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Estimation of magnetisation direction from tripole and quadrupole anomalies in low inclination fields

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ABSTRACT

Magnetisations parallel or anti-parallel to a low inclination magnetic field produce tripole anomalies with two flanking lobes and a central lobe of opposite polarity. Magnetisations perpendicular to the field produce petal-shaped quadrupole anomalies with lobes of alternating polarity. We map the distribution of these anomalies as functions of the inclination of the magnetic field and the direction of magnetisation and we present analyses to determine magnetisation direction from the peak and trough azimuths and amplitude ratios of the anomalies. We demonstrate recovery of magnetisation direction from tripole anomalies measured in aeromagnetic surveys in low inclination fields in Brazil and Malaysia. We have not yet encountered natural quadrupole anomalies in aeromagnetic survey data but we have generated quadrupole anomalies with oriented magnetic sources in a low inclination field in Malaysia and in a Rubens coil set. Analysis of these anomalies returns their correct source magnetisation directions. We also present analysis of similarly generated tripole anomalies due to (reverse) magnetisation directed opposite to low inclination fields.

14.1 INTRODUCTION

Most magnetic field surveys measure the total intensity of the magnetic field (TMI) across a near-horizontal plane above a subsurface magnetisation. Patterns of the measured magnetic field variations are determined by this spatial relationship between the magnetisations and measurements, the direction of magnetisation and the orientation of the magnetic field. At high geomagnetic inclinations (Fig. 14.1A) the main field is almost perpendicular to the measurement surface and a compact steep-inclination magnetisation produces a positive anomaly of near-circular symmetry with the morphology almost of a monopole (the anomaly has a central, sharp, high-amplitude peak with a much weaker and diffuse surrounding outer zone of negative polarity). At intermediate latitudes the TMI expression of a compact magnetisation has the morphology of a

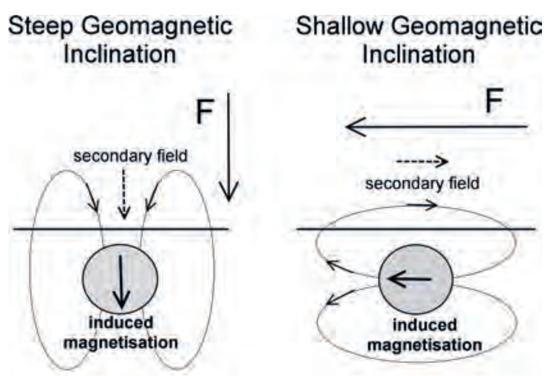

Fig. 14.1. Magnetic field lines for secondary induced fields in an A) polar (vertical) geomagnetic field and B) equatorial (horizontal) geomagnetic field.

dipole with one closed region where the anomalous field sums with the background field to increase TMI and an adjacent closed region where the anomalous field subtracts from the background field to decrease TMI. Close to the equator (Fig. 14.1B) low inclination fields are almost parallel to the measurement surface and field-parallel magnetisations produce oppositely directed secondary fields above them resulting in predominantly negative amplitude TMI anomalies. In low inclination fields anomalies can have more than two closed regions. Throughout this chapter we refer to anomalies by their morphology: tripoles are anomalies with three closed regions and quadrupoles are anomalies with four closed regions.

Figure 14.2 shows a set of anomalies in a zero-inclination field due to magnetisations of north, south, east, west, up and down direction. Horizontal north and south directed magnetisations (Figs 14.2A and 14.2B) that are parallel and anti-parallel to the main field respectively produce tripole anomalies. Of these, field-parallel magnetisations (Fig. 14.2A) have a central trough with peaks to north and south, and magnetisations anti-parallel to the field (Fig. 14.2B) have a central peak with troughs to north and south. Easterly and westerly directed horizontal magnetisations (Figs 14.2C and 14.2D) produce quadrupole anomalies. For easterly directed magnetisations (Fig. 14.2C) the north-east and south-west lobes are positive, and for westerly directed magnetisations (Fig. 14.2D) the north-west and south-east lobes are positive. In steep inclination fields magnetisations are normal or reverse dependant on whether their inclination has the same or

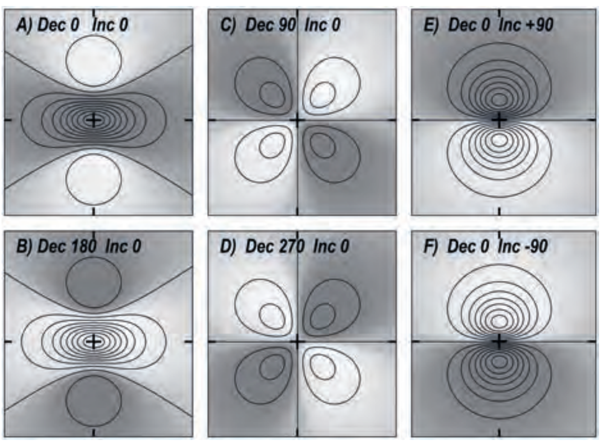

Fig. 14.2. Zero-inclination geomagnetic field TMI anomalies over dipole magnetisations of A) inclination 0° declination 0°, B) inclination 0° declination 180°, C) inclination 0° declination 90°, D) inclination 0° declination 270°, E) inclination +90° and F) inclination −90°.

opposite polarity to the local geomagnetic field. In low inclination fields normal or reverse magnetisations are those with declination parallel to the field (northerly directed) or anti-parallel (southerly directed).

At high geomagnetic inclinations we have the fortunate situation that the azimuth of a line joining the anomaly peak and trough provides an approximate indication of the declination of magnetisation. Also, the peak to trough amplitude ratio indicates the inclination of magnetisation (Zietz and Andreasen 1967). It is more of a challenge to estimate magnetisation direction from key statistics of a dipole anomaly in moderate to low inclination fields but we show here that in low inclination fields estimates of magnetisation direction can be conveniently recovered from the larger complement of statistics available for more complex tripole and quadrupole anomalies. We restrict definition of tripole and quadrupole anomalies to be those anomalies for which the weakest included lobe has an amplitude no less than 10% of the strongest. This definition reduces concern with anomaly classification in analysis of sparse or noisy measured data or where there are overlapping fields from other magnetisations.

The low-inclination magnetic field expression of magnetisations with northerly declination (field parallel) is summarised in Fig. 14.3. For a horizontal northerly directed magnetisation in a horizontal field (the solid black line in Fig. 14.3B) the north–south profile over the centre of magnetisation is symmetric with two flanking positives. If the magnetisation is not horizontal (e.g. curves 'M30s' and 'M30n' in Fig. 14.3) the flanking anomaly peak in the direction of inclination is reduced and the opposite peak is strengthened. A horizontal magnetisation in a horizontal field produces the most prominent tripole anomaly with the highest ratio of the of the weakest lobe to the strongest. For inclined magnetic fields the maximum symmetry of the anomaly and thereby the strongest tendency towards a tripole anomaly is for magnetisations with inclination of opposite polarity to the field (as seen for the 30° south magnetisation in the 30° north field in Fig. 14.3A and the 30° north magnetisation in the 30° south field in Fig. 14.3C).

The international geomagnetic reference field (IGRF) provides an approximate representation of the geomagnetic field. The absolute inclination of the IGFR is imaged in Fig. 14.4 between inclinations of −30° and +30°. This is the range of the field commonly referred to as low inclination. The IGRF magnetic equator (the line where the model has zero inclination) broadly follows

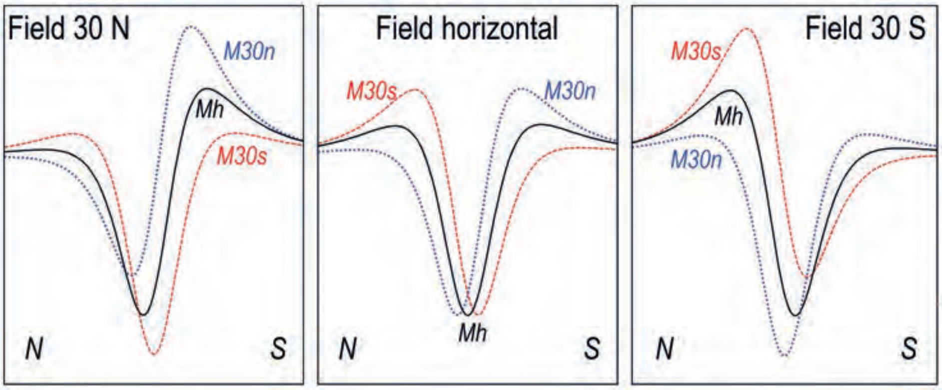

Fig. 14.3. north–south TMI profiles over dipoles with -30° (30°S),0° (horizontal) and +30° (30°N) inclination magnetisations in geomagnetic fields of inclination: A) 30° North, B) horizontal and C) 30° South.

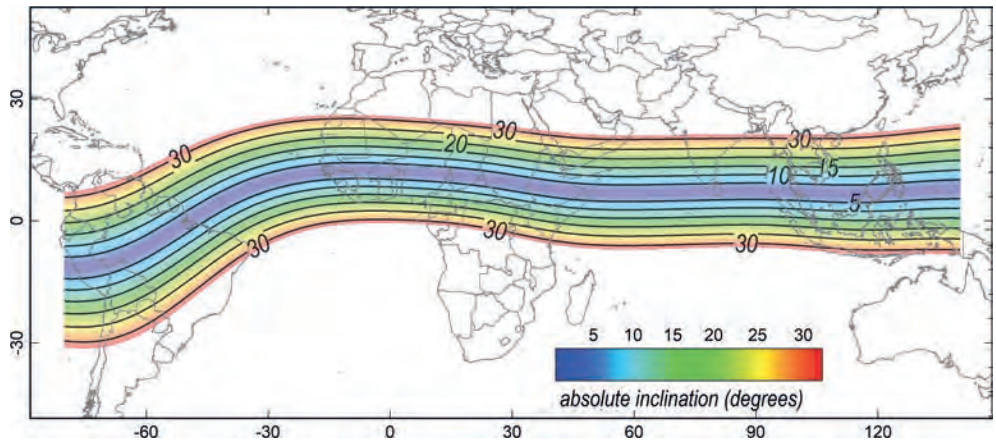

Fig. 14.4. Region of absolute geomagnetic inclination < 30.

the geographic equator but with departures to the north over western central Africa and to the south over the northern part of south and central America. The major land areas with significant regions of low inclination magnetic field are northern Brazil and central America, western Africa to Somalia and Ethiopia, the southern Arabian Peninsula, India and the northern part of South-East Asia and the Philippines. All these regions can be expected to have the tripole anomalies we describe here as well as currently unreported (as far as we are aware) quadrupole anomalies. The average north–south distance between the ± 15° contours is ~1,500 km and between the ± 30° contours is ~3,000 km. The likelihood of finding tripole or quadrupole anomalies is highest closest to the equator. Tripole or quadrupole anomalies can be found at geomagnetic inclinations steeper than 30° but these are mostly due to elongate bodies aligned north–south with polarisation towards their ends.

14.2 THE MAGNETISATION RANGE OF TRIPOLE AND QUADRUPOLE ANOMALIES

To map the range of equidimensional source magnetisations that produce tripole and quadrupole anomalies we made closely spaced computations of their TMI fields and recorded the peak and trough amplitudes. We investigated magnetisations at 10° intervals of declination and inclination (reduced to 5° intervals across ranges of sharp transition). For these synthetic fields anomaly definition is sufficient to reliably determine their morphology, but for measured data anomaly morphology can only be reliably assigned if the field sampling and measurement resolution is adequate and if magnetisations are compact and reasonably isolated.

Figure 14.5 shows the range of tripole and quadrupole anomalies with declination and inclination for compact magnetisations in a zero-inclination field. Bodies of more complex shape must be considered separately. Compact source magnetisations with inclination steeper than 40° generate morphological dipole anomalies (as shown in Fig. 14.5). Anomalies of magnetisations with declination parallel or anti-parallel to the field (declinations close to 0° or 180°) transition between dipole and tripole morphology at inclinations of ± 15°. Anomalies of magnetisations with declination perpendicular to the field (east or west) transition between dipole and quadrupole morphology at steeper angles of ± 35°. Of the 308 results on the 10° × 10° grid plotted in Fig. 14.5, 69% are morphological dipoles, 22% are morphological tripoles and 8% are morphological quadrupoles. On the expectation that many magnetisations are within 15° of the local geomagnetic field direction (because of the contribution of induced magnetisation) tripole anomalies should be common and possibly the dominant anomaly morphology in near-horizontal fields. From our limited experience of such low inclination fields tripole anomalies generally appear to be in the minority (some may go unrecognised if the field is insufficiently sampled). If a survey dataset has anomalies of more than one morphology, a selection of anomalies of each morphology should be analysed or inverted to investigate whether the different magnetic field expressions reveal magnetisations of different direction (possibly generated in geological events of different age).

Figure 14.5 maps the range of magnetisations with declination between 0° and 180°. The pattern is symmetric for magnetisations with declination between 0° and −180°. For low inclination, northerly directed magnetisations of declination within the range of ± 90° the tripole anomalies are composed of a central trough flanked by weaker peaks. For low inclination, southerly directed magnetisations (declinations between 90° and 180° or between −90° and −180°) the anomalies are tripoles composed of a central peak and flanking troughs.

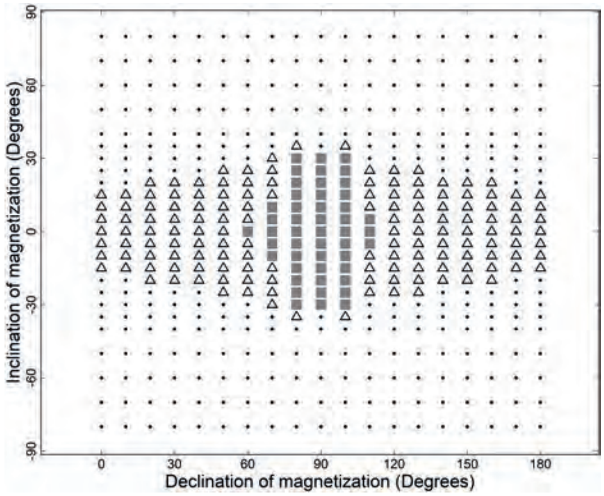

Fig. 14.5. Morphology of compact source anomalies in a horizontal field (points are dipoles, triangles are tripoles and squares are quadrupoles).

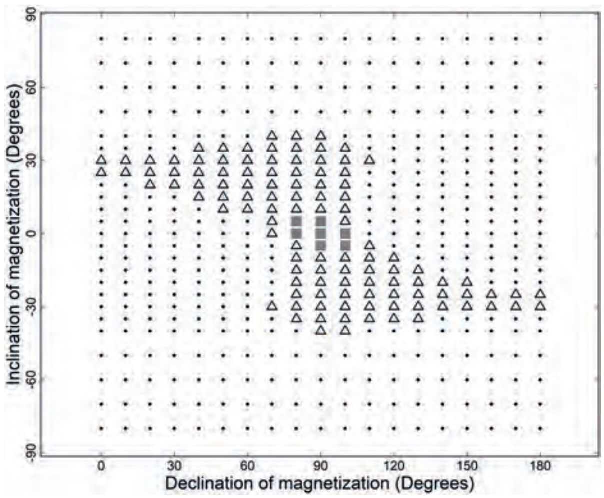

Fig. 14.6. Morphology of compact source anomalies in a 30° S field (points are dipoles, triangles are tripoles and squares are quadrupoles).

Figure 14.6 shows the distribution pattern of anomaly morphologies in a background field of inclination −30°. Compared with the pattern for the horizontal background field in Fig. 14.5 the proportion of dipoles increases from 69% to 81%, tripoles decrease from 22% to 18% and the quadrupoles have a larger relative decline from 8% to only 1%. The non-zero inclination of the background field also skews the distribution pattern of tripole and quadrupole anomalies. Most of the magnetisations with declination between 0° and 90° that generate tripole anomalies have inclination of similar value but opposite sign to the background field. Most of the reverse magnetisations with declination between 90° and 180° that generate tripole anomalies have inclination of magnetisation similar in value and sign to the geomagnetic field. In this steeper geomagnetic inclination field quadrupole anomalies are limited to magnetisation inclinations within 10° of horizontal and declination within 10° of east or west.

Figure 14.7A shows three symmetric anomalies generated by dipolar magnetisations. The lowest amplitude anomaly is generated by a horizontal magnetisation in a horizontal field. A reverse magnetisation in a vertical field has double the amplitude and very similar shape. A reverse magnetisation in a 45° inclination field has a similar shape and an intermediate amplitude. In Fig. 14.7B the three curves are scaled to a common trough amplitude. This highlights the decrease in relative amplitude of the flanking peaks with increase in inclination of the background field. Of the three curves shown in Fig. 14.7 the 10% criteria line we use to define tripole or quadrupole anomalies only intersects the profile for the 0° inclination background field.

The disappearance of tripole and quadrupole anomalies with increase in magnetic field inclination is further investigated in Fig. 14.8. Figure 14.8A plots the percentage amplitude ratio of the weakest lobe of tripole and quadrupole anomalies relative to the strongest lobe for declination of magnetisation parallel and perpendicular to the field respectively. At zero inclination this ratio is much higher for quadrupole anomalies (100%) than for tripole anomalies (20%). However, quadrupole anomalies attenuate more rapidly with increasing field inclination to create a crossover between the relative amplitudes of the two anomalies at less than 15° field inclination. The quadrupole anomalies cross the 10% classification threshold at the lower inclination angle of ~20° compared to tripole anomalies at ~40°. This is consistent with the greater loss of quadrupole anomalies than of tripole anomalies with increase in steepness of inclination of the background field from 0° to 30° as shown in Figs 14.5 and 14.6.

The absolute increase in anomaly amplitude with background field inclination for magnetisations of inclination opposite to the field (optimum candidate magnetisations for tripole and quadrupole anomalies) is plotted in Fig. 14.8B. In a zero-inclination field the anomaly amplitude due to a 0° declination magnetisation is significantly greater than for an identical strength 90° declination magnetisation and it remains higher across the relevant range of field inclinations up to 45°. Combining Figs 14.8A and 14.8B, Fig. 14.8C plots the amplitudes of the weakest anomaly lobes normalised to the anomaly peak for a 0° declination, 0° inclination magnetisation in a 0° inclination background field (point

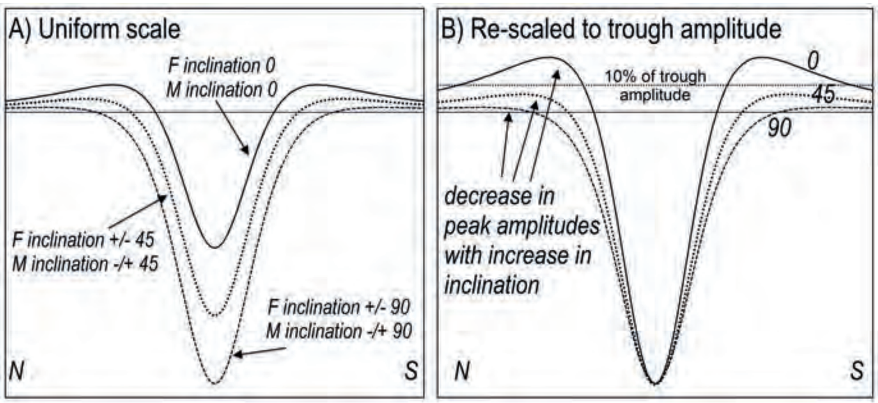

Fig. 14.7. TMI Profile from dipole with inclination of magnetisation 0° in field of inclination 0° and similar profiles of magnetisations +/− 45° and +/− 90° in fields of -/+ 45° and -/+ 90° respectively.

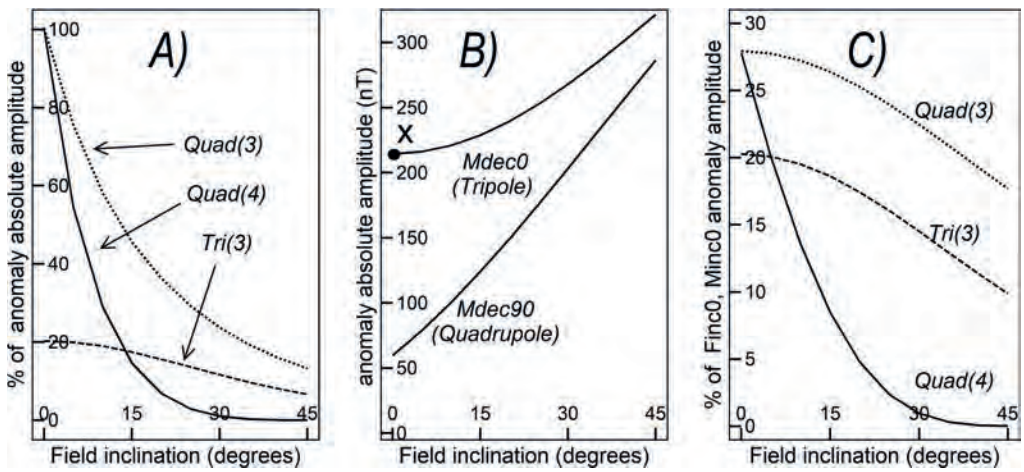

Fig. 14.8. A) decrease in amplitudes of minor lobes as percentage of the total anomaly amplitude with increase in background field inclination, B) increase in absolute anomaly amplitude, C) resulting change in true amplitude of the lobes.

'X' in Fig. 14.8B). Figure 14.8C reveals the considerable discrimination against detection of the weaker fourth lobe of quadrupole anomalies (the curve labelled 'Quad(4)') and also shows favoured detection of the third lobe of those anomalies (the curve labelled 'Quad(3)') compared to the third lobe of tripole anomalies (the curve labelled 'Tri(3)').

14.3 ESTIMATION OF MAGNETISATION DIRECTION FROM A TRIPOLE ANOMALY

We use a similar approach to estimating magnetisation direction from tripole anomalies in low inclination fields that Zietz and Andreasen (1967) used for dipole anomalies in steep northern geomagnetic fields. Figure 14.9 shows TMI maps produced in a zero-inclination field by magnetisations with four rotations, each of 30° (the field of the non-rotated magnetisation is shown in Fig. 14.2A). In Figs 14.9A and 14.9B the magnetisation has 30° rotations of declination, clockwise and anti-clockwise respectively. Consistent with the behaviour noted by Zietz and Andreasen (1967), the primary expression of these rotations of magnetisation direction is a rotation of the peak-trough axis of the anomaly. For tripole anomalies we measure this axial direction of the anomaly from the azimuth linking the two flanking lobes of the anomaly. In Figs 14.9C and 14.9D the magnetisations have 30° rotations of inclination. Also consistent with the high inclination relationships reported by Zietz and Andreasen (1967), these differences in inclination of magnetisation do not change the azimuth of the anomaly axis but change the anomaly amplitude ratios. In low inclination fields this is most pronounced in the amplitude ratio of the two flanking lobes of the anomaly. Encouraged by these relationships, we investigate estimation of the declination of source magnetisation from tripole anomalies using the azimuth of a line joining the flanking lobes and the inclination of magnetisation from amplitude ratios of the flanking lobes.

If the central (main) lobe of a tripole anomaly is negative the declination of the source magnetisation is in the range of ± 90°. If the central lobe is positive the declination of the source magnetisation is in the range of +90° to +180% or −90° to −180%. This polarity of the anomaly determines the sense in which to determine the azimuth between the two flanking lobes regardless of their relative amplitudes. The estimate of declination of magnetisation is given by adding to 0° (for a central negative anomaly) or to 180° (for a central positive anomaly) twice the angle of departure from the azimuth joining the two flanking lobes. For example, in Fig. 14.9A the central lobe is negative and the azimuth of the line joining the flanking lobes is +15°. The declination of magnetisation is derived by adding twice +15° to 0° to give +30°. The cross-plot of estimated declination against true declination in Fig. 14.10 shows that predictions are very close to the true values with only minor departures for declinations close to 90° (these are the anomalies with a fourth, below-threshold lobe that would otherwise qualify as

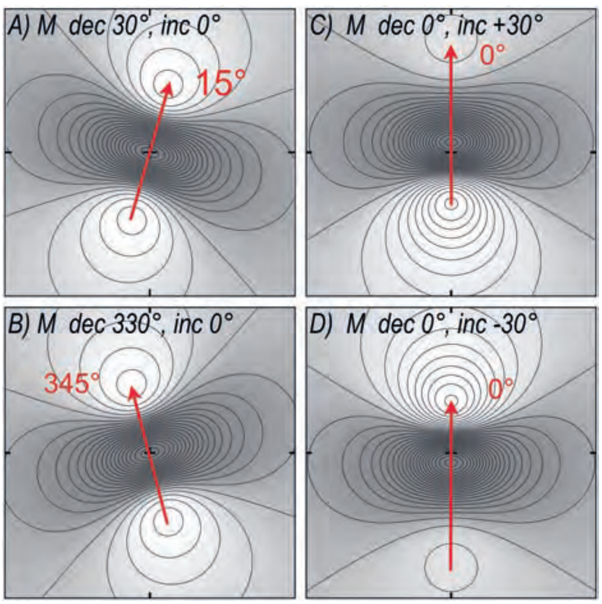

Fig. 14.9. Change of tripole anomaly pattern in a zero-inclination field for four 30° rotations of magnetisation direction.

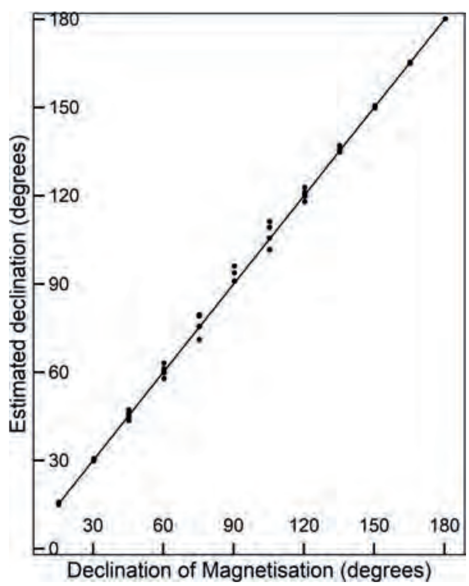

Fig. 14.10. Declination of magnetisation estimates derived from the two flanking lobes of tripole anomalies.

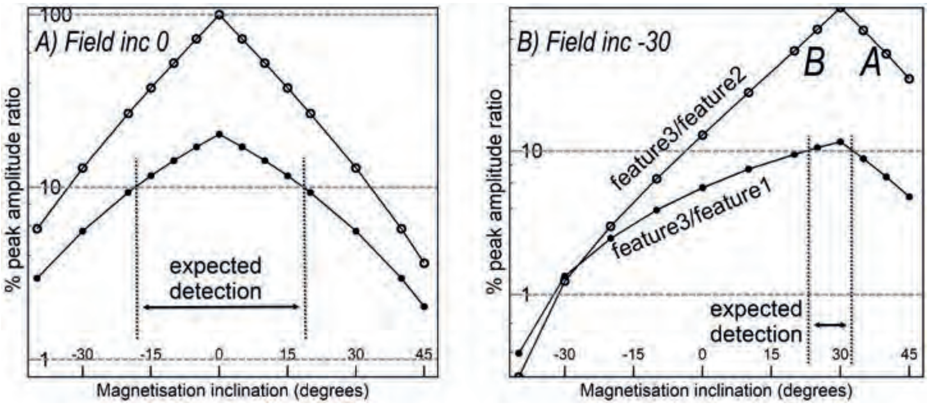

Fig. 14.11. Amplitude ratios of tripole anomalies in A) zero inclination and B) 30°south background fields. Open symbols are ratios of the flanking lobes and closed symbols are ratios of the strongest to weakest lobe (with the dashed line as the 10% threshold for definition of tripole anomalies).

quadrupole anomalies). The points plotted in Fig. 14.10 are for all anomalies detected as tripole anomalies in field inclinations up to 45° at the 15° intervals of field inclination that we investigated.

Estimation of inclination of source magnetisation from tripole anomalies is slightly more complicated than estimation of declination but can be achieved equally effectively. The amplitude ratios of the lobes of the anomaly are sensitive to the inclination of magnetisation and to the inclination of the field. Figure 14.11 shows plots of the percentage amplitude ratio of the two flanking lobes of anomalies due to northerly directed magnetisations in fields of inclination 0° (Fig. 14.11A) and -30° (Fig. 14.11B). Also plotted in those figures is the percentage amplitude ratio of the weakest flanking lobe to the strong central lobe. Following our definition of tripole and quadrupole anomalies, analysis is only required where the weakest to strongest lobe ratio exceeds 10%. In the zero-inclination field (Fig. 14.11A) there is a 40° range of inclination for analysis but this contracts to less than 10° in a field of inclination ± 30° (Fig. 14.11B). Where the inclination of magnetisation is of equal value and opposite sign to the inclination of the background field (the 100% ratio in Figs 14.11A and 14.11B) the flanking lobes of a tripole anomaly have equal amplitudes. The ratio of the minimum to maximum peaks decreases symmetrically away from this central value and on a logarithmic scale the variation is almost linear across the range of analysis. Inclination of magnetisation is to a good approximation given by adding or subtracting to the reverse of the geomagnetic inclination a departure angle from that direction given by:

$$\textit{departure angle}° = 30 * (2 - \textit{log}10\ (\%\textit{amplitude ratio}))/0.88 \qquad \text{(Eqn 14.1)}$$

This leaves the task of determining whether to add or subtract the departure angle because as shown in Fig. 14.11, an amplitude ratio value has two intersections on the prediction curves (marked 'feature3/feature2' in Fig. 14.11B). In a zero-inclination field the departure angle is positive where the larger flanking lobe is towards the south and is negative where the larger lobe is to the north. For non-zero geomagnetic inclination, the departure angle acts to steepen inclination (increase the absolute inclination) if the larger of the flanking lobes is towards the pole and acts to shallow inclination (decrease the absolute inclination) if the larger of the flanking lobes is towards the magnetic equator. For example, in a −30° geomagnetic inclination field (Fig. 14.11B) with the larger flanking lobe towards the pole (in this case to the south) if the amplitude ratio of the two flanking lobes gives a departure angle of 10°, the inclination of magnetisation is +30° +10° = +40° (point 'A' in Fig. 14.11B). Alternatively, with the larger lobe towards the magnetic equator (in this case to the north), the inclination of magnetisation is +30° −10° = +20° (point 'B' in Fig. 14.11B).

14.4 ANALYSIS OF A MEASURED BRAZILIAN TRIPOLE ANOMALY

To investigate the application of relationships between TMI tripole anomalies and magnetisation direction developed in the previous section we have tested the analyses against field data measured in low inclination geomagnetic fields in Brazil and in Malaysia. Figure 14.12B shows a tripole TMI anomaly measured on an aeromagnetic survey in the Goias area of Brazil. Data was downloaded from the Geological Survey of Brazil CPRM website (https://geoportal.cprm.gov.br) from a

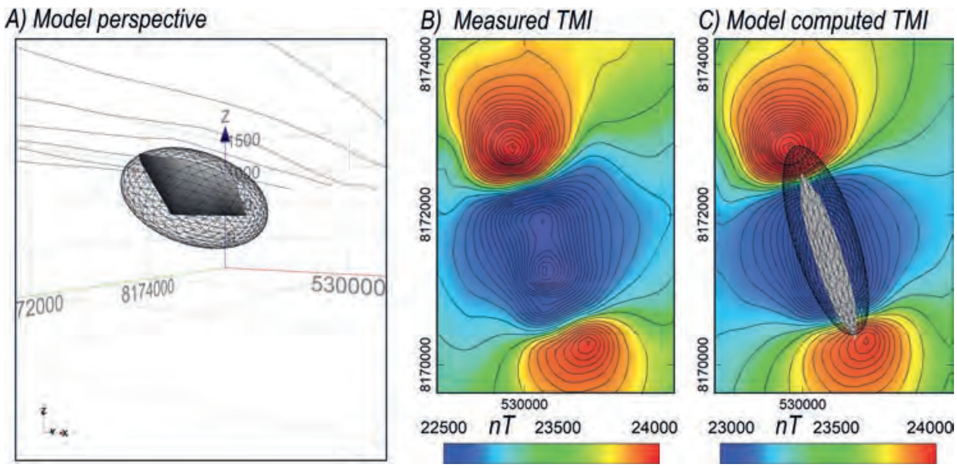

Fig. 14.12. A) perspective view of the ellipsoid (net) and elliptic pipe (solid) models, B) measured and C) model-computed TMI.

survey flown in 2004 with north–south flight lines at 500 m spacing. The mean terrain clearance over the anomaly is 127 m and the IGRF direction at the site is declination 340°, inclination −24°. The anomaly is prominently tripolar with a dominant central trough and two flanking high-amplitude peaks. The peaks are almost 2,800 m apart on an azimuth of 339° (within 1° of the geomagnetic field orientation). We inverted the anomaly using two separate model geometries – a horizontal-top elliptic section pipe and an ellipsoid (Fig. 14.12A) with independent forward modelling algorithms for each body type. The resulting pipe inversion model has a magnetisation direction of declination 344°, inclination +8° and the ellipsoid inversion model has a declination 345°, inclination +11°. The difference between these two directions is only 3°. Both model bodies are elongate in a direction close to the geomagnetic declination. This contributes to their polarisation and may explain the unusually high amplitude of the flanking positive anomaly lobes relative to the central low. The ratio of the three lobes measured from the background field level is (from north to south) 1.34: −1: 0.516. The flanking peak to peak amplitude ratio as used in Fig. 14.12 to estimate the inclination of magnetisation is 39%. This gives a departure angle of 10°. The highest amplitude peak is the northern one, towards the equator for this southern geomagnetic inclination field. Therefore, the reverse of the geomagnetic inclination (+24°) is reduced by 10° to give an estimated inclination of magnetisation of +14°. This inclination is less than 5° from the mean of the two inversion estimates of +10°. The total angular difference between the inversion estimate of declination 345°, inclination +10° and the analysis estimate of declination 339°, inclination +14° is 7°. The difference between the inversion magnetisation estimate and the geomagnetic field direction is 34° so the analysis method is quite sufficient to support inference from the inversion that the source of this anomaly has a significant component of remanent magnetisation different in direction to the local geomagnetic field.

14.5 ANALYSIS OF A MEASURED MALAYSIAN TRIPOLE ANOMALY

Figure 14.13B shows a tripole anomaly in Malaysia measured in a geomagnetic field of declination 0°, inclination −12.6° on the Central Belt aeromagnetic survey flown for the Geological Survey of Malaysia in the 1980s. One of the authors first investigated this anomaly when based at the University of Malaya. We thank the Department of Minerals and Geoscience Malaysia (JMG) for permission to present this example. The line spacing across the anomaly is 570 m and the mean terrain clearance based on radar altimeter measurement is 134 m (the survey was flown before availability of GPS positioning). The anomaly consists of a central negative and two flanking peaks, revealing that the source magnetisation is of low inclination and directed approximately to the north. We inverted the anomaly using two alternative models of a horizontal-top elliptic pipe and an ellipsoid. The elliptic pipe model gave a magnetisation of declination 348°, inclination +12° and the ellipsoid model gave an almost identical magnetisation of declination 348°, inclination +11°. These two inversions

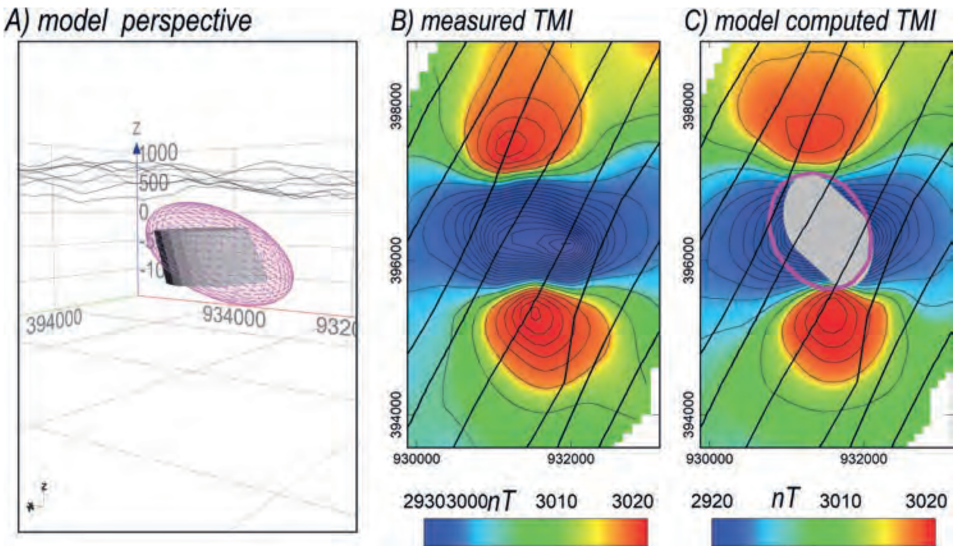

Fig. 14.13. A) perspective of alternative pipe and ellipsoid models, B) the measured TMI anomaly, and C) the anomaly forward computed from the pipe inversion model.

(independent other than for the common input data and regional separation) each closely match the measured field. However, uncertainty in the magnetisation direction is significantly greater than the 1° difference between them because the anomaly peaks and trough are each defined primarily on single and different flight lines. The line joining the two anomaly peaks has an azimuth of 351° (9° from the site IGRF declination) and the relative amplitudes of the three anomaly lobes from north to south are 0.35: −1: 0.45. The 77% ratio of the two flanking peaks gives a departure angle of 4° in the inclination of magnetisation analysis. The stronger southern peak is towards the pole (the survey area lies north of the geographic equator but south of the geomagnetic equator that is the determinant for this magnetic field analysis). For this anomaly orientation the departure angle is subtracted from the reverse field inclination of +13° to give an estimated inclination of +9°. This direction is less than 3° different from the inversion estimates, despite the anomaly being of only modest amplitude and sparsely sampled.

Both tripole anomalies from Brazil and Malaysia conform with the prediction that the most favourable circumstance to find these anomalies is where inclination of magnetisation is of opposite polarity to the inclination of the background field. The results from analyses of both tripole anomalies are also in good agreement with magnetisation directions recovered from inversions that provide the best available bulk estimates of the source resultant magnetisation directions.

14.6 ESTIMATION OF MAGNETISATION DIRECTION FROM QUADRUPOLE ANOMALIES

Figure 14.2C and 14.2D show quadrupole anomalies generated in low inclination fields from magnetisations that are also of low inclination and are directed perpendicular to the field (to east and west respectively). Figures 14.5 and 14.6 show that quadrupole anomalies are generated over a more restricted range of magnetisation directions than tripole anomalies. For a field inclination of 30° (Fig. 14.6) quadrupole anomalies are only found for magnetisations less than 10° from horizontal and less than 20° from magnetic east or magnetic west. We have not yet discovered a convincing example of a natural quadrupole anomaly in aeromagnetic data. The rarity of these anomalies is most likely to be due to the condition that there is a 90° difference between the declination of magnetisation and the geomagnetic field direction. This requires strong dominance of remanent magnetisation and a significant rotation of the resultant magnetisation into either of two small ranges suitable for generation of the anomalies. For young rocks this declination of magnetisation would have to be by a substantial and specific physical (tectonic) rotation. The additional complexity of quadrupole anomalies also places greater demands on the sufficiency of sampling the field, with some quadrupole anomalies possibly unrecognised because they are incompletely sampled.

For analysis of tripole anomalies we utilised statistics that are not available for anomalies of dipole

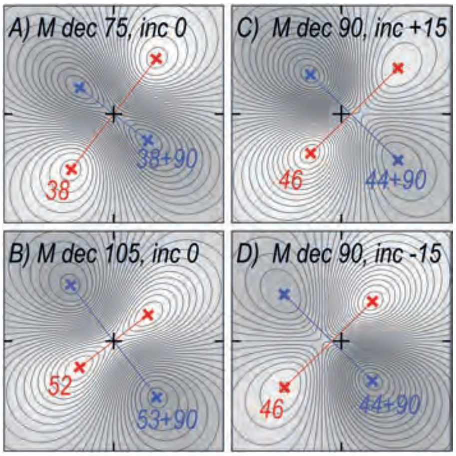

Fig. 14.14. Centres of four quadrupole anomalies with the trends of south-west to north-east positive lobes (in red) and south-east to north-west negative lobes (in blue).

morphology. This advantage of anomaly complexity is further extended with quadrupole anomalies for which several new statistics can be defined. In this study we use statistics derived from the two positive lobes and from the two negative lobes because visual inspection suggests that these features provide the most simple and evident expression of magnetisation direction.

Quadrupole anomalies occur across such small ranges of magnetisation direction that immediately on their recognition, magnetisation directions can be automatically ascribed with reasonable accuracy (an easterly magnetisation for anomalies with north-east and south-west positive lobes and a westerly magnetisation for anomalies with north-west and south-east positive lobes). We use synthetic data analysis to investigate how these approximate magnetisation directions can be refined. Figure 14.14 shows four quadrupole anomalies in a zero-inclination geomagnetic field. The red crosses mark the positive lobe centres and the blue crosses mark the negative lobe centres. For easterly directed magnetisations (north-east and south-west positive lobe anomalies) the declination of magnetisation is approximately given by:

$$\begin{aligned} \textit{declination} &= 90° + 2 * (\textit{azimuth of sw to ne positive lobes} - 45°) \\ &= 90° + 2 * (\textit{azimuth of nw to se negative lobes} - 135°) \end{aligned} \qquad \text{(Eqn 14.2)}$$

and for westerly directed magnetisations (north-west and south-east positive lobe anomalies) the declination of magnetisation is approximately given by:

$$\begin{aligned} \textit{declination} &= 270° + 2 * (\textit{azimuth of se to nw positive lobes} - 315°) \\ &= 270° + 2 * (\textit{azimuth of ne to sw negative lobes} - 225°) \end{aligned} \qquad \text{(Eqn 14.3)}$$

Declination of magnetisation for 52 quadrupole anomalies with easterly directed magnetisation generated in magnetic fields from 0° to 40° inclination are plotted in Fig. 14.15A. Only five estimates of declination in both the peaks and the troughs analyses (Eqns 14.2 and 14.3) are in error by more than 5° and the mean error of each analysis is 2.2°. In almost all cases the errors in the negative and positive lobe analyses for each

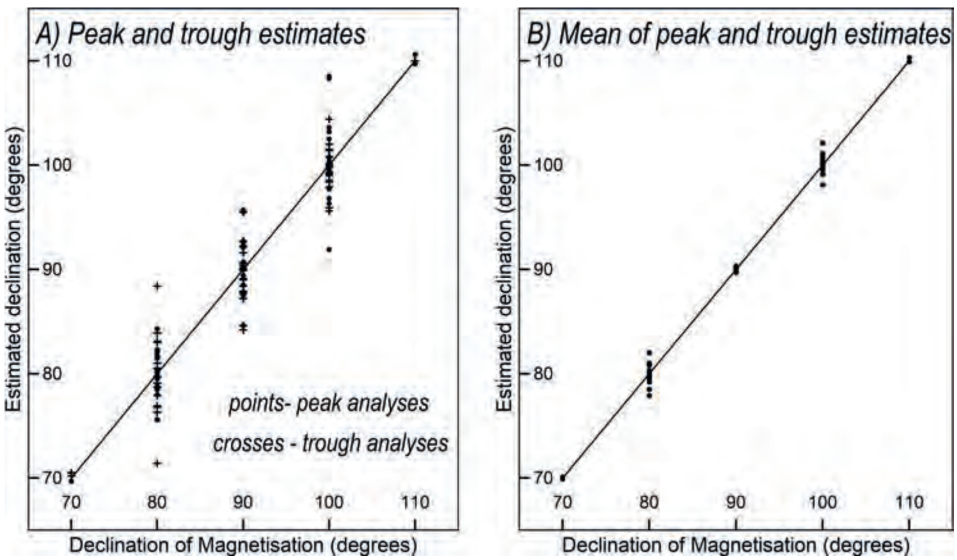

Fig. 14.15. Quadrupole anomaly declination of magnetisation estimates.

magnetisation are of opposite sign and the mean error of the combined analyses (plotted in Fig. 14.15B) reduces further to 0.6°.

We can also use the positive and negative lobe pairs to estimate inclination of magnetisation from the quadrupole anomalies in the same way that we used the single flanking pair of lobes to estimate magnetisation direction from tripole anomalies. Two (generally different) departure angles are estimated from the negative and positive polarity lobe pairs of quadrupole anomalies using Eqn 14.1. There are several combinations and permutations to consider in the search for rules to estimate inclination of magnetisation from quadrupole anomalies. We can expect to find separate rules for the negative and positive lobe pairs, and we need to investigate influence of polarity of inclination for both the magnetic field and the magnetisation, as well as which angle is steeper or shallower than the other. Our systematic tests found a surprisingly simple and condensed set of rules:

1) For analysis of the negative lobe pair the reference inclination (at which the peak to trough amplitude ratio is 1) is that of the background field and for the positive lobe pair the reference inclination is the negative of the field inclination.
2) For analysis of negative lobe pairs the departure angle is added to the reference inclination if the stronger negative lobe is to the north and subtracted if it is to the south. For positive lobe pairs the departure angle is added if the stronger lobe is to the south and subtracted if it is to the north.

We determined these rules from model computed anomalies for which we knew the background field value was zero. However, for analysis of measured anomalies (should they be found) separation from their background fields will be critical (this is required to determine the lobe amplitudes). Determination of the background field level is complicated by the complexity of the anomalies and is best done from field values around their margins. The field value at the saddle point towards the centre of an anomaly can be very different to the background value. Fortunately, there is a considerable advantage that error in estimating the background field value causes opposite errors in estimating inclination from the negative and positive lobes, with the mean of the two estimates far less susceptible to the error in background field separation.

Figure 14.16 shows two quadrupole anomalies due to magnetisations of 90° declination in a background field of inclination −15°. The quadrupole anomaly in Fig. 14.16A has a magnetisation of the same inclination (−15°) as the background field. The negative lobes of this anomaly have identical amplitudes and the minimum to maximum ratio of 100% gives a departure angle of 0° (from Eqn 14.1). The magnetisation inclination estimate (point ‘A’ in Fig. 14.17B) is the reference direction of −15°. the positive lobe amplitude ratio is 14.6%. This gives a departure angle of 28.5° (from Eqn 14.1). Subtraction of this departure angle from the reference angle of +15° gives an estimate of the inclination of magnetisation of −13.5° (point ‘B’ in Fig. 14.17B) only 1.5° different from the estimate derived from the negative lobe pairs. Identical results are found from analysis of the anomaly from a magnetisation of opposite inclination shown in Fig. 14.16B. This analysis gives inclination estimates plotted as points ‘C’ and ‘D’ in Fig. 14.17B, again with a mean

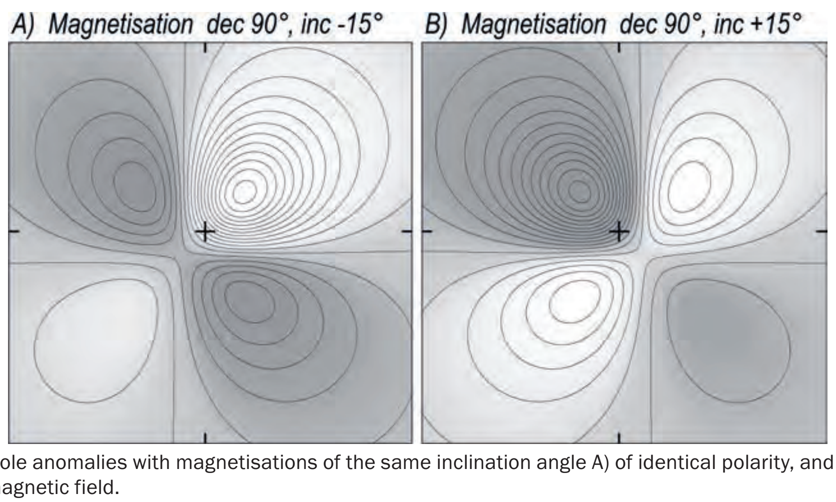

Fig. 14.16. Quadrupole anomalies with magnetisations of the same inclination angle A) of identical polarity, and B) of opposite polarity to the 15° south geomagnetic field.

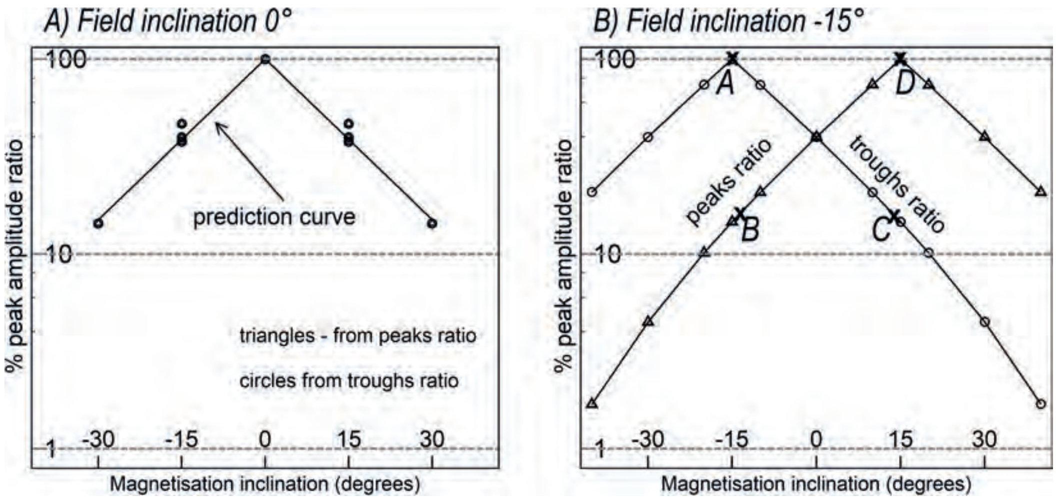

Fig. 14.17. Quadrupole anomaly peaks and troughs amplitude ratios in: A) zero-inclination field and B) inclination 15° south field.

error of less than 1° in estimation of inclination from analysis of the negative and positive lobe pairs.

Figure 14.17A shows the prediction curve for inclination of magnetisation derived from both positive and negative polarity lobe pairs for anomalies in a zero-inclination field. The reference angles of each curve are zero and the two curves overly each other. Figure 14.17B shows corresponding curves for quadrupole anomalies in a −15° inclination field. In this non-zero inclination field the positive and negative lobe curves separate. The apex (the reference point) of the positive lobes curve is at the inclination of opposite sign to the background field and the apex (reference point) of the negative lobes curve is at the same inclination as the background field. It is these reference points from which the departure angles of Eqn 14.1 are measured. Points A, B, C and D plotted in Fig. 14.17B are from analysis of the two anomalies in Fig. 14.16. In the general case most points would be expected to have non-zero departure angles and lie at different distances along the curves. The negative and positive lobe estimates are generally displaced from each other because of their different amplitude ratios, but most importantly the abscissa values for both should be close to provide consistent inclination estimates.

14.7 QUADRUPOLE ANALYSIS TEST ON MEASURED ANOMALIES

We have an analysis with which to estimate source magnetisation direction from quadrupole anomalies – we need measured quadrupole anomalies on which to perform this analysis. We have not yet encountered a natural quadrupole anomaly in aeromagnetic survey data but we are able to generate them. Figure 14.18A shows a quadrupole anomaly measured in a Rubens coil set in Sydney, set to generate a low inclination (+4°) field, and Fig. 14.18B shows a quadrupole anomaly measured in a natural low inclination field of −10° at Kuala Pilah, Malaysia. The sources of the anomalies are magnetite-gabbro cylindrical palaeomagnetic plugs of diameter 2.5 cm and height 2.5 cm. The source of the Kuala Pilah anomaly has a natural (NRM) magnetisation selected because of its high strength and convenient orientation almost along the axis of the cylinder. This plug was laid horizontally with the magnetisation directed to the east. The survey was performed in a mostly wooden 'kampong' (village) house distant from electrical sources other than the winch used to pull the magnetometer along its track and the battery used to power the magnetometer and record the data. The sample has a Koenigsberger ratio > 20 and its induced magnetisation has an almost imperceptible contribution to the anomaly. The source of the anomaly measured in the Rubens coil set is also a strongly magnetic paleomagnetic plug, in this case with an isothermal remanent magnetisation (IRM) of even higher Koenigsberger ratio applied along its axis using a pulse magnetiser. This core was laid horizontally with its magnetisation directed to the west.

We measured the magnetic field data with a three-component fluxgate magnetometer drawn along a 1.3 m track and measured distance along the track with a potentiometer connected to the axis of the winch drawing the magnetometer. We performed the survey by moving the magnetic source at 2 cm intervals along a baseline perpendicular to the track between measurement of each survey 'flight' line. We measured background fields with the source removed before, after and at regular intervals during the survey, and from the averages of those check lines we generated background profiles for each field component. We then subtracted those background field component profiles from the corresponding survey line component profiles as a very effective isolation of the anomaly (unfortunately this is not possible in standard aeromagnetic surveying). This process supresses superimposed field variations, time variations of the field during the survey and long-wavelength variations due to slight bends along the track that disorient the component sensors. We performed repeatability tests and found that we could improve the results by placing the paleomagnetic plugs in three-dimensional printed holders to achieve more precise orientation and positioning before measuring each survey line. In processing the data we added fixed (survey average) background component values back to each survey line to correct for the base shift applied in subtracting the background field. We then gridded each of the three component channels and generated two synthetic 'tie-lines' perpendicular to the survey line and beyond the main anomaly and interpolated the gridded component data onto those lines. From analysis of these tie-lines we applied base shifts as required to reduce line-to-line level variations. Finally, we generated a TMI channel on each survey line from the three level-adjusted component values. This TMI channel is the data we inverted (we also separately inverted the individual component channels and recovered consistent estimates of magnetisation from each of those inversions).

14.7.1 The Kuala Pilah anomaly

The Kuala Pilah magnetic field has a declination of 0°and inclination −10°. The core sample was oriented with the intention to generate a magnetisation with declination and inclination of ~90° and 0° respectively. Inversion of the resulting TMI anomaly shown in Fig. 14.18B gave an optimum estimated magnetisation direction of declination 85°, inclination 0°. The amplitude ratios of the negative and positive lobes are 47% and 70% respectively for departure angles of 11° and 5°. The inclination of magnetisation estimate from the negative lobe pairs is given by adding the departure angle of 11° to the reference inclination of -10° to give an inclination of +1°. The inclination of magnetisation estimate from the

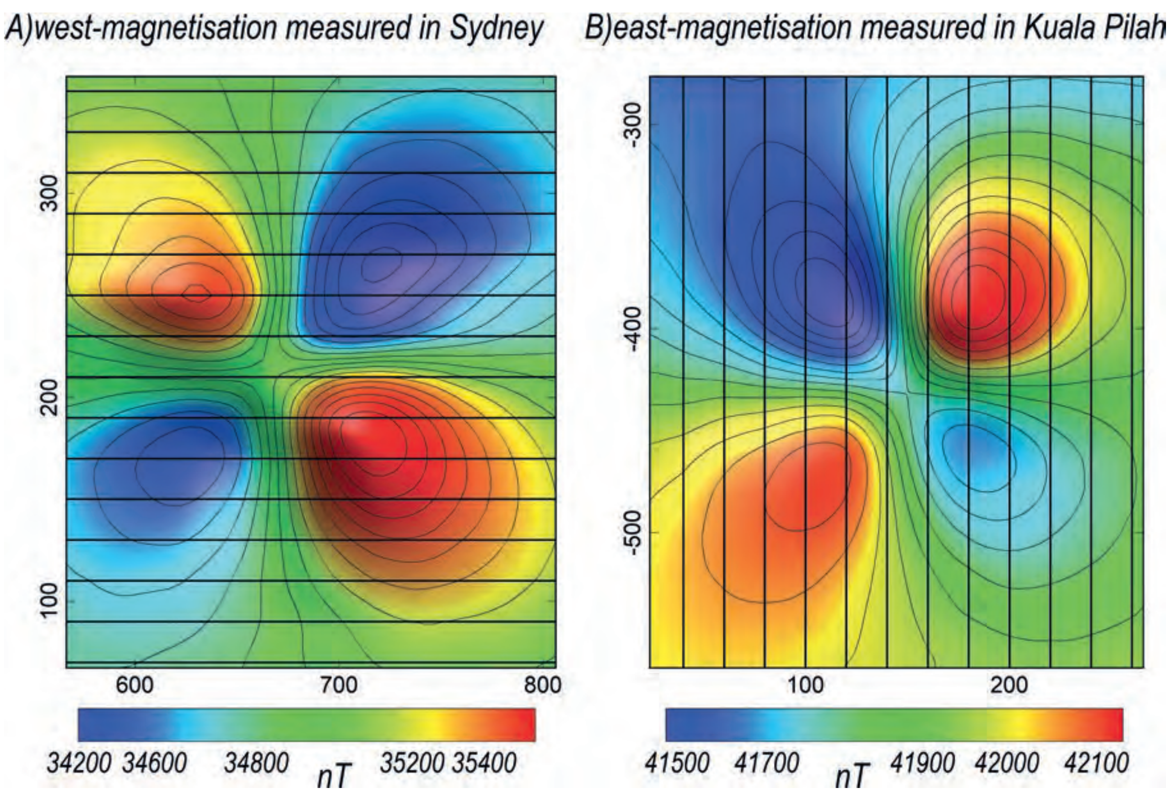

Fig. 14.18. Measured quadrupole anomalies A) in a +4° inclination field in a Rubens coil set and B) in −10° inclination field at Kuala Pilah, Malaysia. Distance scales are in millimetres.

positive lobe pairs is given by subtracting the departure angle of 5° from the reference inclination for that curve of +10° to give an inclination of +5°. There is a difference of 4° between the two estimates and the mean estimated inclination of +3° is only 2° different to the inversion result.

The declination of magnetisation is estimated from Eqn 14.2 (the anomaly pattern reveals that it is an easterly directed magnetisation). The trend of the positive lobes in Fig. 14.18B is 42° and Eqn 14.2 gives an estimated declination of magnetisation of 84° (90° + 2* (42° – 45°)). The trend of the negative lobes in Fig. 14.18B is 138° and from these lobes Eqn 14.2 also gives an estimate of 84° for the declination of magnetisation (90° + 2* (135° – 138°)). These declination estimates from the quadrupole analysis are within 1° of the estimate provided by inversion.

14.7.2 The Sydney Rubens coil set anomaly

The field in the Rubens coil set in Sydney was set to a declination of 2° and inclination +4°. The optimum estimated magnetisation direction from inversion of the TMI anomaly shown in Fig. 14.18A is declination 269°, inclination +8°. The amplitude ratios of the negative and positive lobes of this anomaly are 75% and 54% respectively, giving departure angles of 9° and 4°. The inclination of magnetisation estimate from the negative lobe pairs is given by adding the departure angle of 4° to the reference inclination of +4° to give an inclination of +8°. The inclination of magnetisation estimate from the positive lobe pairs is given by adding the departure angle of 9° from the reference inclination for that curve of −4° to give an inclination of +5°. There is a difference of 3° between the two estimates and the mean inclination of 6.5° is less than 2° from the inversion result. From inspection of the orientation of the positive lobes of the quadrupole anomaly in Fig. 14.18A we can determine that it is caused by a westerly directed magnetisation and we estimate the declination of magnetisation using Eqn 14.3. The trend of the negative lobes is 227° and of the positive lobes is 314°. Equation 14.3 gives corresponding estimates of the declination of magnetisation of 274° and 268°, a difference of 6°, with a mean value of 271° that is only 2° away from the inversion result.

14.8 TRIPOLE ANALYSIS OF MEASURED REVERSE-MAGNETISATION ANOMALIES

We found several tripole anomalies in Brazilian and Malaysian aeromagnetic survey data but all are due to normal magnetisations. Normal magnetisations are more common than reverse magnetisations – in large part due to the bias from contribution of induced magnetisation. However, it is quite feasible that an extensive search of low-inclination magnetic field data from multiple areas will find reverse-magnetisation tripole anomalies (particularly in areas with young volcanic sequences that span one or more geomagnetic field reversals). Reverse magnetisation tripole anomalies are likely to be more common than quadrupole anomalies. To confirm that the tripole anomaly analysis can also be applied to study of reverse magnetisation we generated these anomalies using the same methodology as for quadrupole anomalies, but with magnetisations oriented anti-parallel to the field rather than perpendicular to it. Figure 14.19 shows tripole anomalies generated in a Rubens coil set in Sydney (Fig. 14.19A) and in the natural field at Kuala Pilah, Malaysia (Fig. 14.19B). The central peak of the tripole anomalies immediately reveals that they are due to low-inclination magnetisations approximately anti-parallel to the field (with declinations close to ± 180°).

The TMI anomaly shown in Fig. 14.18B is due to a near-horizontal reverse magnetisation placed in the Kuala Pilah magnetic field of declination 0°, inclination +10°. Inversion of the anomaly gives a best estimate of the direction of magnetisation of declination 183°, inclination −2°. The azimuth joining the flanking anomaly minima is 180° and the amplitude ratio of the two minima (measured from the background field) is 42%. This ratio gives a departure angle (Eqn 14.1) of 13°. The higher amplitude minima is towards the equator and so the estimated inclination of magnetisation is +10° −13° = −3°. This is only 1° different to the inversion estimate of −2°.

The TMI anomaly shown in Fig. 14.18A is due to a near-horizontal reverse magnetisation placed in a field of declination 2°, inclination +4° generated in a Rubens coil set in Sydney, Australia. The azimuth joining the flanking minima is 0°. The amplitude ratio of the weaker to stronger flanking lobes is 91%, generating a low departure angle of 1.4° (Eqn 14.1). The stronger flanking lobe is towards the pole (to the north for this positive inclination field) and steepens the angle of inclination from the field inclination value of +4° to +5°, only 1° from the inversion result of +4°. For both of these generated anomalies the tripole analysis returns a close estimate of the magnetisation direction.

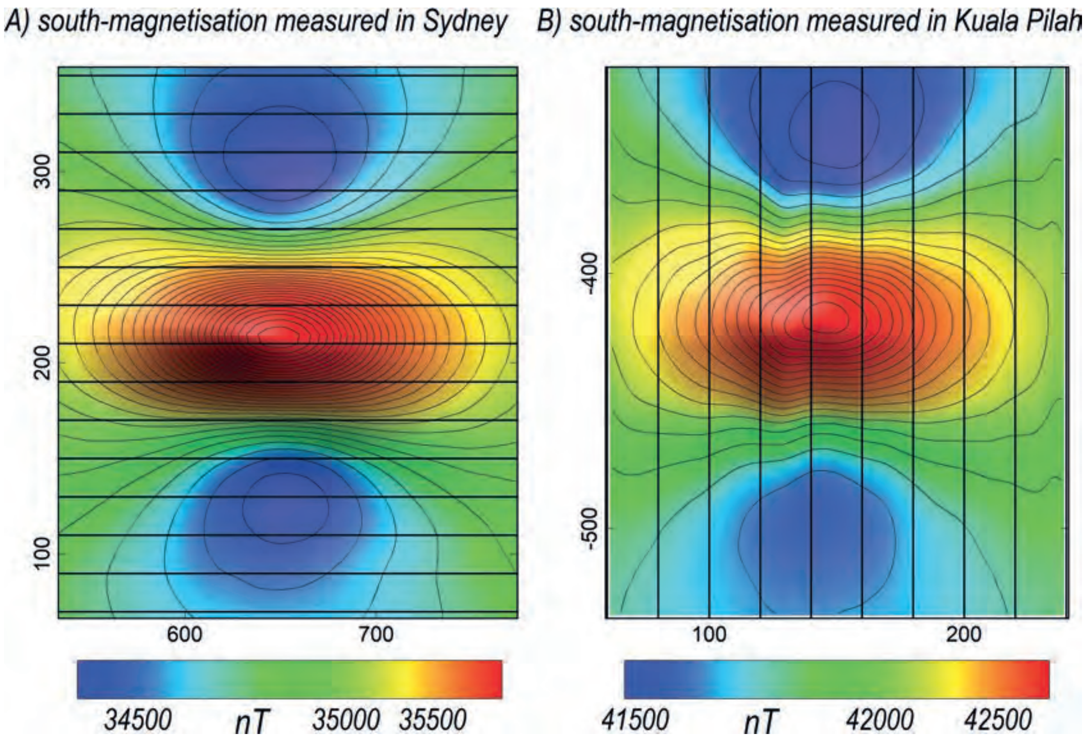

Fig. 14.19. reverse-magnetisation tripole anomalies measured A) in a Rubens coil set in Sydney and B) in the natural field at Kuala Pilah, Malaysia. Distance scales are in millimetres.

14.9 CONCLUSIONS

Low-inclination magnetisations parallel or anti-parallel to field generate tripole anomalies with two flanking lobes to either side of a central lobe of opposite polarity. Low-inclination magnetisations perpendicular to the field generate quadrupole anomalies with lobes of alternate polarity. We present analyses to recover magnetisation directions from these anomalies. We have demonstrated successful application of the analyses to tripole anomalies in aeromagnetic data measured in Brazil and Malaysia. We have also successfully applied the analyses to quadrupole and reverse-magnetisation tripole anomalies we generated with an oriented magnetic source in a low inclination field in Malaysia and in a Rubens coil set in Sydney. These analyses recover estimates of magnetisation more reliably than would be expected for anomalies of dipole morphology in fields of steeper inclination.

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