Mapping remanent magnetizations at regional scales

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ABSTRACT

The magnetization of a rock is possibly the most information-rich physical property it has, with the direction of magnetization a function both of the age of processes giving rise to that magnetization and of any post-acquisition tectonic rotations. This information is best recovered by laboratory measurements, but magnetic field interpretation provides a powerful method of mapping the extent of these magnetizations. With suitable geological constraints magnetizations mapped by magnetic field interpretation can reveal the extent of igneous, thermal, alteration and fluid flow events, even from rocks buried beneath cover. I present a case study showing how the recent British Geological Survey Tellus SW airborne magnetic survey reveals the extent of (possibly mineralizing) fluids to the north of the Bodmin Moor and Dartmoor Granites, and how recognition of anomalies due to a diagnostic remanent magnetization reveals correlation between as-yet-unknown small igneous(?) bodies to the south of the granites. I then describe the design and use of a database of anomalies due to remanent magnetization which has been developed to assist geoscientists in geological mapping and resource exploration across large areas of sparse or non-existent exposure in Australia. Finally I discuss the application of regional automated magnetization mapping, again using as example an Australian study.

INTRODUCTION

The objective of magnetic field interpretation is to supply geological information. This is possible because geology determines the distribution of ferromagnetic minerals and the magnetizations they carry, and in turn those factors cause variation in the magnetic field measurements. The magnetization of a ferromagnetic mineral is a combination of magnetization induced by the local geomagnetic field as a result of its magnetic susceptibility, together with a remanent magnetization. Rock magnetization measurements commonly show remanent magnetizations of comparable strength to induced magnetizations (e.g. Dunlop et al., 2010), but despite this many magnetic field interpretations neglect the likely role of remanent magnetization, only acknowledging it in specific cases where it is dominant and undeniable. In this paper I focus on aspects of magnetic field interpretation related specifically to remanent magnetizations oblique to the local geomagnetic field direction. I hope to establish that a more productive approach to magnetic field interpretation is to assume that remanent magnetization is a contributor to most magnetic field measurements, and that there is advantage in making the effort to recover geological information from those magnetizations. Many methods are available to estimate magnetization direction from individual magnetic field anomalies and these are supported by plentiful case studies. However, there are as yet few studies of the regional distribution of magnetizations derived from magnetic field interpretation. Mapping distribution of magnetization should be a prime objective for geological mapping and resource exploration because these are distributions of geological events such as igneous activity, thermal pulses, fluid flow, mineralization and deformation.

The ratio of remanent to induced magnetization (the Koenigsberger ratio or 'Q' factor) is used as a measure of the significance of remanent magnetization but it cannot be recovered from magnetic field interpretation without additional information (magnetic susceptibility values or remanent magnetization directions). Of greater significance for magnetic field interpretation is the deviation of the resultant magnetization from the geomagnetic field direction, termed ARRA (apparent resultant rotation angle) which is the primary factor determining detectability of remanent magnetization in magnetic field data. Relationships between induced and remanent magnetization, Koenigsberger ratio and ARRA are shown in Figure 1.

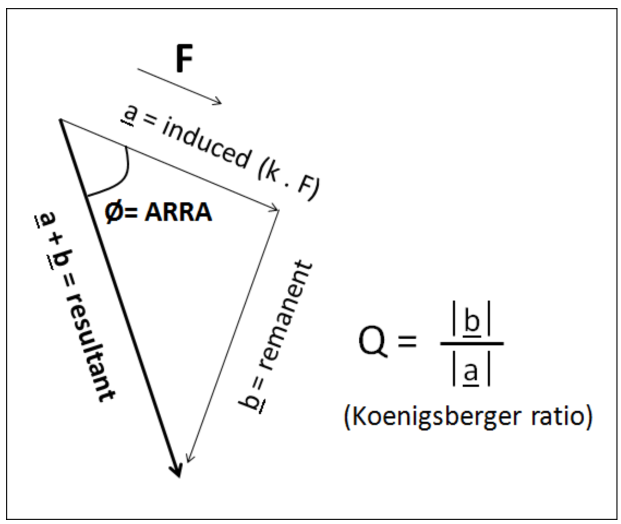


Figure 1 Vector relationships of induced, remanent and resultant magnetization, Koenigsberger ratio and ARRA

Figure 2 is a schematic representation of the population of ARRA values for magnetizations giving rise to measured magnetic field variations. I have shown distributions only up to 90° but they continue to 180°. The shape of the curve will vary from area to area depending on the age of the magnetizations most strongly expressed in the magnetic field, their Koenigsberger ratios, and any post-magnetization tectonic rotations. These postulated curves highlight the value of improving detection of magnetization direction from magnetic field data, to allow a larger proportion of anomalies to be investigated.

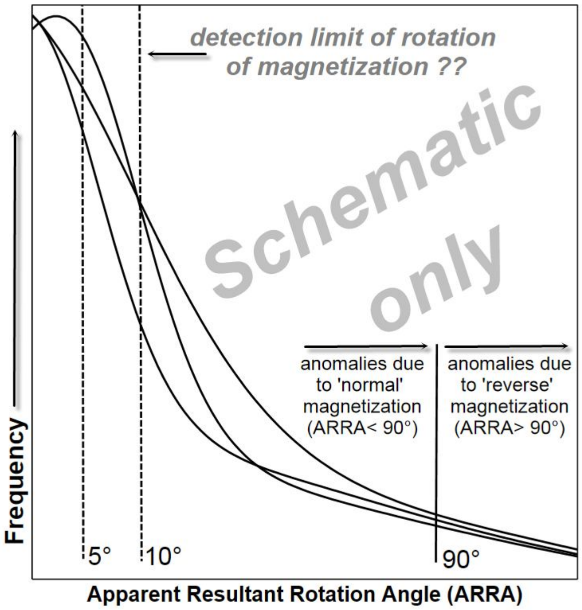


Figure 2 Schematic illustration of populations of resultant magnetization directions

A CASE STUDY: MINERALIZATION-RELATED REMANENT MAGNETIZATION ASSOCIATED WITH THE GRANITES OF DEVON AND CORNWALL

Figure 3 shows an image of total magnetic intensity over parts of Devon and Cornwall from the Tellus South West survey flown for the British Geological Survey (BGS) on north-south flight-lines at a 200 meter spacing and nominal terrain clearance of 80 meters (Beamish and White, 2014). The most prominent feature in Figure 3 is a band of negative anomalies to the north of Bodmin Moor and Dartmoor. These anomalies cannot be due to a negative susceptibility contrast because the flat, higher magnetic field values immediately to the south overlay low susceptibility granites. These anomalies are instead due to a reverse remanent magnetization. The magnetic field variations within the most westerly onshore section of the band are shown in detail in Figure 4. These complex variations are also imaged in figure 5, which shows contours of total gradient of TMI overlying a Bouguer gravity image (derived from gravity data downloaded from the BGS website). The total gradient transform highlights shallow high-intensity magnetization with little sensitivity to orientation of the source magnetization. A 250 meter upward continuation was applied prior to the total gradient transform to suppress the shortest wavelengths. The width of the magnetic anomaly band varies between 4 and 8 kilometers, and the inner margin is almost coincident with the steepest gradient of the negative gravity anomalies which approximately maps the contacts of the low density granites.

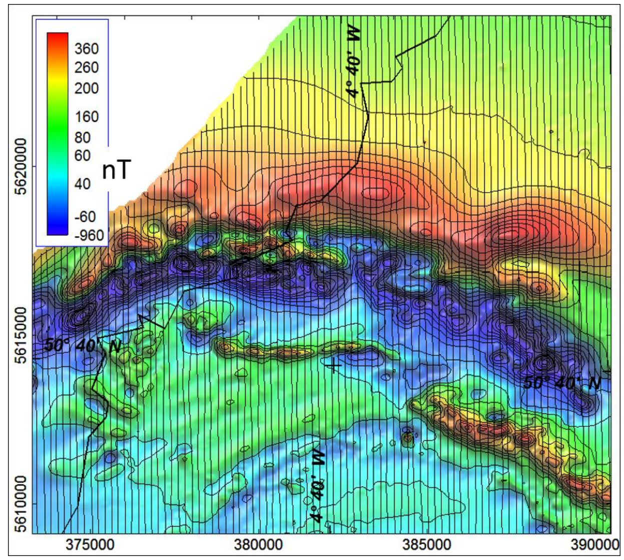


Figure 4 TMI detail of a section of the intense anomaly band (contour interval 50 nT)

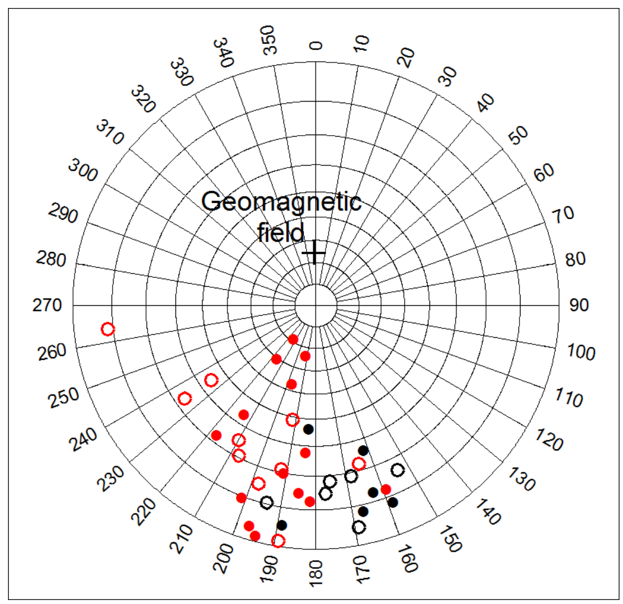


Figure 7 Creer (1967) site mean NRM directions (red) and magnetic field inversion model magnetization directions (black). Solid symbols positive inclination, open symbols negative inclination.

Creer (1966), Cornwell (1967) and Green (1979) who have conducted palaeomagnetic studies in this area have established that the reverse remanent magnetization is carried in pyrrhotite. All three studies report large within-site scatter of magnetization directions and inconsistent results from application of structural corrections to determine if the magnetization is pre- or post-folding. However the magnetizations are considered to be consistent with a Lower Carboniferous to Early Permian age, with the pyrrhotite generated from metasomatic fluids associated with emplacement of the granites. The distribution of sample sites from the Creer (1966) study plotted in Figure 6 lie either within or just outside the band of magnetization defined by the magnetic field survey. Mean NRM (natural remanent magnetization) directions from the Creer (1966) sites are plotted with the red symbols on the stereonet in Figure 7. These measured magnetization directions are consistent with the patterns of localized anomalies within the main negative magnetic anomaly band. The low and negative inclination magnetizations generate predominantly negative TMI anomalies, and the southerly declination of the magnetizations causes the troughs of the anomalies to be to the south of the peaks (although these patterns are also moderated by any regional gradients on which the anomalies are superimposed). It is difficult to accurately determine source magnetization directions from the local anomalies within the main band because the diffuse background and overlapping magnetic field variations cause uncertainty in isolation of anomalies. This irregular distribution of magnetization is consistent with the suggested metasomatic origin of the pyrrhotite believed to carry the magnetization. The widely distributed magnetization may result from a diffuse fluid flow, with local anomalies arising where there are higher concentrations of pyrrhotite in structurally favourable zones or in rocks which may have chemically interacted with the fluids.

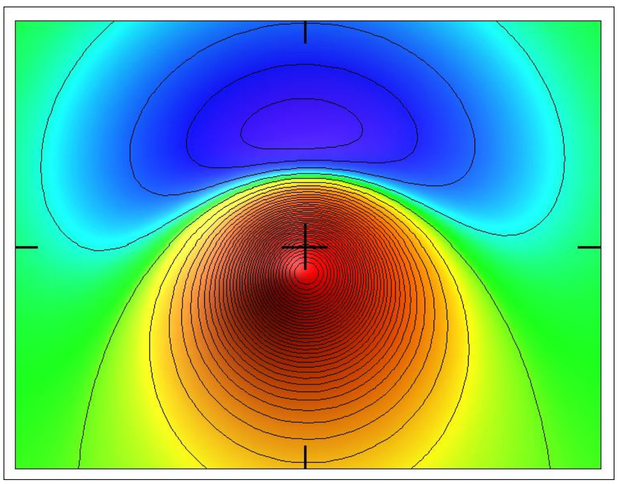


Figure 8 Induced dipole TMI anomaly in a geomagnetic field of declination -2°, inclination +65° (blue – low to red – high).

The shape of an anomaly expected from a compact induced magnetization in the local geomagnetic field is shown in Figure 8. This anomaly is predominantly positive with a minor negative to the north. To the south and west of Bodmin Moor and Dartmoor a number of discrete well-defined anomalies can be found which are different to this pattern. The locations of these anomalies are plotted in Figures 3, 5, 6 and 10, and their TMI images are shown in Figure 9. Source inversions have been performed on these anomalies, with resulting magnetization direction estimates annotated in Figure 9 and with the directions plotted as the black symbols in the stereonet in Figure 7. Note that these are directions of resultant (induced plus remanent) magnetization, as opposed to remanent magnetization directions from the palaeomagnetic study. Some of the scatter of inclination of the inversion-derived magnetizations can be explained as differences in Koenigsberger ratio (with the steep negative inclinations having highest Koenigsberger ratios) or might alternatively be due to differences in remanent magnetization direction. The Creer (1966) remanent magnetization measurements show an overlapping and larger variation in inclination, which may be due to mixtures of more than one remanence direction (for instance including low temperature re-magnetization in a more recent field). The wider range of the palaeomagnetic measurements may also be due in part to preferential selection of anomalies of a common pattern in the inversion study.

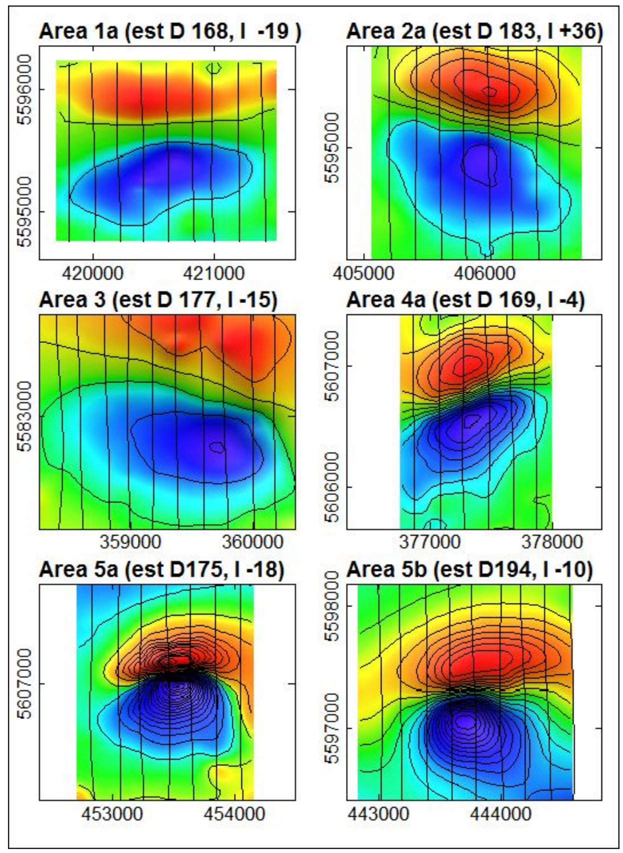


Figure 9 TMI anomalies from areas to the south and west of the granites clearly due predominantly to remanent magnetization. Images individually color coded but with common 20 nT contour intervals.

The similarity of magnetization directions derived from the anomalies show in Figure 9 suggest that they record magnetization at a common or similar time, allowing correlation of the source bodies across a large area. If any one magnetic anomaly is associated with mineralization then it raises interest in all other anomalies, even though the sources are not necessarily of identical lithology or share a common mineralization. The inversion solutions suggest that several of these sources do not outcrop (those which may outcrop have not yet been checked against the mapped geology). Figure 10 plots mines in the region recorded to have produced copper, and mines reported to have produced lead. These are subsets of mine locations provided by the Northern Mine Research Society. The distributions of these two subsets of mines reveal a regional zonation of mineralization (which is further defined by additional subsets of the database not shown here). These particular sets of mines are mostly located around the margins of the granites. There is a conspicuous break in the ring of mines around the northern margin of Dartmoor. This gap is occupied by only two mines, reported as tin mines, which may have been alluvial (they would otherwise be quite anomalous as most of the hard-rock tin mines are located within or immediately adjacent to the granites). The gap is either due to the local absence of mineralization, or mineralization which has not yet been discovered or mined. In the magnetic field this gap is marked by a prominent expression of reverse remanent magnetization, suggesting high concentrations of pyrrhotite, and therefore presumably high fluid flows, with the presence of the pyrrhotite also attesting to the availability of both metal and sulphur, favorable for mineralization. There are also no copper or lead mines in the broad zone of strong reverse remanent magnetization towards the north Cornwall coast. This area is further from the granites as mapped by the gravity data (Figure 5), but the strong magnetic anomalies suggest that it has also been influenced by the same or similar fluids to those which elsewhere have an association with mineralization. The two mines recorded within this particular band of strong magnetization produced manganese, which indicates possible proximity to other metals.

Figure 10 also shows association variously of copper and lead mines to the remanence dominated anomalies in areas 1 to 5b, so that the source of those anomalies might also have a relationship to mineralization; either being mineralized themselves, or being a component of the mineral system. There is undoubtedly more that can be learnt from further study of the distribution of remanent magnetization and mineralization in this area, and the magnetic survey data is clearly relevant to any future mineral exploration programs. Benham et al. (2005) reviewed the mineral prospectivity of the region between Bodmin Moor and Dartmoor using the Iberian Pyrite Belt as a model for possible stratiform massive sulphide mineralization. As shown by the distribution of mines plotted in Figure 10, this region has well proven mineralization. Much of this mineralization is in hydrothermal veins and stockworks within or immediately adjacent to the granites, but Benham et al. (2005) also report stratiform lead-zinc mineralization intersected in a borehole into the thrust-disrupted Carboniferous and Devonian sandstones and slates. They incorporate total gradient of TMI anomalies in their prospectivity analysis (using pre-existing regional coverage because their study pre-dated the Tellus SW survey). The Iberian Pyrite Belt model they propose can be adapted or extended by analogy with the Cobar Basin of New South Wales (Fitzherbert et al., 2017). Mineralization in the Silurian-Devonian Cobar Basin is associated with hydrothermal alteration in volcanogenic sediments adjacent to major faults. Magnetic pyrrhotite is associated with much of that mineralization, and the major Elura orebody was discovered because of its magnetic anomaly arising from remanent magnetization in pyrrhotite (Clark and Tonkin, 1994). Benham et al. 2005 report that the Wilsey Down borehole close to one of the local negative magnetic anomalies north of Bodmin Moor intersected disseminated pyrrhotite, but with no mention of associated mineralization. Despite this, the local negative magnetic anomalies north of Bodmin Moor and Dartmoor would be prominent drill targets if encountered in the Cobar Basin.

THE AUSTRALIAN REMANENT ANOMALIES DATABASE

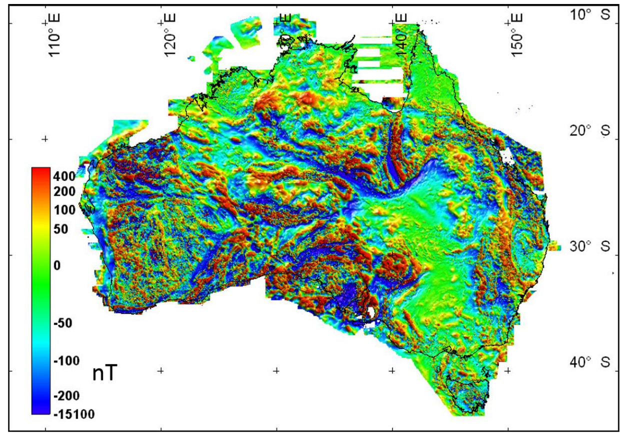


Figure 11 TMI image of Australia

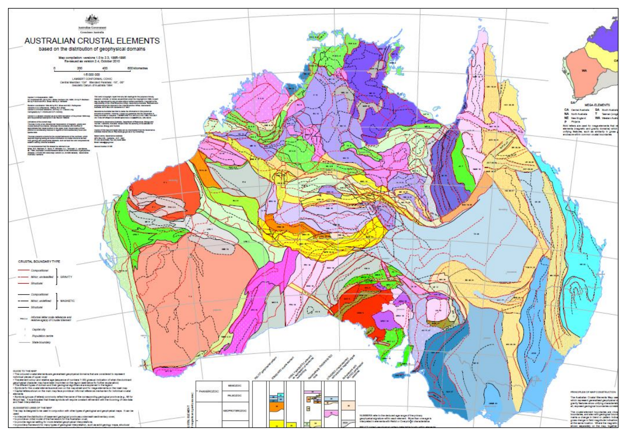


Figure 12 Australian crustal elements map (Shaw et al. 1995)

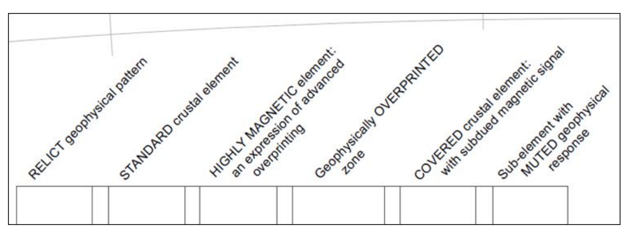


Figure 13 Index headers for the crustal elements map

Outcropping mineralization and alluvial deposits developed from surface mineralization were of critical importance in the history of mineral exploration and discovery in Devon and Cornwall, but most areas of prospective mineralization in Australia have either extremely deep weathering or younger cover which obscures mineralization. This increases the value of geophysics as a remote sensing tool for geological mapping. Figure 11 shows a TMI image of Australia compiled by Geoscience Australia (Milligan et al. 2010) generated from regional surveys flown by Geoscience

Australia and by State and Territory surveys as part of exploration initiative programs. Many prospective areas are additionally covered by higher-resolution company surveys. Imagery from the measured magnetic field and its enhancements are used as proxies for geological maps of shallow basement in areas where extensive cover and weathering restrict direct geological mapping. Figure 12 shows a crustal elements map (Shaw et al. 1995) derived with substantial guidance from the regional magnetic field and gravity data. A clip of the index headers for the map is shown in Figure 13. Terms such as 'relict geophysical pattern', 'highly magnetic element', 'geophysically overprinted zone', 'subdued magnetic signal' and 'muted geophysical response' reveal the importance of magnetic imagery in generating this map. This map has been recognized to be of strategic importance for encouragement and assistance of exploration beneath cover, and is being re-released in digital format (Claoué-Long, 2011). The domains in the map are based primarily on intensity, texture and trend of the magnetic field variations which are controlled by distribution of ferromagnetic minerals, structural fabrics and metamorphic history. Variation in direction of magnetization in most cases has a more subtle expression in the magnetic field data and provides a secondary mapping of geological events. For instance, if a set of anomalies can be found with magnetization of a characteristic direction carried in intrusive or volcanic bodies then the extent of that igneous event can be mapped from those anomalies even though they may have only a minor expression in any of the primary domains, or may extend across several domains.

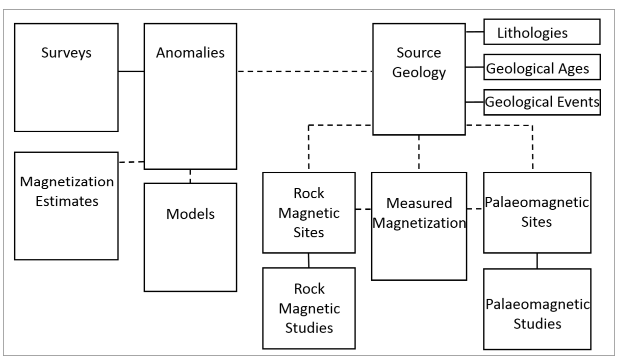


Figure 14 Simplified database structure

The Australian Remanent Anomalies Database (Foss et al., 2012, 2014) has been developed to help map geological events characterized by their magnetization directions. The database is a repository where magnetization direction estimates can be located, interrogated and downloaded. A simplified map of the database structure is shown in Figure 14. The primary entry in the database is a magnetic anomaly for which the minimum requirement is location, the survey in which the data was measured, spatial extents and data range. Magnetization estimates and source model details can be assigned to anomalies and optionally be made available as digital downloads. Anomalies can also be attributed to a geological source, with options to nominate lithology, geological age and geological event. The geological source itself can be separately linked to measured magnetizations or magnetic properties supplied from palaeomagnetic or rock magnetic studies. The objective of these links is to correlate magnetization studies from magnetic field investigations with any palaeomagnetic or rock magnetic studies.

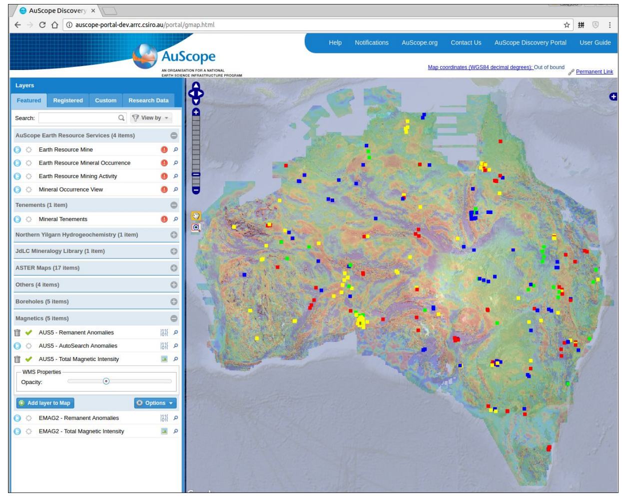


Figure 15 Distribution of database entries color coded by ARRA (blue 0 to 45°, yellow 45 to 90°, green 90 to 135°, red 135 to 180°)

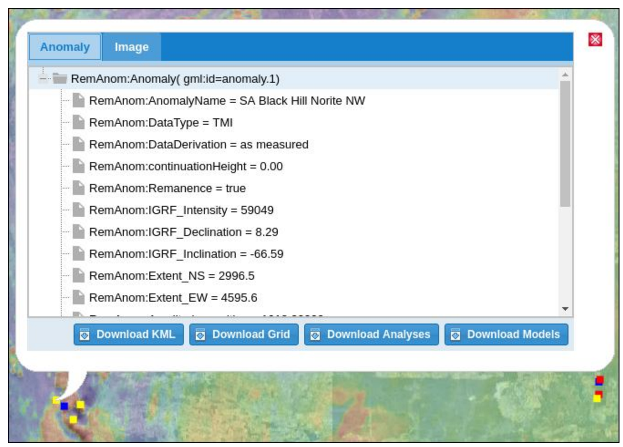


Figure 16 Anomaly detail display with download buttons.

The database currently has just over 300 anomaly entries, each of which has a TMI image for display in Google Earth™ and a grid download. Most anomalies also have downloads of inversion models, and some have downloads of magnetization estimates made by non-inversion methods (such as Helbig analysis). Figure 16 shows the pop-up window on selecting one of the anomalies in the 'anomaly' setting, which displays the anomaly parameters stored in the database. Figure 17 shows the pop-up window in 'image' setting, which displays the anomaly image. Figure 18 shows a download available for several of the more extensively studied anomalies. This download is a Discover PA™ template (which can be loaded into a freely available viewer) displaying TMI and total gradient images, flight-line measured and model-computed channels, source models in 3D display, and tabulated model details. It is hoped that database users with little experience or knowledge of remanent magnetizations can still find the database useful through being able to cross-reference anomaly patterns with any nearby anomalies they may be investigating, so as to recognize possible complications arising from remanent magnetization (e.g. in the siting of boreholes).

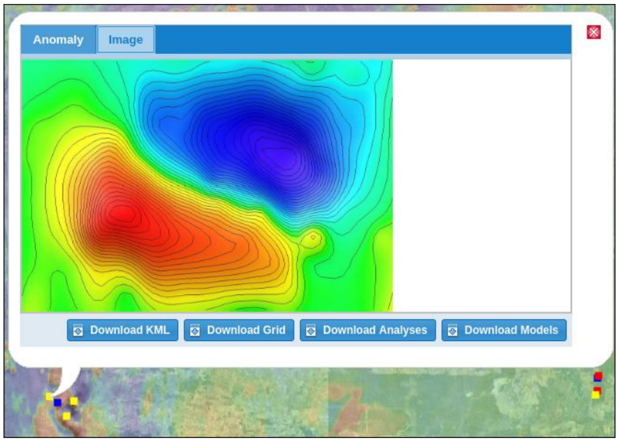
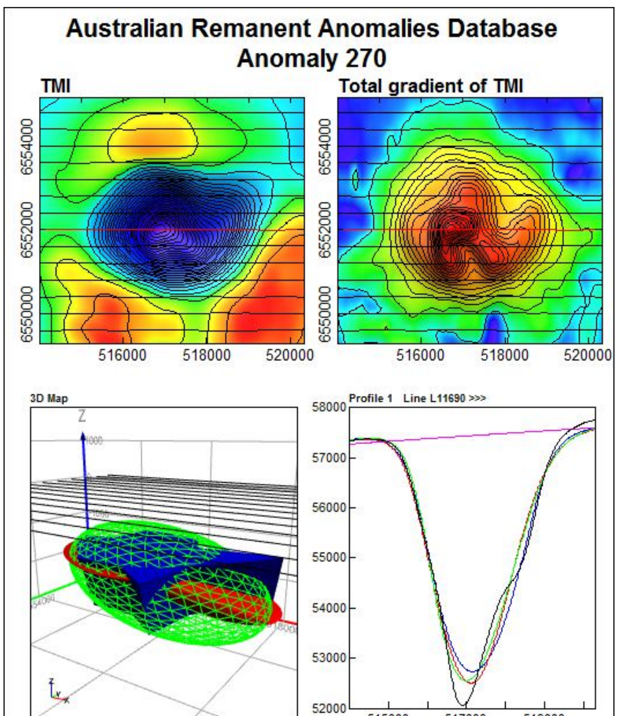


Figure 17 Anomaly image display with download buttons



model	Amp/m	Declination	Inclination	volume m^3	moment Amp.m^2
model_287	17.04	354.2	52	6.78 E09	1.15 E11
model_288	58.28	354	49.6	2.03 E09	1.18 E11
model_289	30.6	346.4	51.6	3.76 E09	1.15 E11

Figure 18 Example download template

A further intended use of the database as more anomalies are added is to provide correlation between sources of anomalies with similar magnetization direction, ideally including magnetizations of known ages. One of the challenges in correlating magnetizations derived from analysis of magnetic field anomalies is that even with identical remanent magnetization directions, the resultant magnetizations may differ because of variation in the Koengsberger ratio. Figure 19 demonstrates the range of magnetization directions consistent with an estimated resultant magnetization, with the remanence directions for different Koenigsberger ratios strung out along a segment of a great circle. A second complication in correlating magnetization directions across large areas is spatial variation in the geomagnetic field direction. This effect can be reduced by processing the data using a simple geomagnetic dipole model to transform magnetization direction to the equivalent apparent position of the magnetic pole. This transformation can be applied to the recovered resultant magnetization directions on the assumption that the magnetization is dominated by remanence, or can more correctly be applied to each possible remanent magnetization direction (as illustrated in Figure 19). Cordani and Shukowsky (2009) proposed a process of selecting those magnetization directions which give poles consistent with established apparent polar wander paths (which they term VPMAs – virtual poles from magnetic anomalies).

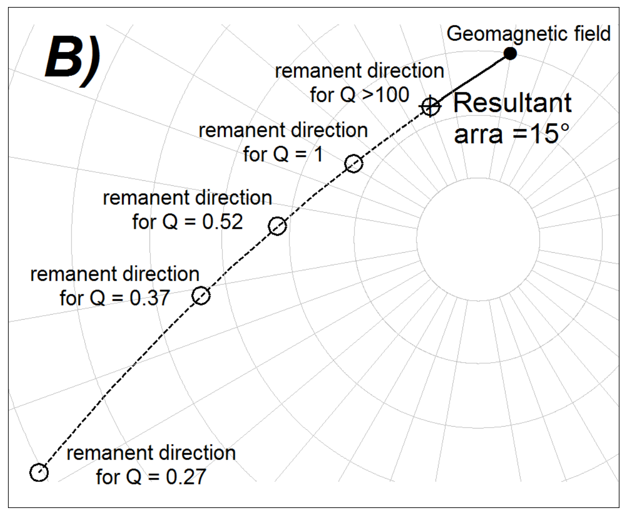


Figure 19 Possible remanent magnetization directions consistent with a recovered estimate of resultant magnetization.

The Australian Remanent Anomalies Database is currently accessible through the AuScope portal (http://portal.auscope.org/portal/gmap.html) but there are plans to transfer it to the AusGin portal (http://www.geoscience.gov.au/). A CSIRO link to the database is maintained at: https://confluence.csiro.au/display/cmfr/Home.

THE ROLE OF AUTOMATED ANALYSIS IN MAPPING REGIONAL DISTRIBUTIONS OF MAGNETIZATION

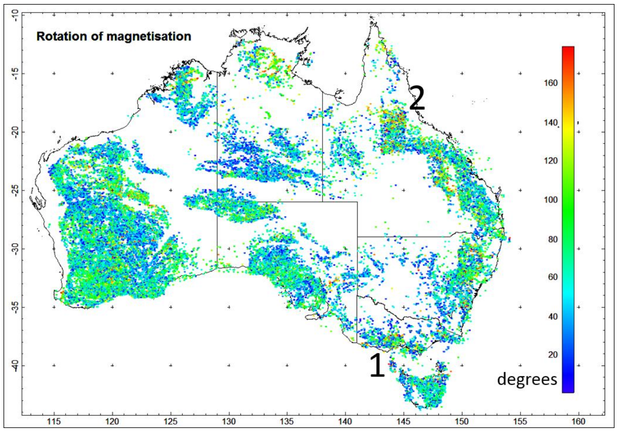


Figure 19 Distribution of automated magnetization estimates color coded for ARRA.

Individual hand-selected anomalies as used to populate ARAD only deliver a sparse sampling of magnetization. These high-quality results provide the best-estimates of the direction of magnetization. A much higher density of solutions (even if of lower individual validity) is required to map the extent of those magnetizations. For this purpose an automated search process is applicable. Figure 19 plots the distribution of almost 40,000 solutions derived in the first national-scale automated scan of magnetization directions from a moving window analysis of magnetic field data using the algorithm of Hillan et al.(2013). The symbols are color coded for apparent resultant rotation angle ARRA. Few of the individual results are well justified, but the population of results detects areas within which there is substantial expression of magnetizations oblique to the local geomagnetic field direction. It detects for instance, mixed polarity magnetizations in Tertiary volcanics in southern Victoria (Area 1 in Figure 19) and the substantial reverse polarity magnetization of the Permo-Carboniferous Newcastle Range Volcanics in the Georgetown region of Queensland (Area 2 in Figure 19). With experience gained from this initial proof-of-concept test a new search algorithm is under development to upgrade the reliability of individual solutions and to add an associated quality factor which can then be used to filter selection of solutions for specific objectives (for instance, a selection of high reliability solutions would be expected to most closely match the same anomalies selected for focused inversion in ARAD).

CONCLUSIONS

Regional aeromagnetic data over Devon and Cornwall maps a substantial swathe of reverse remanent magnetization to the north of Bodmin Moor and Dartmoor. Previous palaeomagnetic studies have measured this magnetization and shown it to be carried by pyrrhotite. The magnetic field and palaeomagnetic studies combine well to provide more information than could have been obtained by the two studies independantly. The magnetic field data also reveal distributed, discrete magnetizations to the south and west of the granites that are consistent with the palaeomagnetic measurements. The distributions of mines reported to have produced copper and lead show a general correlation with both the swathe of negative magnetization to the north of the granites and the distributed magnetizations to the south, confirming the value of the magnetic field data for any future mineral exploration in the area. The remanent magnetizations carried by pyrrhotite suggest a new exploration model for this area based on similar magnetizations in the Cobar Basin of New South Wales.

I have described the Australian Remanent Anomalies Database which has been developed to record and make available information about magnetizations recovered from magnetic field interpretation. This database has been developed to map remanent-dominated magnetizations, which is of particular value where the rocks carrying these magnetizations are buried beneath cover. The database is presently populated with over 300 solutions from inversion of hand-selected well-defined anomalies due mostly to compact magnetizations. On-going research aims to augment these high fidelity solutions with a much higher density of (lower reliability) solutions generated by an automated search algorithm. A promising candidate algorithm is based on initial transformation of the TMI data to vertical component (B_z) data and its vertical derivative (B_{zz}). If a search algorithm can be developed capable of detecting and resolving magnetizations with ARRA <15° then automated analysis will become a powerful method of mapping magnetization extents at a regional scale.

ACKNOWLEDGEMENTS

The magnetic field data for Bodmin Moor and Dartmoor study was downloaded from the British Geological Survey - NERC Tellus SW site (www.tellusgb.ac.uk). The gravity study is based upon the British Geological Survey land gravity data (http://www.bgs.ac.uk/data/gravAndMag.html) by permission of the British Geological Survey. I would like to thank Mike Gill, recorder of the Northern Mine Research Society (http://http//www.nmrs.org.uk/) for supply of the Devon and Cornwall mine location database. The TMI compilation imaged in Figure 11 and the Crustal Elements Map in Figures 12 and 13 are provided by Geoscience Australia. Peter Warren and Lingbo Jiang generated the ARAD screen captures, and are upgrading the database resources. Phil Schmidt, Peter Milligan and Robert Musgrave advised and supported development of the database. The automated solutions shown in Figure 19 were generated by Dean Hillan.

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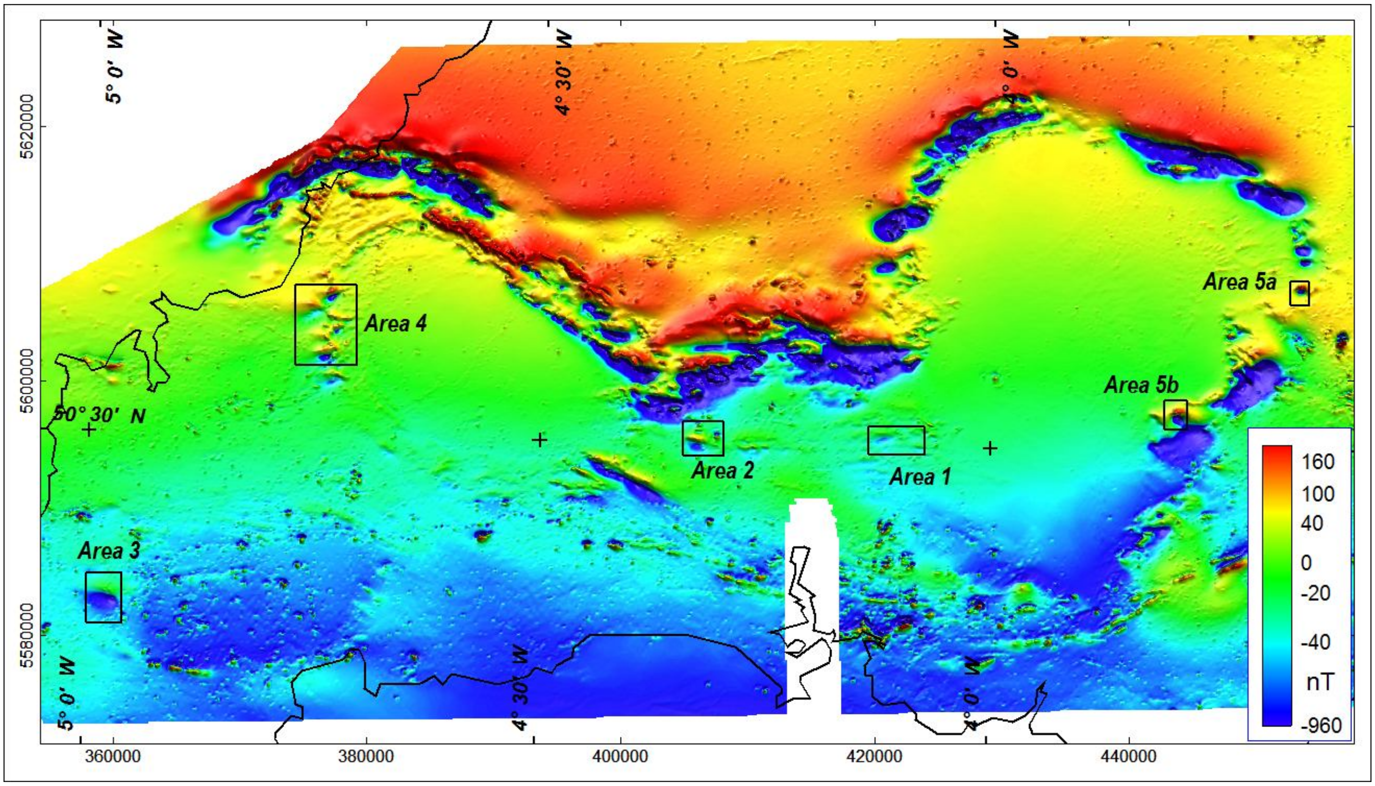

Figure 3 TMI image from the Tellus SW survey. Boxes show location of discrete anomalies of unusual pattern.

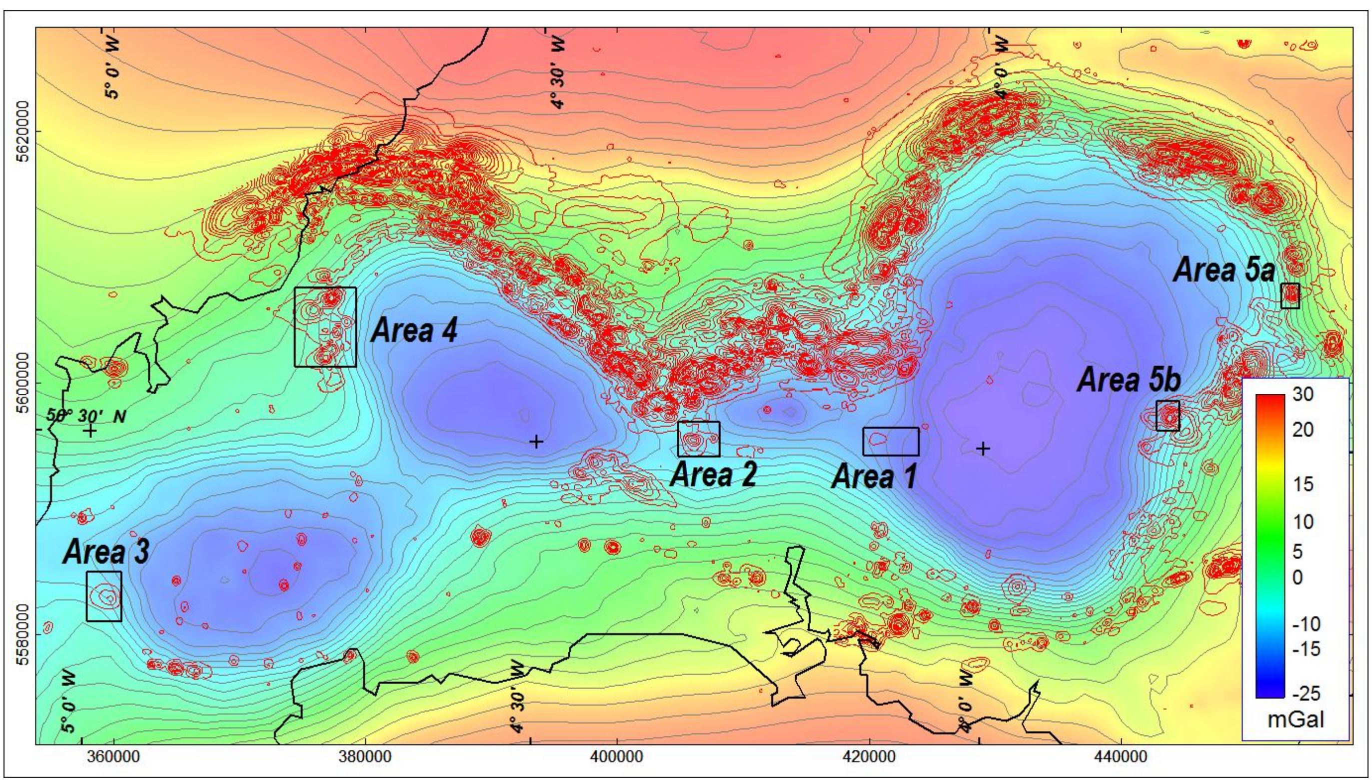

Figure 5 Bouguer gravity image with (red) contours of total gradient of TMI.

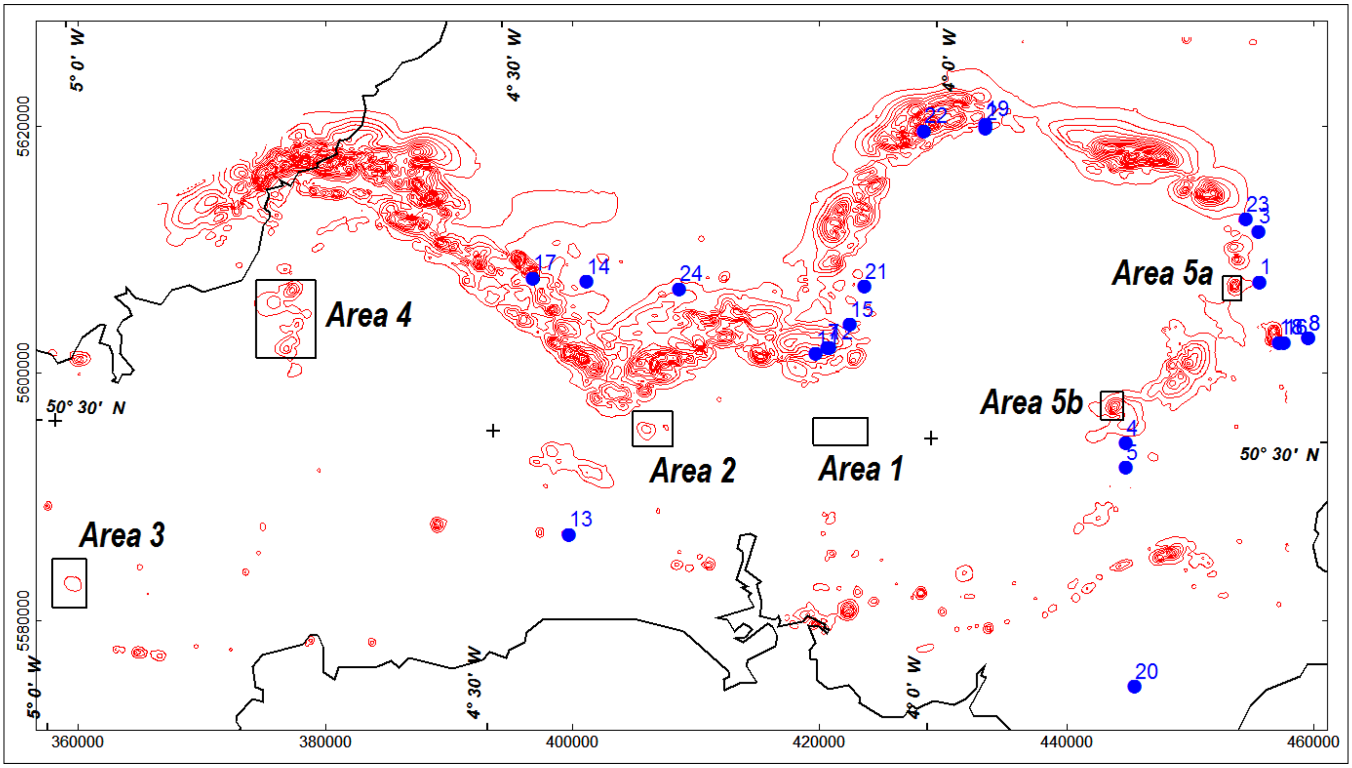

Figure 6 Contours of total gradient of TMI with palaeomagnetic sites from Creer's 1966 study (blue circles).

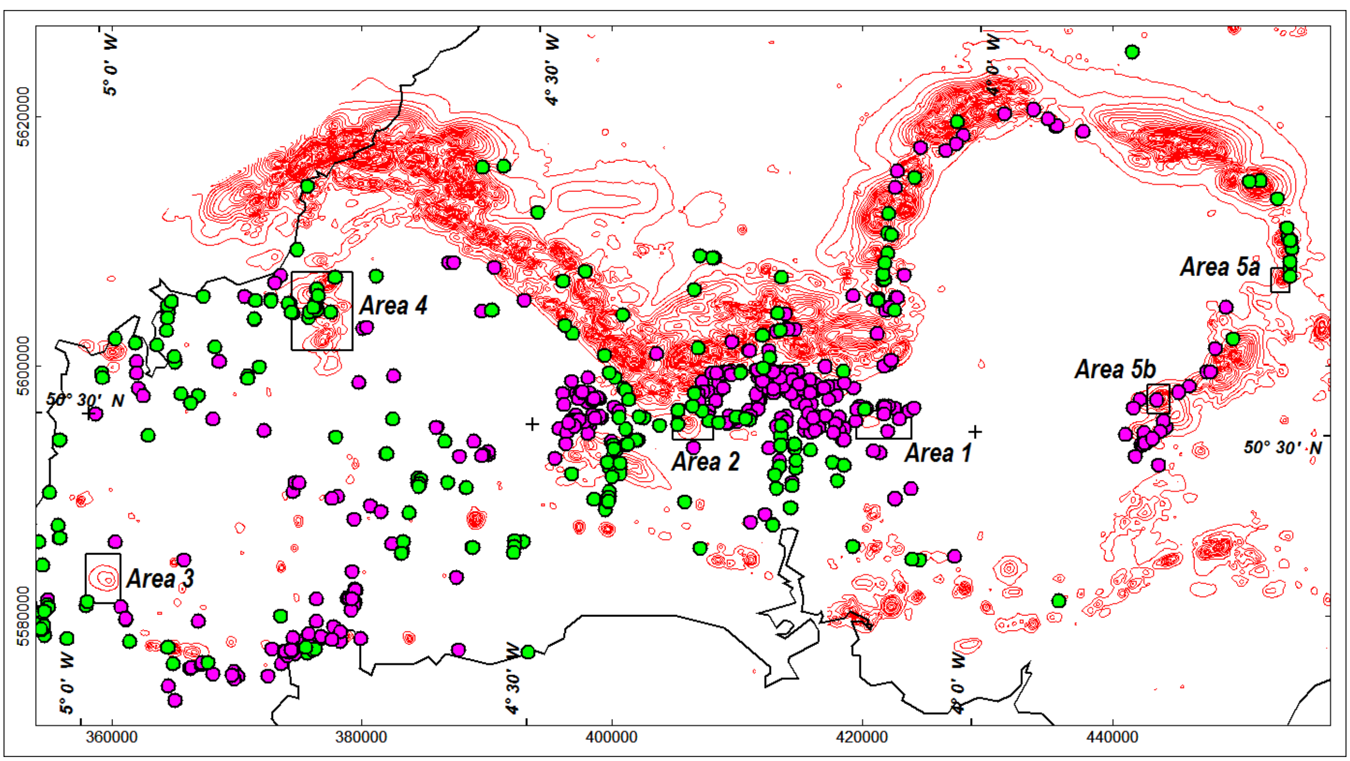

Figure 10 Total Gradient of TMI contours with mines that produced lead (green circles) and copper (purple circles)