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Microlevelling procedures applied to regional aeromagnetic data: an example from the Transantarctic Mountains (Antarctica)[1]

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Abstract

The extensive application of digital enhancement and filtering as a powerful tool for aeromagnetic interpretation, not only of high resolution but also of regional data, requires an improved levelling. Two microlevelling techniques were thus compared in order to find an effective but relatively simple procedure to remove, or at least to reduce, residual magnetic errors remaining after standard levelling processes. This study was carried out on regional aeromagnetic data recently acquired at high magnetic latitudes along the Transantarctic Mountains in Antarctica, where it is particularly critical to remove time-dependent magnetic variations. Two-dimensional FFT filters applied to the gridded data, namely the Butterworth and a directional cosine filter, proved to be more effective than previously proposed one-dimensional space-domain filters in the reduction of the 'residual corrugation' not removed by statistical levelling. Tectonic interpretation of trends detected in the total field magnetic anomaly map and in the 3D analytic signal improved after application of frequency-domain microlevelling. However, we also show that when interpreting microlevelled data, two factors must be considered: (i) the possible presence of real geological trends aligned along the flight lines; (ii) modifications in the results yielded by depth estimates of magnetic sources due to the FFT filters applied during the microlevelling procedure. Such changes were seen both in the well-established 2D FFT method, based on the slope of the energy spectrum, and in the more recent 3D Euler deconvolution technique. Overall our results indicate that microlevelling could profitably be applied to older gridded aeromagnetic data sets in Antarctica, thus improving the accuracy and geological significance of future regional magnetic compilations, as already seen in other continents.

Introduction

Aeromagnetic surveys typically require a well-planned flight grid composed of profile lines and roughly perpendicular tie-lines. As known, the airborne system used to perform the grid measures both spatial and time variations in the earth's magnetic

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field. As the interest is focused primarily on the crustal structural interpretation, the geomagnetic reference field and magnetic time variations must be removed as accurately as possible. Regarding time variations, one way to perform this cleaning is to install ground magnetic base stations monitoring the external magnetic field. If the deep electrical conductivity is not constant throughout the large survey area, the time variations measured at the ground stations will not be equivalent to those measured from the aircraft. The magnetic anomaly maps produced by simple ground station data subtraction will probably still contain non-geological features related to an imperfect removal of time variations. These errors can, however, be reduced by a variety of procedures referred to as levelling, which basically involves the estimation and reduction of differences in the magnetic values at crossover points between profiles and tie-lines (e.g. Green 1983; Ray 1985). The differences are related not only to temporal magnetic changes but also to other causes, such as errors in 2D navigation and in flight altitude. The discrepancies caused by the mislocation of the crossovers are nowadays much smaller, due to the remarkable advances in navigational systems such as the Global Positioning System which, in differential configuration, can achieve accuracies better than ± 10 m with 1 second updates.

However, whilst the residual errors after the levelling and magnetic base station removal are usually small, the widespread use for interpretation purposes of digital enhanced images and filtering procedures (Broome 1990) greatly amplifies their presence. The enhanced magnetic images produced from recent high-resolution aeromagnetic surveys require a precision of at least 0.1 nT. Such high-resolution techniques have been applied successfully, for example, to the assessment of natural hazards (e.g. U.S. Magnetic Anomaly Task Group 1995) or, even more recently, to sedimentary basins petroleum exploration (e.g. Fichler *et al.* 1997), and obviously call for very high-quality and reliable levelling. In our study we show that, though precisions in the 1–5 nT range are sufficient for regional aeromagnetic surveys, accurate levelling can be an essential basis even for broader scale magnetic anomaly mapping and interpretation.

Though several approaches exist for improving on the standard levelling, such as the use of pseudo-tie-lines in low-gradient areas, of statistical methods and of measured horizontal gradients (Nelson 1994), a somewhat simpler but less rigorous procedure is referred to as microlevelling (Minty 1991).

Microlevelling techniques

According to Bullock and Isles (1994), the term 'microlevelling' refers to a variety of new processing schemes which attempt to minimize very small (even less than 1 nT) line-to-line level shifts in the magnetic data which are mainly due to imperfect removal of diurnal variations and to uncertainties in the altitude of the survey flight. The prefix 'micro' is somewhat misleading since it is really appropriate for high-resolution aeromagnetic surveys, which are typically flown by the mineral and petroleum industry at a line spacing of 100–200 m, a terrain

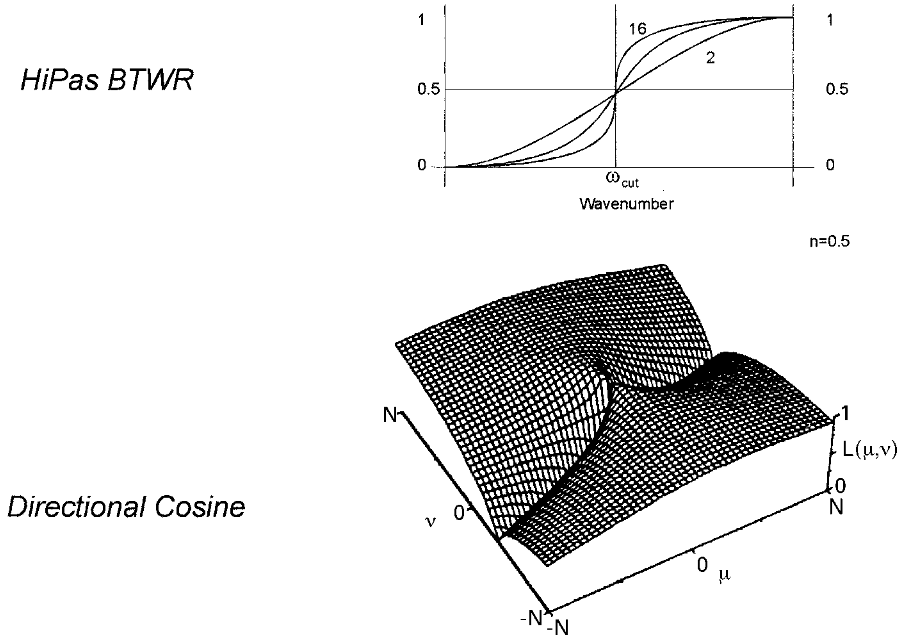


Figure 1. Microlevelling in the frequency domain is accomplished by applying a high-pass FFT Butterworth (BTWR) and directional cosine filter (GEOSOFT®) to the standard levelled magnetic grid. Tuning of the central wavenumber ω of the BTWR and of the degree of the cosine filter is necessary to achieve best results.

clearance of 50 m and a sampling interval of 5 m with optically pumped caesium magnetometers.

For widely spaced regional surveys (4–5 km line spacing and over 20 km for tie-lines), the errors at the crossovers remaining after levelling and base station correction can be much more intense, reaching amplitudes well above 10 nT. On the other hand, the contour interval achieved by standard high-resolution aeromagnetic surveys of 0.1 nT must be compared to the 1–5 nT contour interval adopted for regional surveys to evaluate correctly the relative influence of microlevelling procedures on magnetic anomaly mapping. It is also worth mentioning that the spurious elongated anomalies remaining after inadequate levelling have a distinct spectral signature as described by Minty (1991). The errors are characterized by a wavelength in the profile direction greater than the tie-line spacing and by a wavelength perpendicular to the profiles of about 2–4 times the profile-line spacing. Considering the large tie-line interval normally used for regional surveys, it is clear that the 'residual corrugation' is also highly relevant for focusing on the long wavelength geological features.

With these premises two different microlevelling techniques are briefly described here and are based on 1D and 2D directional filters in the space and the frequency domains, respectively.

Method 1: 1D filters in the space domain

As shown by Minty (1991), if one of the grid axes is parallel to the profiles, 1D filters in the space domain can be applied to the magnetic anomaly grids. This is achieved by low-pass filtering the standard levelled magnetic anomaly grid in the flight-line direction with a wavelength greater than the tie-line spacing. This grid is then high-pass filtered (wavelength 2–4 times the profile-line spacing) in the direction perpendicular to the previous one (tie-line direction). The raw levelling error grid containing the elongated anomalies is subtracted from the original one. The resulting filtered grid is sampled at every measuring point along the profile lines. The difference between the levelled line-data and the sampled gridded-data then gives the error string. This is finally low-pass filtered and inspected to account for the gridding error and for real anomalies related to geological trends parallel to the profile lines.

Method 2: 2D FFT filters

Another strategy of microlevelling is to use 2D directional filters in the frequency domain for the first steps of the process (the sampling and further filtering is conceptually unchanged). These filters have been employed extensively in the past for easier detection of linear anomalies (Thorarinsson, Magnusson and Bjornsson 1988 and references therein). Preprocessing is necessary before applying the forward FFT; it basically involves trend removal (order 1), expansion to square dimensions and filling of dummy values within the grid.

The actual microlevelling is then performed by applying a Butterworth high-pass filter and a directional cosine filter (Fig. 1). The Butterworth filter has a smooth shape and does not alter the signal after the end of roll-off. Normally it is set to four times the profile-line spacing in order to pass frequencies of the order of the line separation. The directional cosine filter is also a smooth filter, so ringing problems are not usually encountered. This second filter is set so as to pass wavelengths only in the direction of the profile lines. As the levelling error is very directional, the pass notch can be narrowed by decreasing the degree of the cosine function, normally to 0.5 or less. The resulting grid is the raw levelling error.

Comparison and example

In this study of microlevelling techniques we use a window of recently acquired 1991/94 GITARA (German Italian Aeromagnetic Research in Antarctica) regional aeromagnetic data (profile-line spacing 4.4 km, tie-line spacing 22 km, barometric flight altitude 9500 ft) collected in Antarctica over the Transantarctic Mountains (Bozzo *et al.* 1997a). It is noteworthy that in this area magnetic time variations are particularly intense and at times unpredictable. Owing to the strong spatial dependence of these time variations, base station recordings are representative to a maximum distance of only 100 km from the station itself (Maslanyj and Damaske

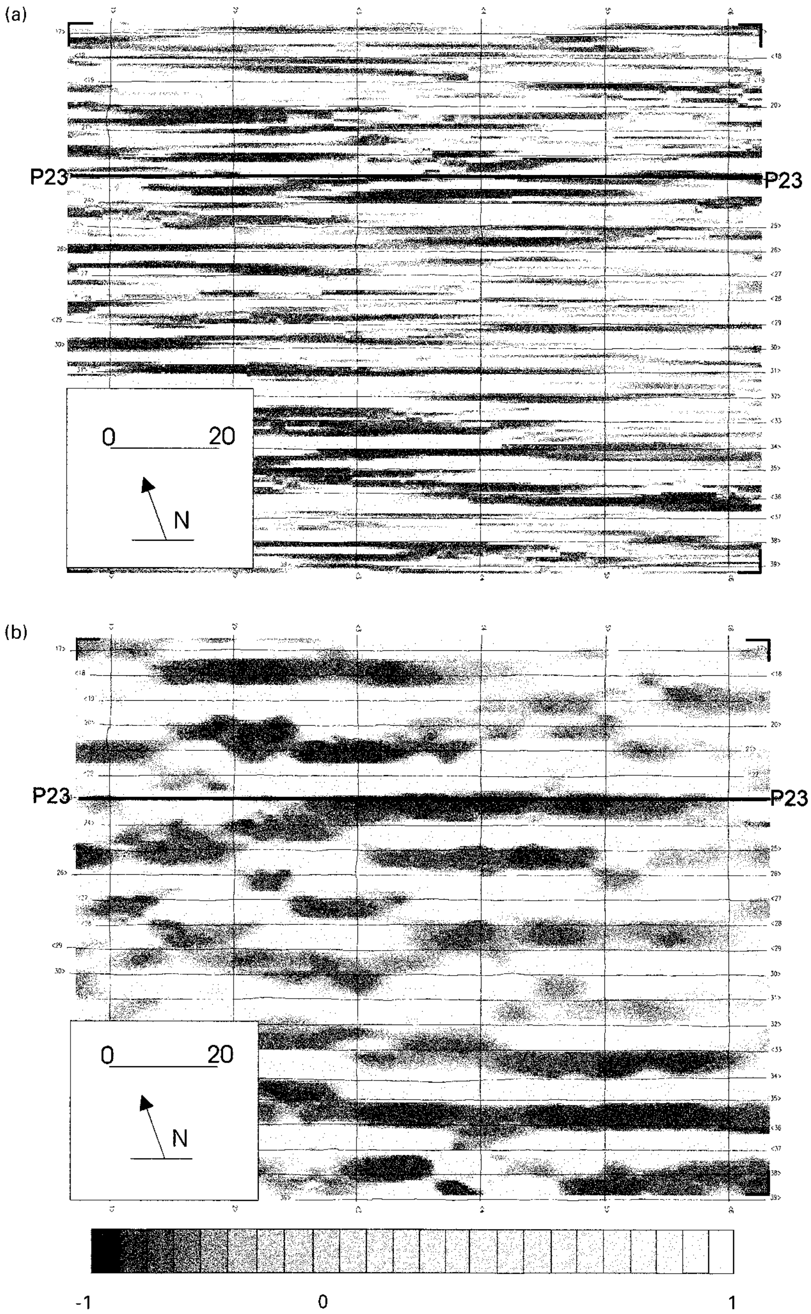


Figure 2. Standard levelling error in (a) the space and (b) the frequency domains, respectively (shaded relief map-illumination perpendicular to profile lines). Note the smoother correction in the frequency-domain approach (the scale is in km).

Table 1. Statistics of the two different microlevelling approaches.

	Min.	Max.	Mean	SD
Space-domain microlevelling	−53 nT	65 nT	0.1 nT	10 nT
Frequency-domain microlevelling	−41 nT	68 nT	0.1 nT	7.6 nT

1986). This means that at these magnetic latitudes, the time variations measured at a fixed base station cannot be subtracted directly from the aeromagnetic line data but have to be low-pass filtered (60 min) first (Damaske, Kothe and Dürbaum 1989). Whatever levelling process is then applied to the base station levelled data (least-squares or statistical), it should succeed in removing the residual high-frequency parts of the diurnal variation. In practice, however, despite improvements in navigation accuracy compared to earlier surveys in adjacent areas (Bachem *et al.* 1989; Behrendt *et al.* 1996 and references therein), significant line enforced trends were noted in the GITARA regional data even after best effort statistical levelling of the anomalies, thus requiring microlevelling to be applied.

In Fig. 2(a,b), we can compare the raw error string (previous to the sampling) of the

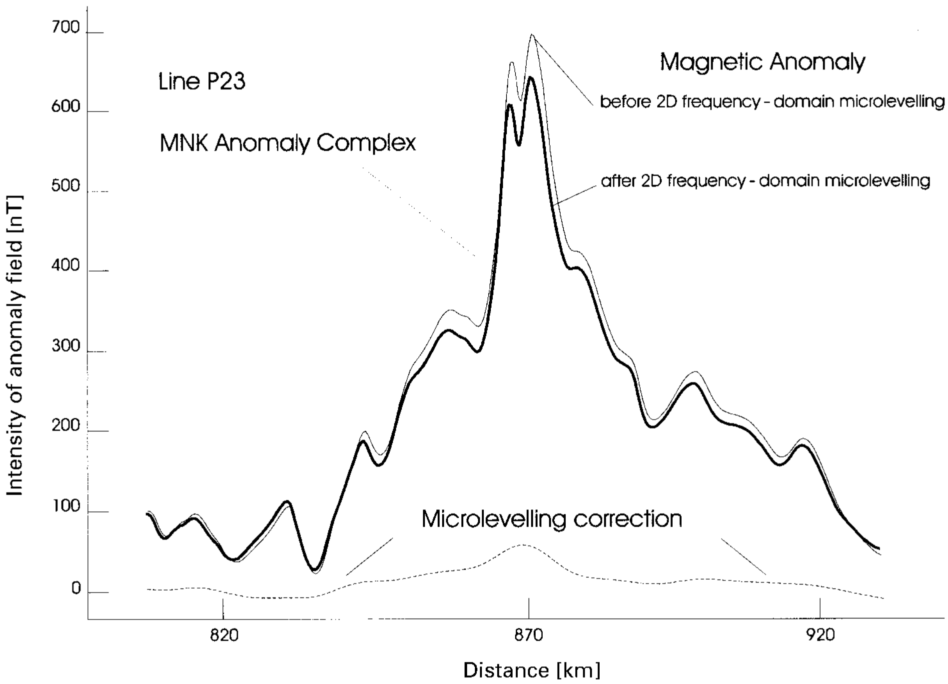


Figure 3. An example of the smoothing of magnetic anomalies along a critical profile (P23) heavily affected by a residual standard levelling error, but also influenced by subparallel geological structures (the Martin Nunataks anomaly complex).

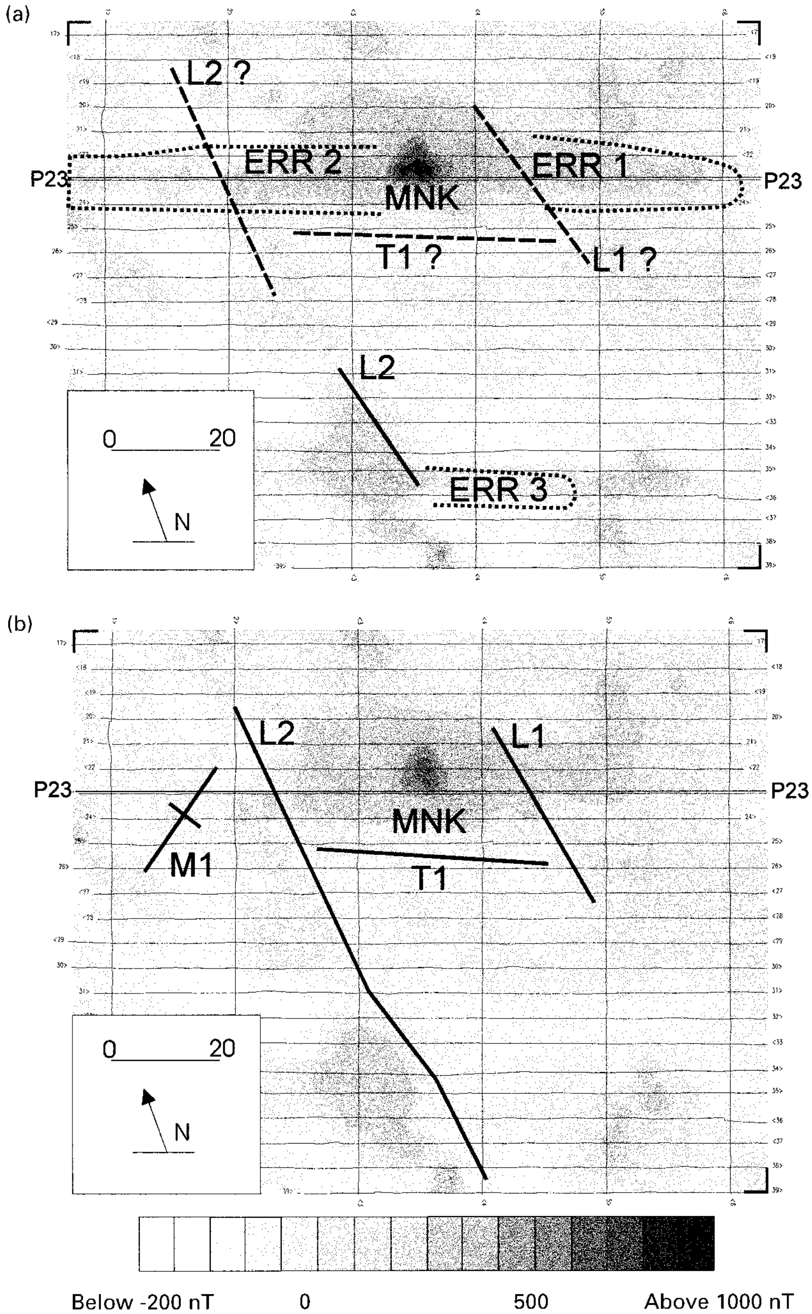


Figure 4. Total field magnetic anomaly map (a) prior to and (b) after the microlevelling process in the frequency domain. Note the improvement in the definition of tectonic structures in the MNK area due to the reduction of the ERR 1 and ERR 2 standard levelling directional errors (the scale is in km).

two different microlevelling approaches in the space and in the frequency domains described above. The grey-scale shaded relief map shown in Fig. 2(a,b) is visually the most effective for enhancing the directional errors remaining after levelling, but does not yield information on the amplitude of the correction which was evaluated by statistical tools. What is apparent from Fig. 2(b) is that the 2D FFT approach leads to a much smoother correction. A drawback is that it also influences some NNW and NNE trends, which are unlikely to be artefacts due to inadequate levelling. The statistics of the two error strings indicated that the FFT filters tend to decrease the amplitude of some positive anomalies a little more than in the space-domain approach, though on average the corrections amplitudes are equal (Table 1).

However, the smaller variations in the spectral characteristics and in the fluctuations at the end and in between the flight lines are in favour of the FFT microlevelling method.

We decided to use this approach, which also avoided grid rotations and was more effective when compiling different surveys (because of the milder edge effects), for the production of our magnetic anomaly maps. The problems of excessive smoothing of the anomalies were partially overcome with tuning of the FFT filters and by the application (on the raw error string) of two to three passes of a space-domain Hanning filter. A judicious analysis of individual profiles also minimized distortion of the anomalies clearly unrelated to ineffective levelling. Non-linear filters were also applied to the processed error string so as to preserve further the intensity of some anomalies.

An example of the result of the complete microlevelling process in the frequency domain on a critical line is shown in Fig. 3. This line was part of an elongated positive anomaly pattern (with its major axis parallel to the flight lines) thought to be the combination of a levelling error and of the local geology (Profile P23). This anomaly pattern has been named the Martin Nunataks anomaly complex (MNK). The amplitude of the broad smooth microlevelling correction is on average small (less than 10 nT), while the effects on the high-frequency double-peak anomaly at the centre of the line are still quite relevant (over 60 nT) even after non-linear filtering of the error string.

Microlevelling and tectonic interpretation

In Fig. 4(a,b), we selected a window (the same as in Fig. 2a,b) of the total field anomaly map of central-southern Victoria Land (Antarctica) prior to and after microlevelling. The reader is referred to Bozzo *et al.* (1997b) for a description of the location, geology and magnetic anomaly patterns and to Ferraccioli *et al.* (1997) for further aeromagnetic interpretative results in this area. Here we simply show the improvement that can be achieved in the definition of ‘geological and tectonic’ features after 2D FFT microlevelling.

Figure 4(a) clearly displays two areas of large error due to poor levelling (ERR 1,2) and a more subtle error (ERR 3). The first two are located mainly along profile 23 (see also Fig. 3) and extend east and west of the above-mentioned remarkable anomaly

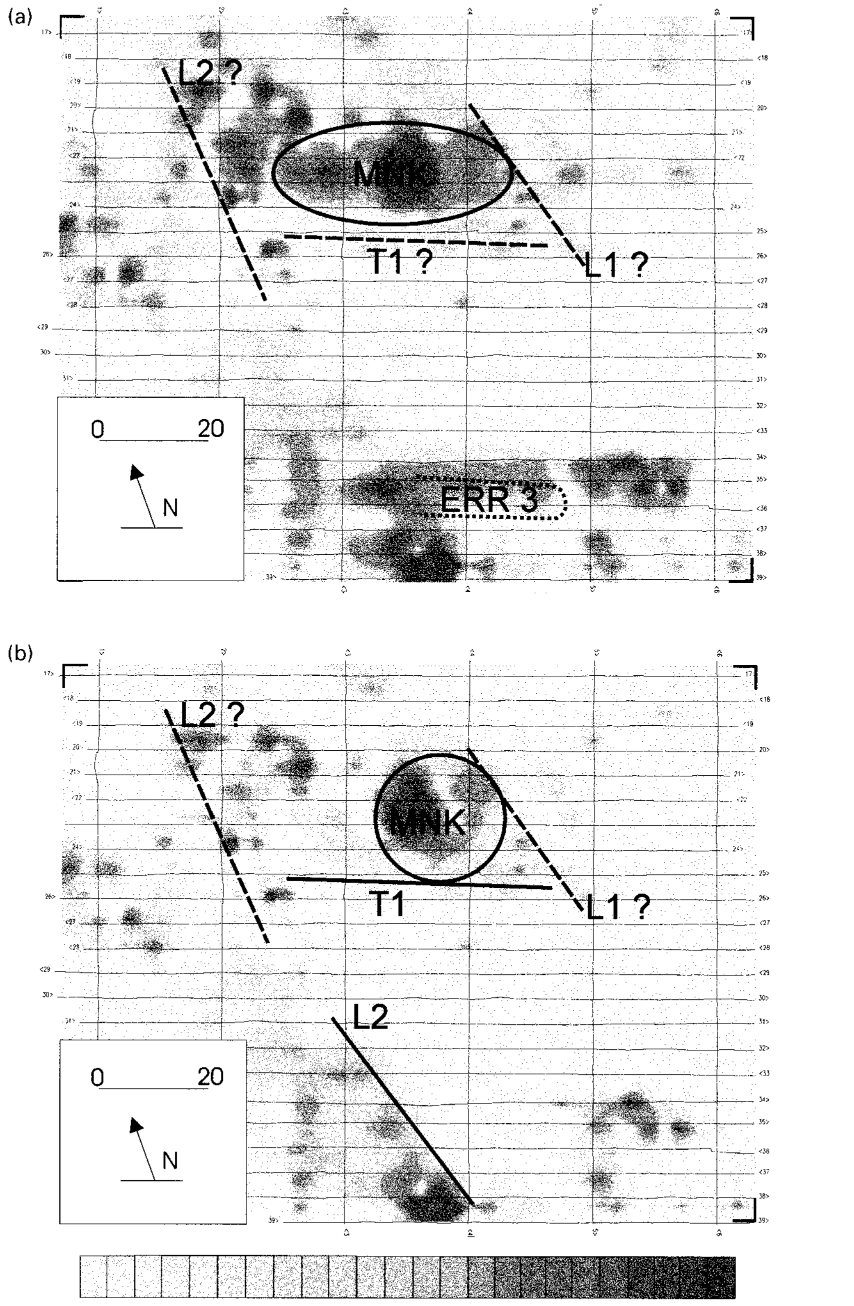
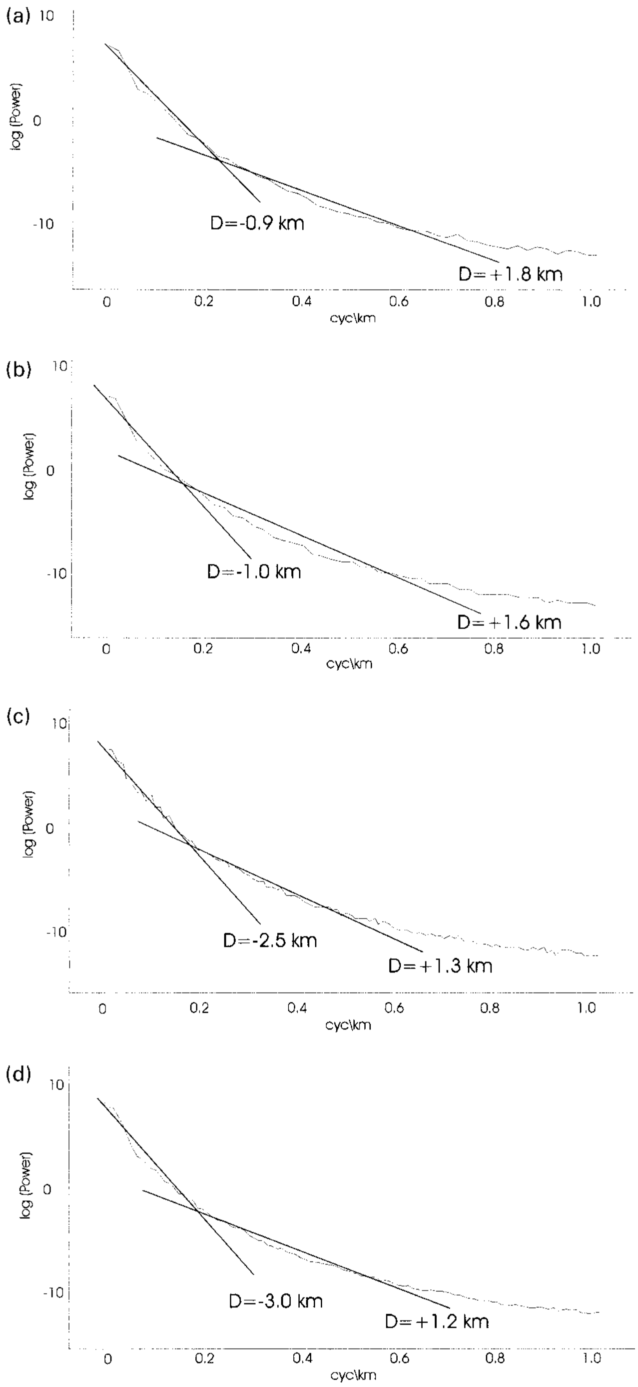


Figure 5. Three-dimensional analytic signal map (a) prior to and (b) after the microlevelling process. Microlevelling clearly leads to an easier detection of the L2 trend by reducing the ERR 3 levelling error; it also modifies the extent of the MNK anomaly (the scale is in km).


(a)
log (Power)
D=-0.9 km
D=+1.8 km
cyc\km
(b)
log (Power)
D=-1.0 km
D=+1.6 km
cyc\km
(c)
log (Power)
D=-2.5 km
D=+1.3 km
cyc\km
(d)
log (Power)
D=-3.0 km
D=+1.2 km
cyc\km

complex (with peaks reaching 700 nT) indicated by MNK. These two WNW–ESE elongated errors must be considered in the tectonic interpretation. In fact they seriously hinder the extent, orientation and nature of the subglacial MNK anomaly source as well as its relationship to the geological features of the region.

After microlevelling (Fig. 4b), the high-frequency component of MNK appears to be approximately NNW while the whole WNW–ESE anomaly complex (parallel to the flight lines) seems to be bordered by linear magnetic gradients interpreted as faults (L1, L2 and T1). West of L2 the M1 magnetic axis now appears to have a NE–SW orientation and also seems to be cut by the L2 structure. This previously unclear cross-cutting relationship may thus be useful for establishing relative timing of motion along supposed faults under ice-cover.

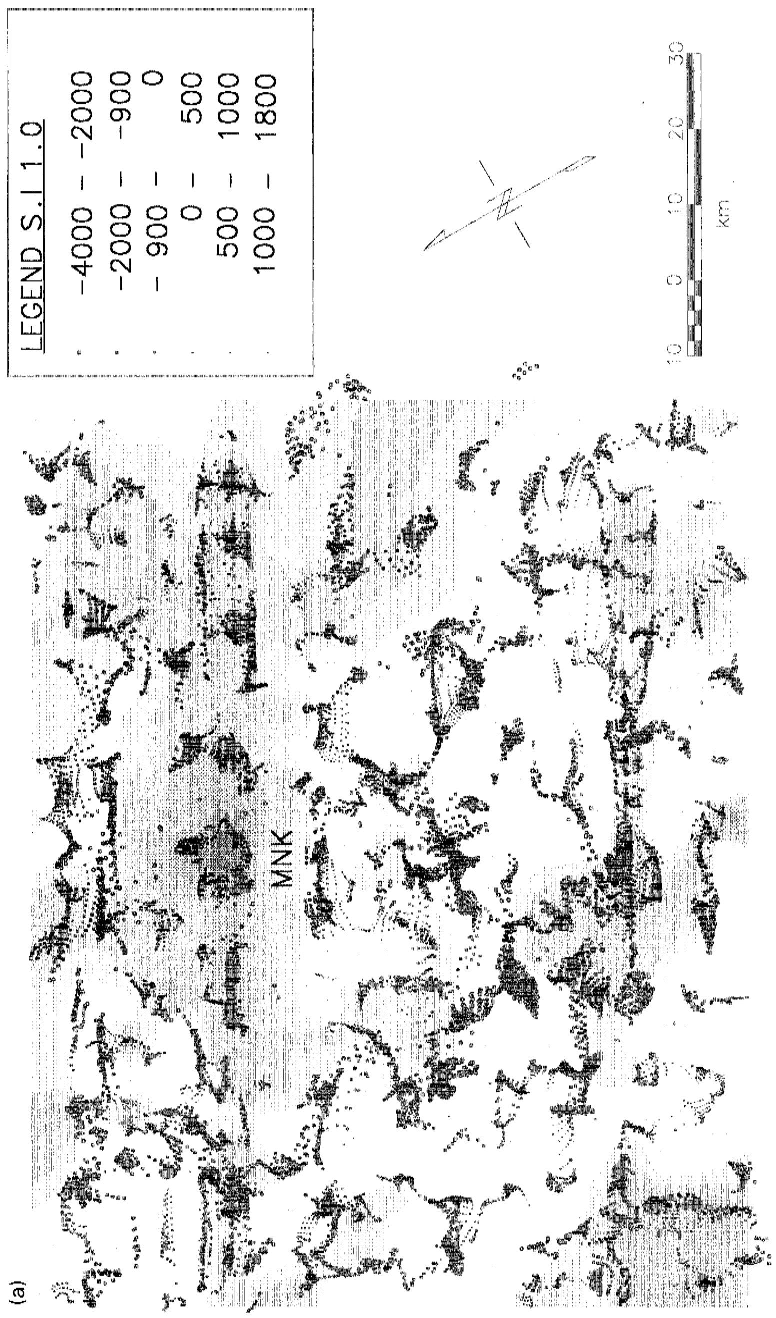
It should be noted that with selective directional filtering parallel to the flight lines, the WNW–ESE orientation of the possible longer wavelength component of the MNK anomaly is maintained. This is in agreement with the following considerations: (i) when we gridded the tie-line data (excluding the profiles), the anomaly still displayed this orientation; (ii) several lines of regional geological and geophysical evidence point to the existence of a major ice-covered fault with this strike and at this location (T1 trend); (iii) there is a prominent topographical trough with this trend imaged by Radio Echo Sounding data south of MNK due to erosion of a major glacier.

The effect of our microlevelling approach on the tectonic interpretation of the 3D analytic signal maps is shown in Fig. 5(a,b). The signal (defined as the square root of the square sum of the derivatives of the total field) exhibits maxima over magnetization contrasts, independent of the ambient magnetic field and magnetization directions, thus determining the outlines of magnetic sources (MacLeod, Jones and Fan Dai 1993).

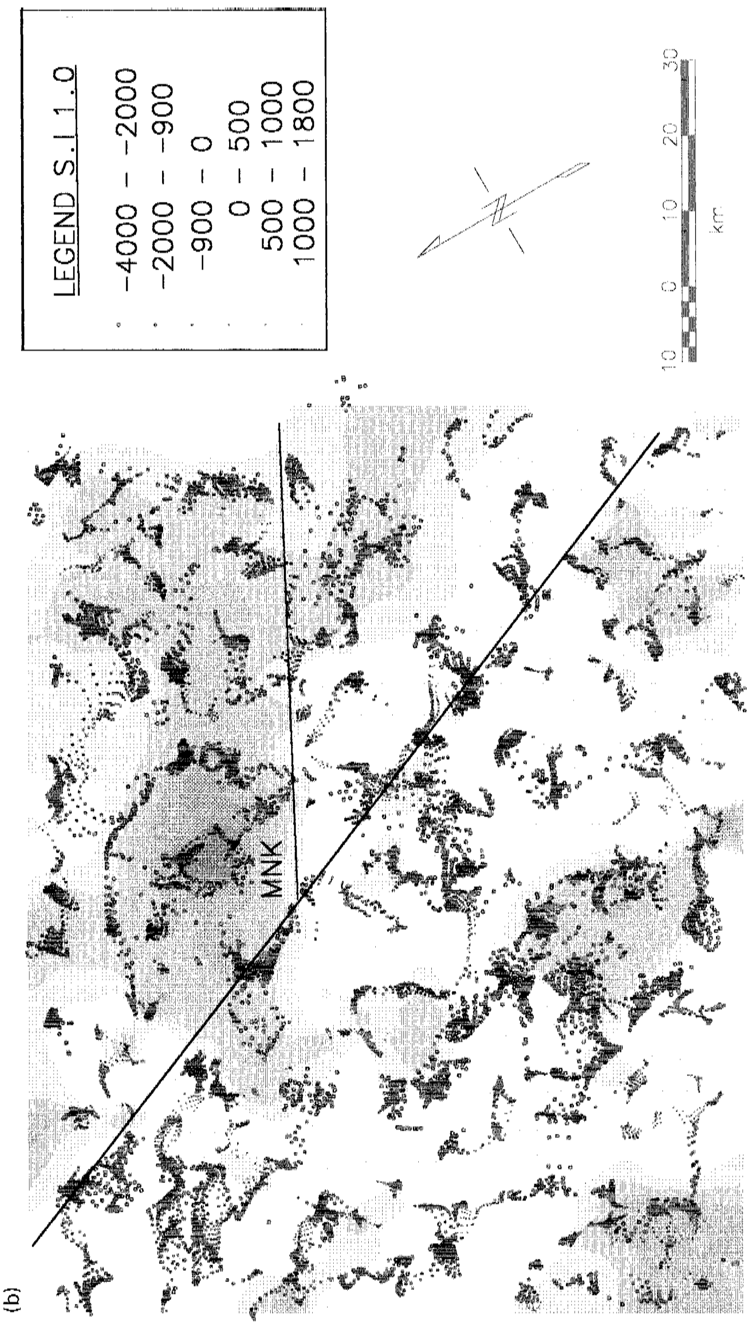
As seen in Fig. 5(a), the combination of spatial derivatives enhances the residual high-frequency component of the levelling error so greatly that ERR 3, which was not particularly misleading in Fig. 4(a), can seriously affect interpretation by indicating the presence of a trend subparallel to T1 and by masking the L2 lineament in the south-western quadrant. The MNK anomaly also appears in Fig. 5(a) as a long-wavelength elliptically shaped feature, while in Fig. 5(b) (microlevelled version), there is a distinct double-peak shorter-wavelength anomaly. As the analytic signal can also be used to estimate the depth of the magnetic sources using a simple amplitude half-width rule (Roest, Verhoef and Pilkington 1992), the role of microlevelling is clearly even more important.

When we put together the information derived from the total field and the 3D analytic signal microlevelled anomaly maps, it appears that we can better define the

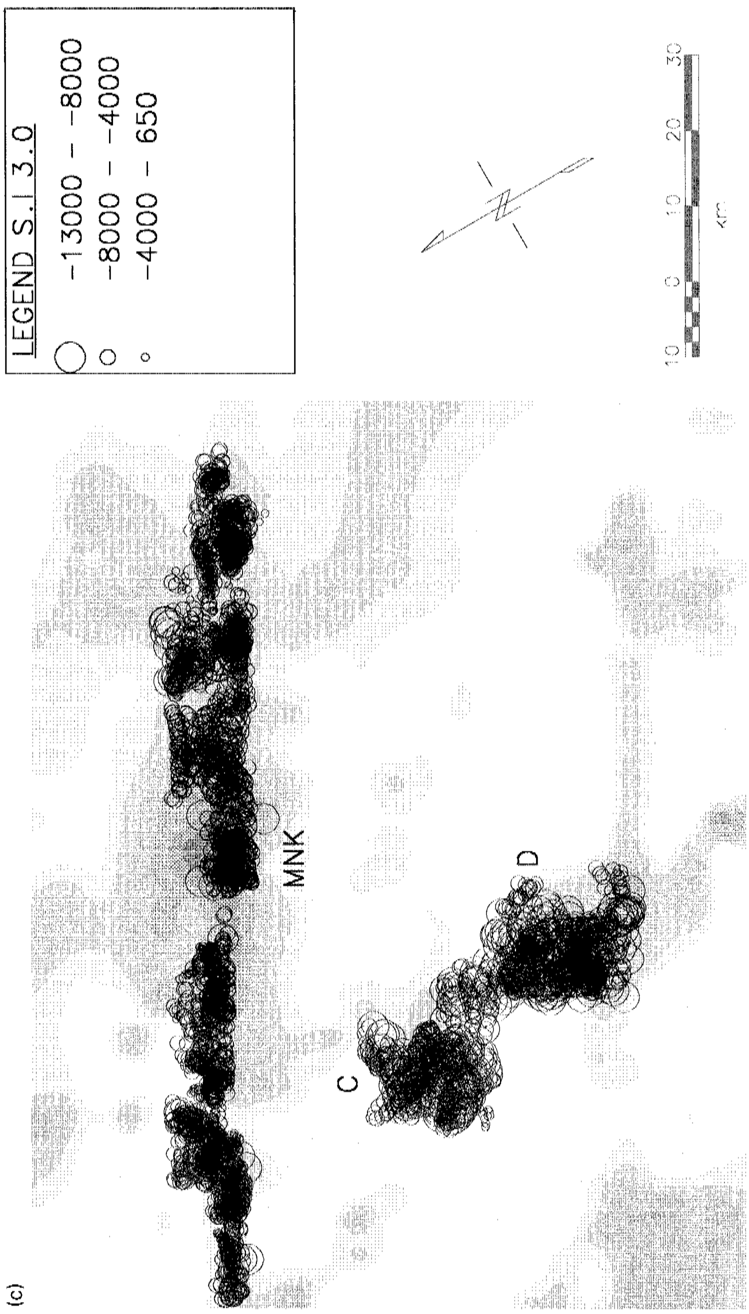
Figure 6. Interpreted 2D FFT power spectra before microlevelling (a and c) and after (b and d). Deeper depths are found after microlevelling when estimating both shallow and deep 'intrabasement' features.



(a)
MNK
LEGEND S.I 1.0
-4000 - -2000
-2000 - -900
- 900 - 0
0 - 500
500 - 1000
1000 - 1800
10 0 10 20 30
km



(b)
MNK
LEGEND S.I 1.0
-4000 - -2000
-2000 - -900
-900 - 0
0 - 500
500 - 1000
1000 - 1800
10 0 10 20 30
km



LEGEND S.I 3.0
-13000 - -8000
-8000 - -4000
-4000 - 650
10 0 10 20 30
km
(c)
MNK
C
D

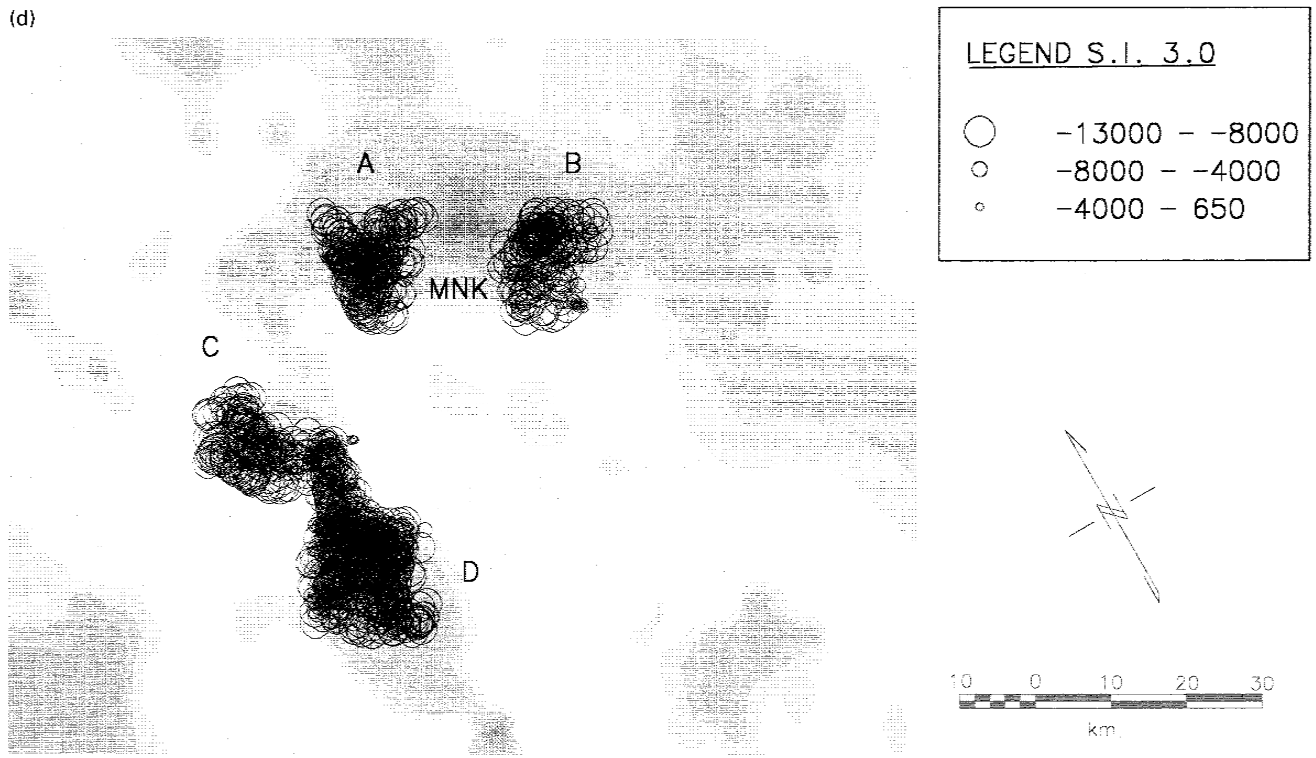


Figure 7. (a) and (b): Effect of microlevelling on 3D Euler deconvolution depth estimates for structural index 1.0. Circles are proportional to depths above (positive) and below (negative) sea-level. In the standard levelled map (a), circles tend to be parallel to flight lines, while as well as these WNW–ESE trends, NW features can be seen in the microlevelled version (b) and are indicated with solid lines; the grey scale magnetic intensity is the same as in Fig. 4. (c) and (d): Three-dimensional Euler depth determinations before and after microlevelling for structural index 3.0. While the probable intrusions C and D are visible both in the standard levelled (c) and in the microlevelled (d) maps, intrusions A and B, which are the deep source of the MNK anomaly complex, can be recognized only in the latter, thus further demonstrating the utility of microlevelling; the grey scale magnetic intensity is the same as in Fig. 4.

extent, orientation and significance of individual anomalies and clarify the role of tectonically significant trends.

Microlevelling and depth estimates

One of the most compelling applications of magnetic exploration is to determine the depth to the top of the 'geological sources' that are thought to produce the observed anomalies.

In Fig. 6(a–d), the results of 2D FFT spectral analysis are presented; the depth estimate is based on the slope of the energy spectrum (Spector and Grant 1970). Four square windows were masked from the standard levelled and microlevelled grids. The size of the windows (centred on the MNK anomaly) is equal to 100 grid units (corresponding to 44×44 km) for Fig. 6(a,b) and is appropriate for the evaluation of the thickness of basaltic cover rocks (mainly under ice in this area) overlying the metamorphic and igneous basement. The microlevelled data leads to slightly deeper depths for the top of the upper and lower magnetic layers, compared to the results derived from the standard levelled window.

In Fig. 6(c,d), the windows, still centred on the MNK anomaly, are 200 grid units in size. Both depth estimates seem to indicate the presence of deeper-seated intrabasement intrusives beneath the cover rocks. In this case, however, the discrepancies between the estimates based on the levelled and microlevelled power spectra are more evident, but are consistent and show deeper depths after microlevelling.

Another method of depth determination and location of the anomaly sources, which is increasingly utilized, is 3D Euler deconvolution (Reid *et al.* 1990). This procedure is effective for the delineation of magnetic boundaries as well as for the estimation of depth to their upper edges. It also gives an indication of the structural index (SI) which is practically the fall-off rate of the anomaly with distance, and is closely related to the geometry of the source.

In Fig. 7(a), the results obtained from the standard levelled data are shown for the SI of 1.0, i.e. for sill/dyke-like sources. This SI is indeed ideal for the description of the cover rocks of the area (as is indicated by the high degree of clustering of most of the solutions), which, from the sparse outcrop, are known to be slightly tilted thin sill-like basaltic bodies. Topography and faulting of these sills are thought to be the cause of most of the high-frequency low-amplitude anomalies (50–100 nT) of the area.

It can easily be seen, however, that on the standard levelled map, the depth solutions are often distributed along the flight lines, thus allowing very poor detection of other directional trends, which could indeed be a useful indication of faulting of the basaltic cover. The microlevelled version (Fig. 7b) shows quite a remarkable improvement (e.g. in the MNK area) and tends to display, as well as previously recognized tectonic features, the existence of a NW feature.

A comparative statistical analysis indicates that for the standard levelled data 90% of solutions are shallower than +500 m, while only 20% of the microlevelled estimates are within this range and tend to be in the deeper 0–500 m class. This result is thus in basic agreement with the findings of the independent 2D FFT approach on small windows.

In Fig. 7(c), the depth estimates using an SI of 3.0, i.e. for 3D sources, are shown. The poorly clustered solutions, which can be more adequately represented by sill-like bodies, have been manually removed so as to focus on possible deeper intrabasement intrusives. While only small differences are noted in the statistical distribution of the solutions in the depth classes for the levelled and microlevelled data sets, the definition of possible intrusive sources A and B, west and east of the high-frequency double peak of the MNK anomaly, is feasible only for the microlevelled version (Fig. 7d).

Overall this study seems to indicate that some modifications can be expected in depth and location determinations of magnetic sources prior to and after microlevelling, on both shallow and deep sources, calculated using different approaches. This is probably due to the filtering procedures involved in microlevelling which clearly affect the data within the chosen wavelengths and amplitudes; this should thus be kept in mind during interpretation and carefully checked with the geology or other constraints, especially in the case of real trends aligned along the flight lines.

Conclusions

The application of microlevelling procedures in the frequency domain improved the quality of regional aeromagnetic data, collected in Antarctica within the framework of the GITARA surveys flown over the Transantarctic Mountains, by increasing the ratio of signal to noise due to diurnal variation and altitude effects along the profile lines. The microlevelling approach based on the application of the 2D FFT filters is, just like the 1D space-domain approach, non-rigorous and cannot lead directly to the distinction between levelling errors and real elongate anomalies parallel to the flight-line direction; therefore it must be used selectively and with due care. However, as the raw levelling error can be inspected and further filtered, we found that these anomalies can still be preserved. They can then be interpreted, while other directional trends and anomaly patterns become easier to recognize, both on standard and on enhanced magnetic anomaly maps, thus leading, in our opinion, to an overall improvement in the tectonic and geological description of an area.

The effects on depth determination also indicate that interpretation of the results after microlevelling must also rely on comparison with standard statistically levelled data, to verify that geological information has not been lost or significantly altered. It is also clear that the frequency-domain microlevelling cannot replace the conventional tie-line levelling which should be performed as a best effort process to minimize the amplitude of the additional corrections.

In a similar fashion to the GITARA surveys, microlevelling has also been applied to newly acquired regional British aeromagnetic surveys in the Antarctic Peninsula

(Johnson 1996) to improve on standard levelling. Our study indicates that microlevelling could profitably be applied to older gridded aeromagnetic data obtained in Antarctica, which probably suffer from inadequate levelling, related above all to unreliable positioning, thus improving the overall accuracy and the geological significance of the ongoing regional INTRAMAP (INtegrated Transantarctic mountains Ross sea Area Magnetic Anomaly Project) and the continental scale ADMAP (Antarctic Digital Magnetic Anomaly Project) magnetic compilation efforts (Chiappini *et al.* 1997; Johnson *et al.* 1997). Amongst the first examples of successful application of microlevelling to regional magnetic compilation, there are the USA compilation in the Norwegian-Greenland seas (Oakey *et al.* 1994) and the GICAS Project on the Greenland Ice Cap (Thorning *et al.* 1994), as well as the AGSO Australian compilation (e.g. Bullock and Isles 1994). Microlevelling has nowadays become a common and useful practice in magnetic anomaly mapping and compilation worldwide, as recently shown by many authors (e.g. Black *et al.* 1997; Green, Misener and Barrett 1997) during Session 5.19 (First Approach to a Digital Magnetic Anomaly Map of the World) of the IAGA 97.

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