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Transfer faults in the western Ross Sea: new evidence from the McMurdo Sound/Ross Ice Shelf aeromagnetic survey (GANOVEX VI)

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Abstract: Aeromagnetic data collected on the GANOVEX IV and GANOVEX VI expeditions are combined in this report to give a synoptic view of the western Ross Sea, Antarctica. The addition of the new GANOVEX VI data allows the identification of the southern boundary of the "Ross Sea Unit" — a magnetic unit containing rift-fabric anomalies of the West Antarctic rift system in the Victoria Land basin. Although this boundary has a similar WSW–ENE orientation to the northern boundary, as identified in the GANOVEX IV survey, the newly identified southern magnetic unit (called the "Ross Island and Ice Shelf Edge Unit") includes evidence of the S–N rift-fabric that is not found in the north, i.e. the rift-fabric continues farther south. The linear boundaries themselves are interpreted as transfer faults as proposed by previous workers for the tectonic development of the Ross Sea area.

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Introduction

In 1990/91 the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover carried out their GANOVEX VI expedition in cooperation with the Alfred-Wegener-Institute (AWI) and the United States Geological Survey (USGS). We made aeromagnetic surveys over the north-western Ross Ice Shelf and the McMurdo Sound area (Fig. 1), and over northern Victoria Land.

The survey area lies directly adjacent to that of GANOVEX IV (BGR & USGS 1987, Bachem *et al.* 1989a, Behrendt *et al.* 1991a) which terminated along an approximately east-west line just north of Ross Island. That survey covered the entire Victoria Land basin (VLB) – the most western of the three north/south striking basins in the Ross Sea – from its northern end in the Terra Nova Bay area to its known southern end at Ross Island. A possible southern extension of the VLB and its central graben structure (Terror rift as found from seismic surveys (Cooper *et al.* 1987)) and what has been referred to as Victoria graben in the aeromagnetic interpretation of the GANOVEX IV data (Bosum *et al.* 1989) was one of the major targets for this survey.

Small magnetic anomalies of short wavelength and of roughly circular shape have been found in the area of the VLB. They were interpreted by Behrendt *et al.* (1987, 1991a) as small volcanic intrusions piercing through the thick sedimentary succession in the basin. One of the objectives of the Ross Ice Shelf survey was to investigate of the Mesozoic–Cenozoic rift system and its western margin, i.e. the rift-shoulder manifested by the Transantarctic Mountains.

The most prominent magnetic anomaly in the GANOVEX IV (1984/85) survey area over the western Ross Sea is the "Polar 3 anomaly" (Bosum *et al.* 1989). This anomaly north-east of Terra Nova Bay is likely to be the magnetic expression of late Cenozoic volcanic rocks and an associated subvolcanic intrusion in the displacement zone between the graben structures near the coast running parallel to the Transantarctic Mountains. Another objective of the survey was to search for the existence of a magnetic anomaly of similar shape and strength over the Ross Ice Shelf and south of Ross Island which would strengthen the argument for a postulated displacement in the coastal structures in this area as well (Tessensohn & Wörner 1991). Behrendt *et al.* (1991b) suggested that the Polar 3 anomaly was the magnetic manifestation of a transfer fault such as suggested by Fitzgerald *et al.* (1987), Wörner *et al.* (1989) and Cooper *et al.* (1991).

Survey, data acquisition, and processing

The lay-out of the survey over the north-western section of the Ross Ice Shelf and the McMurdo Sound area closely followed that of the GANOVEX IV survey to assure compatibility and direct continuation between the two data sets. Line spacing was chosen again to be 4.4 km with a tie-line separation of 22 km. The survey altitude of 610m correspondeded to that of the Ross Sea section of the GANOVEX IV survey. The profile lines were aligned approximately east-west, and the tie-lines north-south. The Lambert conformal conic projection (used for the maps of the USGS Antarctica Reconnaissance Series 1:250000 which cover parts of the survey area) was used for the preparation of the GANOVEX VI flight line grid.

We measured the total intensity of the magnetic field with a proton precession magnetometer (Geometrics G813) installed in a Dornier 228–100 ski-equipped aircraft in a wingtip configuration; the aircraft was partially magnetically compensated. BGR chartered the aircraft, owned by the AWI and maintained by the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), for this survey. The aircraft was equipped with a Honeywell Lasernav inertial navigation system

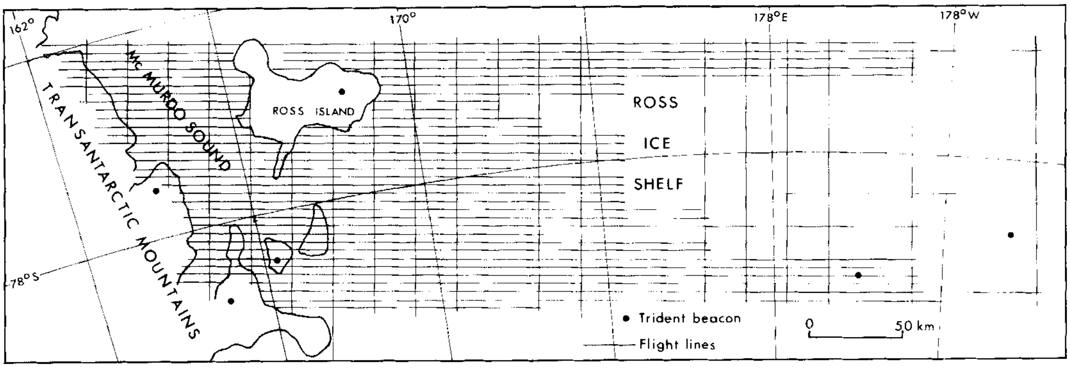

Fig. 1. Flight lines of the aeromagnetic survey over the Ross Ice Shelf and McMurdo Sound during the GANOVEX VI expedition.

(INS). As the INS navigation was insufficiently accurate, a "Trident IV" navigation system was also installed. The "Trident IV" is a radiolocation system using a frequency of 1.2 GHz for distance measurement between the aircraft and fixed transmitter stations on ground. When receiving at least two stations, the position of the aircraft can be calculated to an accuracy of the same order as the locations of the ground transmitters are known (about 30 m). More details can be found in Bachem *et al.* (1989b). Navigation and magnetic data were read into the digital data acquisition system, specially developed system for the standard scientific installation in the aircraft. In-flight monitoring of the data was possible via a screen and a printout.

A base station magnetometer (Geometrics G856) set up near Williams Field air strip, about 10 km from McMurdo Station, monitored geomagnetic activity simultaneously with the survey flights and throughout the survey period to determine the daily pattern of the magnetic variations with time. In general, the level of geomagnetic activity during the 1990/91 season was higher than in previous years as was expected because the geomagnetic activity is known to trail behind the solar cycle, which passed its maximum in 1989/90. The daily pattern of magnetic activity in this region (Damaske 1989), however, remained unchanged; the quietest interval was found to start in the early afternoon until after midnight local time. We carried out survey flights only during this period.

During a three week period an area of about 36 800 km^2 was surveyed. The 12 700 km of profile- and tie-lines (Fig. 1) were flown during 70.5 h flying time (47.5 h on line) on 19 flights.

GECO-PRAKLA, Hannover, Germany, processed the data, in close collaboration with the BGR. As the coverage with Trident position data was insufficient to be used as the sole positioning source over the whole grid, information from the INS-system was also used. Because the absolute position in the INS was insufficient for our desired accuracy, the continously available INS data were updated and corrected whenever a Trident position was available or another source of positioning information such as landmarks could be used. In most cases it was possible to position the flight lines to within less than 100 m.

The raw magnetic field values were checked for data quality and magnetic effects of the aircraft. Apparent jumps in the raw data, due to switching on and off the aircraft heating as well as effects due to radio communication, were eliminated. As the compensation of the aircraft was not complete (and unstable over a time period of more than one flight) the effect of the aircraft roll was determined for each flight from single events and corrected for. The other components of aircraft manoeuvring were of minor importance.

The one-min values of geomagnetic activity recorded at the base station were smoothed using a 60-min low pass filter. These values were used to correct the magnetic field values on a survey line for the long period variations. This procedure (c.f. Damaske 1989) takes into account that the diurnal variations vary considerably between different locations especially in polar regions (Maslanyj & Damaske 1986).

Profile and tie-lines were submitted to a levelling procedure in which the differences at the intersection points are minimized according to a least square-fit. The IGRF for the epoch 1991.0 and for an altitude of 610 m was subtracted from the field values. To adjust with the magnetic anomaly map of the Ross Sea area of GANOVEX IV a constant value of 50 nT was added to all data. The data were subsequently gridded using a weighted gridding routine with influence radii of 13 and 3 km and a grid mesh of 1/10th of the profile spacing (440 m).

Structural interpretation

The map of the anomalies of the total magnetic field in Fig. 2, covering the GANOVEX VI survey area only, shows a distinct partition into two different magnetic units (see also the structural interpretation map of Fig. 3). There is a smooth, magnetically quiet pattern which can be traced from the northern limit of the survey area through to the south and from the west, over McMurdo Sound to the easternmost parts over the Ross Ice Shelf (Ross Sea Unit, see below). It is interrupted by a high amplitude, magnetically "active" pattern over Ross Island (Robinson 1964) and adjacent areas south and east. This zone of large anomalies of circular and extended shape shall hereafter be referred to as the "Ross Island and Ice Shelf Edge Unit" (see below).

Ross Sea Unit

The magnetically quiet pattern consists of anomalies of moderate amplitude (about 50–100 nT) trending predominently N–S. There is a strong similarity with the magnetic pattern north of the survey limits, i.e. in comparison with the GANOVEX IV

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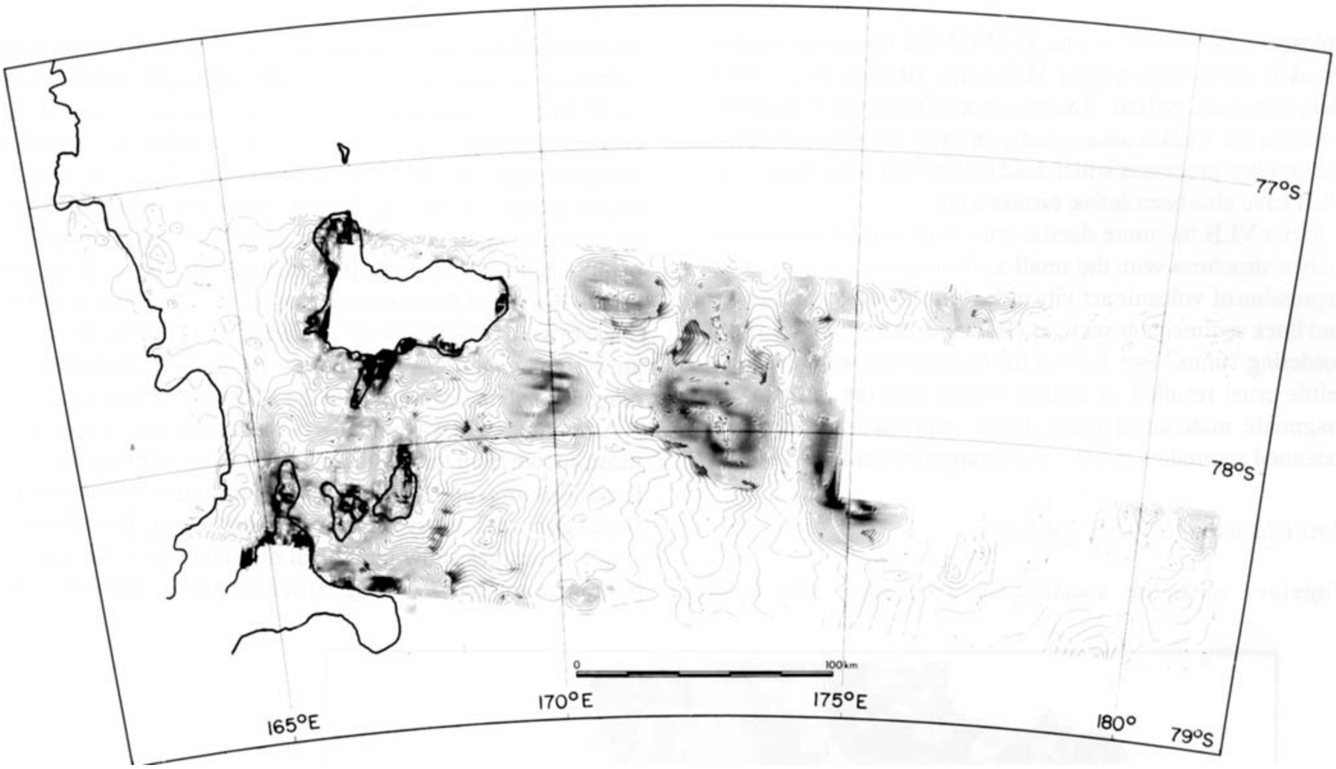

Fig. 2. Contour map of the anomalies of the total magnetic field over the northwestern Ross Ice Shelf and McMurdo Sound area. Contour interval is 5 nT.

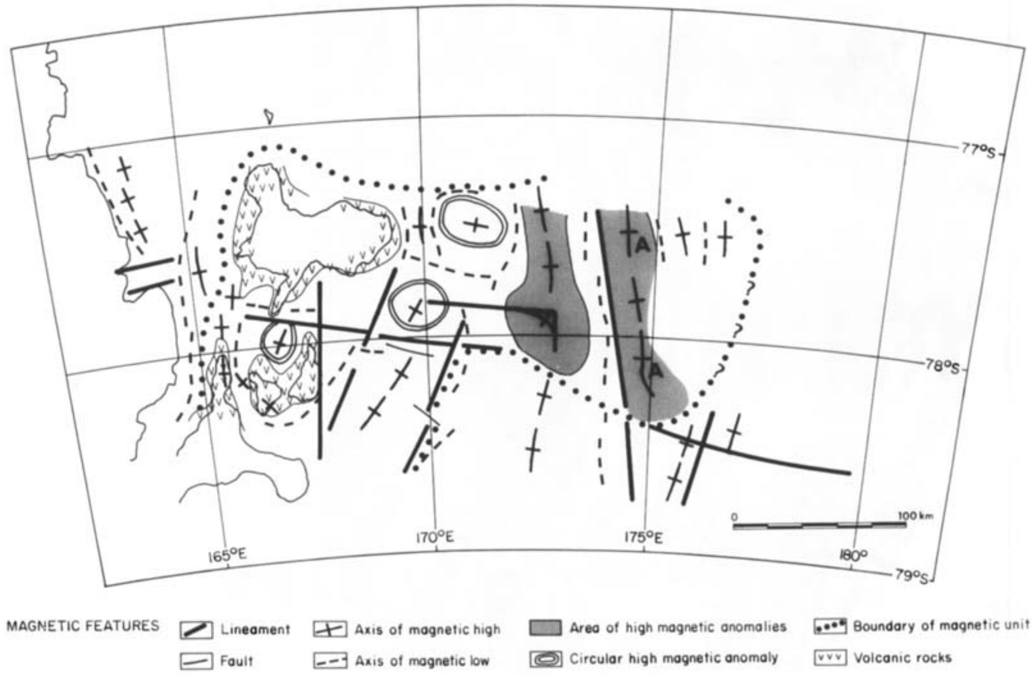

Fig. 3. Principal magnetic structures derived from the anomaly map of Fig. 2. A dotted line marks the boundary between the magnetically "active" pattern of the "Ross Island and Ice Shelf Edge Unit" (including the prominent N-S aligned anomaly "A") and the "quiet" pattern of the "Ross Sea Unit".

in Bosum *et al.* (1989) under the Ross Ice Shelf south-east of Ross Island is reasonable.

As the area covered in this survey is not of sufficient extent, more details in this part of the "Ross Sea Unit" cannot be detected. There is an indication of a continuation of the VLB pattern into the McMurdo Sound area: small-amplitude anomalies extend into the area between Ross Island and the Transantarctic Mountains. However, high-amplitude anomalies over Ross Island (discussed below) would mask any low amplitude signature which might be present in the data.

Other small-scale anomalies can be traced throughout the area of Ross Island and the islands of late Cenozoic volcanic rocks in southern McMurdo Sound. Their anomaly pattern (Figs 2 & 3) corresponds to that known from the late Cenozoic

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volcanic rocks covered by the GANOVEX IV survey, such as Franklin Island and Mount Melbourne (Bosum *et al.* 1989, Behrendt *et al.* 1991b). The presence of this type of anomaly, which in the VLB is associated with axial volcanism supports the idea that processes which lead to their formation within the VLB have also been active further south.

In the VLB the more ductile crust lead to the formation of graben structures with the small-scale magnetic pattern as the expression of volcanic activity in the form of basaltic intrusions into thick sedimentary sections (Behrendt *et al.* 1987). In both bordering "units" (see below) the tectonic stress on the more brittle crust resulted in distinct breaks and the intrusion of magmatic material at great depth, expressed as large and extended anomalies in the crustal magnetic field.

Ross Island and Ice Shelf Edge Unit

Together with the small-scale anomalies, the Ross Island/McMurdo Sound magnetic complex shows some high amplitude anomalies (250–750 nT) of longer wave length (> 20 km). Judging solely on the structural appearance in the contour map (Fig. 2), it is not quite clear whether they underlie the small-scale pattern or occur separately. They can also be found farther east over the Ross Ice shelf where they are more pronounced (amplitudes reach up to 950 nT), but not accompanied by the small-scale anomaly pattern discussed above. Robinson (1964) discussed these anomalies over Ross Island in a survey made by E. Thiel in 1958–59. Pederson *et al.* (1981) also made an aeromagnetic survey of Ross Island and discussed the magnetic anomalies caused by the McMurdo volcanics.

Amplitudes and wavelengths of the anomalies are similar to those known from the Southern Cross Unit in northern Victoria Land (Bosum *et al.* 1989). Both magnetic units indicate a trend running approximately south-west to north-east. In both cases, single anomalies show individual different trends (as e.g. the prominent anomaly "A" (Fig. 3) at the eastern edge of the fully

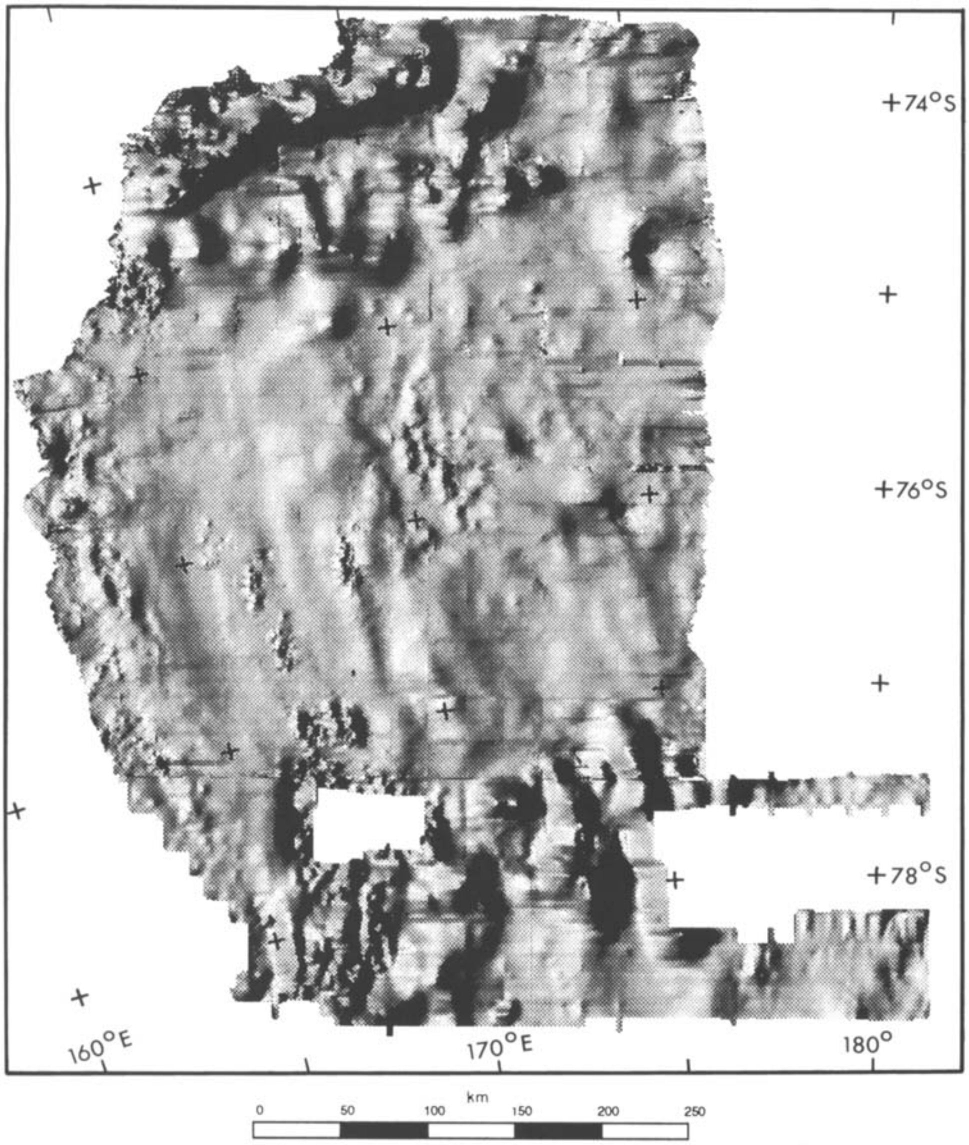

Fig. 4. Combined magnetic anomaly map of the western Ross Sea area (GANOVEX IV) and the northwestern Ross Ice Shelf (GANOVEX VI). Illumination of the shaded relief presentation is from west (sun elevation 45°).

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prominent anomaly "A" (Fig. 3) at the eastern edge of the fully mapped section is N–S aligned). The sources of these anomalies are broad and deep bodies.

The western Ross Sea rift pattern

In Fig. 4, the combined GANOVEX IV+VI surveys, the rift fabric noted by Behrendt *et al.* (1991b) is clearly visible (N-trending lineations commonly accompanied by small scale anomalies). Rift fabric interpreted from N-trending lineations was also reported from the 1991–92 CASERTZ survey over the West Antarctic Ice Sheet and suggested to be part of the West Antarctic rift system (Behrendt in press). We consider that these lineations define the trends of the rifting in the particular areas of the surveys.

The pseudogravity map of Fig. 5 shows the larger regional structures between the Ross Sea coast of Victoria Land and the Ross Ice Shelf. The pseudogravity transform (Baranov 1957) converts magnetic data to the equivalent gravity field that would be produced if magnetic intensity sources were converted to density sources. The pseudogravity map emphasizes the total amount of magnetic material in the crust and is less sensitive than the magnetic field to the near-surface details of crustal structure. The northern and southern limits of the western Ross Sea area are clearly distinguishable as pseudogravity highs above the lower values of the Ross Sea area. To the north the pseudogravity version of the Polar 3 anomaly trends in an aproximately WSW–ENE direction, cutting off the predominently S–N trending anomalies associated with the Victoria Land basin. A similar directional trend (as that of the Polar 3 anomaly) can be observed in the south. The boundary follows the zero-pseudo-mGal contour line stretching from just east of Ross Island in the northern McMurdo Sound area to about 77°S, 176°E, just north of the Ross Ice Shelf edge. However, in contrast to the apparent continuous feature of the Polar 3 anomaly in the north, this "Ross Island and Ice Shelf Edge Unit" is composed of several single high-amplitude long-wavelength anomalies aligned in approximately the same direction as the

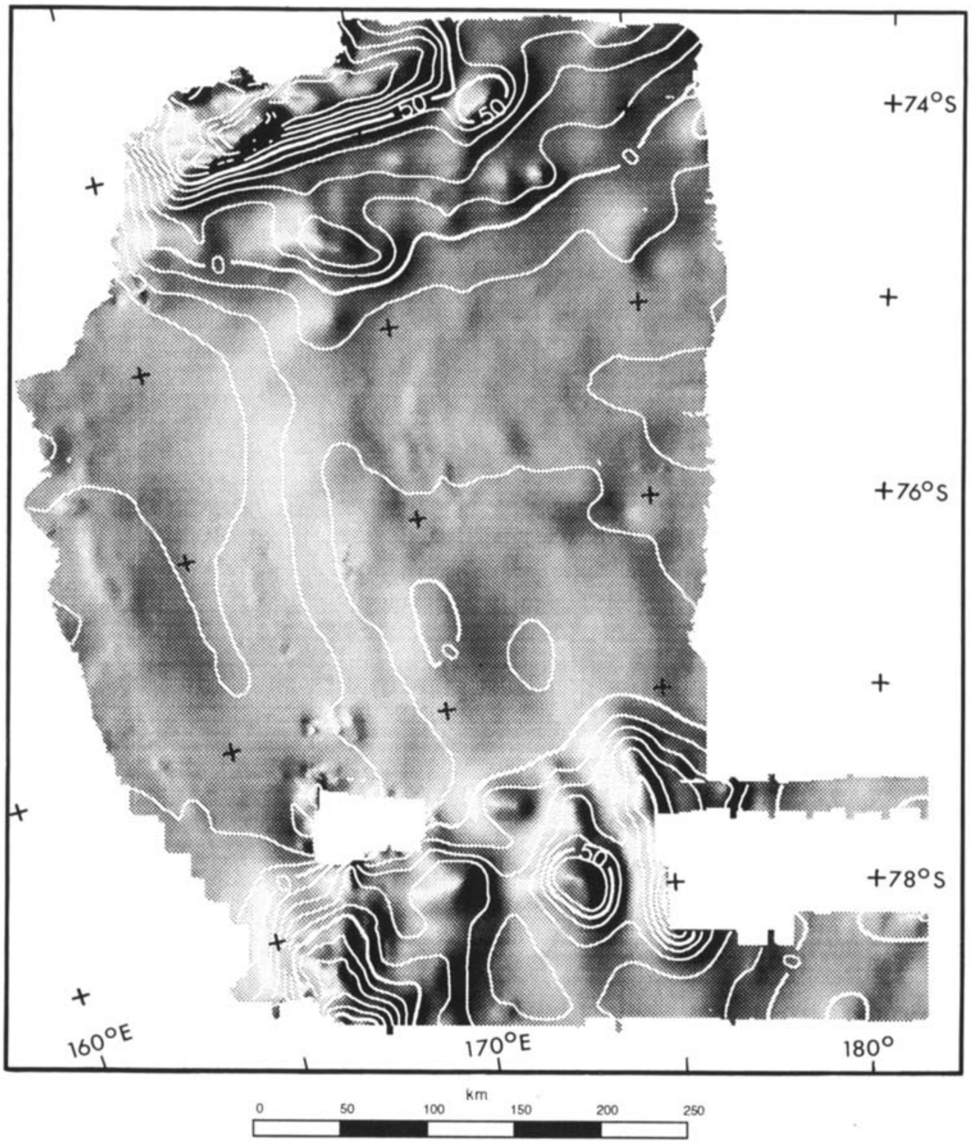

Fig. 5. Pseudogravity shaded relief (illumination from west, sun elevation 45°) of the western Ross Sea and north-western Ross Ice Shelf areas. Contour lines are in intervals of 10-pseudo-mGal.

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low amplitude anomalies within the Ross Sea area.

As noted above various authors have inferred transfer faults in the Ross Sea area from aeromagnetic data (Behrendt *et al.* 1991b), marine seismic data (Cooper *et al.* 1991) and geological data (Fitzgerald *et al.* 1987, Wörner *et al.* 1989, Tessensohn & Wörner 1991). The magnetic maps of Figs 4 & 5 well illustrate the presence of transfer faults in the extended crust (Behrendt *et al.* 1991b). The prominent parallel ENE-trending breaks in the anomaly pattern of Figs 4 & 5 in the northern and southern areas of the combined GANOVEX IV and VI surveys are apparent. Although we do not see unequivocal evidence of lateral offset across this break, the pattern has the appearance of a transfer fault (i.e. a transform fault in continental crust; e.g. Etheridge *et al.* 1985). Possibly the Victoria Land basin is offset in a right lateral sense at this magnetic break. Because transfer faults were suggested associated with the Polar 3 anomaly (Wörner *et al.* 1989, Behrendt *et al.* 1991b) and a N–NE trending transverse fault zone in the Ross Sea crust (Cooper *et al.* 1991) in the area of the break in magnetic anomalies that we report here, we interpret this break as evidence of a transfer fault also. Fitzgerald (1992) interpreted the inflection point in the trend of the Transantarctic Mountain front as evidence for a major transfer fault up or near the Skelton Glacier. This transfer fault is on trend with the structure defined by the magnetic anomalies.

Conclusions

The results of the 1990/91 survey extend the interpretations made from the 1984/85 survey south to the McMurdo Sound and north-western Ross Ice Shelf area. Prominent, high amplitude magnetic anomalies indicate the presence of probable late Cenozoic volcanic rock beneath the ice shelf correlated with exposures on and in the vicinity of Ross Island. We interpret the ENE-trending break in the magnetic pattern as evidence of a transfer fault in this area previously suggested in the adjacent Transantarctic Mountains. In a regional tectonic frame of the West Antarctic rift system, one can look at the "Southern Cross Unit" and the "Ross Island and Ice Shelf Edge Unit" as magnetic evidence of major transfer faults as proposed by Tessensohn & Wörner (1991) in the model for the tectonic development in the Ross Sea depression of the West Antarctic rift system.

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