Localised gross-error detection in the Australian land gravity database

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ABSTRACT

We have used two complementary, data-driven gross-error detection methods to clean the 2004 release of Geoscience Australia's (GA's) land gravity database. The first uses the DEM-9S (version 2) Australian digital elevation model to help verify the gravity observation elevations stored in the database. The second method uses locally interpolated complete/refined Bouguer gravity anomalies, under the assumption that these are smooth and suitable for interpolation, to crosscheck each gravity observation against those surrounding. Together, these methods only identified a total of 237 points (0.021%) in the database that were suspected to be in gross error (differences greater than 250 m and 35 mGal, respectively), of which only nine were identified by both methods. These points will be removed before the computation of the new Australian geoid model, and also supplied to GA for its evaluation. The small number of points identified is a very positive result, in that it shows that the Australian gravity database appears relatively gross-error-free, which bodes well for all previous studies that have relied upon it. However, it is important to point out that this evaluation is inevitably localised and thus only verifies the high-frequency gravity anomaly signal content. Subsequent studies using dedicated satellite gravimetry will be used to identify long-wavelength errors.

Key Words: gravity databases, gross error detection, data cleaning, gravity anomalies, digital elevation model.

INTRODUCTION

In exploration geophysics, errors in gravity datasets can cause the misinterpretation of subsurface structures. For instance, a gravity anomaly error may incorrectly identify a prospective target that may result in needless expensive drilling and field sampling, especially in remote areas. In physical geodesy, gravity anomaly errors propagate into geoid models thus affecting the transformation of GPS-derived heights. Gross errors (blunders) in gravity anomalies can be caused by, among other things: meter reading errors, transcription or data download errors, incorrect basestation ties, and incorrect 3D coordination of the gravity observation. Other errors are discussed in Heck (1990). It is essential to identify and remove such errors for both disciplines.

Several gross error detection options can be used to clean gravity databases, such as visual inspection of contoured/imaged gravity anomaly maps, simple gross error detection methods from the complete database records (e.g., Featherstone et al., 1997), and cross-validation against dependent and independent data sources. This paper focuses on the latter issues because the former two have already been applied to the Australian national gravity database for physical-geodetic studies (ibid.; Featherstone et al., 2001). We also acknowledge that Geoscience Australia (GA) (and its predecessors AGSO and BMR) has probably applied cleaning procedures to the database (cf. Murray, 1997; Fraser et al., 1976), though the details do not seem to have been reported in the open literature.

We first acknowledge that the gross errors suspected because of this data-driven gross-error validation are subject to a number of caveats (detailed later), which means that the users and producers of GA's national gravity database should themselves verify the so-identified points as best they can before outright rejection. However, since our procedures are very easy to implement, they can very efficiently identify points to investigate further. Moreover, since there is little auxiliary information in the on-line GA database with which to apply such a check, data-driven procedures become attractive. Nevertheless, for exploration geophysicists, 'anomalous' anomalies should be carefully investigated before simple rejection, as correctly pointed out by one of the reviewers of this paper.

GROSS ERROR DETECTION METHODS AND RESULTS

Cross-Validation of Gravity Observation Elevations

The majority of gravity observation elevations in the Australian gravity database (i.e., those from the reconnaissance surveys; Fraser et al., 1976) were determined using aneroid barometers, with an expected elevation error of 3–10 m (Barlow, 1977; Murray, 1997; Wynn, 2003, pers. comm.). In addition, the horizontal positions of these reconnaissance gravity observations were determined using scaling from aerial photography (Wynn, 2003, pers. comm.), which may only be accurate to a few hundred metres depending on the scale of the photography. In areas of steep elevation changes, any horizontal mis-registration will result in a discrepancy between the recorded station height and the elevation derived from a digital elevation model (DEM). In addition, a latitudinal error will cause an error in the latitude correction. More recently, GPS has been used to coordinate regional and local gravity surveys, so these are probably less prone to such errors (e.g., Featherstone, 1995).

A DEM can be used to validate the gravity observation elevations, and thence the computed gravity anomalies. To be completely effective, this requires the DEM to be generated from independent data sources, which is not the case for the version 2 DEM-9S of Australia (Hutchinson, 2001); the gravity observation elevations were used in the construction of this DEM. However, they were not the principal data source, so DEM-9S still provides a more-useful-than-not check on the gravity observation elevations. Another consideration is that DEM-9S provides [assumed mean] elevations over each 9-arc-sec by 9-arc-sec (~250 m) cell, whereas the gravity observation elevations are at discrete points. As such, a rejection threshold of the height difference must be chosen so as not to incorrectly disregard correct gravity observations in areas of rugged topography, where the DEM elevation is not representative of the topographic variability in each cell.

In this study, we subtracted the DEM-9S elevation, bi-cubically interpolated from the 9-arc-second grid, from the recorded elevation of each gravity observation in the 2004 release of the Australian gravity database. This used a slightly modified version of the software in Featherstone (2001). We produced a histogram of the differences (Figure

1), and then empirically deduced a threshold above which the gravity observation elevation may be suspect. For each threshold tested, the outlying observations were spatially mapped to determine if there were spatial correlations or clusters in the so-identified points that may indicate that the choice of threshold was inappropriate (Figure 2). Clearly, the selection of the threshold value is a key issue: one has to be careful not to reject valid data. However, it remains somewhat subjective.

Simple statistical or stochastic gross error detection by way of the Z-score, where observations greater than three standard deviations from the mean are considered outliers (under the assumption of a normal or Gaussian distribution) was inappropriate for this distribution because it exhibits high positive kurtosis (Figure 1). If we had [incorrectly] assumed a normal distribution, then blindly applied the usual Z-score=3 threshold, then a large amount of valid data would probably have been disregarded. This is to be expected because local topography is rarely a stochastic variable with a Gaussian distribution.

Instead, we empirically determined the threshold to be 250 m, which corresponds to the approximate position where the distribution curve in Figure 1 becomes irregular. This value is much larger than the combination of the expected errors in the DEM (say ~20 m, depending on location; Hutchinson, 2001) and the gravity observation elevations (3–10 m; Barlow, 1973), strongly indicating that these are gross errors. This approach resulted in the identification of 173 suspect points that we deem to be gross errors. We did not choose a smaller threshold because of the abovementioned limitations of correlated data and the comparison of mean and point values.

From Figure 2, most of the so-identified gross errors coincide with the more mountainous regions of Australia, notably the Great Dividing Range and Tasmania. However, a few gross errors are detected in other low-lying regions. The errors identified along the Great Dividing Range are probably due to incorrect coordination of the gravity observations, as mentioned earlier. For instance an incorrect horizontal position of the gravity observation will map it to an elevation different to that defined by the DEM. However, DEM interpolation errors and the problem of comparing mean and point data cannot be ruled out as the reasons for the differences. Nevertheless, given the small number of points, not much gravity information will be lost by deleting them from the database.

Finally, we acknowledge that the above thresholding appears somewhat arbitrary, but the high kurtosis in the data distribution prevents us from using standard statistical outlier detection routines. Nevertheless, the small number of points rejected makes the exact selection of the threshold less critical. Also, a threshold value of 250 m is very much greater than the expected precisions of the DEM and gravity observation elevations. Recall also that there is a correlation between the gravity station elevations and the DEM, so one would expect that this method would identify fewer points. Perhaps when the Shuttle Radar Topography Mission (SRTM) DEM product is properly cleaned over Australia, it may assist in the identification of more points because it is a truly independent source of elevation data; that could be the subject of a later validation.

For the purpose of illustration, we plot an example in Figure 3 of a case where there is a clear difference between the gravity observation elevation and the mean elevation stated in the version 2 DEM-9S Australian digital elevation model. Clearly, the elevation difference is anomalous, indicating a likely error in the gravity station elevation.

Self-Consistency of Nearby Gravity Anomalies

This method rests upon the assumption of a high spatial correlation of proximal gravity anomalies after the best-possible reduction of short-wavelength gravitational contributions (notably terrain effects). However, this assumption is violated in regions where there are steep horizontal gravity gradients in areas of small topographic variation (as is common on the heavily weathered Australian continent). These are mostly due to lateral variations in topographic mass-density. Therefore, it should be used in conjunction with prior knowledge of the local geology (where available).

Complete (or refined) Bouguer gravity anomalies were recomputed from the national gravity database using second-order free-air corrections, a closed (not Chebyshev polynomial) approximation of normal gravity in the so-called latitude correction (Featherstone and Dentith, 1997), a planar simple Bouguer correction, and band-limited terrain corrections computed by Kirby and Featherstone (2002). The terrain corrections were bi-cubically interpolated from the precomputed 9-arc-second grid to the gravity observation locations. All Bouguer gravity anomalies used a constant topographic density of 2670 kg.m^{-3} as no nation-wide digital topographic mass-density model is currently available. The error in the so-determined Bouguer gravity anomalies is coarsely estimated to be 2–3 mGal (Featherstone et al., 2001).

For this method to be effective, the interpolation of gravity from surrounding points to the point of interest must be as accurate as possible. Here we use complete Bouguer anomalies because these are smoother than the raw gravity observations or free-air anomalies, and thus less subject to aliasing. However, Goos et al. (2003) have shown that the inclusion of terrain corrections in Australia does not make an appreciable difference on the interpolation accuracy. We acknowledge that there are several options for interpolating gravity data, such as tensioned splines (e.g., Smith and Wessel, 1990; Featherstone et al., 2001) or least squares collocation (e.g., Tscherning and Forsberg, 1981). In this study, we used inverse-distance weighting. From our earlier (unpublished) work, the choice of the interpolation algorithm is not critical, so we chose the inverse-distance weighting principally for reasons of computational convenience.

All complete Bouguer gravity anomalies within a spherical cap of 0.125° (~13 km) radius, centred on the location of each gravity observation being considered, were interpolated to that point through the inverse-distance-weighted mean. This search radius of ~13 km was chosen because this is slightly larger than the typical ~11 km spacing of the majority of the reconnaissance gravity surveys (Fraser et al., 1976; Murray, 1988). As a result, each interpolation generally included at least four surrounding points, except for points (notably, coastal) that could not be validated in this way. These points were ignored. Naturally, the number of points used in the inverse-distance-weighted mean increases in areas where more recent, spatially dense surveys have been conducted. The validation is therefore more powerful in these regions (Figure 4). It should also be noted that many instances of repeated observations were found within the database. Since it could not be established whether these repetitions were database errors or re-observations, they were not removed from the database.

As with the elevation-based validation, a histogram of the differences between each complete Bouguer gravity anomaly in the Australian gravity database and the value interpolated from the surrounding points was plotted (Figure 5), and then the threshold determined empirically. Statistical outlier detection by means of a Z-score=3 was also inappropriate for this distribution because of its high positive kurtosis. A threshold level of 35 mGal was identified as the approximate position where the distribution in Figure 3 becomes irregular. This is much larger than the expected error in the gravity anomalies (2–3 mGal) and the interpolation error, even in areas of likely high topographical density contrasts (e.g., the Darling Basin).

As well as this empirical selection of the threshold, a certain amount of subjectivity was also necessary to avoid the problem of incorrect gross error detection due to geology. The threshold of 35 mGal was verified by plotting the locations of the so-identified gross errors (Figure 6), to confirm that they were more-or-less randomly distributed. This resulted in the detection of 73 suspected gross errors. Still, several of the points in Figure 6 still correlate well with areas of known steep horizontal gravity gradients (notably the Darling Fault in Western Australia and the Macdonald Ranges in central Australia). However, it is unlikely that 35 mGal inconsistencies with surrounding anomalies are *always* caused by geological structures, and are more likely to be gross errors.

For the purpose of illustration, we plot an example in Figure 7 of a case where there is a clear difference between the gravity observation and the surrounding observations. Clearly, the difference is anomalous, indicating a likely error in the gravity observation.

It was pointed out by one reviewer of this paper that a 35-mGal surface gravity anomaly contrast corresponds to 2800 m of sediments adjacent to a basement with a mass-density contrast of 300 kg.m^{-3}. While this could be accounted for by the Darling Basin, more than a handful of gravity observations should identify such a massive feature. Nevertheless, the clustering observed in Figure 6 warrants external validation to support the data-driven validation given here. In such cases, geology- and original-observation-informed validation is a useful supplement, as mentioned in the Introduction.

SUMMARY, DISCUSSION AND CONCLUSIONS

This study has used two complementary, yet data-driven, approaches to detect gross errors in Australian land gravity anomalies: a consistency check against a partially independent DEM, and a consistency check against surrounding gravity anomalies. Care was needed in the selection of a realistic threshold value to avoid the rejection of good data. Standard statistical outlier detection could not be used because the histograms of the differences exhibited high positive kurtosis, thus invalidating any outlier detection based on the Z-score.

The DEM-based validation identified 173 suspect points, where the magnitude of the differences between gravity observation and DEM elevations were greater than 250 m. The gravity-based validation using inverse-distance-weighted means of neighbouring gravity anomalies identified 73 suspect points, where the magnitude of the differences between point and interpolated complete Bouguer gravity anomalies were greater than 35 mGal. Only nine points in the dataset of 1 106 984 observations were identified by both methods, giving a total of 237 suspected gross errors (0.021%). It does not necessarily follow that a point identified as a gross error by the elevation validation will also be detected by the gravity validation, because some of the elevation error is likely due to error in the horizontal position of the gravity value, which will not affect the computed Bouguer anomaly.

It is important to recapitulate the limitations of the techniques used: 1) the DEM is not totally independent of the gravity observation elevations so will not be completely effective in areas where the DEM elevations are controlled largely by gravity observation elevations; 2) the gravity-based validation does not fully take into account variations in geology because it is data-driven; and 3) the validations only consider the high-frequency gravity field as governed by the 250-m resolution of the DEM and the ~13 km search radius for neighbouring gravity anomalies.

Despite these caveats, this validation does give a positive result in that it shows that the high-frequency content of the Australian land gravity database is extremely good. A subsequent study will investigate the presence of long-wavelength [systematic] errors in the land gravity anomalies using gravity anomalies implied by the GRACE dedicated satellite gravity mission (cf. Featherstone, 2003). Finally, is it is still important for exploration geophysicists and physical geodesists to be cognisant whether discrepancies indicate features of interest or simple gross errors.

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REFERENCES

Barlow, B.C., 1977, Data limitations on model complexity; 2-D gravity modelling with desk-top calculators: *Bulletin of the Australian Society of Exploration Geophysicists*, **8**, 139–143.

Featherstone, W.E., 1995, The Global Positioning System (GPS) and its use in geophysical exploration: *Exploration Geophysics*, **26**, 1–18.

Featherstone, W.E., 2001, Absolute and relative testing of gravimetric geoid models using Global Positioning System and orthometric height data: *Computers and Geosciences*, **27**, 807–814, doi: 10.1016/S0098-3004(00)00169-2.

Featherstone, W.E., 2003, Regional gravity anomalies from global spherical harmonic models: *Preview*, **104**, 28–33.

Featherstone, W.E., and Dentith, M.C., 1997, A geodetic approach to gravity reduction for geophysics: *Computers and Geosciences*, **23**, 1063–1070.

Featherstone, W.E., Kearsley, A.H.W., and Gilliland, J.R., 1997, Data preparations for a new Australian gravimetric geoid: *The Australian Surveyor*, **42**, 33–44.

Featherstone, W.E., Kirby, J.F., Kearsley, A.H.W., Gilliland, J.R., Johnston, G.M., Steed, J., Forsberg, R., and Sideris, M.G., 2001, The AUSGeoid98 geoid model of Australia: data treatment, computations and comparisons with GPS-levelling data: *Journal of Geodesy* **74**, 239–248, doi: 10.1007/s001900100177

Fraser, A.R., Moss, F.J., and Turpie, A., 1976, Reconnaissance gravity survey of Australia: *Geophysics*, **41**, 1337–1345.

Goos, J.M., Featherstone, W.E., Kirby, J.F., and Holmes, S.A., 2003, Experiments with two different approaches to gridding terrestrial gravity anomalies and their effect on regional geoid computation: *Survey Review*, **37(288)**, 92–112.

Heck, B., 1990, An evaluation of some systematic error sources affecting terrestrial gravity anomalies: *Bulletin Géodésique*, **64**, 88–108.

Hutchinson, M.F. (ed.), 2001, *GEODATA 9 second DEM (version 2): Data users guide*: Geoscience Australia, Canberra, 46pp [Web document]. Accessed 21 April, 2006. Available at <http://www.ga.gov.au/image_cache/GA4783.pdf>.

Kirby, J.F. ,and Featherstone, W.E., 2002 A high-resolution grid of complete Bouguer gravity reductions over Australia: *Exploration Geophysics*, **33**, 161–165.

Murray, A.S., 1997, The Australian national gravity database: *AGSO Journal of Australian Geology and Geophysics*, **17**, 145–155.

Smith, W.H.F., and Wessel, P., 1990, Gridding with continuous curvature splines in tension: *Geophysics*, **55**, 293–305.

Tscherning, C.C., and Forsberg, R., 1992, Harmonic continuation and gridding effects on geoid height prediction: *Bulletin Géodésique*, **66**, 41–53.

Wessel, P., and Smith, W.H.F., 1998, New, improved version of Generic Mapping Tools released: *EOS - Transactions of the American Geophysical Union*, **79(47)**, 579.

FIGURE CAPTIONS

Fig. 1:

Histogram of the differences between the 1 106 984 gravity station elevations stored in the 2004 release of the Australian gravity database and elevations bi-cubically interpolated from the version 2 DEM-9S Australian digital elevation model (units are metres).

Fig. 2:

Map of suspected gross errors in the Australian gravity database as determined from the version 2 DEM-9S Australian digital elevation model, with a threshold level of 250 m. (Lambert conformal conical projection).

Fig. 3:

Example of a gravity observation elevation that differs from the version 2 DEM-9S Australian digital elevation model of Australia (units are metres; linear projection).

Fig. 4:

Spatial coverage of the 1 106 984 Australian land gravity observations in the 2004 data release from Geoscience Australia (Lambert conformal conical projection).

Fig. 5:

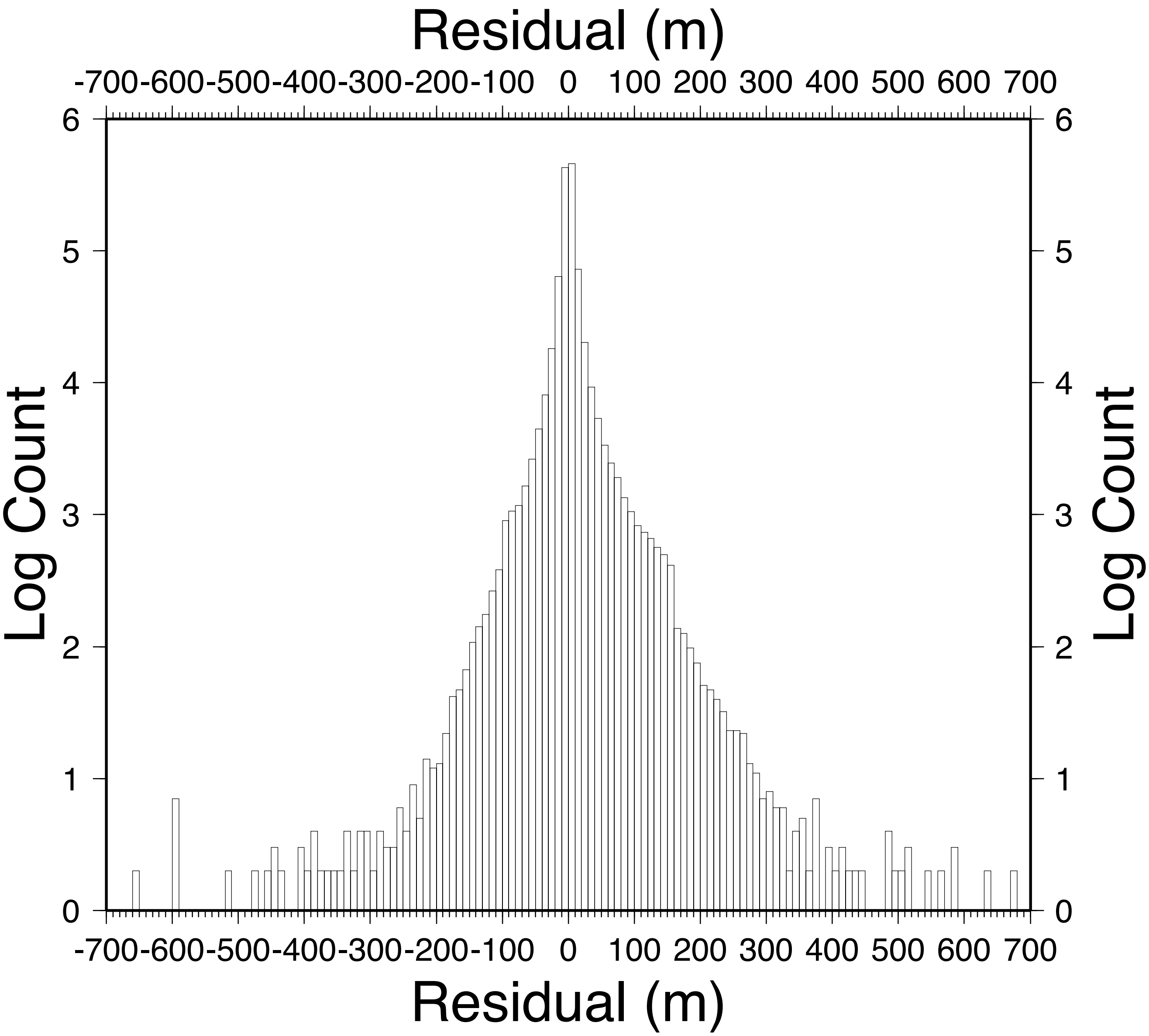
Histogram of the differences between the 1 106 984 gravity observations and the inverse-distance-weighted mean of its neighbours (units are mGal).

Fig. 6:

Map of suspected gross errors in the Australian gravity database as determined from the weighted mean of neighbours, with a threshold level of 35 mGal (Lambert conformal conical projection).

Fig. 7:

Example of a gravity observation outlier (units are mGal; linear projection).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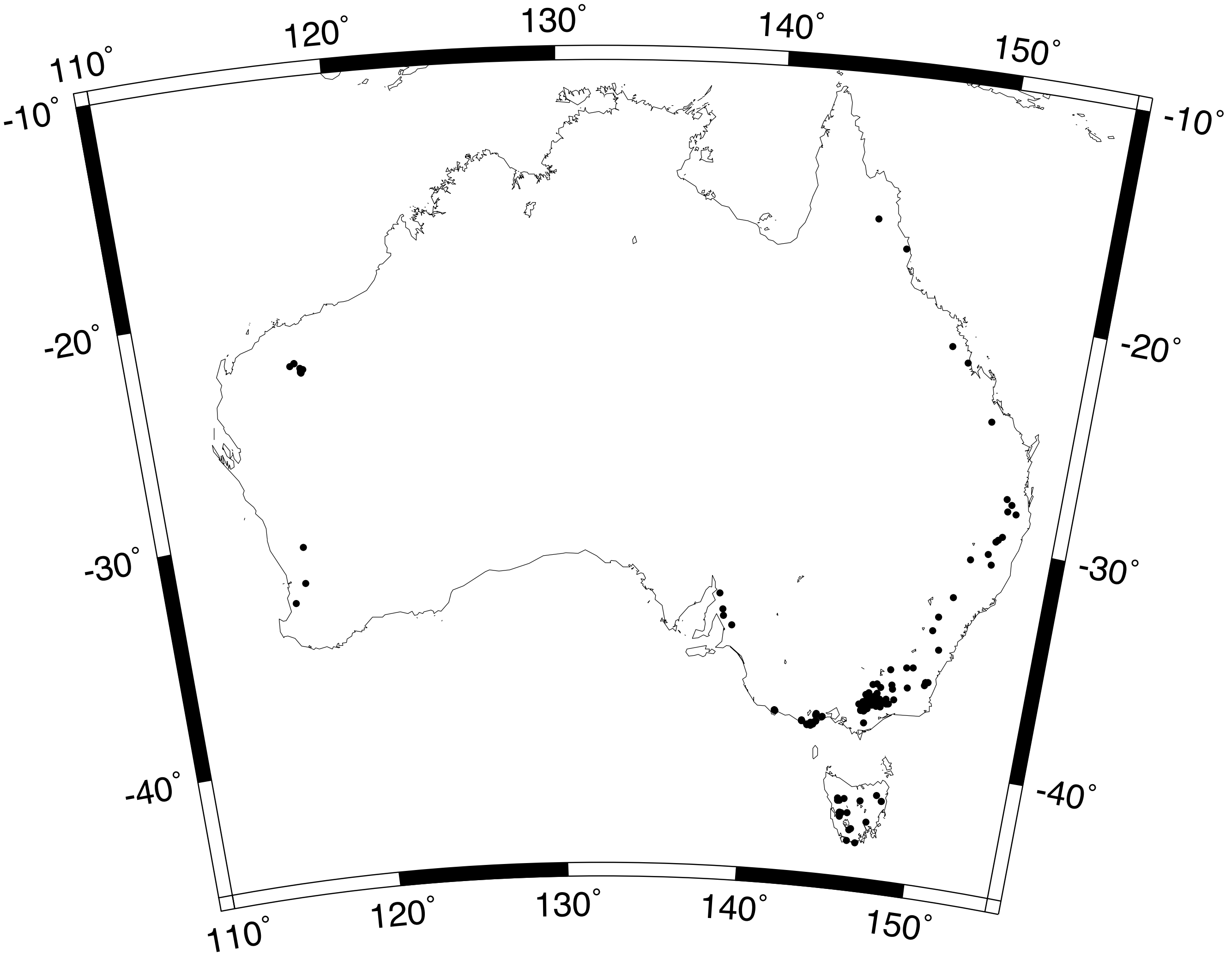
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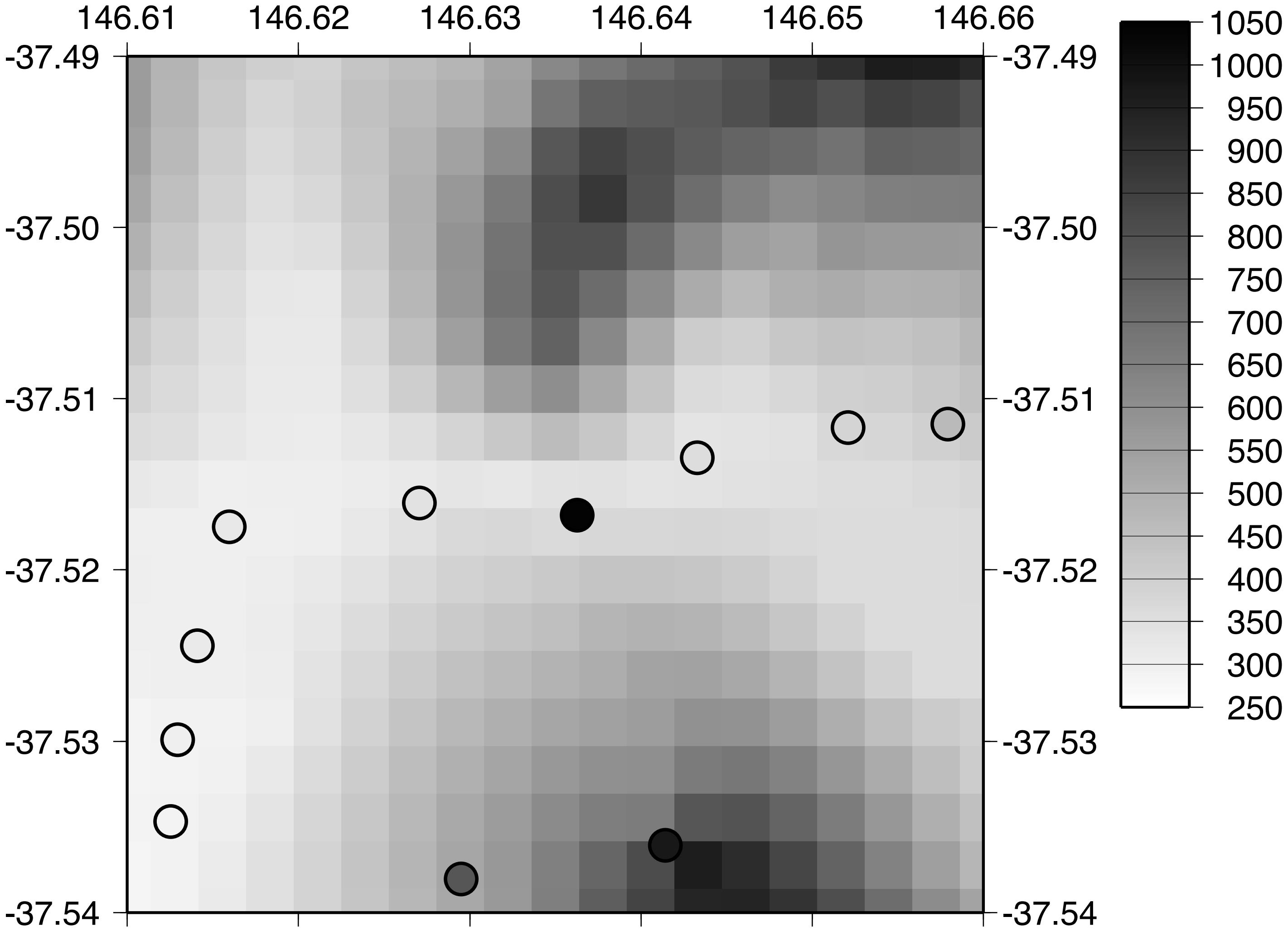
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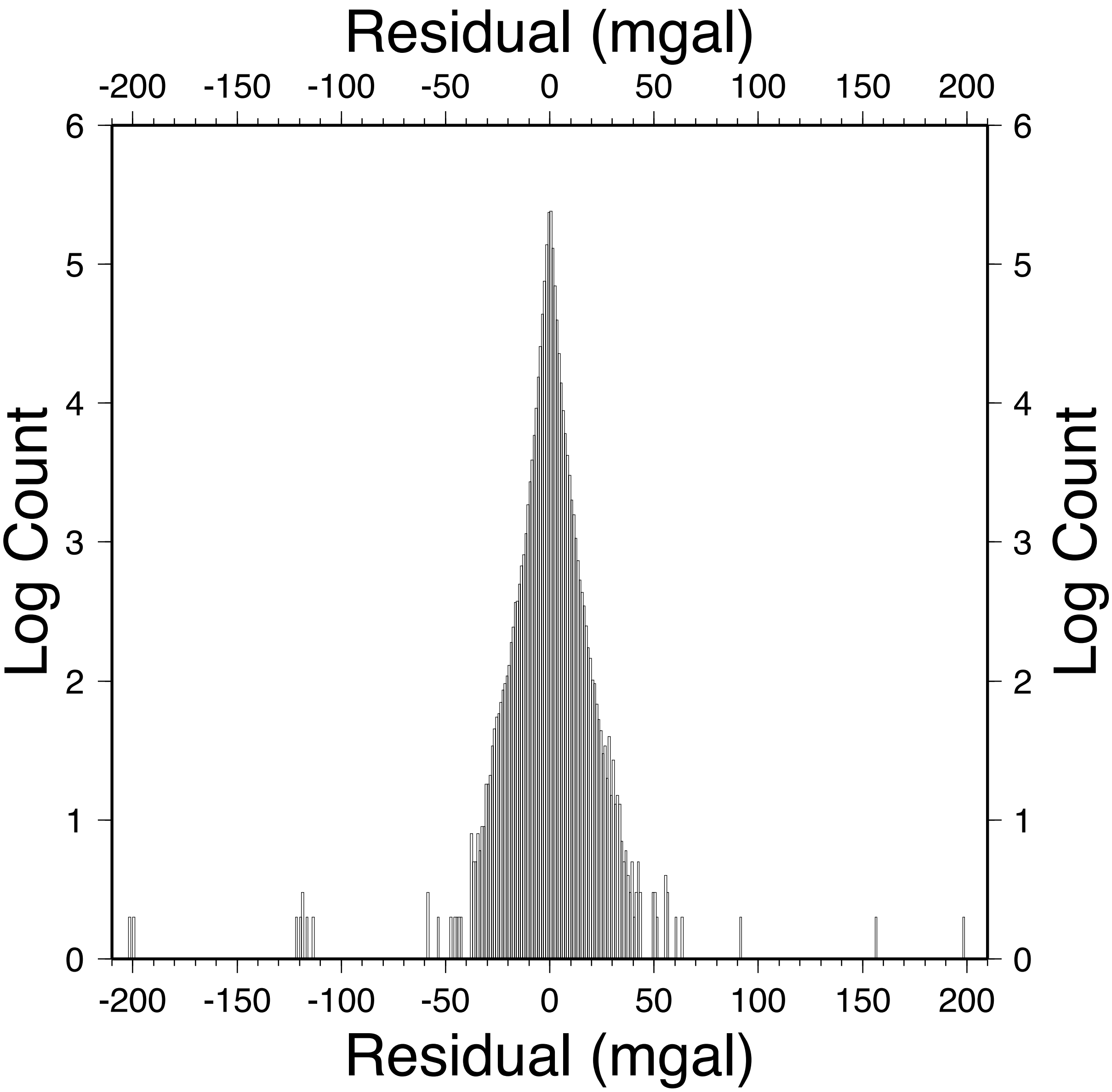
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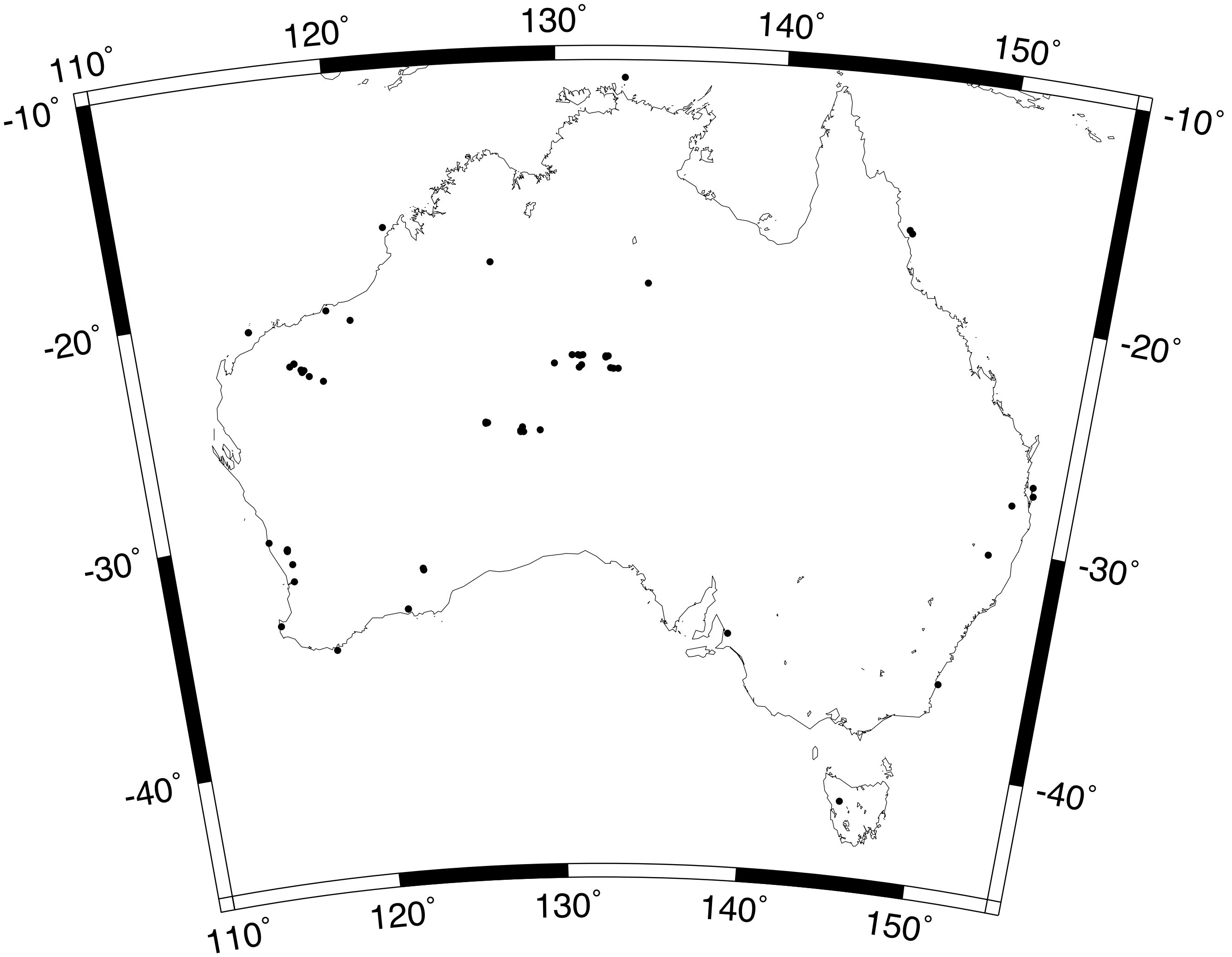
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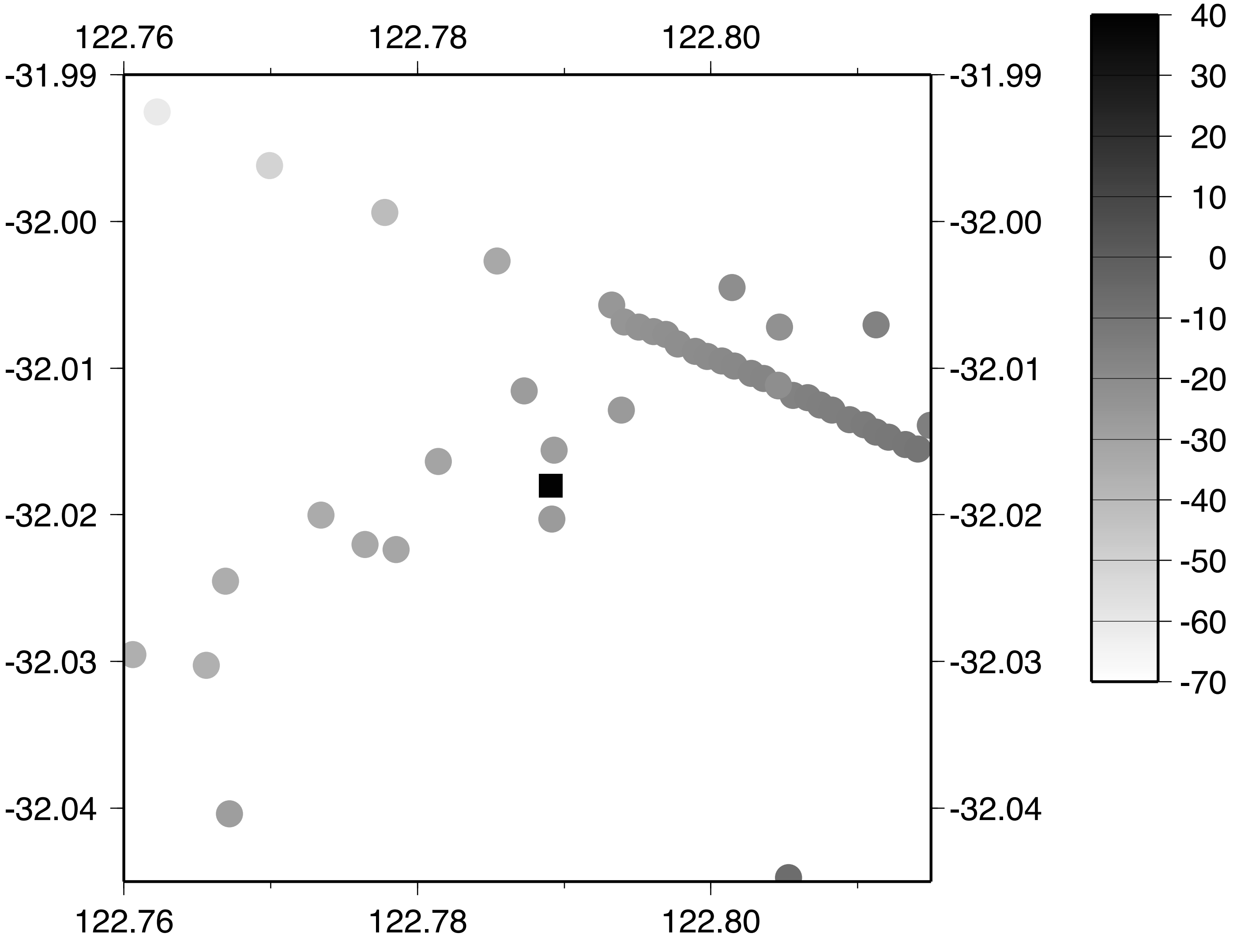
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