GEOPHYSICAL AND PETROLOGICAL APPLICATIONS OF NEW-GENERATION SATELLITE-DERIVED GRAVITY DATA: WHAT CAN AND NEEDS TO BE DONE?

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ABSTRACT

New-generation satellite-derived gravity and gradient data from CHAMP, GRACE and, in particular, GOCE will be especially useful for studies of the Earth's crust and upper mantle. The advantage of these new models is that they provide gravity information (1) for areas previously lacking data and (2) that is continuous and consistent across natural and artificial boundaries. However, before the new satellite gravity and gradient data are applied to geophysical applications, new methods must be developed and tested. In particular, methods are required for dealing with the computation of Bouguer anomalies. The resolving power of the satellite gravity must also be quantified in order to ascertain the degree to which the satellite data resolves lithospheric structures. This can be achieved by comparing the satellite data to gravity and gradients predicted from existing 3D density models. Another test of the satellite-derived data is to compare it to the gravity field predicted by independently-determined density models that use new petrologically- and thermodynamically-based methods.

Potential applications of the new satellite data in studies of the crust and upper mantle are numerous. The long-wavelength nature of the satellite gravity data mean that they may be useful for regional–residual field separation. New density models constrained by satellite data will extend existing interpretations and provide new insight into frontier regions where little or no surface data exist. In subduction zones, static density modelling and finite-element modelling can be used to study asperities and to examine the temporal variation of the gravity field in response to fore-arc deformation.

Key words: satellite gravity; geophysics; petrology; crust; mantle; subduction; frontier regions.

1. INTRODUCTION

The new gravity data that is being provided by the CHAMP and GRACE satellites, and the gradient data that will be available from the GOCE satellite, provide new opportunities for constraining mass distribution and transport within the Earth. In geological and geophysical applications, there are two main advantages to using the new models: they provide gravity information (1) for areas previously lacking data (or where data is inaccessible) and (2) that is continuous and consistent across natural and artificial boundaries (e.g. coastlines and political borders).

In this paper, we first summarise some issues that need to be addressed before the new-generation satellite gravity and gradient data are used for geological and geophysical studies of the Earth's crust and upper mantle. We then highlight some of the key applications and opportunities provided by the new data.

2. ISSUES SPECIFIC TO THE APPLICATION OF NEW-GENERATION SATELLITE DATA

To date, the use of new-generation satellite gravity data in geophysical interpretation of the crust and upper mantle is limited. This is probably because most users of gravity data are still unaware of the benefits of the new satellite-derived data. However, the limited use of the data is also partly related to the need to quantify the degree to which the satellite data can resolve lithospheric structures. In addition, data that are useful in geophysical applications are necessary (i.e. Bouguer anomalies).

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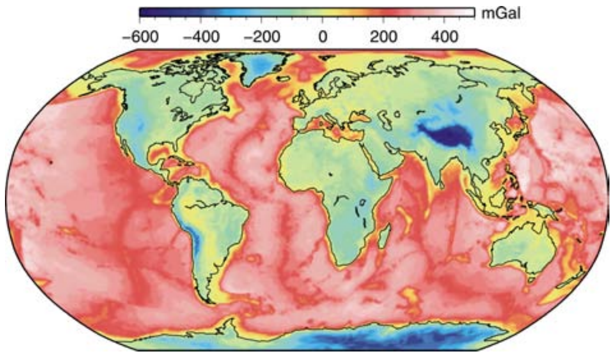

Figure 1. Global map of Bouguer disturbances derived from the EIGEN-GL04C model [1]. The Bouguer disturbances were computed in both onshore (ρ=2670 kg/m^3) and offshore (ρ=1640 kg/m^3) areas using an infinite flat-slab approximation. No terrain corrections have been applied and anomalies in ice-covered areas do not take into account the reduced density of ice.

2.1. Deriving Bouguer gravity

Current global gravity models are provided as free-air anomalies or disturbances [e.g. 1, 2]. However, in lithospheric applications, Bouguer disturbances are required so that structures at depth can be isolated from the gravity signature of topography. For geophysical applications, these disturbances must be determined at the Earth's surface [e.g. 3, 4], meaning that the satellite data must be downward continued to the irregular topographic surface of the Earth. To our knowledge, such models are currently not available.

Fig. 1 shows a global map of Bouguer disturbances. For simplicity, the Bouguer corrections used to produce this figure were computed using an infinite flat-slab approximation without terrain corrections. For some applications, this approach may be adequate, but for many applications, simple approximations of the Bouguer correction may not be sufficient. Therefore, an appropriate method needs to be developed that allows quick and accurate computation of terrain-corrected Bouguer disturbances for application to lithospheric studies.

2.2. 3D density models and the resolving power of satellite gravity

Until now, 3D density modelling has not utilized the benefits of new-generation satellite gravity data. However, the long-wavelength nature of the satellite data means that it is not always clear to what degree the data can be used to constrain crustal and lithospheric structure. To clarify this issue, the satellite gravity data can be compared to the gravity field predicted from existing 3D density models. These models could include, for example, large-scale regional models of entire mountain ranges [5], rift systems [6] or other continental provinces. The resolving power of the satellite data could be tested further by comparing the data to more detailed models of, for example, subduction zones [7] or models of continental transform zones [8].

Through this approach, guidelines would be developed to assist in determining the different scales of modelling that are possible using satellite gravity data and to identify the resolution that is necessary for gravity modelling. For example, if a model of an entire mountain range or large continental province is required, satellite data alone may provide sufficient constraints. This will negate the time consuming and costly process of compiling and reprocessing surface data.

2.3. Gradient simulation

It remains to be determined whether the gradient data provided by GOCE will have sufficient resolution for direct application to lithospheric studies. This is because the gradient data will be measured at $\sim$250 km elevation and will require downward continuation to the surface. However, given that downward continuation is an unstable process, its applicability in the case of GOCE data needs to be examined. In order to quantify the resolution required of the GOCE data, gradients can be calculated from existing forward gravity models, then upward continued to various levels in order to determine the minimum elevation to which GOCE gradient data must be downward continued in order to resolve the most important structures.

2.4. Validation through petrological studies

Lithospheric density is generally inferred from seismic velocities or from modelling of gravity data. However, it is now possible to determine density independently of gravity data and seismic velocities using compositionally-constrained thermodynamic modelling. Such models of mass distribution (density) can be developed at lithospheric scales. These models would be constrained by geology, heat flow variations in 3D and petrological data. They would, therefore, implicitly take into account the dynamics of the target areas.

The petrological approach to density determination involves numerical modelling to precisely determine stable metamorphic assemblages for different chemical compositions and known temperature and pressure [9–12]. Precise determination of stable mineral assemblages allows the calculation of rock density and other physical parameters and means that the influence of changes in rock density and water release on geodynamic processes can be examined.

Because densities vary strongly with rock chemical composition, the first step toward developing a petrological density database involves the careful synthesis of geological and petrological data of the areas to be studied. These data will come from both geological maps and from seismic profiles. To gain information on temperature gradients, heat flow data must also be compiled.

Using this approach, maps of density distribution that represent the petrological view of crustal-scale mass distribution can be produced. Once such maps are prepared, they can be verified by constructing 3D forward gravity models and comparing the gravity predicted from those models to satellite gravity data.

3. FRONTIER REGIONS

An important aspect of the new-generation satellite-derived gravity models is that they provide gravimetric constraints in regions where previously little or no data were available, or where data are difficult to obtain. These data can be used, for example, for qualitative interpretation [13] or for constraining plate tectonic reconstructions.

Forward modelling in frontier regions would also be greatly aided by the satellite gravity data. By initially constructing 3D density models in a limited number of key frontier regions (e.g. Antarctica, Himalaya), the applicability of satellite gravity in geophysical modelling could be demonstrated. This would facilitate the inclusion of satellite-derived gravity data into main-stream geophysical modelling and interpretation.

Figures 2 and 3 demonstrate why the satellite-derived gravity data are useful in frontier regions. These figures show the gravity field of the Wilkes Basin in Antarctica (Fig. 2), where crustal structure and evolution is poorly constrained and controversial, and the Himalayan region (Fig. 3), where the extension of profile-based interpretation to 3D would be facilitated by the satellite data.

The Wilkes Basin was formed either by rifting or by flexure in response to uplift of the rift-flank Transantarctic Mountains. Rift and flexural basins have distinctly different gravity signatures — an isostatically compensated rift would have near-zero anomalies, whereas a flexural basin would coincide with long-wavelength negative gravity anomalies [14]. This means that gravity data can provide a clear indication of the likely geometry of the Wilkes Basin. However, surface data in this region are limited to measurements along a few seismic profiles and narrow swaths of airborne data [15–19]. The new-generation satellite gravity data provide complete coverage of the long-wavelength gravity field associated with the Wilkes Basin (Fig. 2). Therefore, the construction of simple 3D models of the Wilkes Basin would place constraints on its geometry and evolution.

In the Himalayan region, models could be constructed that incorporate existing 2D constraints along geophysical traverses [e.g. 20, 21]. These 2D models could then be extended to 3D by filling the regions between traverses with structure constrained by the long-wavelength satellite-derived gravity data.

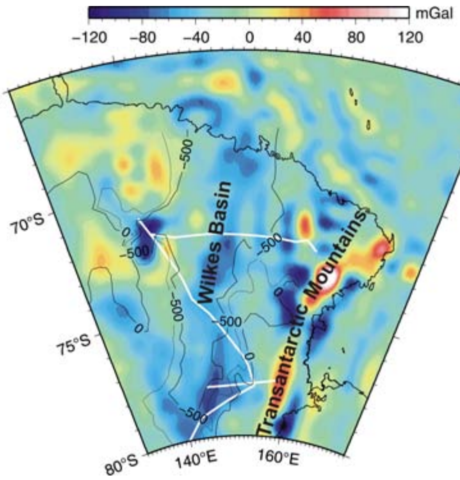

Figure 2. Free-air anomalies for the Wilkes Basin in Antarctica. Data are from the EIGEN-GL04C model [1]. Contours show bedrock topography and white lines indicate some of the geophysical traverses along which gravity data, of varying quality, exist.

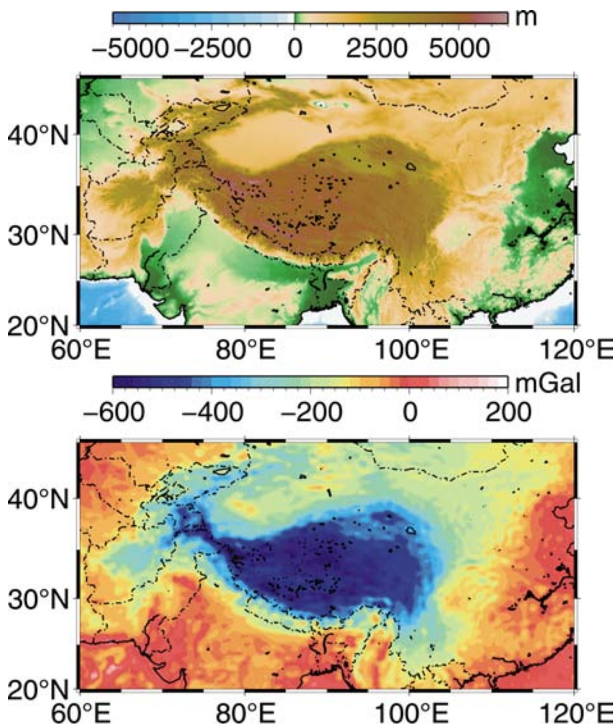

Figure 3. Topography and Bouguer anomalies for the Himalayan region. Topography data are from GEBCO (http://www.ngdc.noaa.gov/mgg/gebco/gebco.html) and gravity data are from the EIGEN-GL04C model [1].

4. LITHOSPHERIC STUDIES

4.1. Regional–residual field separation

In studies of the crust and upper mantle, the long-wavelength nature of the new-generation satellite gravity models can be a disadvantage. This disadvantage can be overcome by combining the satellite data with surface data to produce hybrid models. However, to date the resolution of these combined models is also limited to wavelengths greater than about 100 km (spherical harmonic degree and order 360). When details are important, this limitation can potentially be overcome by taking advantage of the accurate long-wavelength data provided from CHAMP and GRACE to isolate local anomalies related to shallow features within the Earth (e.g. Fig. 4). In geophysics, this process of regional–residual field separation is common, but it often relies on subjective methods like polynomial fitting, filtering or isostatic modelling to define the long-wavelength regional field. It may be more appropriate to define the regional gravity field from long-wavelength satellite data, but this approach needs to be verified by making comparisons to existing methods.

4.2. Continent-wide studies

The uniform global coverage of the new-generation satellite-derived gravity data (Fig. 1) means that they are ideally suited to continental-scale studies, especially in regions lacking surface data or where data are not freely available. Such studies might include regional synthesis, tectonic reconstructions (Fig. 5) or computation of lithospheric rigidity for entire continents.

Calculations of lithospheric rigidity, an important constraint on strength and composition, require the use of gravity data. To date, rigidity studies utilize surface data, meaning that the results are of limited significance in areas where little or no data exist. Despite the limited short-wavelength information contained in the new-generation satellite gravity data (meaning that regions with very low rigidity are not well resolved [24]), there is significant potential to utilize the new data for studies of rigidity, particularly across entire continents [24] or in frontier regions where surface data are lacking.

Current methods for determining rigidity mostly incorporate simple elastic plates. However, when rigidity is determined using elastic plates, it is a time-invariant quantity that only represents the long-term strength of the lithosphere. In reality, the response of the lithosphere to loading also depends on the time-scale of loading, which means that it is best to examine lithospheric strength using visco-elastic rheology. This is not possible using currently-available, gravity-based methods. However, the results from gravity modelling, rigidity estimation and numerical modelling can be combined to constrain lithospheric viscosity and the results compared to those from studies of post-glacial rebound.

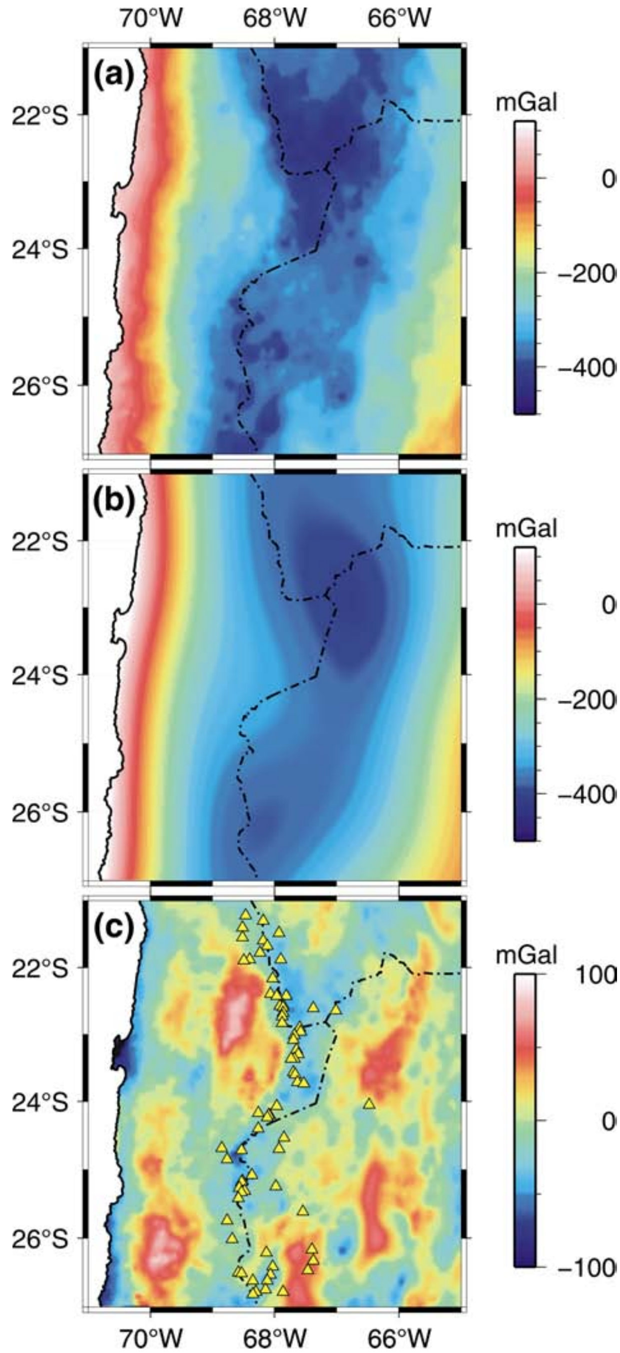

Figure 4. (a) Bouguer anomalies for the Central Andes based on surface measurements [22]. (b) Regional gravity field from the GGM02S model [2] (to degree and order 120, i.e. wavelengths greater than about 300 km). (c) Residual gravity field derived by subtracting the regional field in b from the terrestrial data in a. Negative residual anomalies associated with volcanoes (triangles) probably reflect fluids and melting within the crust [23].

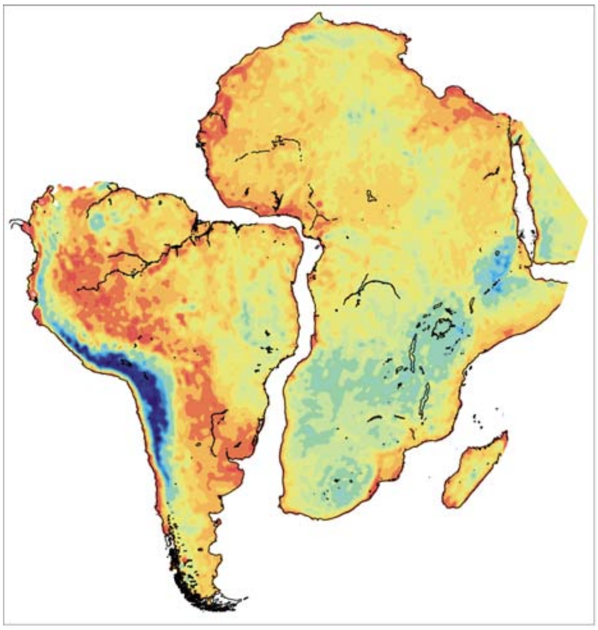

Figure 5. Approximate reconstruction of Africa and South America to give an impression of how satellite data may be used to constrain continental reconstructions. The map shows EIGEN-GL04C [1] Bouguer anomalies.

5. SUBDUCTION ZONES

Understanding the structure and evolution of subduction zones warrants considerable attention. Satellite gravity data also have a role to play in such studies. The data can be used to constrain structure and data from GRACE can possibly be used to monitor the temporal evolution of subduction zones. In fact, it has recently been demonstrated that the new-generation satellite data can detect co-seismic deformation associated with great earthquakes [25].

The regional–residual field separation methods described in Section 4.1 may also be useful for identifying subduction zone asperities (regions of maximum seismic moment release during earthquakes). This is particularly important in light of the suggestion that gravity anomalies may predict where (not when) the plate interface in subduction zones will rupture during great earthquakes [26, 27].

Numerical models of subduction zones can be used to constrain the processes that lead to the formation of asperities and to examine why these asperities appear to be related to negative gravity anomalies. Rather than constructing generic numerical models, a better approach may be to construct models for specific regions whose geometry and physical properties are constrained by 3D density models. This would result in models that apply explicitly to specific situations.

The approach described above requires the integration of static forward gravity models and dynamic numerical modelling. One way in which this can be achieved is to combine forward gravity modelling using the IGMAS software [28] and numerical modelling using the ABAQUS software. The combination of IGMAS and ABAQUS modelling requires that a suitable process for interchange of geometry and physical properties between the two software packages is developed and implemented. Such methods do exist [29, 30], meaning that as a first step, the geometry from existing IGMAS models of the Chilean subduction zone [5, 7] can be exported to ABAQUS in preparation for numerical modelling.

There are two main contributions that numerical modelling can make to our understanding of the hazards associated with subduction zones. The first is motivated by the interpretation that negative gravity anomalies in subduction zone fore-arcs tend to correlate with earthquake rupture zones (regions of high shear stress on the plate interface). However, it is not clear how rupture relates to the trench–fore-arc density distribution that causes the negative gravity. Explanations for the cause of the negative gravity are varied and include subdued fore-arc topography [26], basin formation due to basal subduction erosion [27], fore-arc strengthening related to sedimentation [31] and a relatively deep slab below the fore-arc [32]. Numerical modelling could be used to determine the stress distribution of the chosen subduction zones in order to constrain the likely cause of the negative anomalies. Such modelling will also allow us to understand the evolution of subduction-zone asperities.

The geometry used in the numerical models could be constrained from existing IGMAS 3D density models, but these models could be updated based on results from petrological modelling (Section 2.4). The models could be extended to regions lacking data using the new-generation satellite gravity data. These data have the distinct advantage of providing continuity across the coastline and probably provide sufficient resolution to constrain the large-scale structure of subduction zones (Fig. 6).

Forward gravity models are static and, as a result, are limited in the degree to which they can contribute to the understanding of the evolution of subduction zones and their associated asperities. This means that the numerical models will “add value” to the static models by allowing the incorporation of time.

It has already been demonstrated that GRACE data can be used to detect co-seismic deformation from the largest subduction zone earthquakes [25], but numerical modelling can be used to determine to what degree GRACE repeat models can detect inter-, co- and post-seismic deformation in subduction zones. From a starting model based on the static gravity models, the changes in geometry with time can be monitored using the numerical modelling. By transforming geometry from ABAQUS models back to IGMAS for discrete time steps, the time-variable gravity field caused by subduction zone deformation can be examined. This will allow us to determine whether or

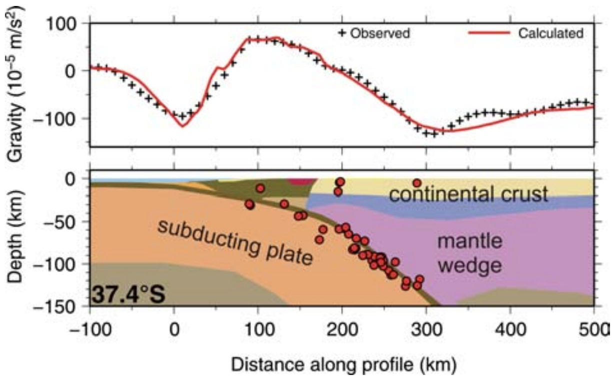

Figure 6. Example profile through a 3D model of the south-central Chilean subduction zone at 37.4°S [7]. The model is constrained in part by geological and seismological information (e.g. seismicity, red circles). The red curve in the upper panel shows the gravity calculated from the model that was matched to a detailed dataset of surface gravity measurements (not shown). The crosses show gravity anomalies from EIGEN-GL04C [1] and indicate that the satellite data are probably sufficient to resolve the major structures associated with subduction.

not GRACE data can also provide a tool for monitoring strain in subduction zones.

In the near future, GOCE gradient data will provide additional constraints on subduction zone geometry. Numerical modelling of subduction-zone evolution could also be used to estimate changes in gradients with time and, ultimately, the gradient data may have sufficient resolution to directly identify subduction-zone asperities.

6. CONCLUSIONS

The benefits of the new-generation satellite-derived gravity and gradient data provided by the CHAMP, GRACE and GOCE satellites are numerous and the data allow studies that were not previously possible. The selection of applications presented in this paper define a series of tasks that will form the basis for research activities in coming years.

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