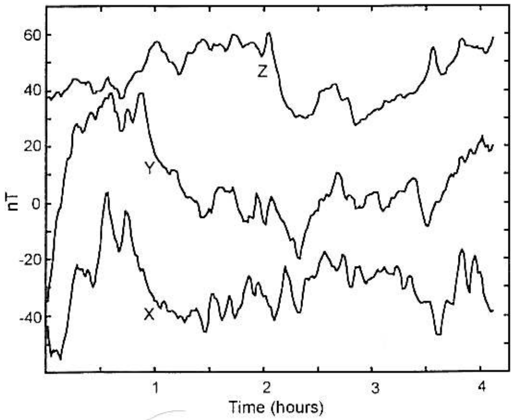

Fig. 3. Example of raw data at JCK station. The three components (X = south-north; Y = west-east; Z = up) of the geomagnetic field are reported starting at 22 November 1996 13:13:00 LT. The zero level of the nT scale is arbitrary.

After visual inspection and detection of outliers, 256 min segments have been chosen from raw data, windowed and Fourier transformed for further processing.

MV investigations on the electrical conductivity of Antarctic lithosphere suffer the strong-

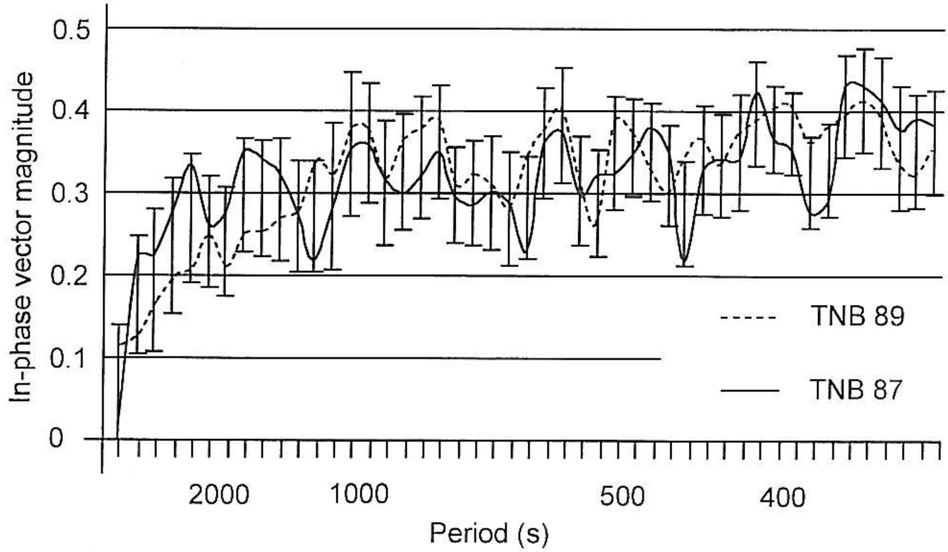

Fig. 4. Comparison of the magnitude of in-phase induction vector at TNB for the two different time periods 3 January-10 February 1989 (TNB 89) and 10 January-2 February 1987 (TNB 87). The vertical bars represent the standard deviations of the difference between the two estimates.

ly non-uniform spatial distribution of the geomagnetic field time variations in polar regions due to the particular configuration of the magnetospheric current system (Mareschal, 1986; Viljanen *et al.*, 1993). This represents the main problem connected with the application of the MV method, with respect to middle latitudes. To reduce induction source effects, the computation of single site transfer functions (Schmucker, 1970) has been performed for each station by means of robust estimation (Egbert and Booker, 1986). This approach accounts for the systematic increase of errors with increasing the power of external variations and automatically downweights source contaminated outliers. In the analysis, only Fourier coefficients with magnitudes between frequency-dependent thresholds were considered, in order to omit the highest power events (that likely show the strongest deviations from the uniform source field assumption) and ensure good signal to noise ratio.

To test the consistency of the processing scheme, the transfer functions at the Terra Nova Bay geomagnetic observatory (TNB station) have been estimated from two different data sets: 133 events in the period 3 January-10 February 1989 and 42 events in the period 10 January-2 February 1987. The magnitude of the two real induction vectors are plotted in fig. 4. The two estimates are consistent within their errors, suggesting that the robust estimation approach we have adopted furnishes reasonable results.

4. Results

Transfer functions are presented, in fig. 5a,b, as in-phase induction vectors (Schmucker, 1970) for the periods 8.2 and 42.6 min which well show the high and low frequency behaviour over the array. Taking into account the 'skin depth effect' (Hermance, 1995), the two periods can be considered to be roughly indicative of the crustal and lithospheric depth respectively. The induction arrows are reversed to point towards current concentrations which are interpreted as zones of high internal electrical conductivity.

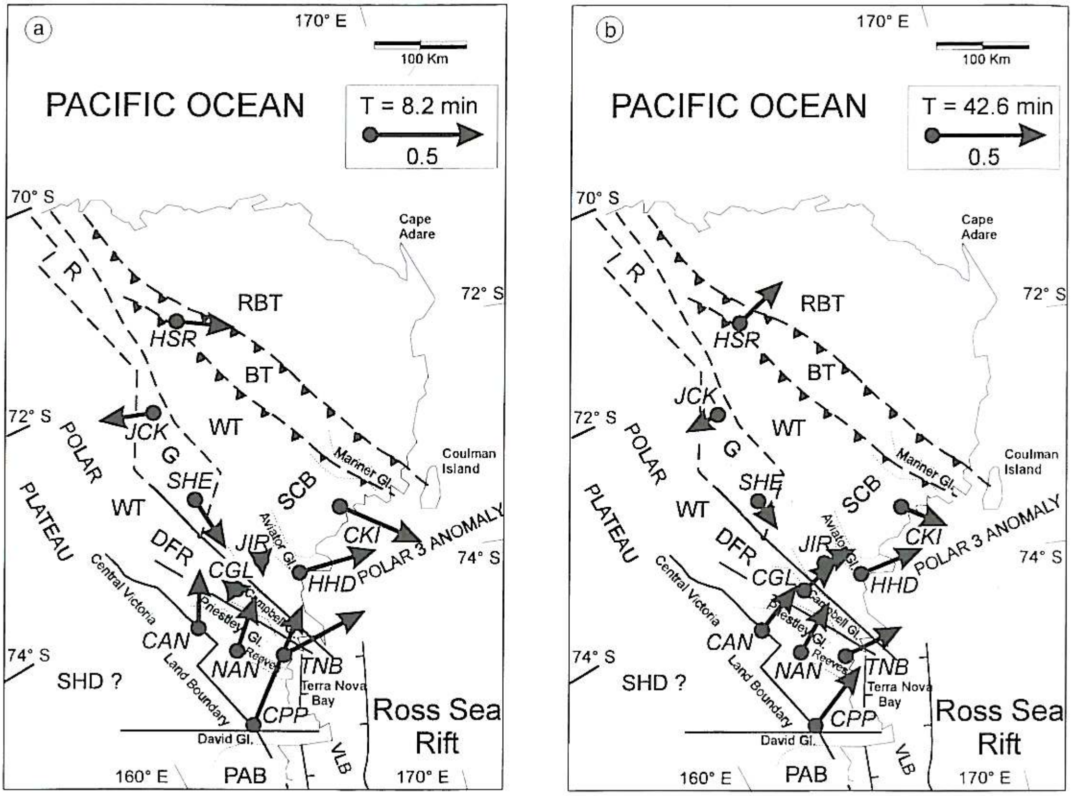

Fig. 5a,b. In-phase induction vectors for the periods 8.2 (a) and 42.6 (b) min. The arrows are reversed to point towards current concentrations that are interpreted as zones of enhanced internal electrical conductivity.

An alternative image of transfer functions is by means of the hypothetical event maps (Bailey *et al.*, 1974). In this case transfer functions are used to compute amplitude and phase of the vertical field related to currents induced by the linearly polarized horizontal field $\boldsymbol{H}$. An electrical induced current flowing along an elongated conductor gives rise to a high gradient in the Z phase, a minima in the Z amplitude over the current and a corresponding maxima on both its sides. In fig. 6a,b we display Z values corresponding to the horizontal field $\boldsymbol{H}$ linearly polarized at azimuth 101°, in fig. 7a,b relative to 191° clockwise from the north.

We first examine the behaviour of the induction arrows (fig. 5a,b). CAN, NAN and CPP arrows point towards N-NE and the magnitude of CGL and JIR is very small. This is interpreted to reveal the existence of an elongated NW-SE trending conductor located between the Priestley Glacier and the Aviator Glacier. The conductor may be spatially associated to the DFR block, imaged from magnetics (Ferraccioli and Bozzo, 1999), though it seems to extend more to the east. The interpretation of a conductive DFR block is supported by the hypothetical event map which indicates reduced Z values (< 0.1) over the same region and a gradual increment both in the magnitude (fig 7a) and in the phase (fig. 7b) towards SW. The contours show an apparent asymmetry in the horizontal gradient perpendicular to the strike of the «DFR» conductor. The gradient is considerably sharper to the SW with respect to the NE likely due to the anomalous behaviour of CPP, which has higher Z values compared to other coastal stations of the array. Whether this low conductivity is linked to the Central Victoria Land Boundary, interpreted to mark the transition between the Terra Nova Bay region and the Prince Albert Mountains Block (PAB), is speculative. The TNB induction arrow is roughly consistent with CAN, NAN and CPP but it is rotated about 30° clockwise.

Over the highly uplifted Southern Cross Mountains Block (SCB), the CKI and HHD induction arrows are not perpendicular to the coastline itself but point towards the area of the POLAR 3 magnetic anomaly. Clearly however the possible spatial association between a conductor and the magnetic anomaly related to Cenozoic plutonism must take into account the coast effect.

Within the Rennick Graben (RG), JCK and SHE arrows show a different orientation but both point outside the graben itself. SHE vector is directed towards southeast that is towards the high conductivity region revealed by CGL and JIR. JCK points west towards the Polar Plateau. At the transition between the Wilson Terrane and the Bowers Terrane, HSP is oriented to ESE at the 8.2 period and to ENE at the 42.6 period, that is in both cases away from the RG. Apparently once again the induction arrows do not reveal a major conductivity anomaly over the RG itself.

Interpretation of the hypothetical event map linearly polarized at azimuth 101° (fig. 6a,b) may in part be hindered by the fact that this polarization is not ideal to mitigate the coast effect. However, as discussed in the following, the coast parallel alignment of contours may also be significant from the tectonic point of view.

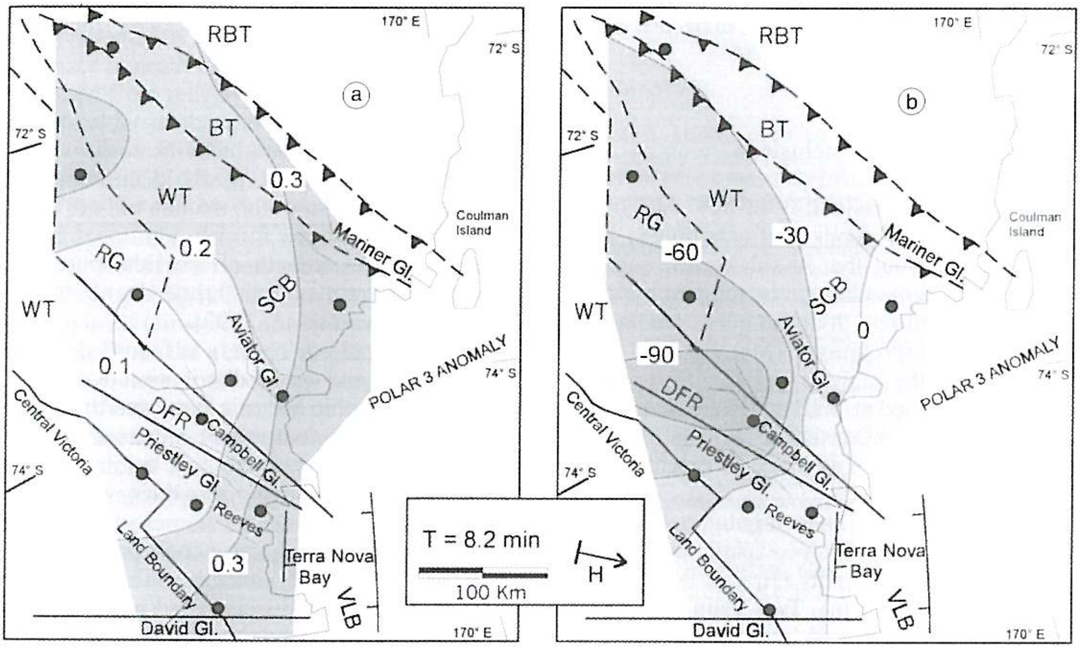

Fig. 6a,b. Hypothetical event map for the period 8.2 min and horizontal field ***H*** linearly polarized at azimuth 101° clockwise from north (approximately perpendicular to the coast). Amplitude (a) and phase (b) of the corresponding vertical field are shown.

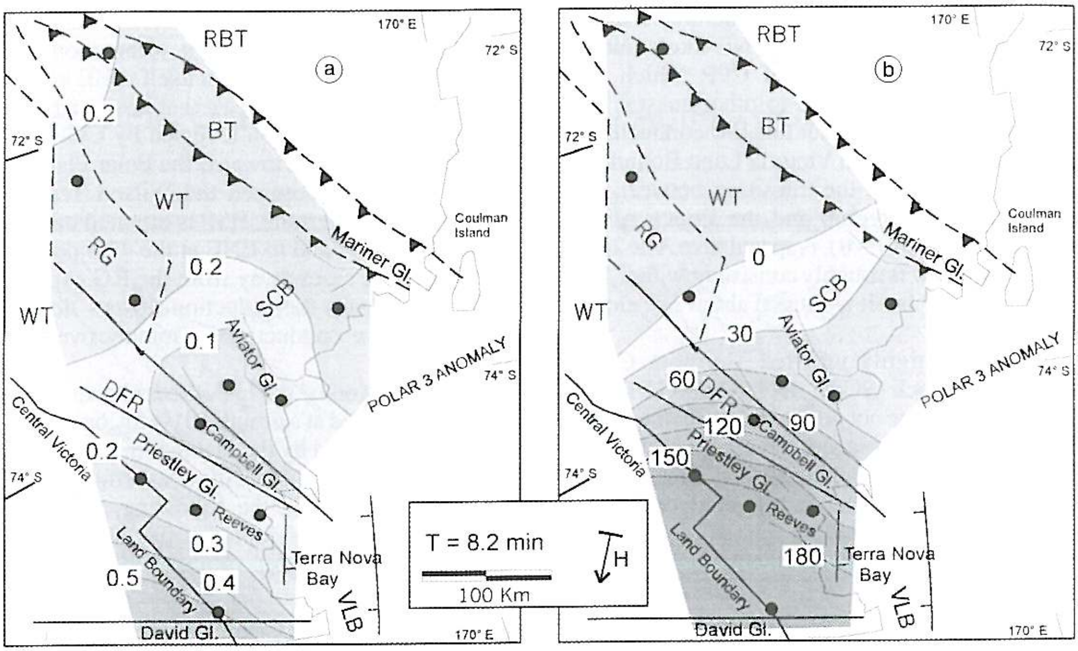

Fig. 7a,b. As in fig. 6a,b but with horizontal field ***H*** linearly polarized at azimuth 191° clockwise from north (approximately parallel to the coast).

5. Discussion and conclusions

Regarding the reliability of MV data interpretation at high geomagnetic latitudes, it is worth to point out that in sub-auroral regions conductivity anomalies can be masked by three dimensional current loop sources, leading to erroneous interpretations (Mareschal, 1986). Nevertheless, the analysis on two different time periods performed at TNB station (discussed in Section 3) reveals consistency in the obtained results which can be assumed to extend to the whole array.

Conductors have been highlighted at mid-lower crustal levels in close spatial association to active continental rifts (Jiracek *et al.*, 1995 and references therein). Two main key issues regard: a) the depth and lateral extent of conductive zones within the crust and their relationship or lack thereof to extensional features revealed independently from seismics, gravity, magnetics and geology; b) the origin and significance of enhanced conductivity zones within the extended crust; *e.g.*, is the deep enhanced conductivity due to water, magma or both? Can conductivity patterns furnish additional information on the strength of the lithosphere by placing constraints on the brittle-ductile transition? (Hyndman *et al.*, 1993).

In this paper our concern is focussed on the lateral extent and spatial distribution of conductivity zones within Victoria Land and their possible association to tectonic blocks along the Cenozoic TAM rift flank and to interpreted Mesozoic and Cenozoic tectonics within the Rennick Graben.

The existence of a broad coast parallel zone of high conductivity over the Transantarctic Mountains was previously noted by Armadillo *et al.* (1997). One might speculate that such conductivity structure could reflect Ross Sea rift margin processes leading to the uplift of the TAM. It cannot be disregarded that independently both gravity and seismic data (Reitmayr, 1997; O'Connell and Stepp, 1993) are interpreted to indicate the existence of a major coast parallel discontinuity, possibly a major fault, between the rift and the TAM. Crustal thickening from the Ross Sea rift to the TAM is also interpreted from seismics and gravity. In particular, Stern and ten Brink (1989) proposed a flexural uplift model of the Transantarctic Mountains. This model calls for lateral thermal conduction from the rift to about 60 km beneath the TAM leading to an average temperature increase in the upper mantle at the Victoria Land rift basin-TAM discontinuity of 450°C. Such an upper mantle thermal anomaly could induce an increase in the conductivity beneath the range itself, since it is well established that high heat flow and enhanced temperatures at depth can lead to the formation of conductivity anomalies (*e.g.*, Adam, 1987).

Induction arrows however seem to indicate that the region of enhanced conductivity is not as broad and randomly distributed over the TAM. It may instead be confined to the SW by a discontinuity trending NW-SE. There is, in fact, an apparently NW-SE elongated conductivity anomaly beneath the DFR, which has been interpreted from magnetics to represent the western shoulder of the Rennick Graben. However there is no clear indication for a high conductivity zone beneath the graben itself. This conductivity pattern may be similar to the Rhinegraben in Europe where some authors discuss the presence of a conductor beneath the eastern shoulder of the graben rather than directly under the graben itself (Jiracek *et al.*, 1995 and references therein). From the geological point of view the lack of a clear conductivity anomaly directly beneath the Rennick Graben of Victoria Land is not unreasonable. In fact though the graben has an extensional history spanning from Permian times onward (Roland and Wörner, 1996), it is thought to be largely amagmatic in post-Jurassic times. On the other hand the location of two recently active volcanoes (Mt. Melbourne and Mt. Overlord) in the area of the western and eastern shoulder of the graben itself could reflect recent reactivation of the graben shoulders. If this is the case, it is somewhat surprising that the area of Mt. Melbourne volcano does not seem to feature a clear conductivity anomaly. A closely spaced GDS array performed during the 1997/1998 Antarctic campaign on Mt. Melbourne volcano edifice may furnish a more detailed picture of the conductivity structure of the region.

At a more regional scale our study gives hints that Cenozoic magmatism, in particular plutonism, may cause conductivity anomalies in Victoria Land though data is too sparse to clearly image their spatial distribution. In fact we observed the small magnitude of the induction arrow directly over the Mt. Jiracek intrusion revealed from magnetics and the possible association between the direction of the induction arrows and the trend of the Polar 3 anomaly.

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