

An airborne gravity gradiometer survey of Broken Hill

Richard Lane ¹, Peter Milligan ¹ and Dave Robson ²

¹ pmd**CRC*, Geoscience Australia, GPO Box 378, Canberra, ACT 2601

² NSW DMR, 23-57 Christie St, St Leonards, NSW 2065

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**MINERAL
RESOURCES
NEW SOUTH WALES**

An airborne gravity gradiometer survey of Broken Hill

Richard Lane & Peter Milligan (*pmd*CRC*)
Dave Robson (NSW DMR)

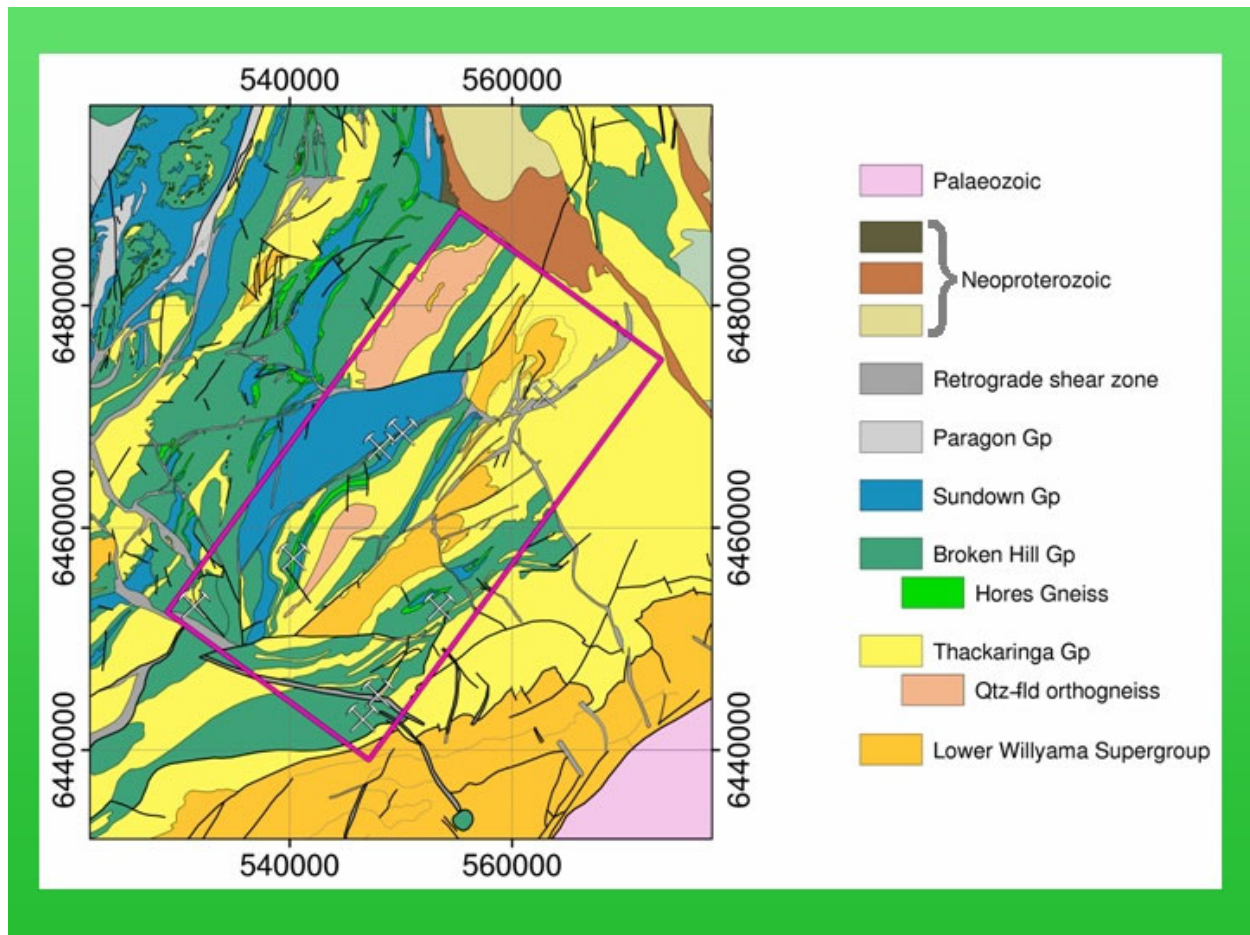
predictive mineral discovery

Geoscience Australia, The University of Melbourne, MONASH, The University of Western Australia, JCU, CSIRO, AMIRA INTERNATIONAL

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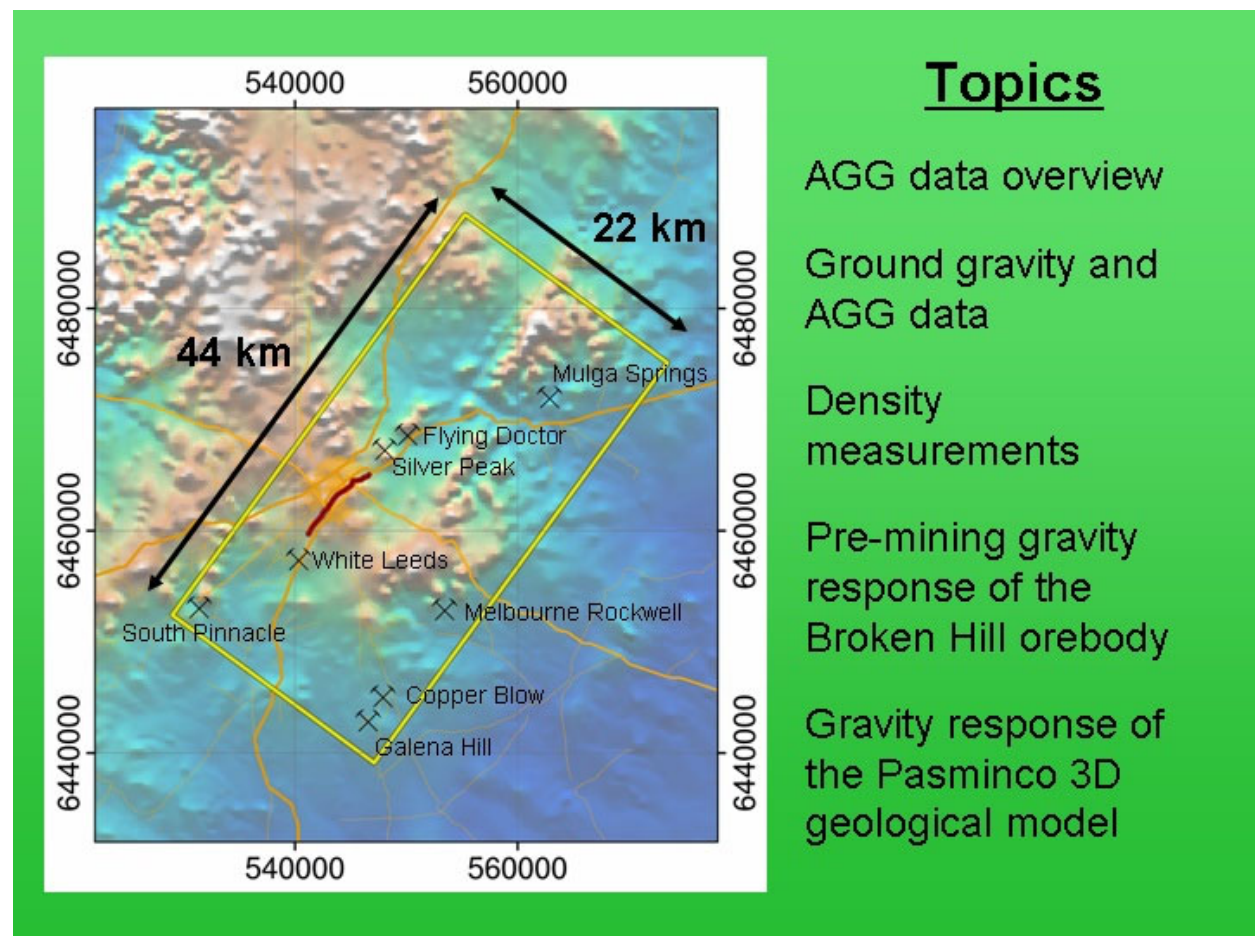
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Slide 1. Introduction



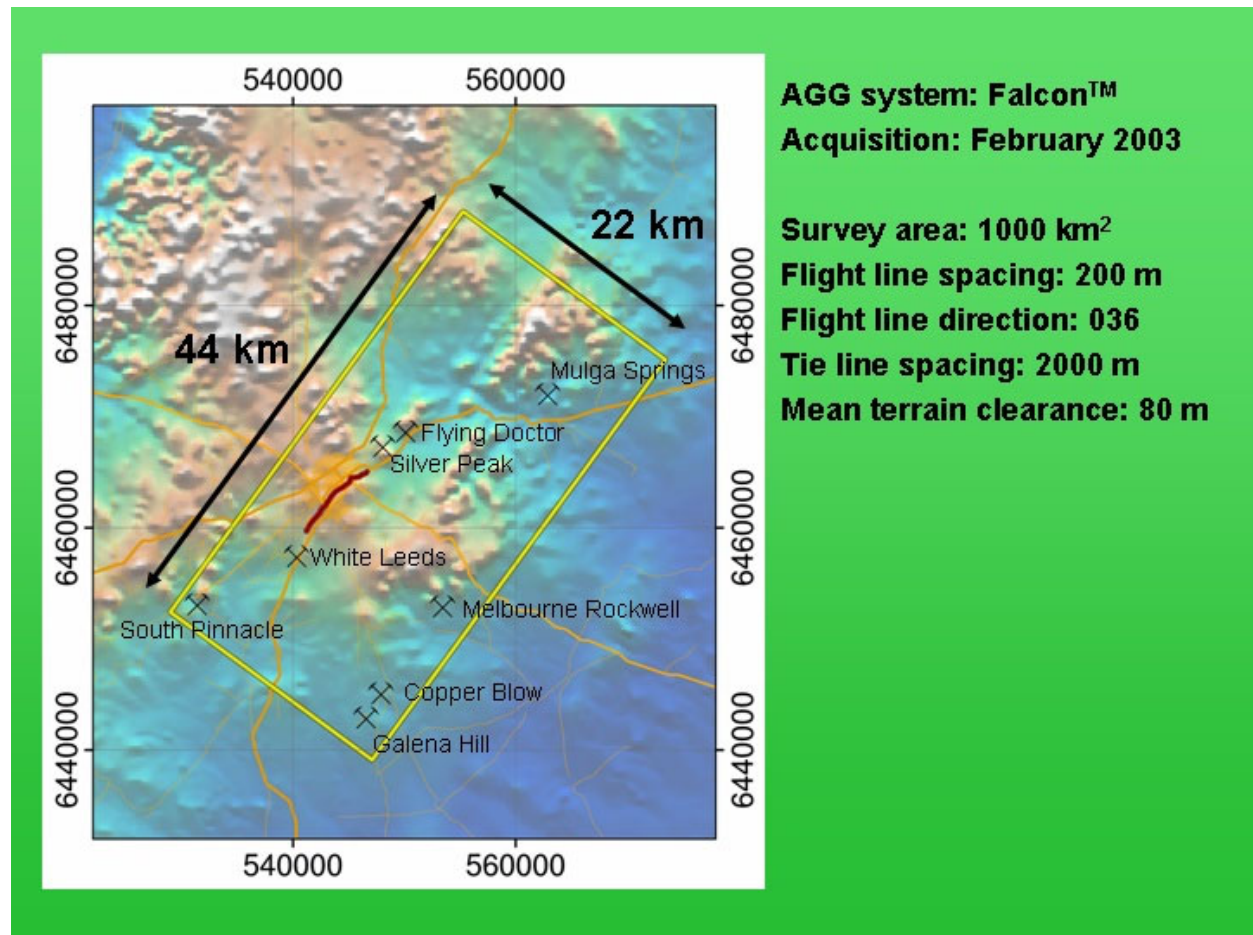
An airborne gravity gradiometer or AGG survey has been flown over the Broken Hill region. The survey involved the NSW Department of Mineral Resources, with pmd*CRC as principal research project sponsor and Geoscience Australia as additional sponsor. This is the first time that an AGG survey has been carried out for Australian government organisations, and the first time that AGG data have been acquired specifically for release to the public.

Slide 2. Introduction (cont.)



Most of the work on this project so far has been in understanding what it is that the system delivers. Hence, I will give an overview of the AGG survey and data products rather than present a detailed interpretation. Ground gravity data will be compared with the AGG data. Density measurements will be examined to determine which lithologies might give rise to discrete gravity anomalies. A simple model of the Broken Hill orebody will be used to see what the gravity response would have been prior to mining activity. Finally, some of the future research activities will be outlined, including plans to evaluate the Pasminco 3D geological model for consistency with the observed gravity data.

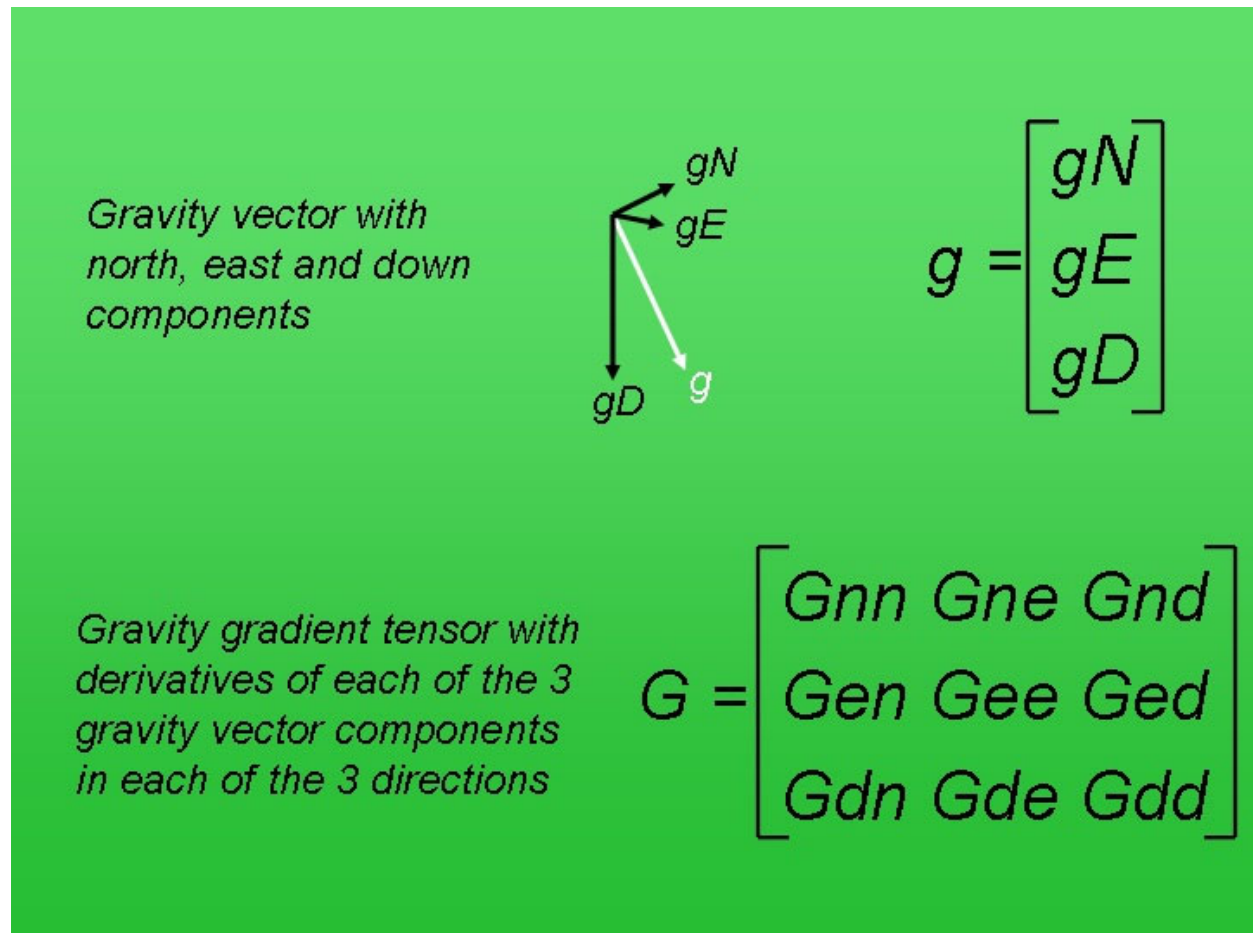
Slide 3. Survey specifications



The acquisition phase of a Falcon™ AGG survey is similar to that of a mag-spec survey. Flight lines were spaced 200m apart, with tie lines spaced at 2000m intervals used for levelling of the data. A limited amount of QC was carried out on site, with the majority of the processing being carried out by BHPBilliton in Melbourne.

Data quality is affected by turbulence, so February was not the ideal time to be flying. Acquisition was limited to a few hours immediately after dawn before turbulence exceeded a preset limit. The rolling average for production was several hundred line km per day.

Slide 4. Gravity and gravity gradients



Gravity is a vector quantity that can be described by 3 components: one in each of the north, east and down directions.

A traditional ground gravity survey measures the vertical component of the force of gravity or gD .

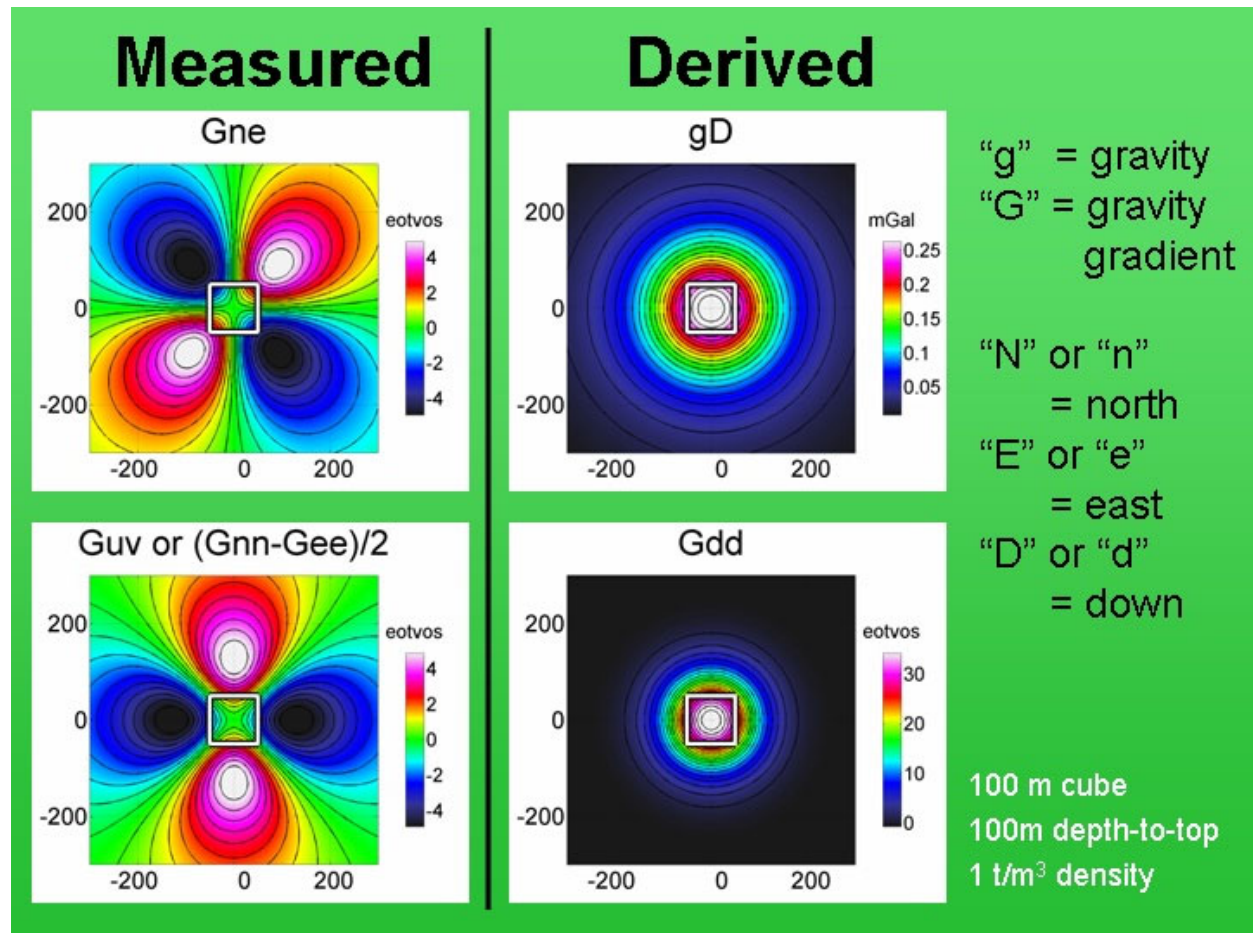
Each of the 3 components varies in magnitude as you move in each of the 3 directions. These 9 spatial derivatives are termed the gravity gradients.

G_{ne} , for example, is the derivative of the north component of gravity in the east direction.

The gradient term that we are most familiar with is the vertical gradient of the vertical component of gravity or G_{dd} . This is the output when a first vertical derivative transformation is applied to a grid of ground gravity data.

This is also the main gravity product from the AGG survey, but it must be remembered that it measured on a drape surface approximately 80 metres above the ground surface.

Slide 5. Gne, Guv, gD and Gdd response example

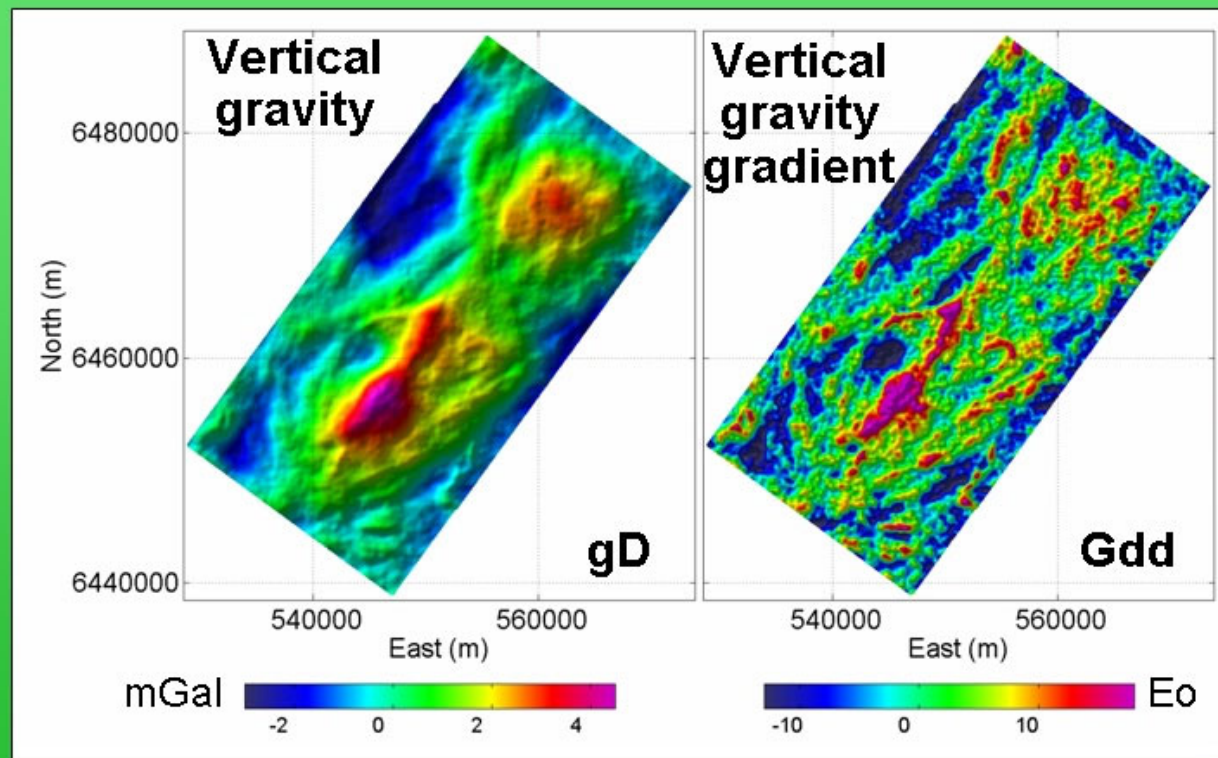


For engineering reasons, the Falcon AGG system actually measures the horizontal gradient quantities Gne and Guv. The plan view response for these quantities for a 100m cube buried at a depth of 100m is shown on the left¹. These measured gravity gradients have quadrupole response functions that are quite complex even for simple source geometries such as the example shown here.

With certain assumptions, it is possible to transform the measured Gne and Guv responses to the equivalent gD or Gdd response using a process similar to reduction to the pole. This transformation is done solely to facilitate qualitative interpretation. For quantitative applications, it would be better to use the measured Gne and Guv responses. The vertical gravity gradient response is particularly suited to qualitative interpretation, since the anomaly is compact and closely hugs the horizontal outline of the source.

¹ Mahanta et al. (2001) provided the inspiration for this slide.

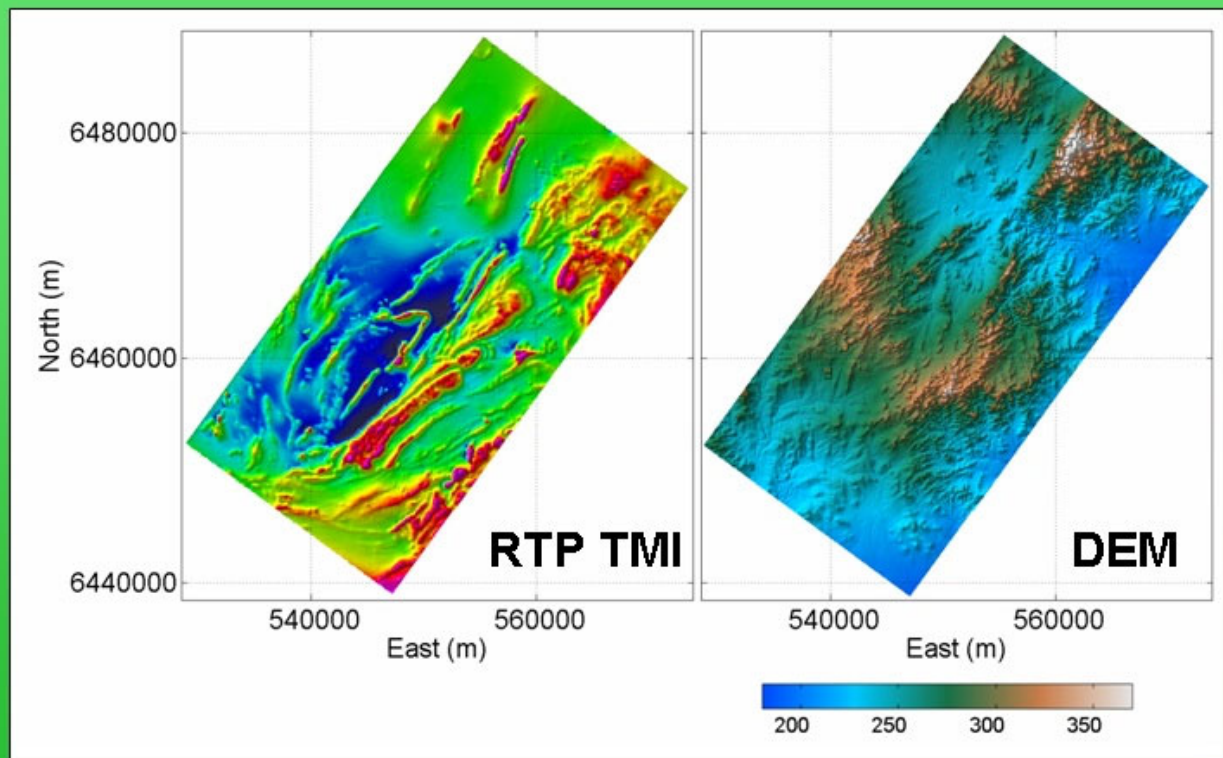
Slide 6. gD and Gdd images



(Equivalent source, 2.75 g/cc terrain density, at ~160 m terrain clearance)

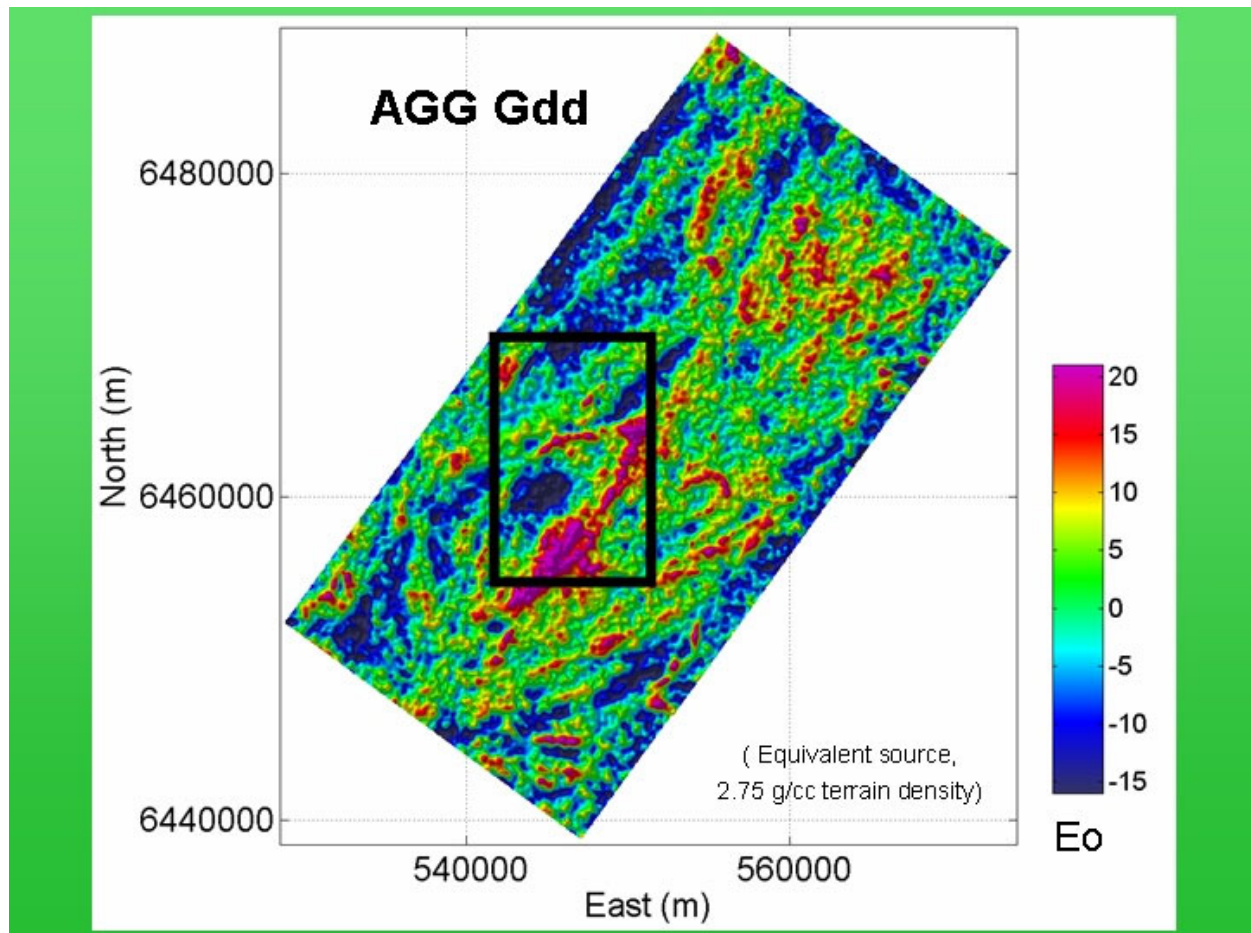
The principal survey products were grids of gD and Gdd. At the mathematical level, these products contain the same fundamental information about density variations. Visually they appear to be quite different with Gdd data having greater emphasis on short wavelengths.

Slide 7. RTP TMI and DEM images



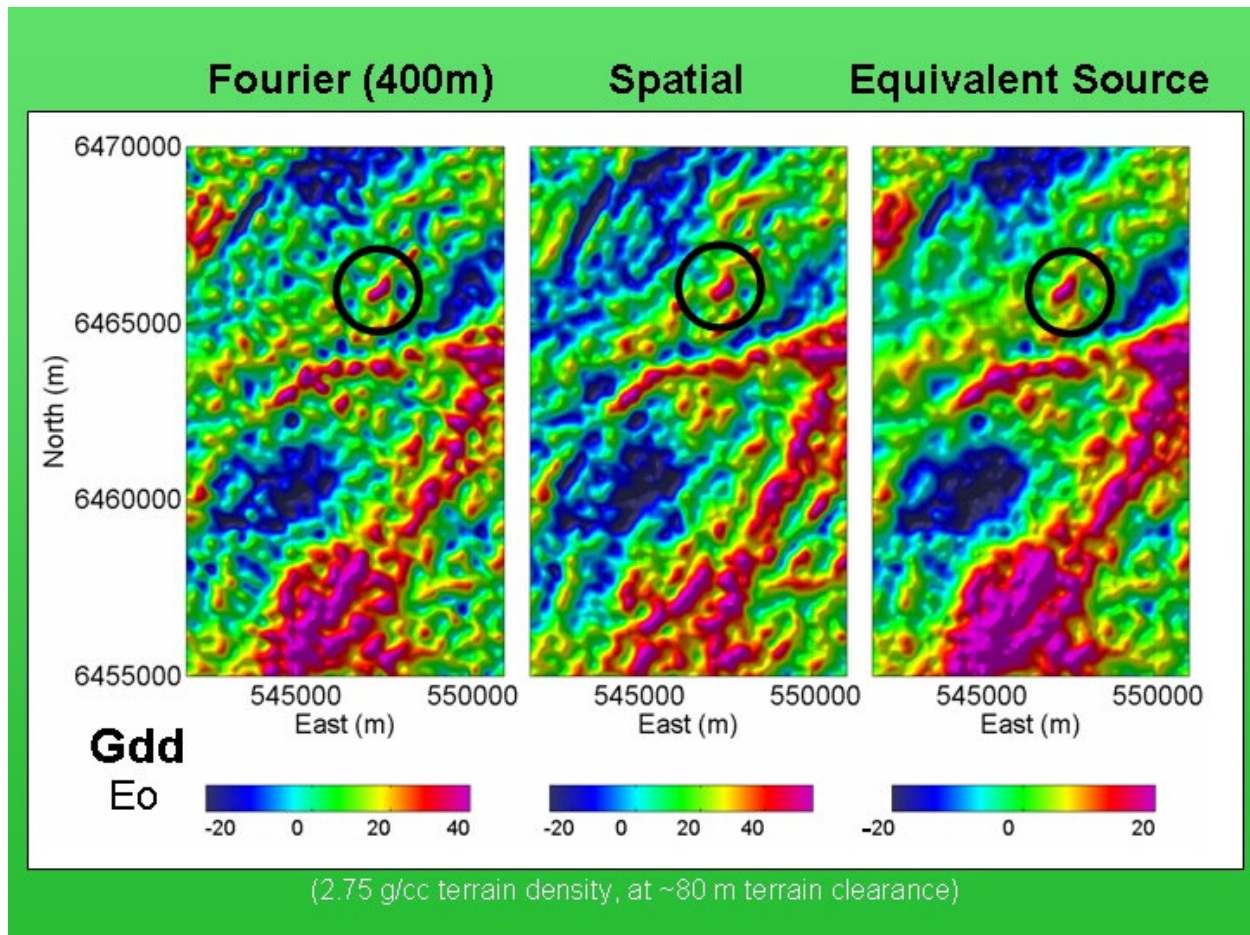
As part of the survey, magnetic data and a high-resolution digital elevation model (DEM) were also acquired. Due to line spacing and terrain clearance factors, the magnetic data do not improve upon the existing 100m line spaced data. The AGG DEM, based on laser ranging measurements taken by a scanner that acquires a swath of data rather than a single profile, is a substantial improvement on the DEM based on radar altimeter measurements from the 100m mag-spec surveys.

Slide 8. Location of subset used for comparisons



The transformation from measured horizontal gradients to vertical gravity or vertical gravity gradient can be done using a number of mathematical procedures that are described by BHPBilliton as being “different in their underlying assumptions and treatment of noise”. Three versions of the vertical gravity gradient are provided. These will be illustrated using a subset of the survey data.

Slide 9. Methods for transforming Gne and Guv to Gdd

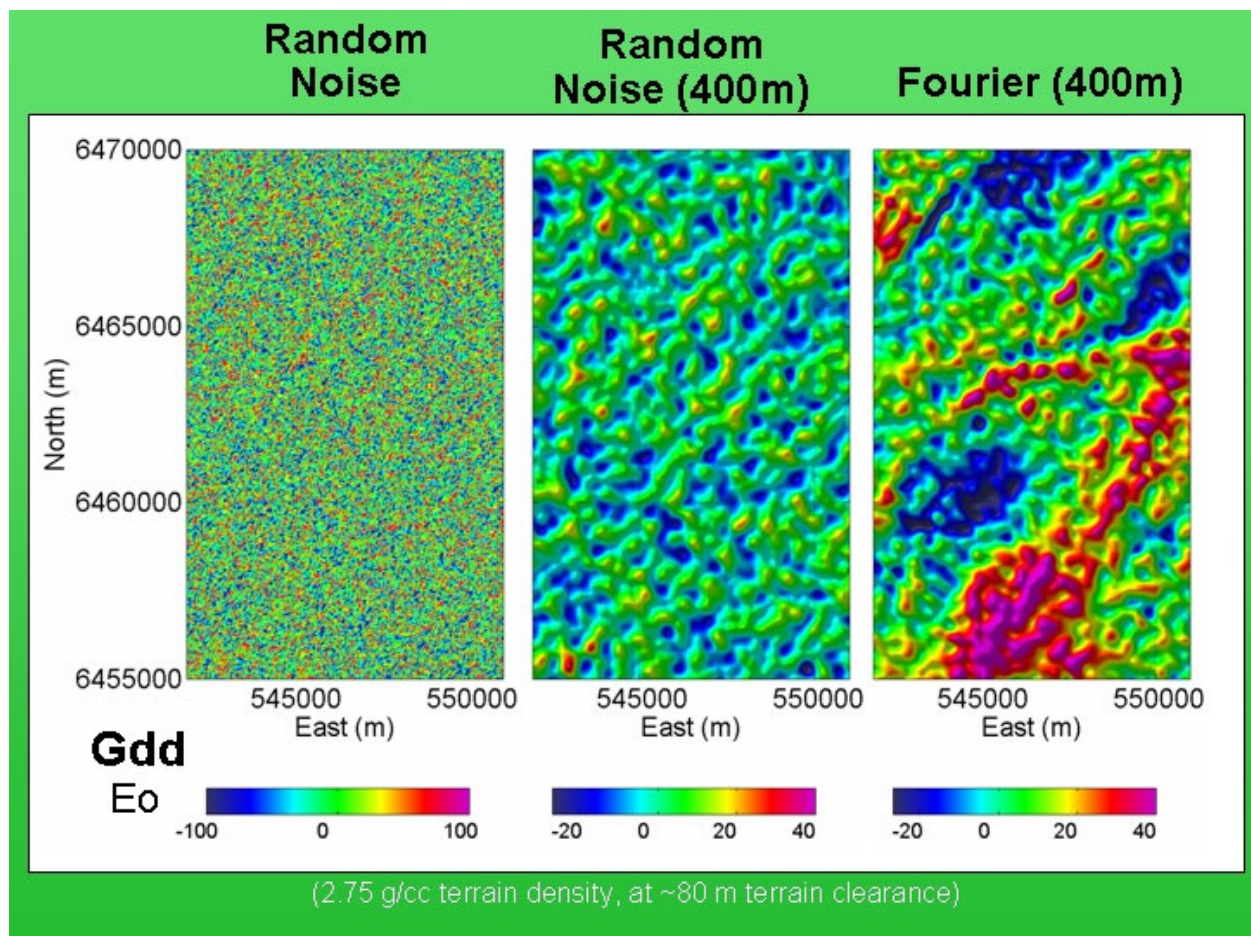


The three different transformations are based on a Fourier domain procedure, a spatial convolution filter and an equivalent source inversion procedure. Robust features have a similar appearance in all three images. Noise related features vary significantly in appearance across the three images.

The Round Hill anomaly provides a useful reference point. It is located immediately to the NE of the North Mine, and is, at least in part, due to amphibolite. The AGG anomaly has been confirmed through comparison with existing detailed ground gravity, and modelling suggests that the anomaly has similar magnitude to that of a significant base metal deposit.

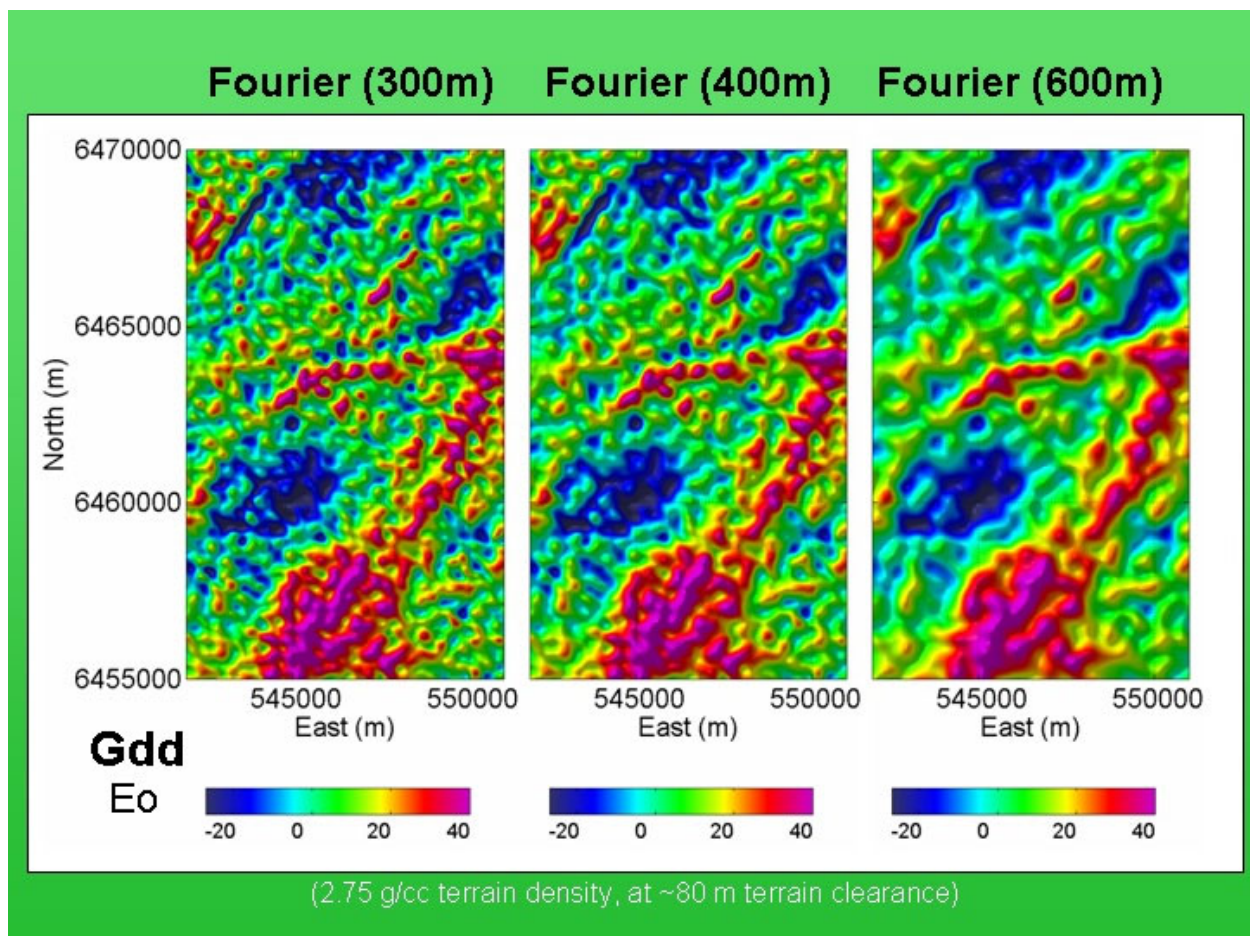
An underlying texture of dimples and short strike length features is a distraction on all of these images. The notion that this is due to noise in the data was investigated with a simple experiment aiming to reproduce this texture.

Slide 10. Simulation of Gdd background texture



Although the raw data are not available for inspection, it is thought to be contaminated by noise spikes induced by turbulence. This was simulated on the left with a grid of random Gaussian noise that was then low pass filtering in the same manner as has been applied to the Gdd data derived via the Fourier procedure. This resulted in a texture that is very similar to the texture observed in the survey data.

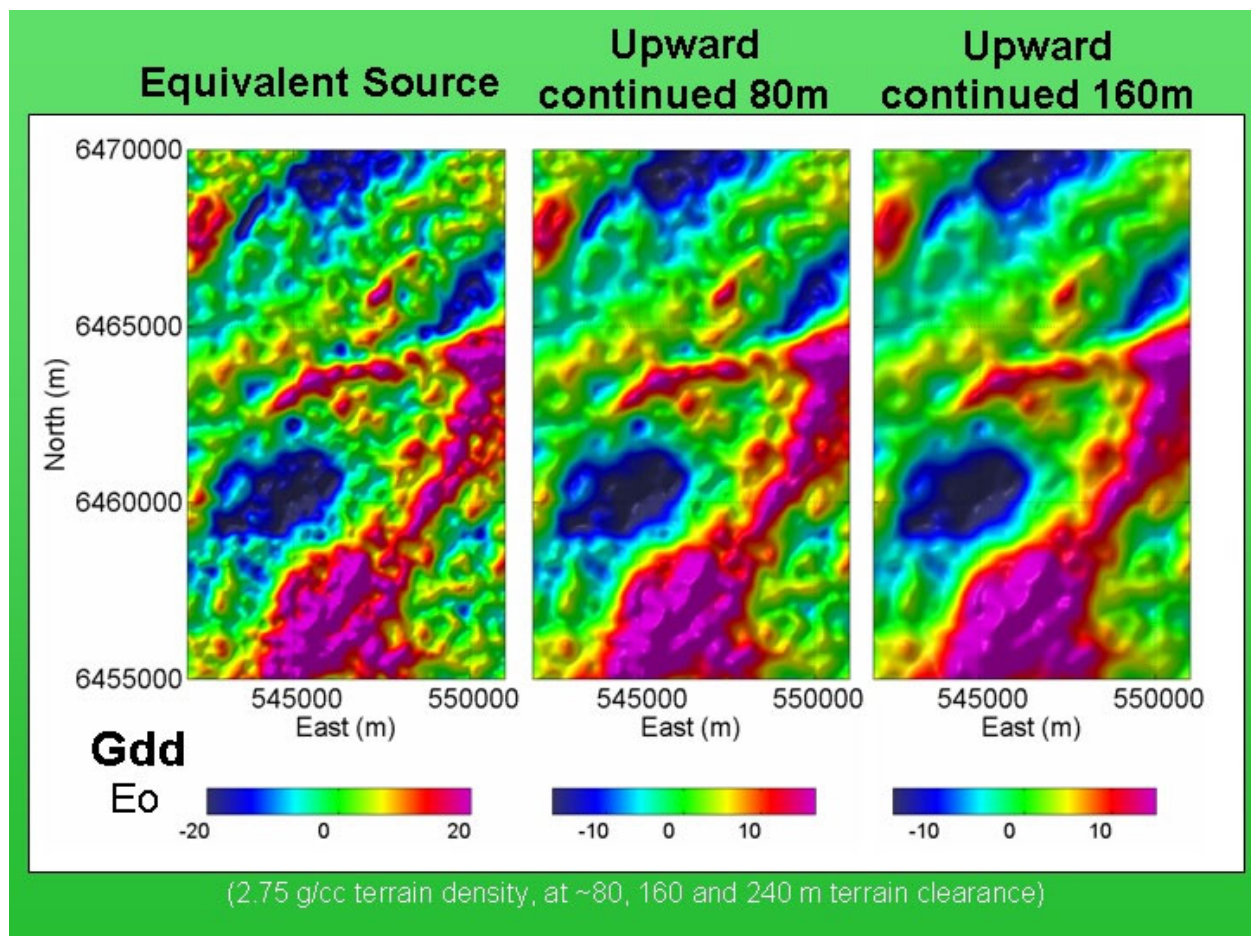
Slide 11. Butterworth low-pass filtering



There are several different ways to reduce the amplitude of background noise, but all involve a reduction in spatial resolution.

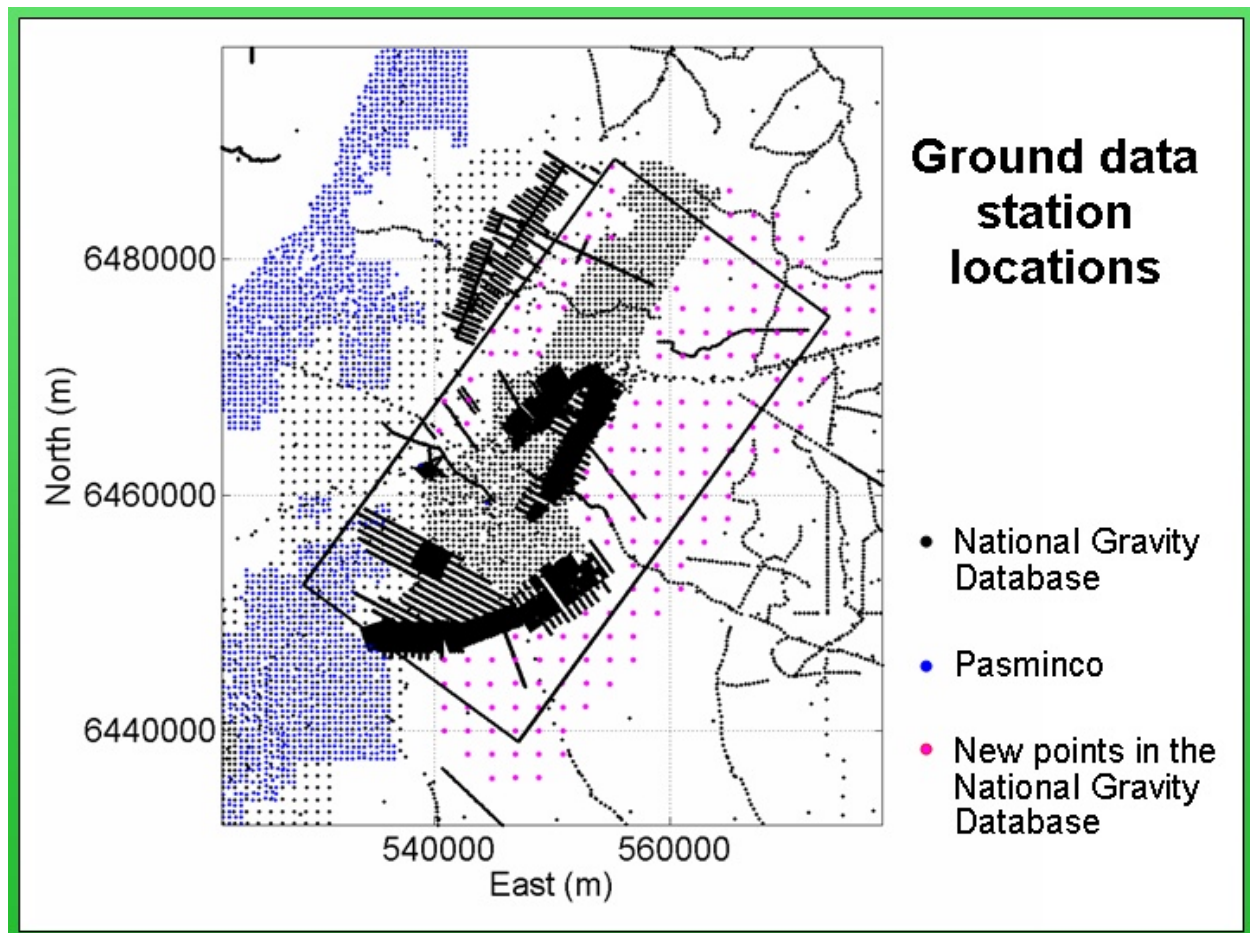
Low pass filtering is applied by BHPBilliton to the Gdd data derived via a Fourier procedure. The effect of filters with thresholds of 300, 400 and 600 metres are shown. The filtering increases the signal to noise but decreases spatial resolution.

Slide 12. Upward continuation as a low-pass filter



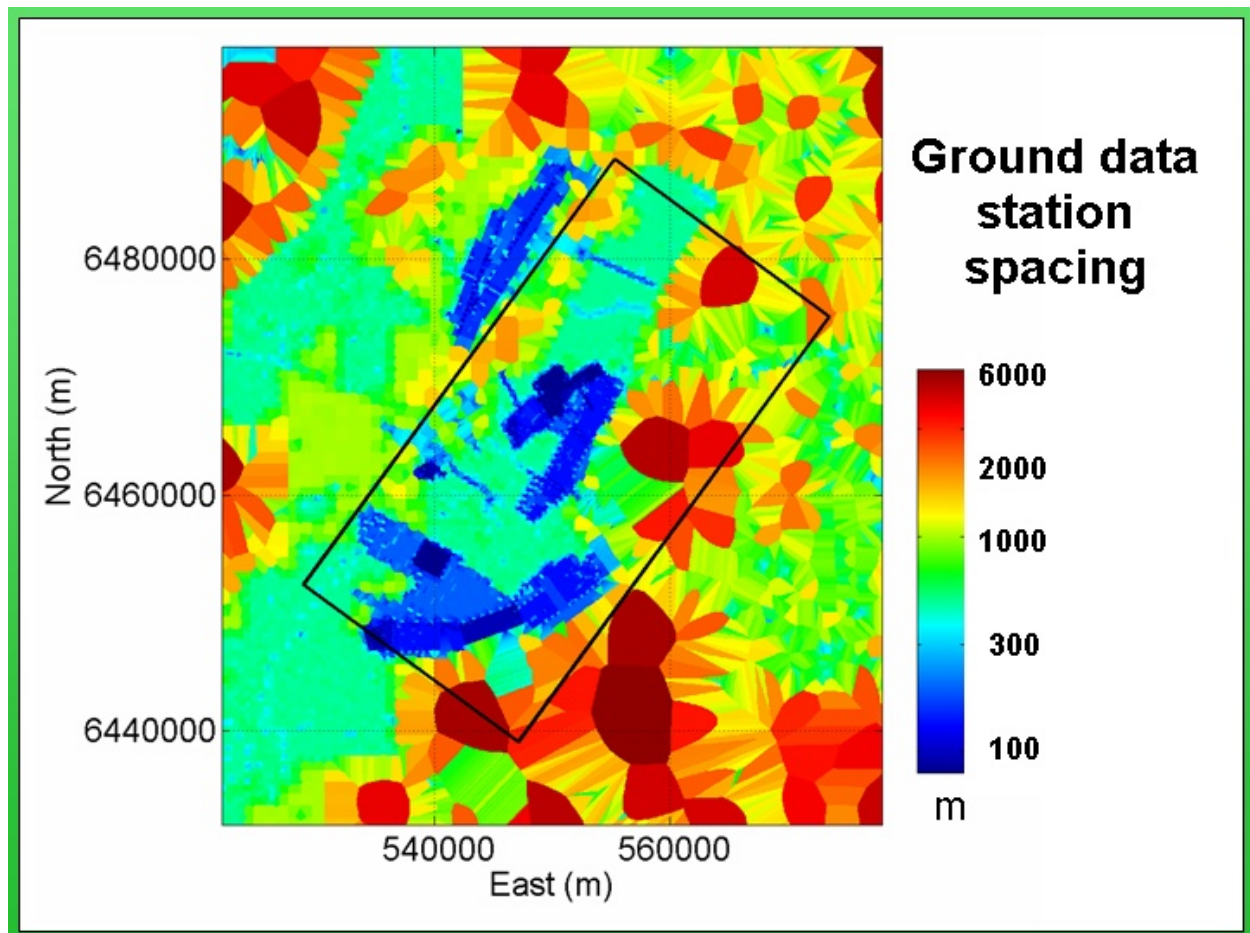
Upward continuation is another form of low pass filtering that can be applied to the data. The optimum trade-off between noise amplitude and spatial resolution is dependent on the application and the preferences of the interpreter.

Slide 13. Location of ground data observations



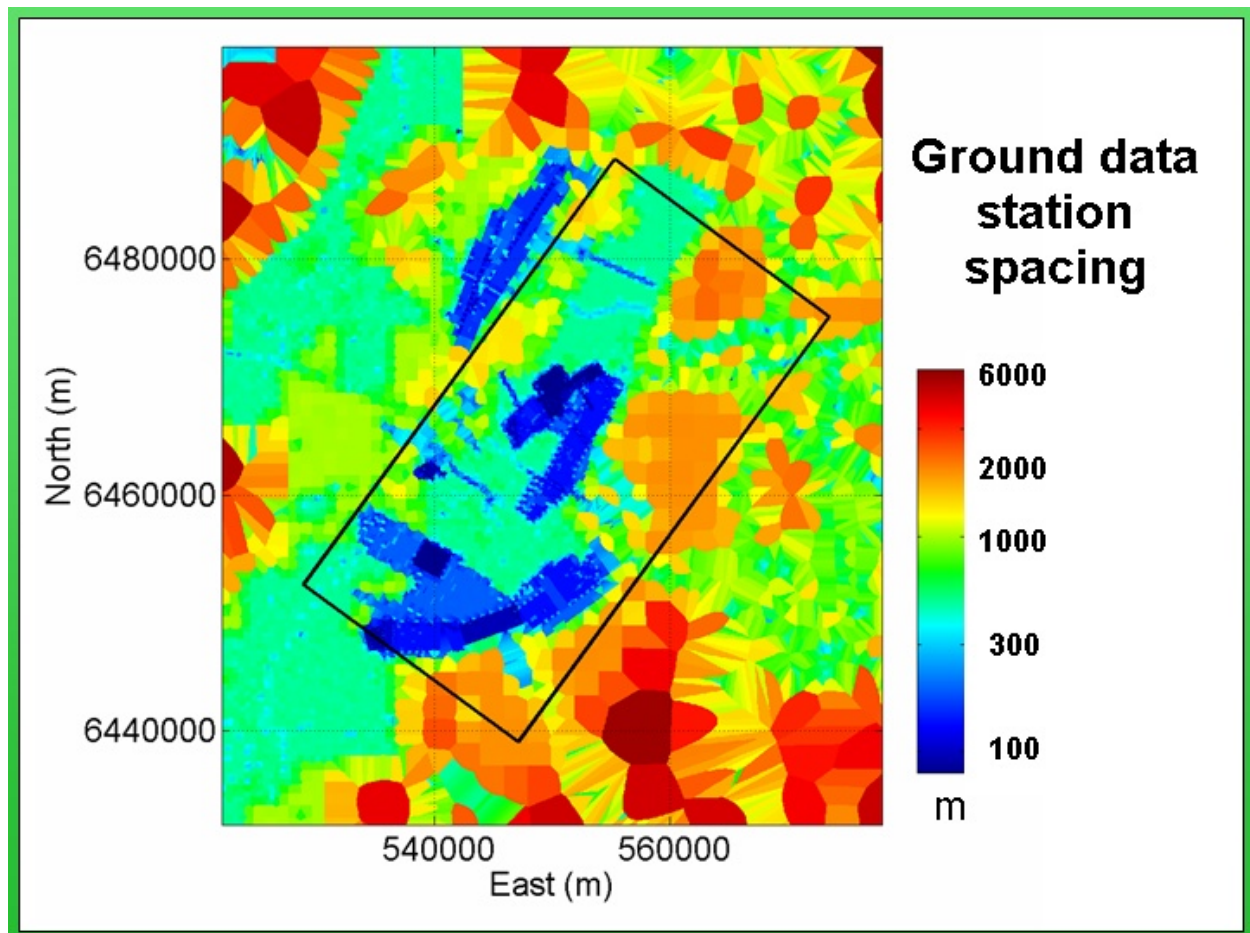
The coverage of ground gravity stations is extremely variable in spacing and quality. To assist in the evaluation of the AGG data, around 200 additional stations were acquired for Geoscience Australia. These data will be available at the end of July.

Slide 14. Station spacing for ground data



Prior to the acquisition of the new ground stations, there were regions within the survey area where the station spacing was around 6 km as indicated by the deep red colour.

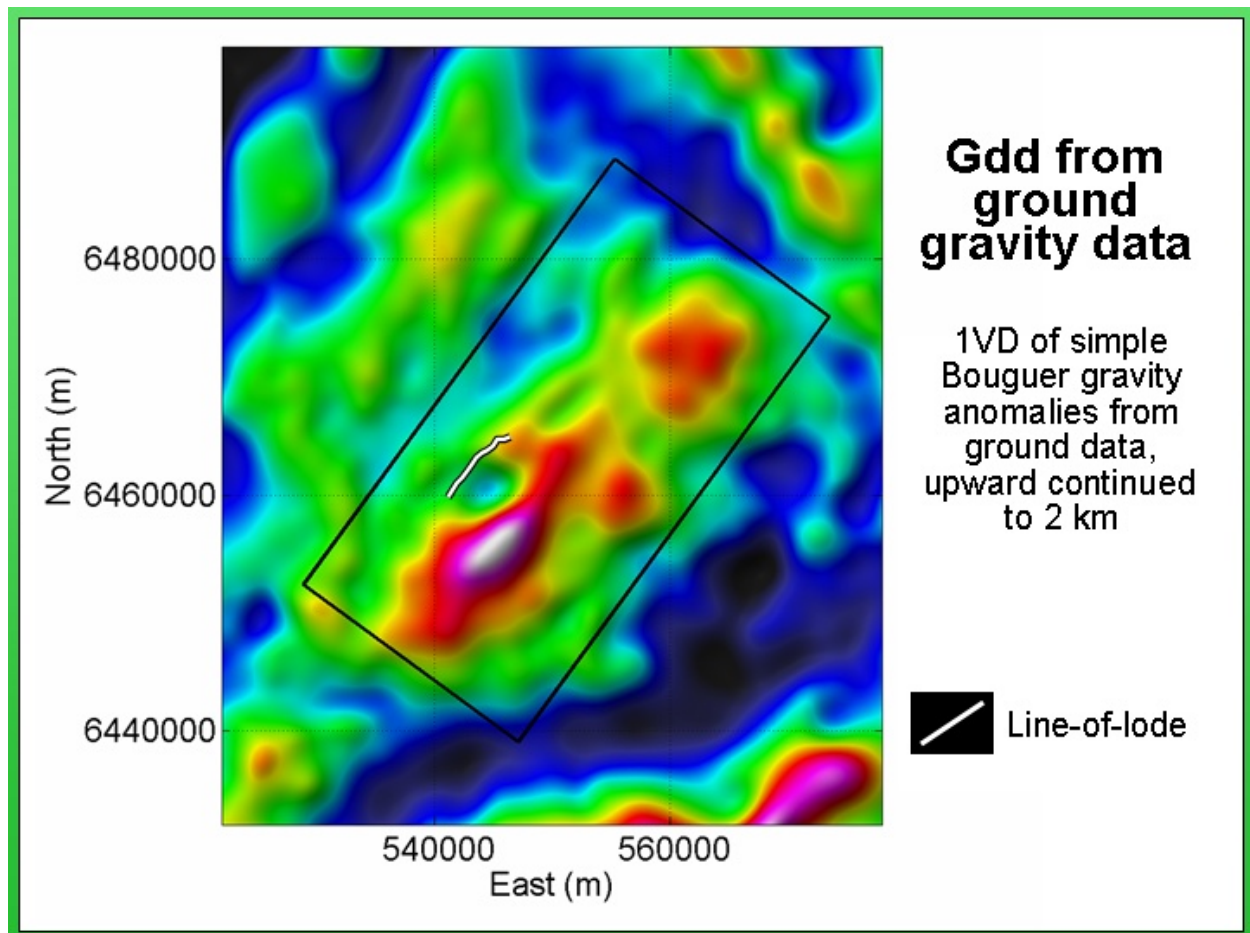
Slide 15. Station spacing for ground data (cont.)



The new gravity data closed down the maximum sample spacing from around 6 km to 2 km and were important for evaluating the long wavelength characteristics of the AGG data.

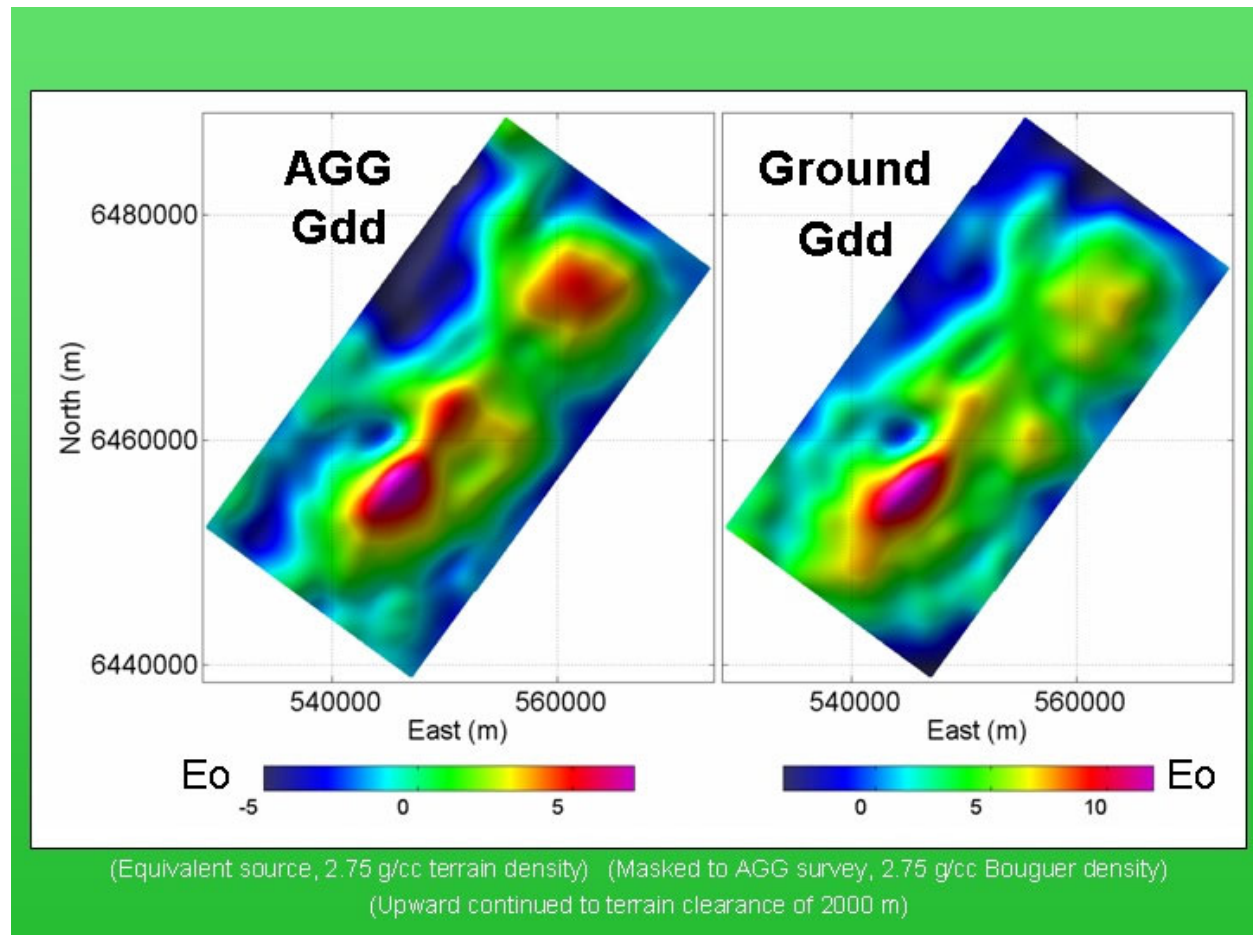
The areas shown in blue have sample spacing less than 300 metres. These areas were used to evaluate the short wavelength resolution and accuracy of the AGG data.

Slide 16. Regional Gdd setting



The AGG survey surrounds the prominent Thorndale and Mt Vulcan gravity highs immediately to the east of Broken Hill. The elongate gravity low to the south underlies part of the Redan sequence. The NW trending low to the north of the survey is associated with a tongue of Adelaidean sediments and with upper parts of the Willyama Supergroup. The elevated plateau to the west of the survey is associated with the central portion of the Broken Hill Block.

Slide 17. Comparison of long wavelengths in ground and AGG data

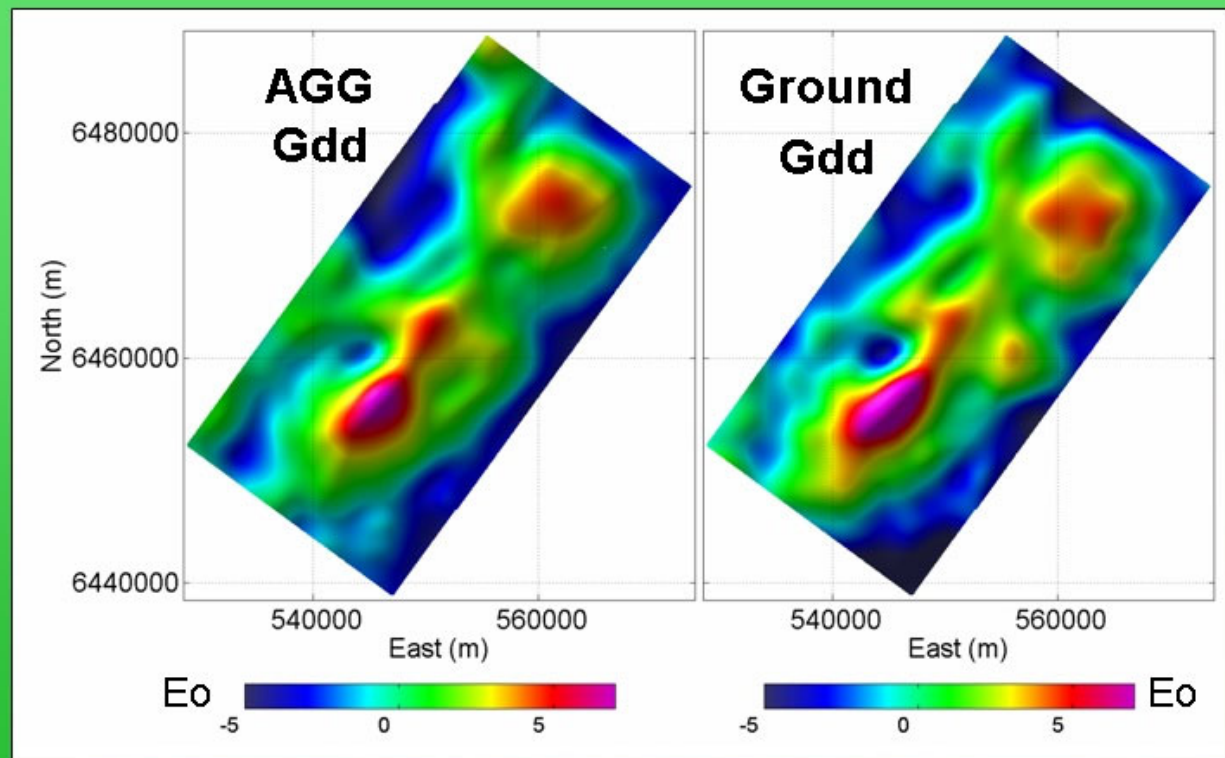


The longer wavelengths in the ground and airborne data can be more easily compared after the short wavelengths have been attenuated by upward continuing both to a height of 2 km above the surface. An analysis of the long wavelengths may seem academic when most of the focus is on short wavelength discrete targets. However, these wavelengths are important when the data are used for mapping, and at some point in the future, when surveys are joined into regional compilations.

The airborne system measures gravity gradients in a relative fashion whilst ground gravity measurements are referenced to points of known absolute gravity. The differences in the absolute level between the two datasets can be seen by noting the annotation on the colour scales. There are differences in the slope or regional gradient of each dataset that are revealed through the differences in the relative amplitudes between the Thorndale and Mt Vulcan highs in the two datasets.

The long wavelength differences can be removed by fitting and then removing a sloping surface from both datasets.

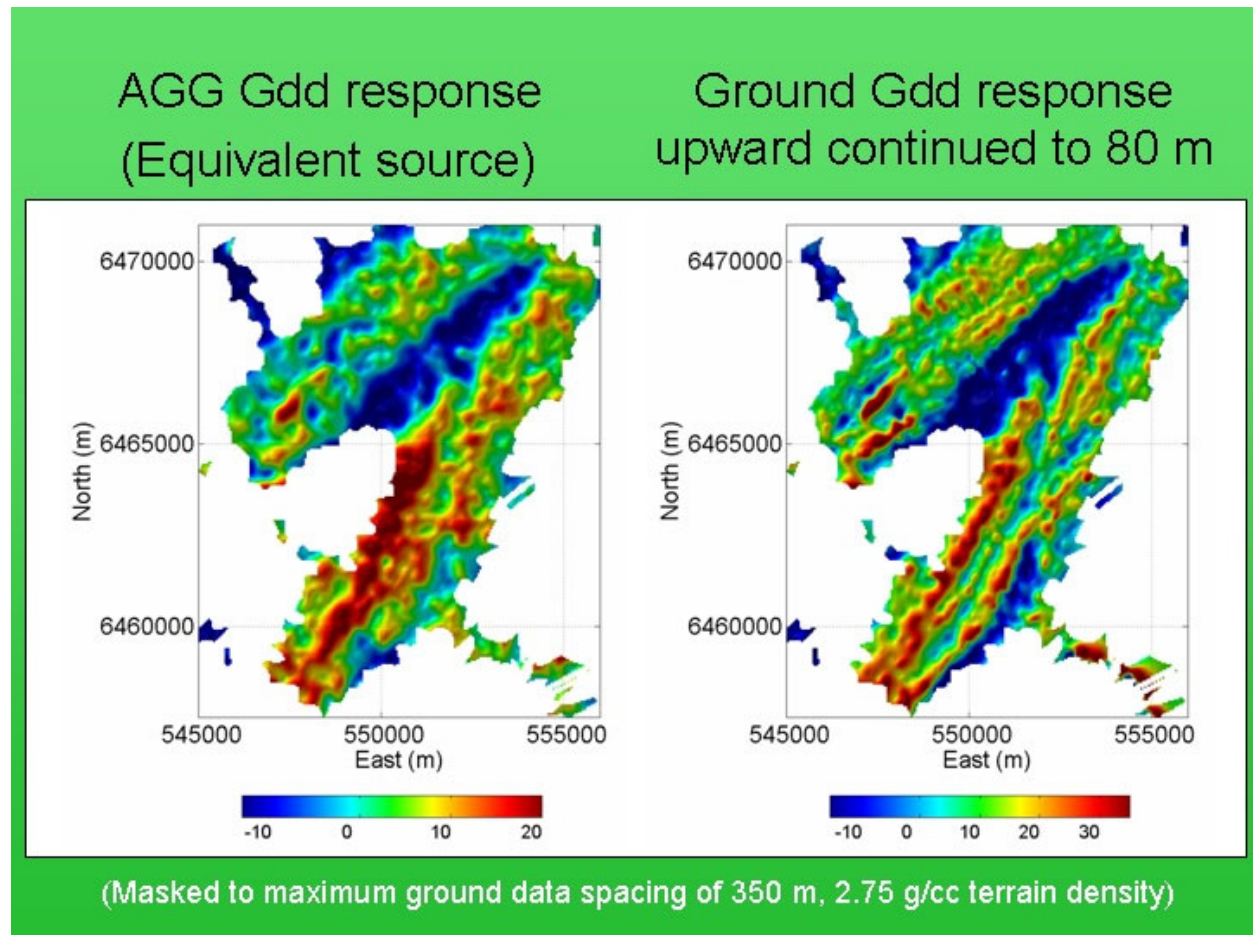
Slide 18. Comparison of long wavelengths (cont.)



(Equivalent source, 2.75 g/cc terrain density) (Masked to AGG survey, 2.75 g/cc Bouguer density)
(Upward continued to 2000 m, first order polynomial, or "tilt", removed from both)

Having done so, the two datasets are now far more compatible as can be judged from the similarities in relative amplitudes between the Thorndale and Mt Vulcan highs and by the use of the same colour scale for both images.

Slide 19. Comparison of detailed ground and AGG data



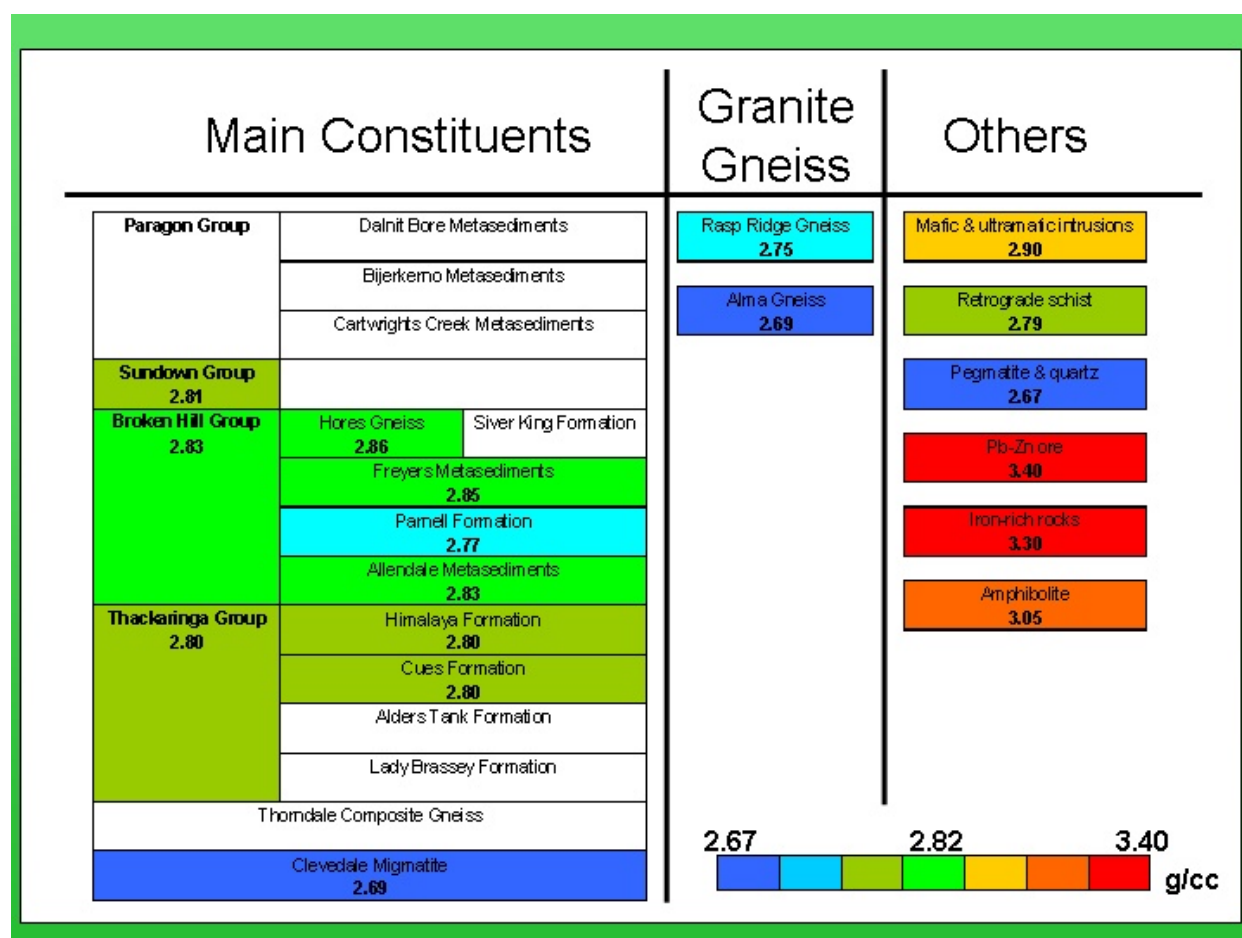
To evaluate the short wavelength resolution of the airborne data, an image of the vertical gravity gradient derived from ground data covering a small portion of the airborne survey is shown on the right, upward continued to 80 metres.

The image on the left shows airborne data masked to the same outline to facilitate direct comparison. The general features are the same in the two datasets. High amplitude features such as the gravity high at Round Hill are evident in both images. However, many of the curvilinear trends evident in the closely spaced ground data are obscured in the airborne data by noise.

To conclude the section comparing ground and airborne data, we see that:

- The absolute level and regional gradient of the airborne Gdd data cannot be recovered. However, relatively broad features such as the Thorndale and Mt Vulcan highs are well defined.
- Detailed ground data can resolve more closely spaced and lower amplitude features than the airborne data. However, higher amplitude features of interest as discrete targets can be readily identified in the airborne data.

Slide 20. Density measurements

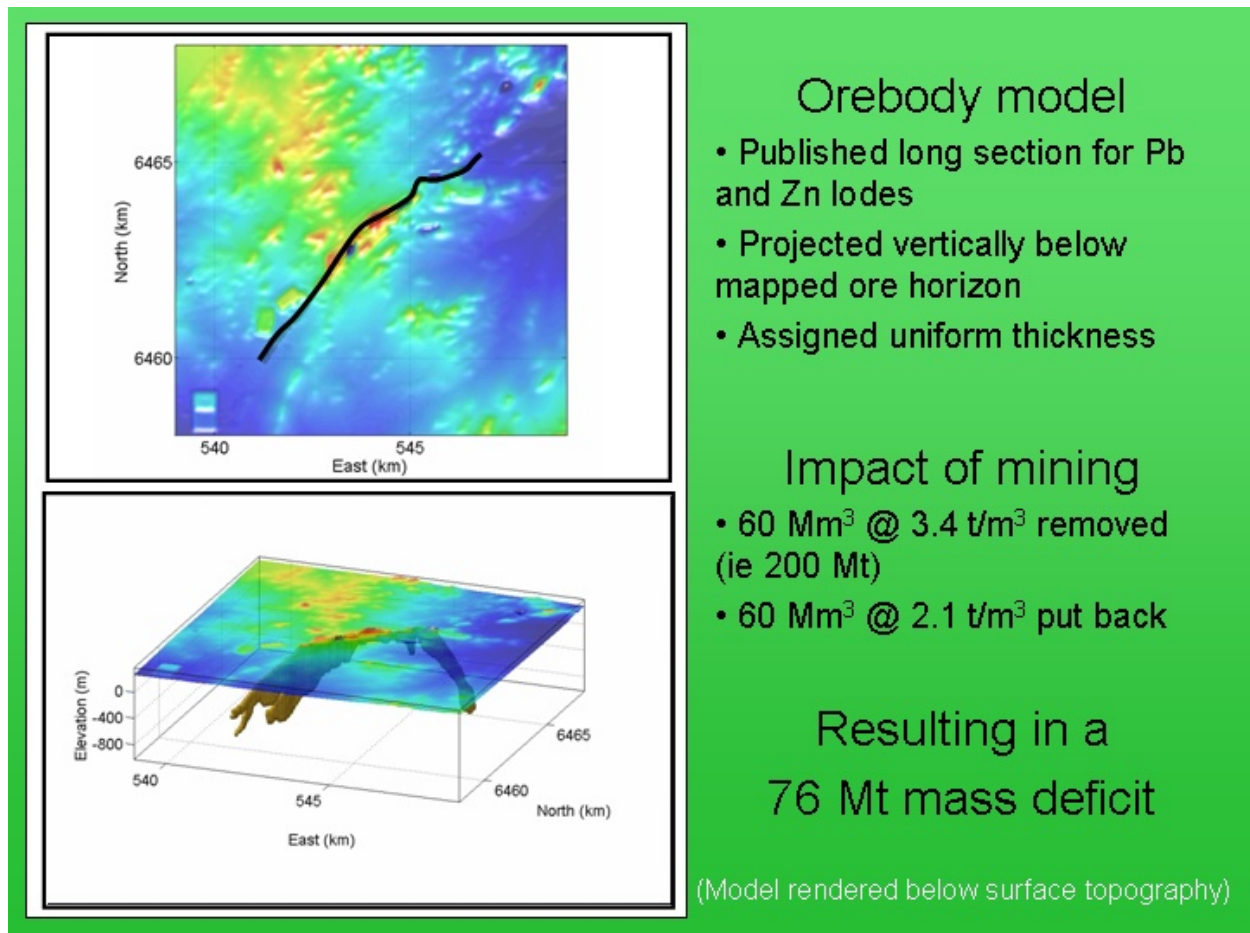


Average density values are shown based on a total of 748 measurements available in the BHEI physical property database. Values from a number of specific lithologies as indicated in the “granite gneiss” and “other” columns were separated from the remainder of the samples.

The average density value of 3.4 g/cm³ for lead-zinc ore was derived from a very large number of measurements given in student thesis, company studies and mining journals. This value is quite low for base metal ore, reflecting the low concentrations of pyrite and pyrrhotite.

Due to similarities in density and geometry, bodies of amphibolite, iron-rich rocks such as banded iron formation and quartz-magnetite rock, and younger mafic and ultramafic intrusions would be expected to have similar gravity anomalies to that of the target base metal mineralisation. Discriminating discrete gravity anomalies due to amphibolite from those due to base metal mineralisation is likely to be the main challenge for explorers in the immediate follow-up to the survey.

Slide 21. Orebody model

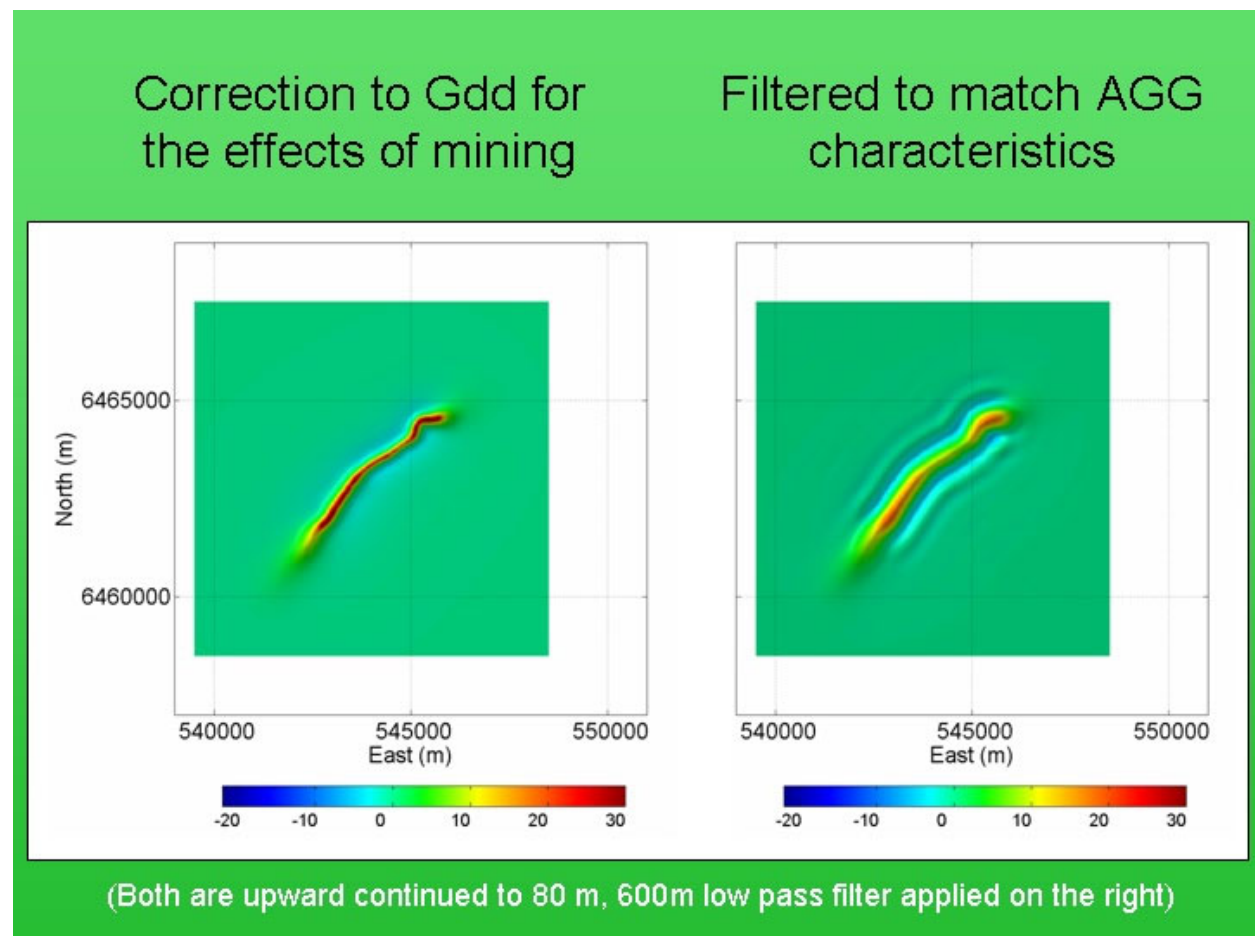


What is the gravity signature of a significant base metal deposit? Ordinarily, you would turn to observations over a known deposit such as Broken Hill for the answer. But in this case, the gravity response has been substantially modified by mining activities. An estimate of the changes has been made and added to the survey data to produce an image of the pre-mining gravity response.

To do this, a very simple orebody shell was built from the general shape of the orebody in long section, projected onto a vertical curtain below the mapped surface expression of the ore horizon.

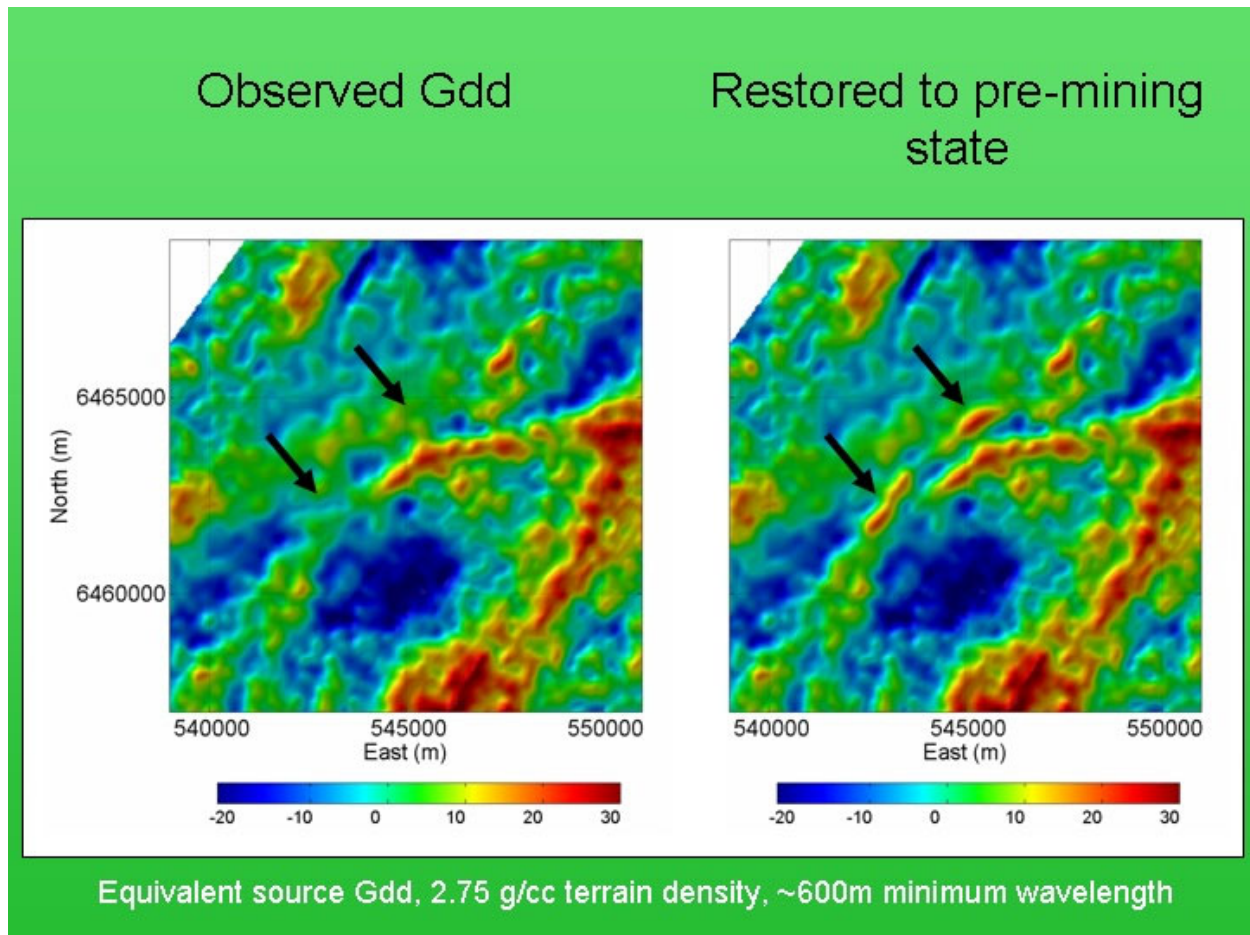
The excess mass was estimated assuming that 200 million tonnes of dense ore has been replaced by backfill that is less dense due to the absence of base metal sulphide minerals and a substantial increase in porosity. The net loss of mass is around 76 million tonnes. The excess mass was distributed with uniform density over the ore shell.

Slide 22. Correction to AGG Gdd for mining activities



The corrections for mining activity calculated at the flying height amount to a narrow anomaly with peak amplitude of around 30 Eo. Before adding this response to the observed data, the anomaly was filtered to remove short wavelengths, in keeping with the characteristics of the AGG data. The filtering broadens the anomaly and reduces the peak amplitude.

Slide 23. Pre-mining AGG Gdd response



Vertical gravity gradient data from a portion of the survey is shown on the left. The corrections for mining activities have been added on the right. There are distinct highs over the northern and southern parts of the orebody which hosted the bulk of the reserves.

There are several important conclusions from this exercise.

- The AGG survey would have detected an anomalous response from the Broken Hill orebody had the survey been flown prior to mining.
- Only the anomalies related to tens of millions of tons of ore present in the northern and southern ends of the deposit would have been detected given the spatial resolution and signal to noise characteristics of the data.
- There are other geological features in the survey area that produce similar anomalies to that expected from a significant base metal deposit, for example the amphibolite body at Round Hill and amphibolite bodies parallel to the Broken Hill orebody.

Slide 24. Outline of future work

Future work

- Complete the processing and delivery of AGG data:
 - Full resolution DEM
 - Processing and analysis of repeat line data
 - Integration of ground and AGG data
- Continue investigations into the suitability of AGG data for improving the regional and semi-regional gravity coverage.
- Calculate the gravity response of the Pasminco 3D geological model and compare this to the observed data.

A number of items remain from the full list of deliverables.

The DEM used in the calculation of terrain corrections for the AGG data did not exploit the full potential of the laser scanner data. A full resolution DEM will be produced.

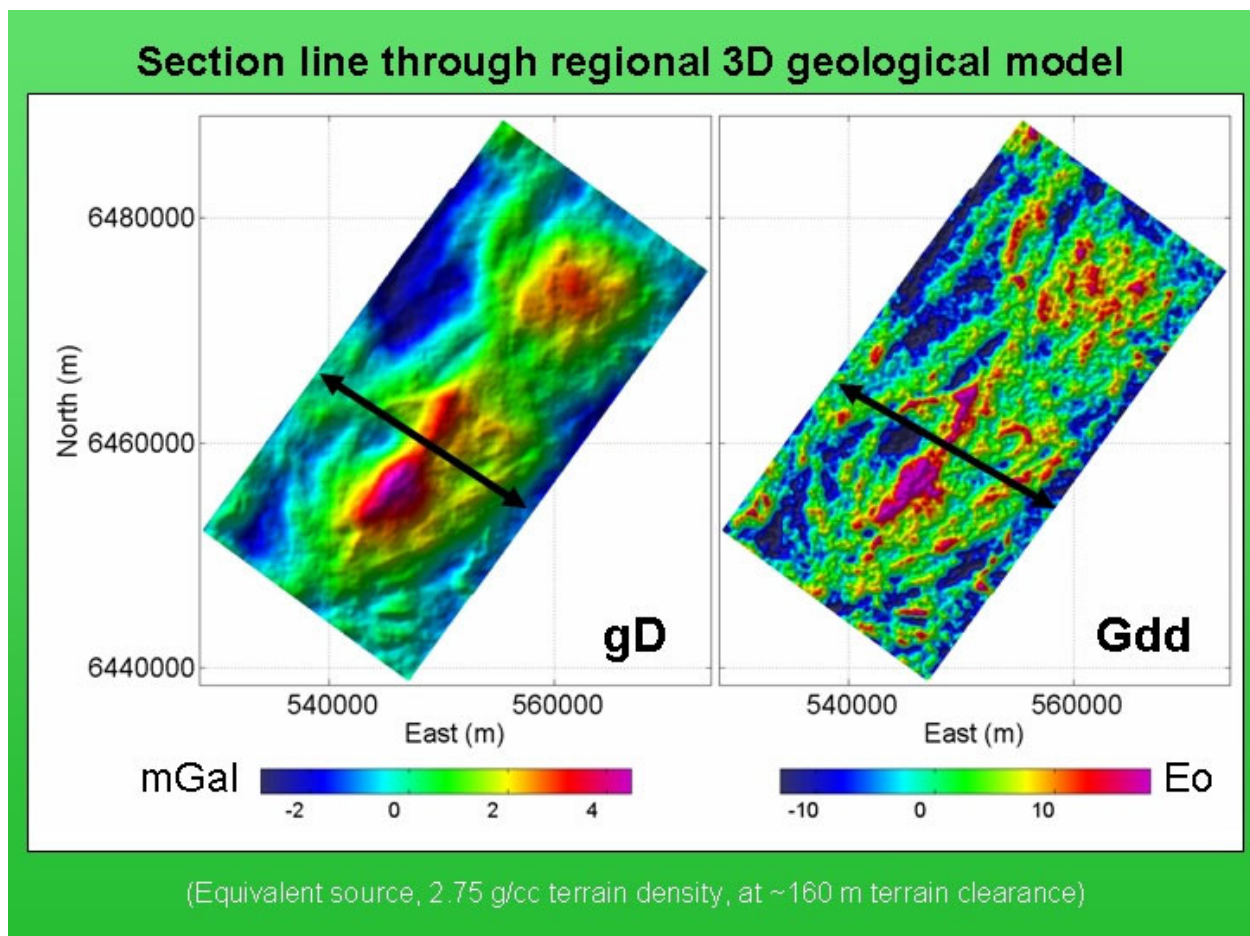
One of the flight lines was flown 4 times. Since the same geological signal is present on each pass along the repeat line, differences for each pass from the average for all passes reflect noise. Quantification of noise levels will help with decisions as to whether features in the data are real or more likely to be noise. It will also provide accurate noise values for use in quantitative applications such as inversions.

Comparisons of ground and airborne data highlighted important differences between the two data types. A single integrated gravity dataset will be produced that combines the better aspects of both data types.

The analysis of the Broken Hill survey data is being used by government organisations to evaluate the role of AGG data for delivering improved regional and semi-regional gravity coverage.

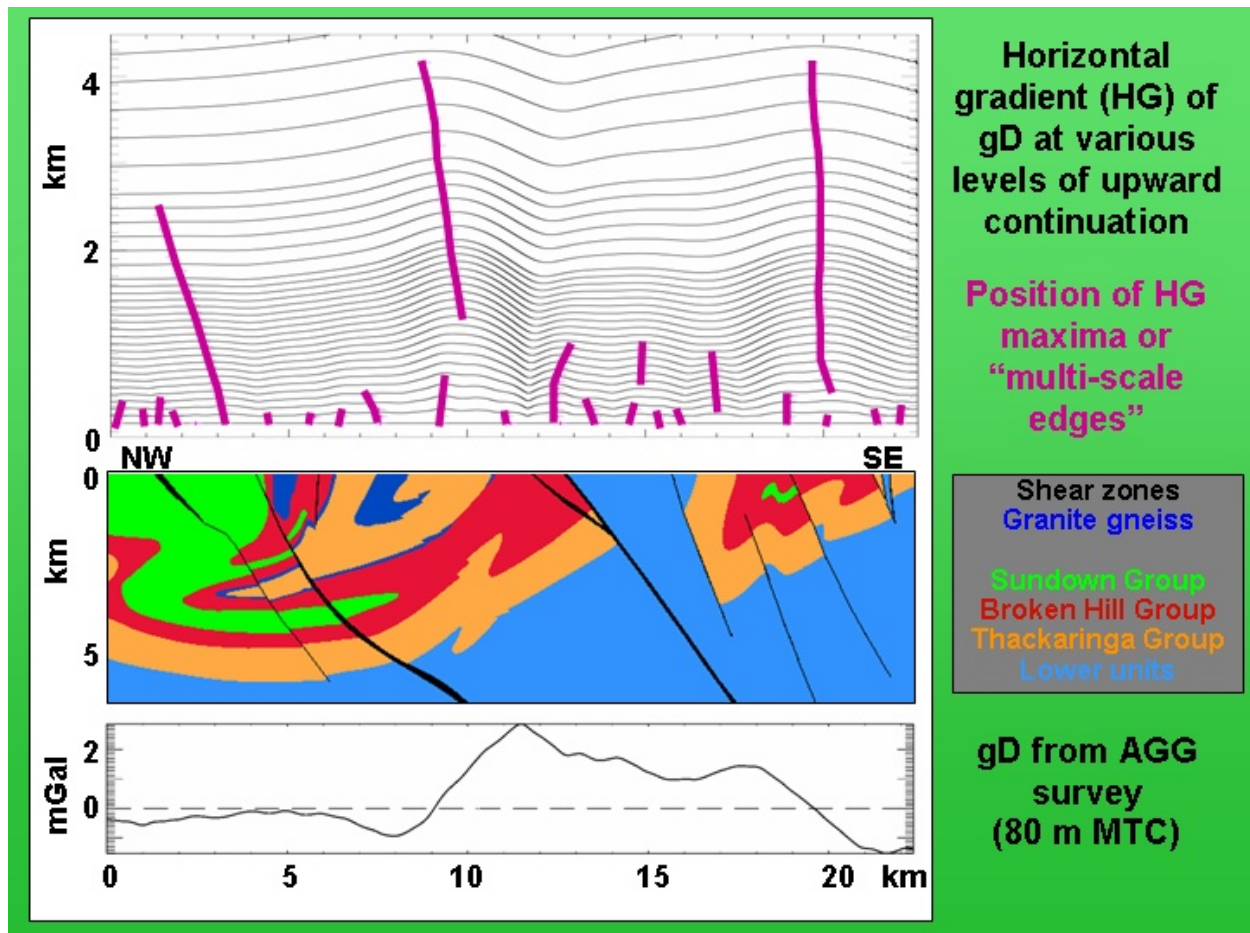
The Pasminco regional and line-of-lode geological models will be tested for consistency with the gravity data. This involves creating a density model based on the geological models then calculating the gravity response to highlight regions of the models where either the density values and/or the geometry need to be revised.

Slide 25. Location of section through 3D geological model



The location of a section extracted from the model is shown in relation to the AGG data. This section will be used to illustrate the level of detail that is present in the geological model and some of the relationships between elements of the model and gravity data.

Slide 26. Section through 3D geological model



In this part of the model, the sequence is represented by 4 stratigraphic units, together with granite gneiss bodies and shear zones.

A gravity profile extracted from the AGG data is shown below the geological section.

Profiles of total horizontal gradient at different levels of upward continuation are shown above the section. The positions of local maxima in these profiles are shown with purple lines. These are the intersection of multi-scale edge or “worm” sheets with the plane of the section. These gradient maxima are increasingly being used during interpretation to identify contacts between bodies of different density.

Gravity highs are present at Thorndale and Little Broken Hill where Broken Hill Group rocks are present at the surface. The Alma Gneiss is associated with a gravity low. The absence of a positive gravity feature at this scale of observation where there are Broken Hill Group rocks along the line of lode is interesting and may be due to compensation for the high density Broken Hill Group rocks by nearby low density granite gneiss units.

Several issues have arisen in the early stages of evaluating the geological model using gravity data.

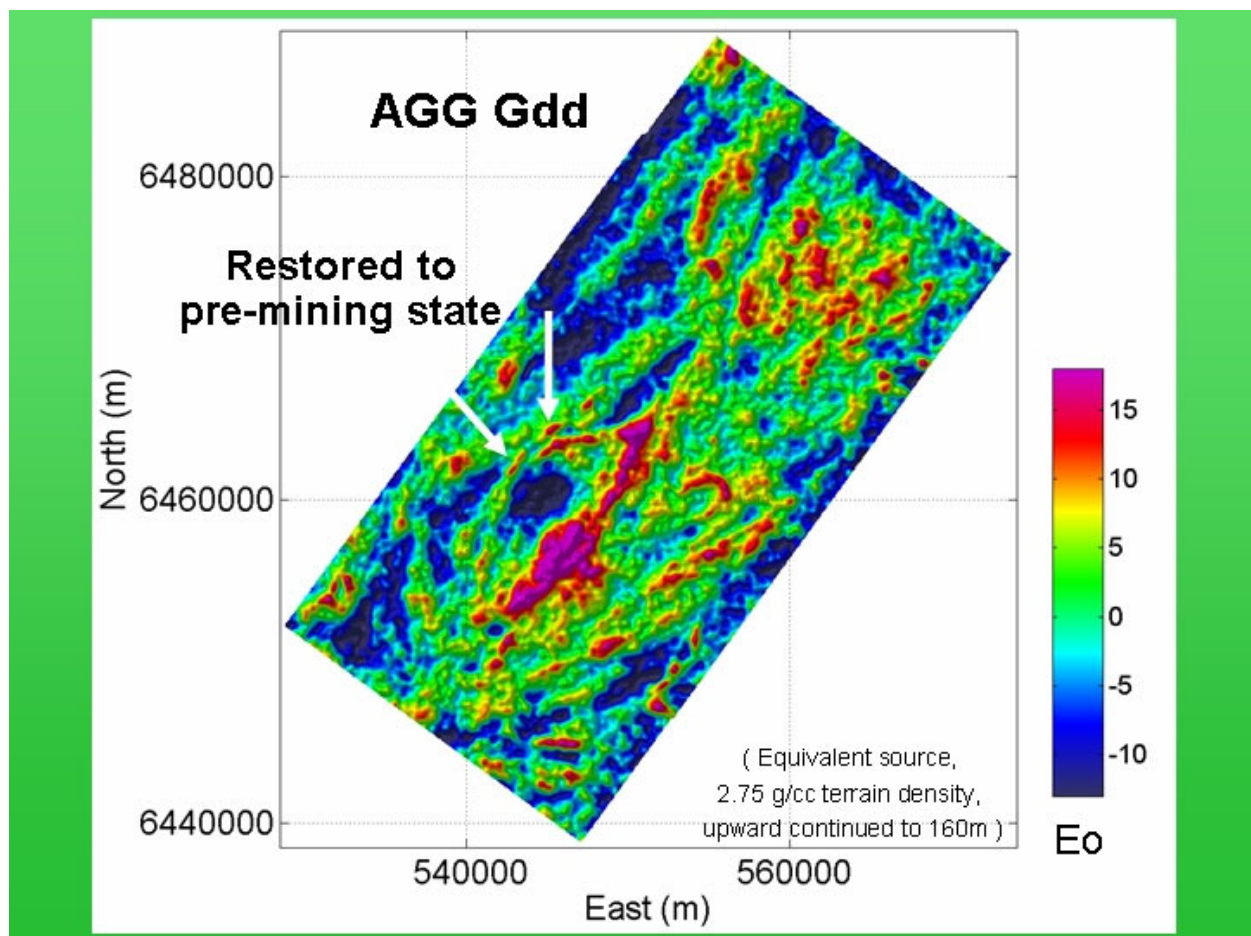
Density values need to be assigned to the units in the geological model. As we saw earlier, there are density values for various lithologies present throughout the sequence. However the relative proportions of constituents such as amphibolite and pegmatite must be quantified for

each of the units before an overall density can be calculated as a weighted average of the density of the constituents.

This leads to an even more difficult question as to how successfully the spatial variability of the density values can be predicted using mapped variations in composition and metamorphic grade.

The locations of the fundamental geological observations that underpin or constrain the geological model need to be identified if the 3D geological model is to be improved. If the gravity response of the model is inconsistent with the observed gravity data, then there are two paths that can be taken to achieve greater consistency; the density values can be amended or the geometry of the geological model can be changed. Changes to the geometry of the model would be pointless if the resultant model was then inconsistent with geological observations. But which parts of the model are more tightly bound by observation and which are more interpretive? Where were the units and structures actually observed and where have they been inferred?

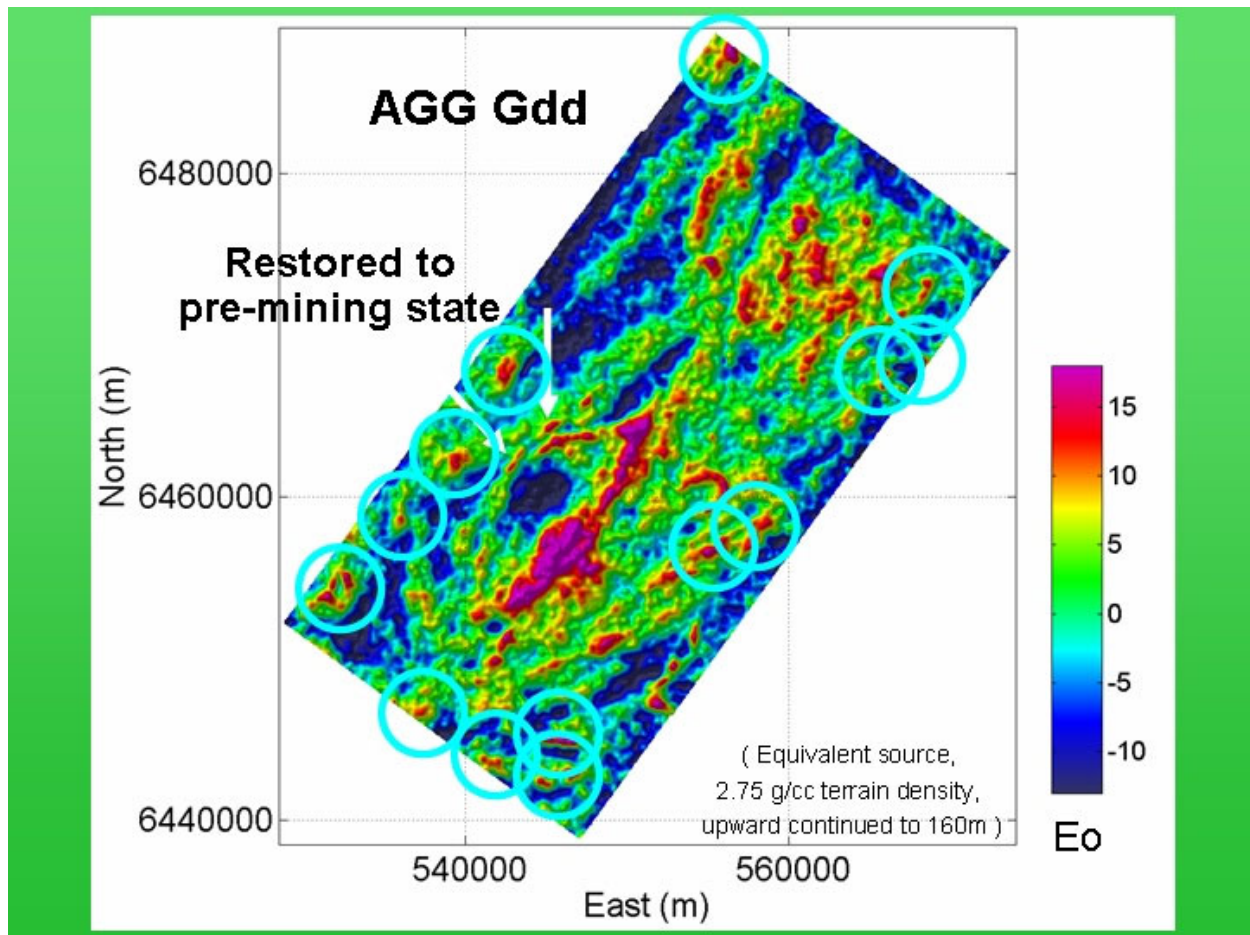
Slide 27. Conclusions



The ground gravity data within the survey area provide complete coverage at the relatively coarse sample spacing of 2 km or more. The AGG survey has revolutionised the level of detail, reducing the effective sample spacing down to 2 or 3 hundred metres.

Restoration of the gravity response for the impact of mining indicated that had the survey been flown prior to mining, the Broken Hill orebody would have been detected as a target for follow-up.

Slide 28. Conclusions (cont.)



The accuracy and sample spacing of the airborne data is sufficient to identify a number of features with geometry and amplitude characteristics that are similar to a prediction of the pre-mining response of the Broken Hill orebody.

Unfortunately, an analysis of density measurements indicated that tabular bodies of amphibolite, iron-rich rocks and younger mafic and ultramafic intrusions could give rise to gravity anomalies of similar character to an orebody.

However, the Broken Hill orebody would once have been one of the selected gravity targets, so it would be foolhardy to dismiss the possibility that there is a second orebody in the remaining targets. Or perhaps an iron oxide Cu-Au deposit? Or an ultramafic-related platinoïd deposit?

Slide 29. Acknowledgments

Acknowledgments

BHPBilliton



Geoscience Australia

Gravity Capital

NSW Department of Mineral Resources

pmd*²CRC

