Incorporating Airborne Gravity Gradiometer Data into Regional Ground Gravity Sets

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Abstract

We introduce a work-flow to incorporate high-resolution, low-noise airborne gravity gradiometer (AGG)-derived gravity data into regional ground gravity data sets. The processing sequence takes into account that: (1) the AGG-derived gravity data has not been computed on the ground; (2) the AGG-derived gravity data only contain fully sampled wavelengths up to the smallest survey dimension; (3) the noise in the AGG-derived gravity data increases with longer wavelengths; and, (4) the AGG-derived gravity data is often over-sampled. We demonstrate the work-flow on an AGG data set from the Eastern Succession in Queensland, Australia.

Introduction

FALCON airborne gravity gradiometer (AGG) systems have been operational since 1999, and over three million line-kilometers of data have been acquired. With this wealth of data, we are facing the problem of how to best incorporate the acquired AGG data into existing national and commercial repositories of geophysical data.

The AGG systems record the gravity gradient curvature components of the Earth's gravity field. In post-mission processing, the AGG equivalent of the fully terrain corrected Bouguer gravity anomaly is derived from the observed gravity gradient tensor components (Dransfield, 2007). The AGG-derived Bouguer gravity data is characterized by good lateral resolution and low noise, when compared with conventional airborne gravity (Dransfield and Christensen, 2013). The lateral resolution of the AGG-derived Bouguer gravity data depends jointly on the along-line filtering applied to the AGG data and on the traverse line spacing of the airborne survey. Typically AGG data is filtered to a resolution of 150 m - 200 m. Recent surveys at the R. J. Smith AGG Test Site in Western Australia indicate that the standard deviation of the noise of the AGG-derived airborne Bouguer gravity data is 0.1 mGal for wavelengths up to 5 km (Christensen, 2013; Christensen and Dransfield, 2014).

Many national geological surveys and commercial groups now maintain extensive repositories of country-wide or regional ground gravity observations. The lateral resolution of these ground gravity data depends on the station spacing of the observations, typically ranging from few hundreds of meters to tens of kilometers. The standard deviation of the noise in the ground gravity data compilations is more difficult to ascertain, as the data sets in the compilations have different provenance and vintage.

It would be beneficial if the high-resolution, low-noise AGG-derived Bouguer gravity data could be included in these repositories in a consistent workflow (Lane, 2004). In order to achieve this, a number of data issues must be addressed:

The AGG-derived Bouguer gravity data has not been computed on the ground: Typically the AGG-derived Bouguer gravity data is computed on a smoothed surface draped over the topography of the survey area. This computational surface is typically placed at the nominal survey height above the ground. In order to incorporate the AGG-derived Bouguer gravity data with the regional ground gravity data we need to first downward continue the airborne data from the smoothed computation surface to the ground surface.

The AGG-derived Bouguer gravity data only contain fully sampled wavelengths up to the smallest survey dimension: The maximum wavelength of the Bouguer gravity data that can be completely recovered from any observed gravity gradiometer tensor components depends on the spatial extents of the survey. If a survey is 20 km by 20 km, then the longest Bouguer gravity data wavelength that can be fully recovered is 20 km. If a survey is 20 km by 40 km, then the longest fully-sampled Bouguer gravity data wavelength that we can fully recover is 20 km. Note that wavelengths between 20 km and 40 km are indeed present in the recovered Bouguer gravity data, but these will be incomplete and potentially erroneous, as these wavelengths have not been fully sampled in all directions. Hence the longest wavelength information that we can reliably recover in the AGG-derived Bouguer gravity data is equivalent to smallest dimension of the survey extents. In order to incorporate the AGG-derived Bouguer gravity data with the regional ground gravity data we ought to remove from the AGG-derived Bouguer gravity data any possibly erroneous wavelength components that are longer than the smallest dimension of the survey extents.

The noise in the AGG-derived Bouguer gravity data increases with longer wavelengths: The noise in any gravity gradiometer-derived Bouguer gravity data is dependent on the wavelength of the data. Generally the noise increases with longer wavelengths. This means the longer wavelength components of derived Bouguer gravity data are not as reliable as the shorter wavelength components (Dransfield and Christensen, 2013). At some wavelength the accuracy of the existing regional ground gravity data will be better than the derived Bouguer gravity. We have found that this typically occurs in the 20 km – 30 km wavelength range. Boggs and Dransfield

(2004) and Dransfield (2010) demonstrated how AGG-derived Bouguer gravity data could be conformed to regional ground gravity by substituting the long wavelength information in the AGG-derived Bouguer gravity data with long wavelength information from the existing regional datasets. In order to incorporate the AGG-derived Bouguer gravity data with the regional ground gravity data we ought to conform the long wavelengths in the AGG-derived Bouguer gravity data to the existing regional ground gravity data.

The AGG-derived Bouguer gravity data is often over-sampled: During data processing the observed AGG data is typically low-pass filtered to 150 m – 200 m resolution. The data is typically delivered at 6 m sampling interval (equivalent to 0.1 Hz at 60 m/s flight speed) in order to provide co-location with GPS, magnetic and other high-rate data streams. In order to incorporate the AGG-derived Bouguer gravity data with the regional ground gravity data it is advantageous to down-sample the data to the actual along-line spatial resolution.

Method

Given the issues discussed above, the proposed method of incorporating the AGG-derived Bouguer gravity data with the regional ground gravity data follows the suggestions by Lane (2004) and Dransfield (2010):

1. Downward continue the AGG-derived Bouguer gravity data from the original computational surface to the ground surface. Over flat survey terrain with a consistent survey drape this may be accomplished by Fourier domain filtering. For surveys in rugged terrain or for surveys with varying terrain clearance this may be accomplished by equivalent source techniques (Phillips, 1996).

2. Low-pass filter the downward-continued AGG-derived Bouguer gravity data to the original resolution to minimize short-wavelength noise amplification from the downward continuation process.

3. Determine the appropriate cut-off wavelength for the conforming process:

   Consider the resolution (average station spacing) of the existing regional ground gravity data in the AGG survey area. Determine the smallest wavelength that has been sampled adequately in the existing regional ground gravity data - both east-west and north-south - through-out the entire AGG survey area.

   Determine the smallest dimensional extent of the AGG survey. This indicates the largest wavelength component that has been adequately sampled in the AGG-derived Bouguer gravity data.

   There should be a good overlap between the smallest wavelength that has been sampled adequately in the existing regional ground gravity data and the largest wavelength component that has been adequately sampled in the AGG-derived Bouguer gravity data. Within this overlap in wavelengths choose a wavelength cut-off for the conforming process to follow. Typically the cut-off wavelength should be in the 20 km – 30 km range (Dransfield, 2010).

4. Conform the AGG-derived Bouguer gravity data to the regional ground gravity data: using the chosen cut-off wavelength, first high-pass filter the downward-continued AGG-derived Bouguer gravity data, then low-pass filter the regional ground gravity data, and finally add the two filtered results together to produce the conformed AGG-derived Bouguer gravity data. To assure a consistency across the filtering range use matching second-order cosine roll-off high pass/low pass filters across a 10km wavelength range centered on the cut-off wavelength. Dransfield (2010) describes the grid-based process in detail.

5. Resample the conformed AGG-derived Bouguer gravity grid to the original survey flight lines, and down-sample the data to the actual spatial resolution (typically 150 m – 200 m).

6. Merge the downward-continued, conformed, down-sampled AGG-derived Bouguer gravity data with the regional ground gravity station data.

Examples

We demonstrate the outlined methodology on an AGG data set from the Eastern Succession in Queensland, Australia. The AGG survey was flown in 2000 by BHP Billiton for base metal exploration. The 30,000 line kilometer survey was flown at 200 m traverse line-spacing, covering an area of approximately 60 km by 120 km (Figure 1a). During the original processing the AGG data was low-pass filtered with 400 m cut-off wavelength, yielding a 200 m along line resolution. Figure 1b shows the regional ground gravity station distribution over the AGG survey area. There are a total of 9,100 ground gravity stations in the region depicted on the map, of which 3,200 fall within the AGG survey area.

Within the AGG survey area there are several ground gravity surveys with station spacing of only a few hundred meters. However, when the entire AGG survey area is considered, then the smallest wavelength that has been sampled consistently by ground gravity is of the order of 4 km. The smallest dimensional extent of the AGG survey area is of the order of 15 km – 20 km. Based on these observations we have chosen a cut-off wavelength of 20 km for conforming the AGG-derived Bouguer gravity data to the regional ground Bouguer gravity data. Figure 2a shows the existing regional ground Bouguer gravity. The low-pass filtered regional ground Bouguer gravity is shown in Figure 2b. The low-pass filtered regional ground Bouguer gravity is masked to the AGG survey extents (Figure 2c). The survey terrain is predominantly flat with only 150 m change in elevation over 120 km. The computational drape is almost constantly 80 m above ground (mean terrain clearance = 80.2 m, standard deviation = 1.7 m). Under these circumstances downward continuation by Fourier domain filtering is warranted. Figure 2d shows the AGG-derived Bouguer gravity, downward-continued 80 m to nominal ground level and low-pass filtered at original 400 m cut-off wavelength to minimize noise contamination from the downward continuation. Figure 2e shows the AGG-derived Bouguer gravity, downward continued, and high-pass filtered at 20 km cut-off wavelength. Finally we have added the low-pass filtered regional ground Bouguer gravity (Figure 2c) and the high-pass filtered AGG-derived Bouguer gravity (Figure 2e) which yields conformed AGG-derived Bouguer gravity conformed to the regional ground Bouguer gravity at 20 km cut-off wavelength (Figure 2f).

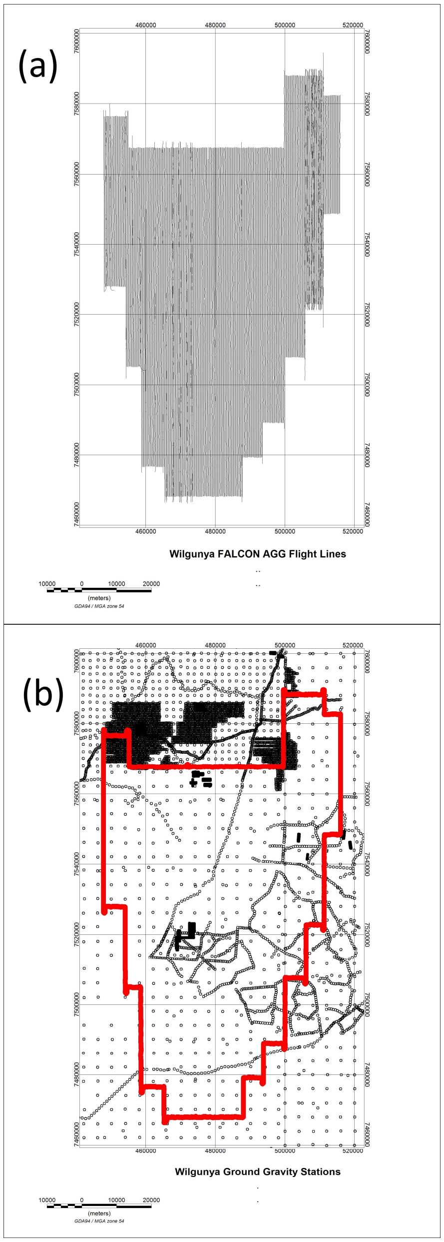

Figure 1 (a) Map of the AGG survey flight lines. (b) Map of the distribution of the regional ground gravity stations. The AGG survey outline is marked in red.

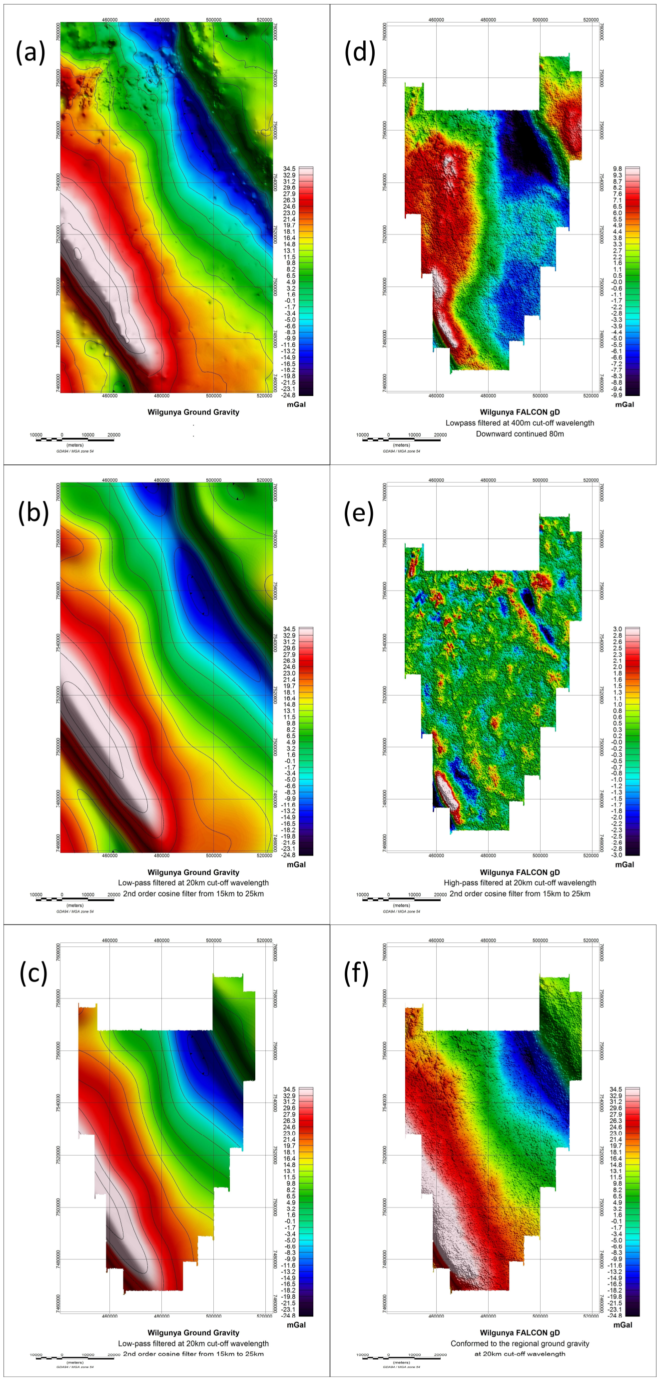

Figure 2 (a) Regional ground Bouguer gravity. (b) Regional ground Bouguer gravity – low pass filtered at 20 km cut-off wavelength. (c) Regional ground Bouguer gravity, low-pass filtered and masked to the AGG survey extents. (d) AGG-derived Bouguer gravity, downward-continued 80m to nominal ground level. (e) AGG-derived Bouguer gravity, downward continued, and high-pass filtered at 20 km cut-off wavelength. (f) AGG-derived Bouguer gravity conformed to the regional ground Bouguer gravity at 20 km cut-off wavelength.

The conformed AGG-derived Bouguer gravity now fits well onto the regional ground Bouguer gravity (Figure 3). We can now get an estimate of the quality of the ground gravity data within the AGG survey area by evaluating the difference between the conformed AGG-derived Bouguer gravity and the 3,200 ground gravity data points on a station by station basis. The differences range from -4.0 mGal to +4.1 mGal, with a mean of 0.4 mGal and standard deviation of 0.7 mGal. Figure 4 shows the spatial distribution of the differences. The figure indicates that the regional 4 km by 4 km ground gravity network is in general good agreement with the conformed AGG-derived Bouguer gravity with differences within the +/- 0.7 mGal range. The local high resolution ground gravity surveys do however appear to have persistent DC level issues. It is a common occurrence that explorers focussing on smaller high-resolution gravity survey work omit to pay sufficient attention to tying in the data to the national data grid. The consistent DC level differences observed with the respect to the conformed AGG-derived Bouguer data, could be used to better tie the high-resolution ground gravity data surveys to the national data grid.

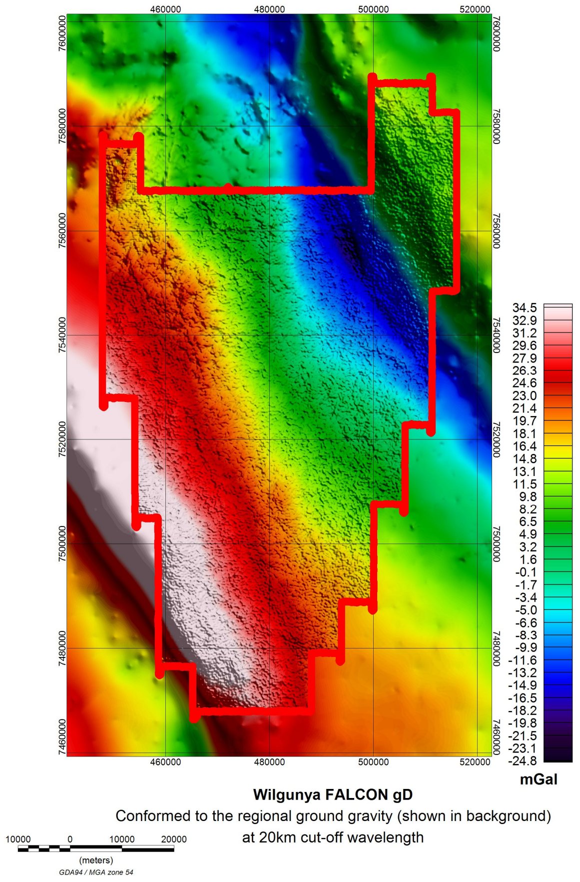

Figure 3 AGG-derived conformed Bouguer gravity with regional ground Bouguer gravity plotted in the background.

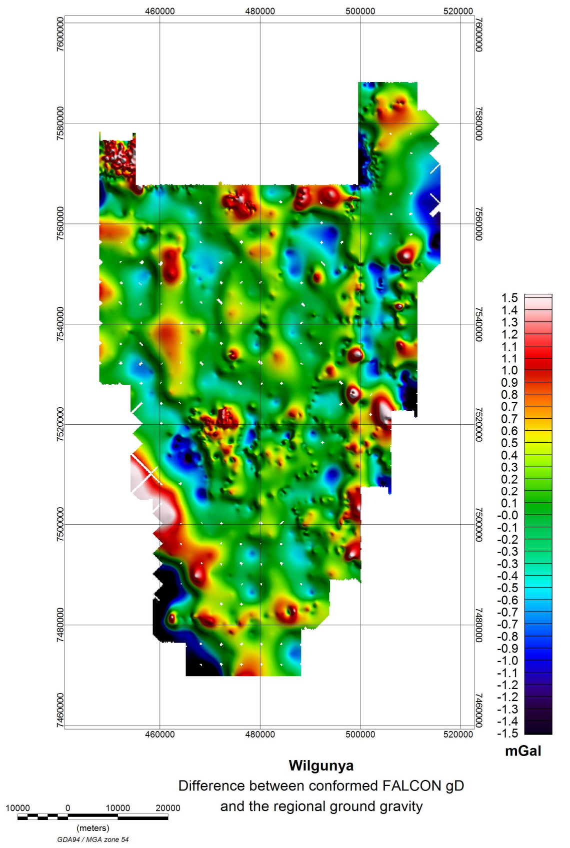

Figure 4 Gridded difference between the conformed AGG-derived Bouguer gravity and the ground gravity stations within the AGG survey area.

An additional source of error in the regional ground gravity data set is inaccurate terrain elevation estimates. In contrast the AGG survey operation includes a laser scanner which yields a high resolution, high accuracy digital elevation model used for terrain correction of the AGG data. Figure 5a shows the Digital Elevation Model (DEM) derived from the on-board laser scanner. Figure 5b shows the alternate DEM derived from the sparse and at times inaccurate terrain elevation values in the ground gravity data set. Figure 5c shows the gridded difference between the AGG laser scanner DEM and the 3,200 terrain elevation values in the ground gravity data set. The differences range from -16 m to +15 m, with a mean of -0.7 m and a standard deviation of 2.3 m. The high-resolution, high-accuracy AGG laser scanner DEM information could be used to reprocess all ground gravity stations with excessive terrain elevation differences.

We then resampled the conformed AGG-derived Bouguer gravity grid onto the original survey flight lines, and down-sampled the data to the actual spatial resolution of 200 m. We finally merged the downward-continued, conformed, down-sampled AGG-derived Bouguer gravity data with the regional ground gravity station data.

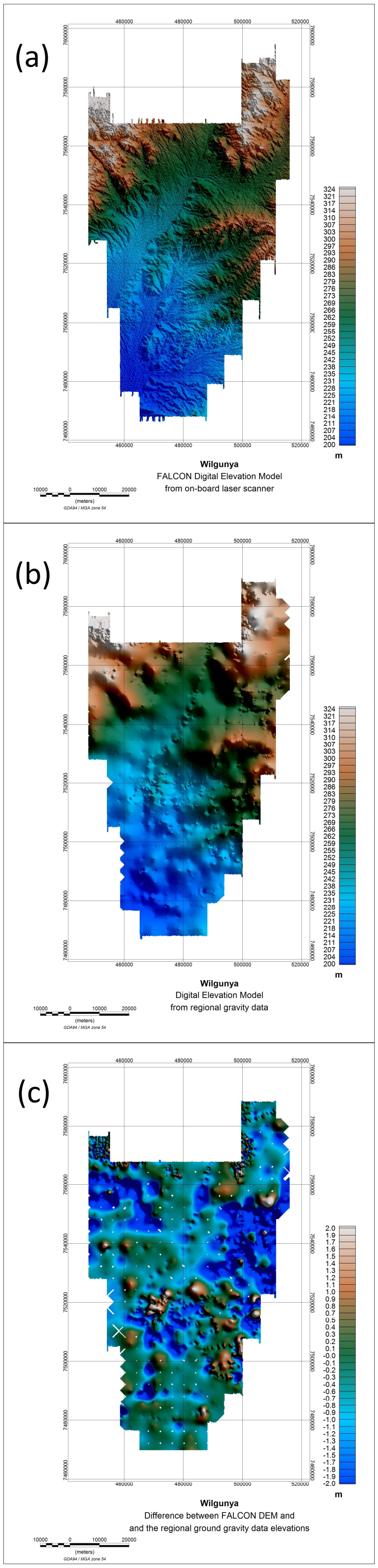

Figure 5 (a) Digital Elevation Model derived from the on-board laser scanner. (b) Digital elevation model derived from the regional gravity data set. (c) Difference map of the elevations derived from the on-board laser scanner and from the regional gravity data set.

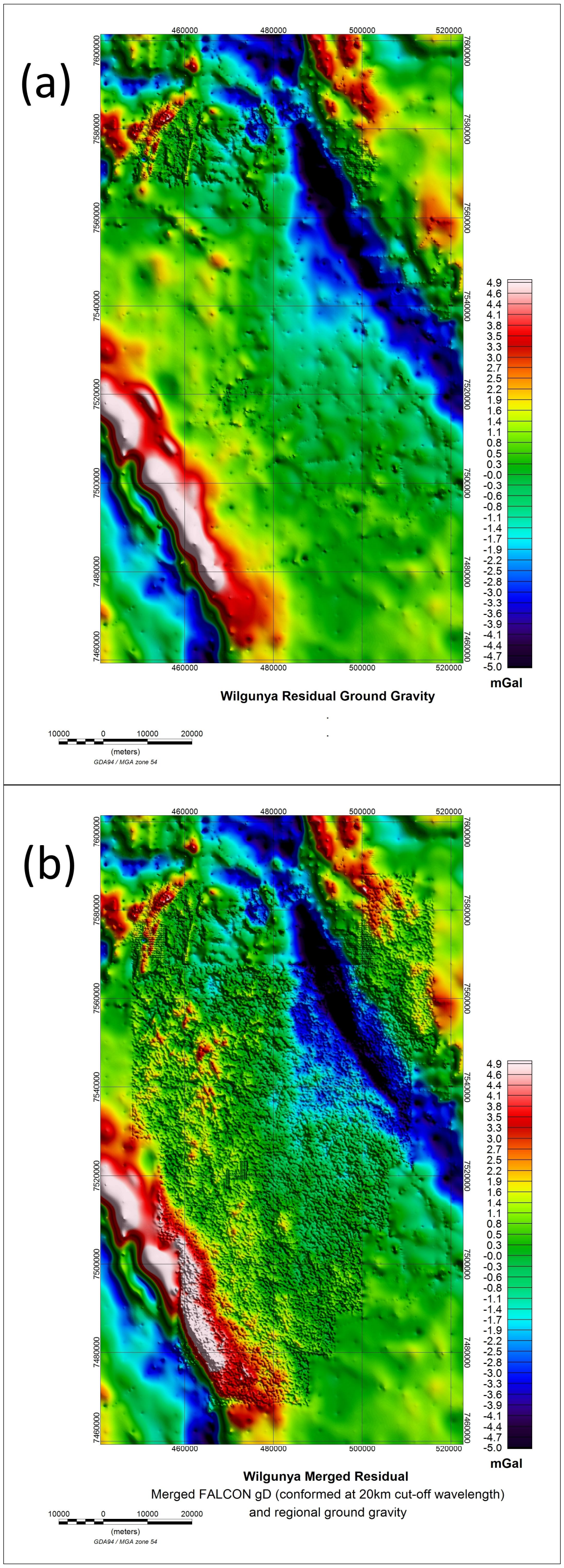

Figure 6 (a) Residual of ground gravity after regional-residual separation filtering. (b) Residual of the merged conformed AGG-derived Bouguer gravity and ground gravity after regional-residual separation.

Results

To demonstrate the improvement in resolution resulting from incorporating the AGG data into the regional ground gravity data set, we now consider the residual gravity resulting from regional-residual separation filtering. We construct a regional-residual separation filter by subtracting 2 km upward continued data from the original data (Jacobsen, 1987). Figure 6a shows the residual of the ground gravity after regional-residual separation filtering. Figure 6b shows the residual of the merged conformed AGG-derived Bouguer gravity and ground gravity after regional-residual separation. Note the improvement in resolution and the imaging of subtle gravity variations over the extent of the AGG survey. Note also the general agreement between the longer wavelengths of the ground gravity and the conformed AGG-derived Bouguer gravity near the perimeter of the AGG survey.

Conclusions

We have outlined and demonstrated a work-flow by which AGG data can be effectively incorporated into regional ground gravity data sets.

The method requires a good overlap between the smallest wavelength that has been sampled adequately in the existing regional ground gravity data and the largest wavelength component that has been adequately sampled in the AGG-derived Bouguer gravity data. If this should not be the case, i.e. a regional ground gravity data set with large station spacing and an AGG survey of limited extent, then the method will fail.

The method requires that we first downward-continue the AGG-derived Bouguer gravity data from the smoothed computation surface to the ground surface. Over flat survey terrain with a consistent survey drape terrain clearance this may be accomplished by Fourier domain filtering. For surveys in rugged terrain or for surveys with varying terrain clearance the downward-continuation may be accomplished by equivalent source techniques. The equivalent source technique requires extensive inversion capacity – especially for large AGG surveys.

Hence, for future large national agency mapping surveys, we recommend that one of the deliverables from the survey provider should be the AGG-derived Bouguer gravity data computed on the topography of the survey area. This will eliminate the downward continuation step in the work-flow.

The inclusion of the AGG-derived data allows us to perform additional QA/QC on ground gravity data within the AGG survey area: we can get an estimate of the quality of the ground gravity data within the AGG survey area by evaluating the difference between the conformed AGG-derived Bouguer gravity and the ground gravity data points on a station by station basis. In addition the high-resolution, high-accuracy AGG laser scanner DEM could be used to reprocess all ground gravity stations within the AGG survey area exhibiting excessive terrain elevation differences.

Acknowledgments

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