

# The potential of remote remanence estimation (RRE) for kimberlite exploration – A case history from the Thomson Fold Belt

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## SUMMARY

In practical exploration, magnetic remanence has been largely ignored in airborne magnetic surveys apart from the use of the analytic signal, yet there is a wealth of geological information available if we can obtain quantitative estimates. In recent years new techniques have emerged to directly compute the resultant magnetization vector direction with a precision that exceeds visual inspection and the quantitative measure of the apparent resultant rotation angle (ARRA) is a useful first order predictor for magnetic remanence. This information can be used in a geological interpretation sense and to improve target geometry estimation during magnetic inversion.

Pratt, McKenzie and White (2012) showed how this method could be combined with polar wander data to estimate the direction of magnetic remanence from which the Koenigsberger ratio (Q), magnetic susceptibility and intrusion age could be derived.

I have applied the RRE method to a systematic study of a large number of intrusive pipes in the Thomson Orogen, NSW and evaluated the results with respect to the new geological information, spatial distribution and underlying uncertainties of the new measures. These results are important to diamond explorers that may consider using this new method to modify target priorities for follow-up drilling.

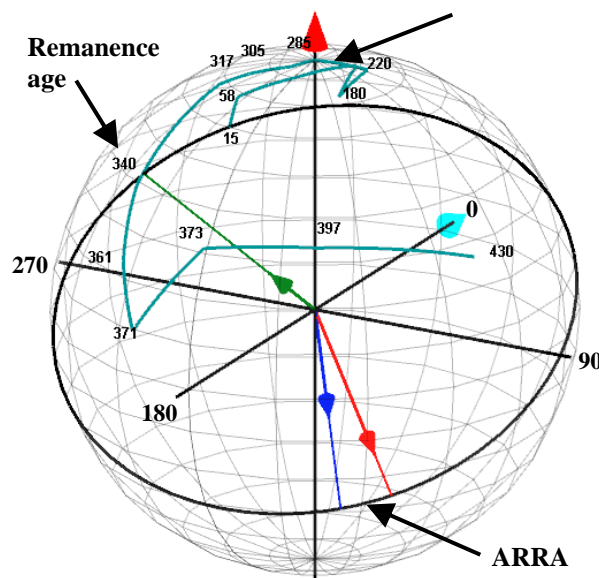
**Key words:** magnetic, remanence, kimberlite, intrusion, inversion.

## INTRODUCTION

The remote remanence estimation method (RRE) was developed by Pratt, McKenzie and White (2012) and validated on theoretical models and the well documented Black Hill Norite in South Australia (Rajagopalan et al, 1995). They applied the method to a limited range of intrusive pipe targets in the Thomson Orogen (Glen et al, 2010) as a demonstration of the capabilities of the method. This research applies the RRE method to approximately 100 intrusive pipes in the southern part of the Thomson Orogen, an area that provides relatively quiet background magnetic fields and easy identification of the target anomalies.

RRE is based upon establishing the direction of the resultant magnetization vector direction and amplitude using geophysical inversion of a geological model for a given target

model. The resultant magnetization vector, induced magnetic field vector and remanent magnetization vector all lie on the same magnetization plane. The transformed apparent polar wander path (TAPWP) for the survey area intersects this magnetization plane in one or more places, thus establishing possible ages of the target (Figure 1). Where more than one possibility exist, geological principles can be applied to determine the most probable age as well as the remanent magnetization vector direction. Given that we know the resultant magnetization vector amplitude and direction, we can then determine the Koenigsberger ratio (Q) and a corrected magnetic susceptibility.



**Figure 1** Image capture of the application used to estimate the remanence age by intersection of the transformed apparent polar wander path (TAPWP) with the plane of magnetization identified by the great circle through the resultant magnetization (blue), induced magnetization (red) and remanent magnetization (green) vectors.

Cordani and Shukowsky (2009) presented a method for establishing the direction of magnetic remanence in a target using the VPMA method. In their work they determine the resultant magnetization direction via iterative reduction to the pole until a symmetric anomaly is produced for the target. They also find the intersection of the polar wander curve with the pole trace of the magnetization plane to find the age of the target. By iterating through a sequence of Q values using vector subtraction, they can also determine the Koenigsberger ratio for their target. The advantage of this method is that no modelling or inversion is required for the analysis and it suits other analytic techniques such as the magnetic moment

method (Foss & McKenzie, (2011), McKenzie, Foss & Hillan, (2012)). It is noted that performing the analysis in “pole-space” is equivalent to using “direction-space” (Pratt et al., 2012) since there is a one-to-one mapping between directions and poles.

The RRE method allows you to estimate a corrected magnetic susceptibility in addition to the age and Q values, but also offers more insights into the geology of the deposit through consideration of the regional magnetic field and interference from other geological sources. Its application to 100 Thomson Orogen intrusions provided the opportunity to look at the sensitivity of the method, how to use clustering of ages to help reduce ambiguity in age determinations and evaluate the method as a possible tool for kimberlite discrimination.

**METHOD**

The study covers an area of approximately 400 x 100 kilometres of the NSW section of the Thomson Orogen (Figure 2).

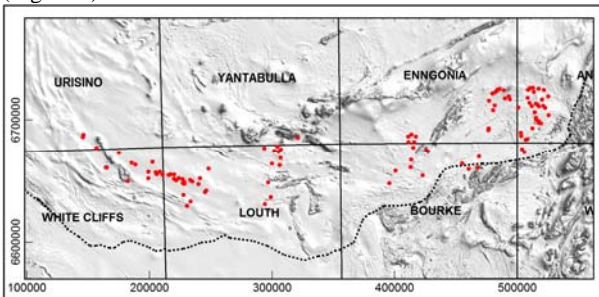


Figure 2 Locality map of the study area showing the 1:250,000 scale map sheet boundaries, targeted intrusive pipes (red) and southern Thomson Orogen boundary (dashed) over a shaded image of the reduced to pole magnetic grid.

The flight line data were acquired by the NSW Geological Survey and downloaded from the Geoscience Australia GADDS web site ([www.geoscience.gov.au](http://www.geoscience.gov.au)). The relevant survey characteristics are summarised in Table 1. The surveys were flown at either 60 or 80 metre terrain clearance.

Survey	Year	Spacing	Direction
Eromanga Thomson	2006	250	NS
Bourke	1995	250	EW
Brewarrina	1996	250	EW
Paka Tank	2001	400	EW
Surat Area D	1995	400	EW

Table 1 Survey used in the project including the year of acquisition, line spacing and line direction.

The author has a natural preference for north-south lines, but only the Eromanga-Thomson survey in the western part of the study area satisfied this criterion. In theory this should not matter if the line data is well levelled and there is adequate multi-line coverage of the pipe anomaly. In reality, the inversion statistics were generally worse for the north-south survey than the others, but this is in part associated with lower magnetic anomaly amplitudes. The Brewarrina and Surat-D surveys had only the radar altimeter data which was combined with regional terrain data to define the elevation of the sensor.

The NSW state 50 metre grid of reduced to pole magnetic (RTP) data was used as the primary data for selection of 110

suitable intrusive pipe targets of which 100 were analysed in detail. The targets were selected from a relatively quiet, 400km wide magnetic zone within the Thomson Orogen, broadly described as undifferentiated metasediments (Glen et al, 2010). The intrusions are covered by younger Eromanga Basin sediments of Jurassic to Lower Cretaceous age.

The flight line and grid data for each intrusion were isolated from the master dataset to simplify estimation of the regional magnetic field. An example is shown in Figure 3 with a series of cross sections plus a map of the line data and image of the RTP grid.

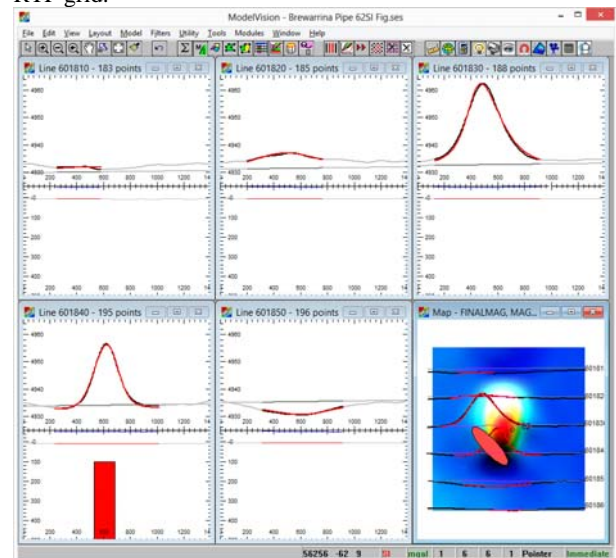


Figure 3 An example inversion result with a series of cross-section plus a map showing stacked profiles and an image of the RTP grid subset. Above each cross section, profiles show the original total magnetic field data (black), regional magnetic field (grey) and inverted model response for an elliptic pipe (red). The pseudocolour image of the RTP grid has a linear stretch that does not distort the gradients.

Encom ModelVision was used to perform the inversions using both the constrained and joint inversion methods each using independent selections of the active data regions. Changes in the RMS values and resultant magnetization directions were used to assist with quality assessment. The magnetic susceptibility was fixed at 0.01 SI units and the resultant magnetization amplitude and direction were inverted as free parameters. The depth extent was fixed at 1,000 metres to reduce the number of free parameters and maintain consistency. The inversions are interactive and the whole process takes approximately 10 minutes per target.

As the project progressed through a range of targets and background magnetic conditions, it became clear that the precision of removal of the regional magnetic field was very important. It also became apparent that it was important to take a larger sample of the data than was required for normal depth modelling to ensure the tails of the anomaly were included in the inversion. Some pipes were close enough to be modelled in pairs which helped to eliminate the influence of the overlapping anomalies. A few targets that were very close proved to be unreliable due to the degree of overlap and lack of adequate coverage and were eliminated from the target list. The data density was generally adequate if the major anomalies were visible on at least two survey lines.

The RRE method was applied to all the intrusions where an inversion result was deemed suitable. Where the ARRA was less than about 3 degrees it became impractical to produce an estimate of the age due to the limited separation of the induced and resultant magnetization vectors. Those solutions where the ARRA was less than 5 degrees were expected to be unreliable, but kept for the purpose of the analysis.

## RESULTS

The interpreted depth to the top of the pipes range from near surface to over 400 metres with an average depth of 185 metres. The spatial distribution of depth values is shown in Figure 5.

The amplitude of the resultant magnetization vector is a useful measure to help discriminate between the intrusions since we cannot resolve magnetic susceptibility directly from the inversion. A map of the resultant magnetization amplitudes is shown in Figure 6. The eastern group of intrusions have characteristically higher magnetizations than those to the west. Four zones have been identified based upon local pipe clusters.

The ratio of the maximum horizontal dimension of the target to the depth below the sensor must be greater than 1.0 to properly resolve the pipe true properties. Where this ratio is less than 1.0, then the magnetization estimate is likely to be higher than the true values.

A cross-plot of the declination and inclination of the resultant magnetization vector is a useful way to look for clustering in the inversion results. Figure 4 shows how the results cluster about the induced field vector which is shown by the black cross. The clustering has the following primary characteristics:

1. Small ARRA deviations clustering to the south west
2. Intermediate ARRA deviations to the east and west
3. Reversely magnetized (inclination >0 degrees)

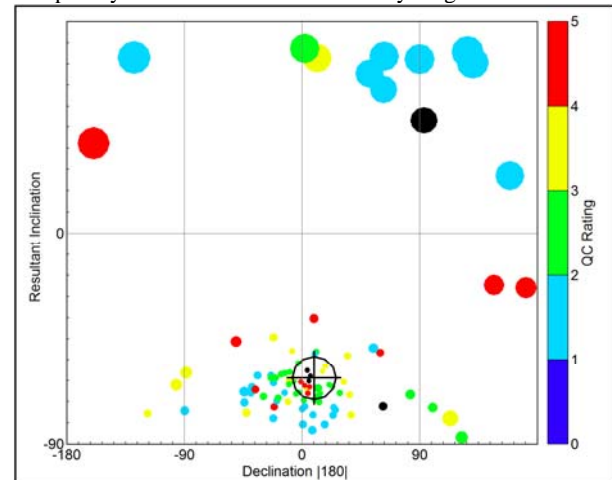
The type 1 clustering to the south west of the IGRF vector was not expected. A scattering of solutions about the IGRF vector was expected due to the secular variation of the poles and the expected rapid cooling time of the pipes. Possibly the south-west bias to steeper inclinations could reflect the direction of movement of the pole during the period of emplacement of the intrusions.

Type 2 clusters often have higher RMS inversion errors and all of them were revisited in an attempt to explain the large ARRA values. Some of the solutions were rejected from the final analysis based upon the regional sensitivity or level of local interference.

Type 3 anomalies are reversely magnetized with a large scatter in declination but inclinations that are generally within 15 degrees of the reversed IGRF field, but with a bias to steeper inclinations.

A quality estimator was introduced during the interpretation to help understand the significance of individual results in the context of a large number of individual intrusions. The QC rating ranges in value from 1 to 5 with one being the best quality and five the worst. The values are assigned based on

an assessment of detrimental factors such as low anomaly amplitude, inversion RMS, small ARRA values, regional complexity and interference from nearby magnetic sources.



**Figure 4** A cross-plot of the resultant magnetization vector direction as a function of inclination and declination and colour coded by the QC rating from the interpretation stage. The size of the symbol is based upon the total departure angle (ARRA) of the remanent vector from the induced field vector direction (black circle and + symbol).

Figure 7 shows the distribution of the apparent resultant rotation angle (ARRA) derived from the inversions where the symbol size and colour are modulated by the ARRA value. There was some expectation that the ARRA values would group in distinct geological zones and thus provide diagnostic geological information that could help differentiate intrusions. Unfortunately, the ARRA distribution appears to be similar in each of the four zones identified during the interpretation (Figure 6).

The remanent magnetization direction, corrected magnetic susceptibility, Koenigsberger ratio (Q) and intrusion age were then estimated by determining the intersection of the transformed apparent polar wander path (TAPWP) with the magnetization plane. The intrusion ages ranged from 58 My to 430 My with the spatial distribution shown in Figure 8.

The primary group ranging in colour from yellow to orange correspond to the Upper Devonian to Carboniferous period. A few of the solutions (red) fall into the Middle to Upper Devonian period. This group is present across all four zones, but dominant in Zones 1 to 3. Note that Zones 1 and 2 also have four green solutions, three of which are reversely magnetized and correspond to the Triassic period. Zone 4 is distinctly different with a significant number of blue and cyan solutions corresponding to the Jurassic period. Only one cyan solution is visible in Zone 3 and none are present in Zones 1 and 2.

It is important to note the ambiguity in selecting ages from the TAPWP curves. In Zones 1, 2 and 3, there was often a choice between a Triassic age solution and one of Carboniferous age, but often there was only one solution and that was generally of Carboniferous age. As a result, the ambiguous solutions were reclassified to Carboniferous or Late Devonian. No geological information was available to help with this classification, but this blind study was designed to test the merits of the method for age dating and further deductions that could be applied to the geological evolution of the region. The

four green solutions in Zones 1 and 2 correspond to the Triassic and there was generally the option of a younger Cretaceous solution available.

Zone 4 has a mixture of intrusions from the Jurassic and Carboniferous periods. It is situated at the south east corner of the Thomson Orogen where its shared margin with the Lachlan Orogen turns north. This is a complex structural region and the age dating provides a way of differentiating intrusion sources. In diamond exploration this could be significant if one age group is more prospective for kimberlites.

Figures 9 and 10 show the distribution of magnetic susceptibilities corrected for remanence and the calculated Koenigsberger ratios (Q). Both these maps show that Zone 4 is unique but there is further differentiation of the intrusion characteristics that could be applied to diamond exploration.

It became apparent during this project that the method could be applied even when the ARRA values were as low as 5 degrees because the intersection between the translated apparent polar wander path (TAPWP) and the plane of magnetization limited the range of possibilities. At steep field inclinations, the resultant magnetization declination becomes the most important parameter. While low amplitude ARRA values are inherently noisy, the natural age binning process associated with the RRE method made it practical to work with noisy solutions.

### CONCLUSIONS

The remote remanence estimation (RRE) method provides data on the age, Koenigsberger ratio (Q) and corrected magnetic susceptibility in addition to the depth and position of igneous intrusive pipes. This new information can help to differentiate targets for kimberlite exploration and as drilling information becomes available reduce the ambiguity in age determinations. While the intrusion age and Q can be estimated from other methods such as VPMA, geophysical inversion of the target also estimates the amplitude of the resultant magnetization vector. This additional information provides the true amplitude of the magnetic remanence and induced field vectors enabling a calculation of a corrected magnetic susceptibility value.

Interactive geophysical inversion also provides the opportunity to isolate the complete target, properly evaluate the regional magnetic field, assess interference from nearby magnetic sources, estimate the local noise levels and judge the quality of the final results.

The resultant magnetization vector is a second order parameter that is sensitive to interference from surrounding magnetic sources and is especially sensitive to inadequate removal of the local regional magnetic field and adjacent sources. Unless the geological problem is properly constrained, the resultant magnetization estimates will be

blurred by the overlapping geological influences and of little or no use for RRE.

More work needs to be done in assessing the impact of errors in regional separation, local interference estimation, development of a more detailed APWP for different geological terranes and methodologies for clustering or binning of target age estimates. If an incorrect age is used, then errors will result in the estimation of Q and the corrected magnetic susceptibility.

RRE is a new method for explorers that can be applied with conventional magnetic modelling tools and available paleomagnetic data. It solves the age old problem of being able to remotely estimate the magnetic remanence properties, corrected magnetic susceptibility and as a by-product estimates the age of the target.

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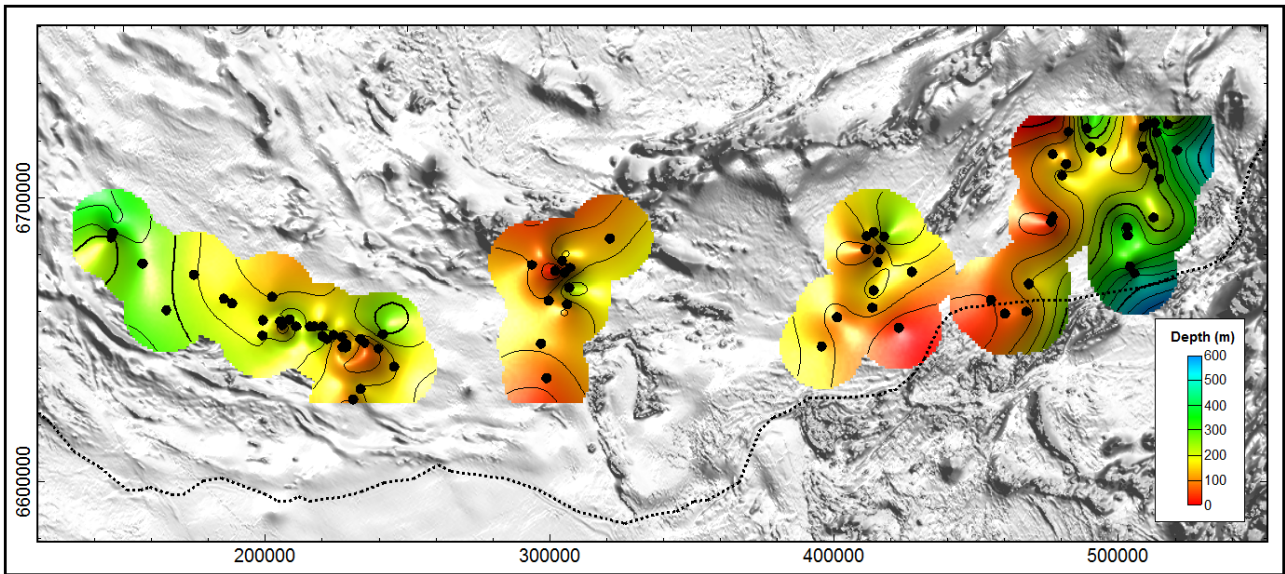


Figure 5. The depth below ground of the intrusive pipes is shown as a pseudocolour image with 50 metre contours. The pipe locations are shown as solid black circles.

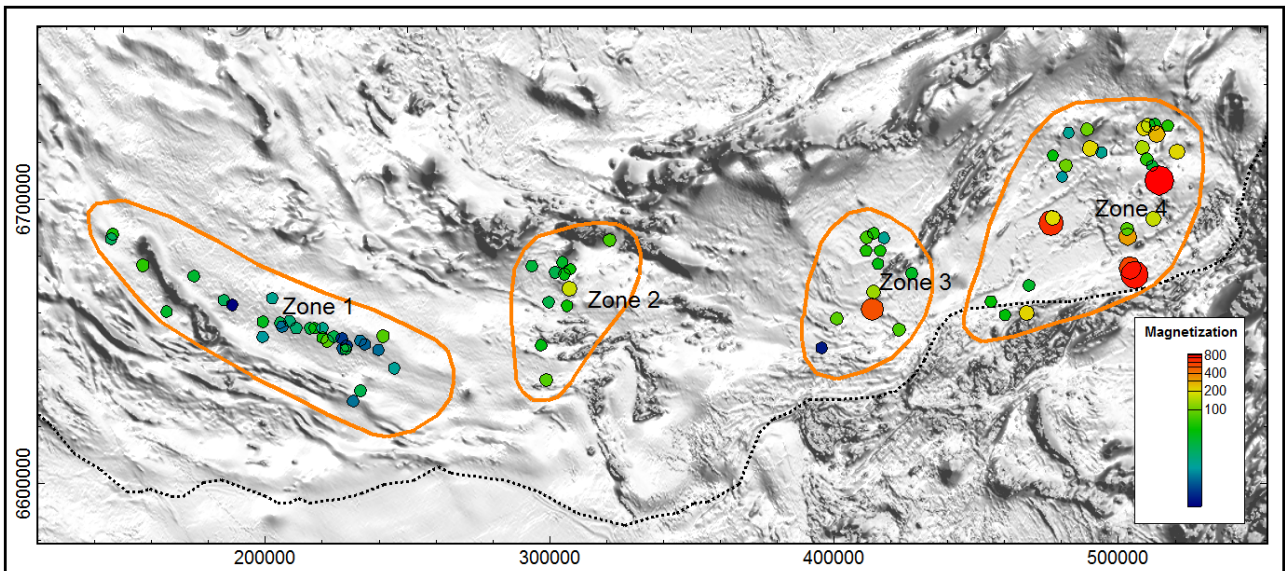


Figure 6. The distribution of resultant magnetization vector amplitudes modulated by symbol size and colour. A logarithmic scale is used for the colour axis. The intrusions are subdivided into four zones based only on their spatial concentrations.

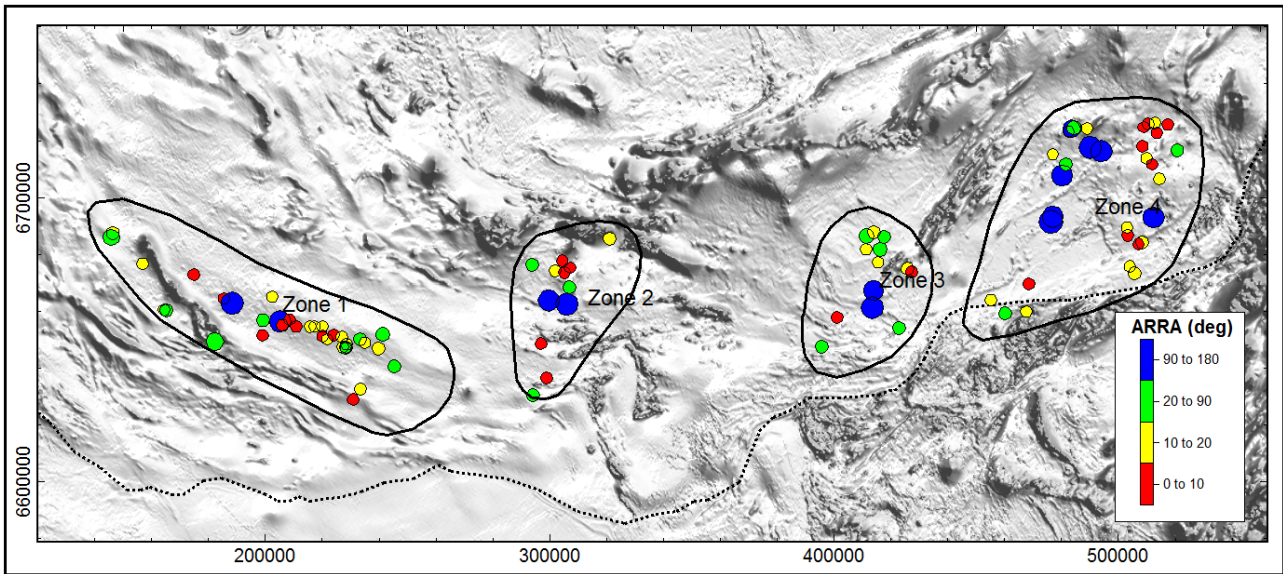


Figure 7. The distribution of the apparent resultant rotation angle (ARRA) modulated by symbol size and colour. Blue circles represent reversely magnetized pipes while red, yellow and green are normally magnetized.

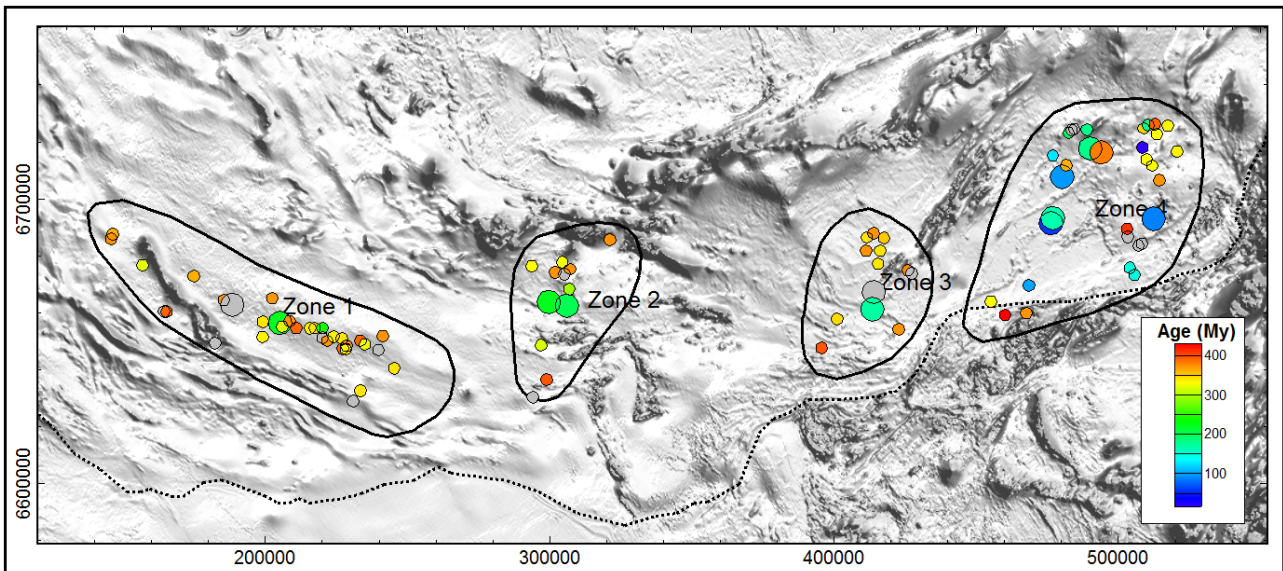


Figure 8. The distribution of intrusion ages modulated by symbol colour but including only higher quality solutions for QC ratings 1 to 3. Large symbols indicate that the anomaly is reversely magnetized. Where the QC class is higher than 3 it is shown as a grey circle. Symbols from yellow to red cover the late Devonian and Carboniferous periods while light blue is the Jurassic period. There are four green symbols that would correspond approximately with the Triassic.

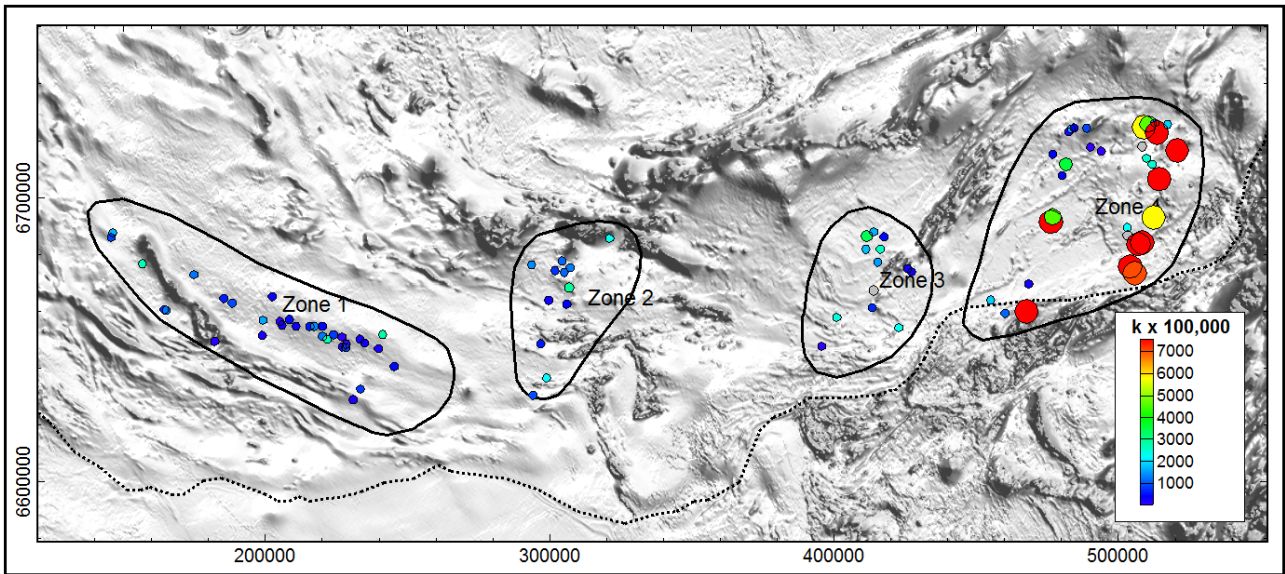


Figure 9. The distribution of magnetic susceptibility corrected for remanence. The magnetic susceptibility ( $SI \times 10^5$ ) is shown as symbols modulated by colour and size using a histogram stretch.

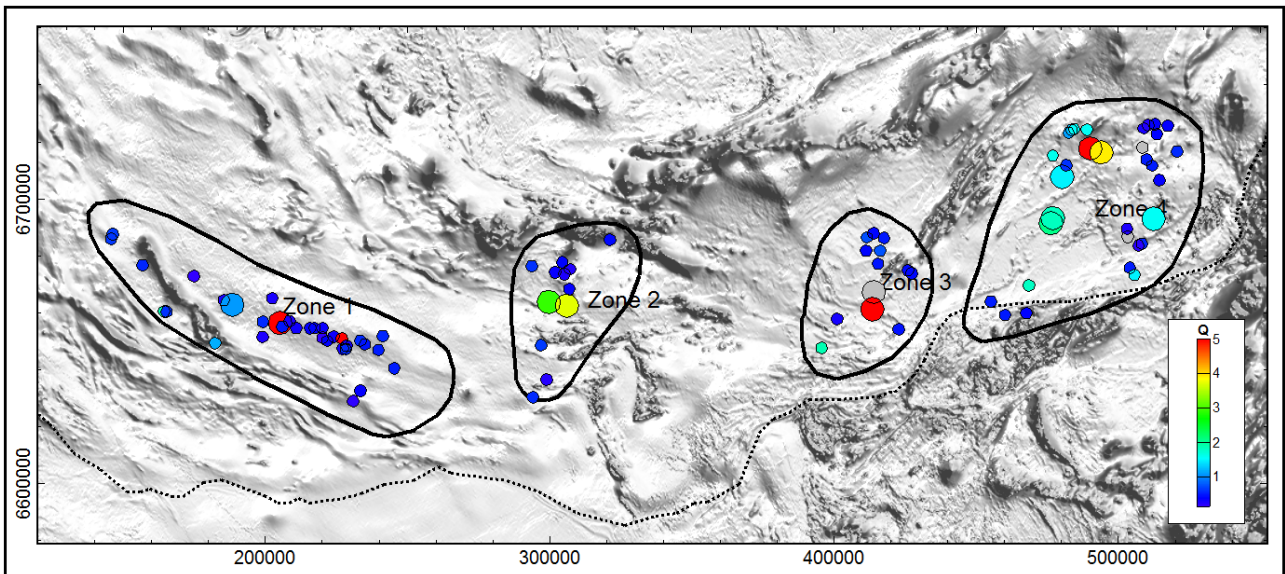


Figure 10. The distribution of the Koenigsberger ratio ( $Q$ ) after estimation of the intrusion age. The large circles are reversely magnetized.