Joint Gravity and Isostatic Analysis for Basement Studies – A Novel Tool

C. Braitenberg[1], S. Wienecke[2], J. Ebbing[2,3], W. Born[2], T. Redfield[2]

[1]Dip. Scienze della Terra, Università di Trieste, Trieste, [2]Geological Survey of Norway (NGU), Trondheim, Norway, [3]Department for Petroleum Technology and Applied Geophysics, NTNU, Trondheim, Norway

Summary

We have created a working tool – named Lithoflex- that is useful for the interpretation of gravity data in oceanic and continental areas. The tool combines gravity forward and inverse calculation with an investigation of the isostatic state. Density models derived from the gravity field are ambiguous if external geological or geophysical constraints are scarce or unavailable. However, because isostasy is a physical condition , some of the native ambiguity can be reduced by checking the compatibility of the density model with the isostatic state. We demonstrate the usefulness of our tool in the analysis of the basement in the Barents Sea and in the South China Sea, where the basement characterization is accomplished by the high-resolution analysis of the equivalent elastic thickness. Other situations for which our tool could be useful include the recovery of depth-to-basement by the inversion of the gravity field, the identification of distinctive terrains by their variation in elastic thickness, or, given a comprehensive gravity field, the interpolation of crustal thickness between seismic lines.

Introduction

Today's broad availability of gravity data includes global satellite derived datasets and extensive terrestrial observations. These data permit modeling of crustal structure in areas where seismic investigations are sparse or non-existent. The accuracy of satellite data in particular has improved dramatically: comparison with ship-track gravity shows that, over oceanic areas, the globally available field (e.g. Hwang et al., 1998; Andersen and Knudsen, 2001) has spatial resolution of 2'x2' and accuracy between 3 and 14 mgal. Data of this quality are of sufficient resolution and accuracy to be useful in the investigation of basement structures.

Typically, the modeling of the gravity field involves the construction of a density model of the crust. Combinbed with the overlying topography, the density model constitutes the load acting on the crust. The internal crustal load is given by the integration along the crustal column of the modeled densities with respect to the reference crustal column. It follows that a density variation within the crust represents a variation in the load, and must be reflected in the isostatic response. The study of the isostatic state and of the regional rheological crustal properties is thus inextricably linked to density modeling.

Thus, isostatic modeling is useful for three reasons. 1) Calculation of the isostatic state emplaces an independent constraint upon a given density model. 2) Given the crustal load and the crustal structure, the study of the isostatic state permits modeling the rheological properties in terms of flexural rigidity. 3) By making some assumptions regarding the Poisson ratio and the Young modulus, flexural rigidity can be interpreted in terms of elastic thickness. The flexural rigidity of the crust is an important parameter in the reconstruction of the formation history of the basin, as it controls the subsidence in response to the causative forces.

Methodology

We have developed a software tool that combines the essential steps of the above analytical sequence within one single application, using advanced methods of calculation developed by the authors. These

include gravity forward and inverse modeling, and the forward and inverse modeling of flexural rigidity, allowing for high spatial resolution of flexural rigidity.
The tool fulfills a series of different functions that are concerned with the study of the gravity field and the study of the isostatic state. In detail, the methodologies applied are as follows. 1) The gravity forward calculation for a single boundary defining a density discontinuity as the Moho or the basement, with laterally variable density difference applies the Parker-series expansion (Parker, 1972). 2) The inverse calculation, that starts from the gravity field and has the goal of obtaining the causative density boundary, uses an iterative algorithm that alternates downward continuation with direct forward modeling (Braitenberg et al.,1999). This method has some analogies similar to the Oldenburg-Parker inversion approach (Oldenburg, 1974). 3) The forward modeling of the gravity field produced by a sedimentary basin, for which the sediment thickness is known, is made by allowing different density variations with depth, as either a sediment compaction model (e.g. Sclater and Christie, 1980) or a linear sediment density increase with depth. 4) The basin is discretized into a series of thin sheets, for each of which the gravity effect is evaluated. The load of the sediment basin is also calculated, and refers to the integrated surplus load with respect to the standard reference crust and given as output.
Isostatic modeling adopts the isostatic lithospheric flexure model (e.g. Watts, 2001). The evaluation method used in forward and inverse calculations allows a relatively high spatial resolution, superior to the spectral methods. We use the convolution approach with the numerical (Braitenberg et al., 2002) or with the analytical flexure response functions (Wienecke et al., 2007). In the forward flexure calculation application, typically the crustal load is given, as it has been obtained from the gravity modeling. We then may calculate the expected Moho or basement undulation assuming isostatic equilibrium. In this calculation we may consider a model for the lateral variation of flexural rigidity, if present. This could be deduced by various methods, for example from the age of oceanic crust. When using the inverse flexure calculation application, we require a crustal load, obtained from the density model and from Moho undulations. We then invert the crustal flexural rigidity in order to match the known loads with the known crustal thickness model. By this procedure it is possible to divide the crust into different areas, which can be geologically significant.

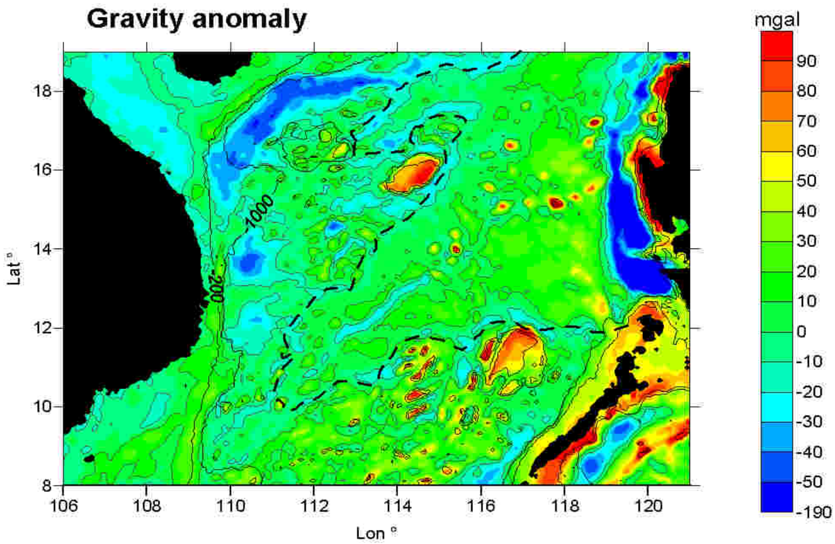

Figure 1. Observed satellite derived gravity anomaly (Hwang et al., 1998). The continental-ocean transition is outlined as a dashed line and the bathymetric isolines for water depths 200 m and 1000 m are shown. The gravity anomaly isolines are traced for –20 mGal and + 20 mGal.

We show as a first example an application that regards the inversion of the gravity field over oceanic areas in order to define a model of the basement underlying the sediments. This problem occurs in areas such as the South China Sea, where the basement is completely covered by sediments. Tectonic structures cannot be identified bathymetrically due to complete infilling. Braitenberg et al. (2006)

demonstrated the gravity anomaly records signals that cannot be found in the bathymetry, here interpreted as a central spreading axis (Figure 2a). This is evident both at the continental margin as well as the oceanic basin, where magnetic anomalies permit a ridge to be inferred. For this analysis the input data were a coarse sediment thickness map (NOAA), gravity anomaly data (Hwang et al., 1998), a bathymetric model, some seismic constraints on crustal thickness and a density-depth relation of sediments recovered from the IODP-drill sites. Our analytical output is the crustal thickness map, the elastic thickness map and the basement map (Figure 2b). The basement is seen to have more structure compared to the bathymetry, and is thus very useful for tectonic interpretation. The central ridge is rendered well evident, as are also the basins.

A) **B)**

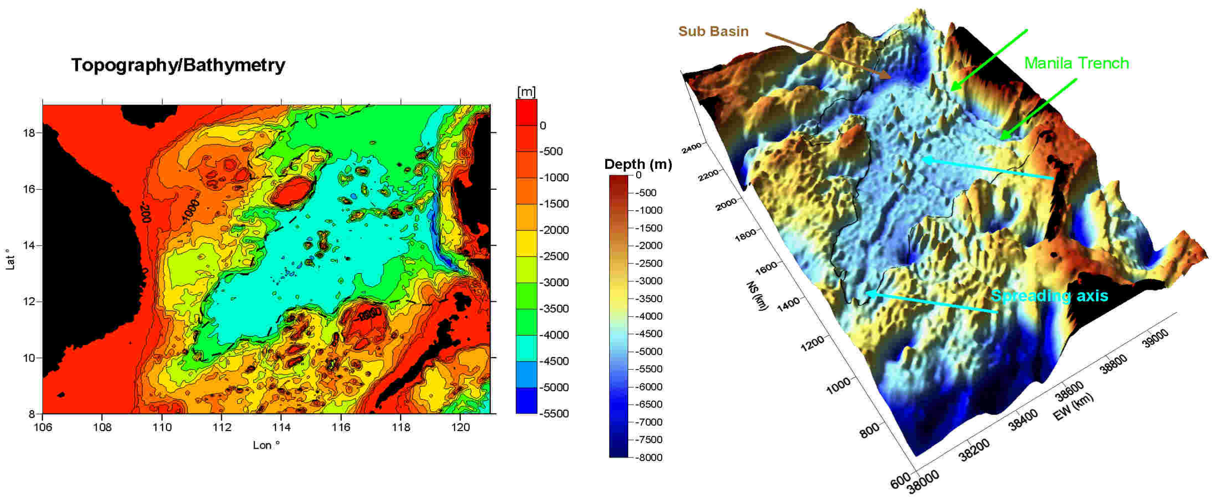

Figure 2. A) Bathymetric map of the South China Sea, The continental-ocean transition is outlined as a dashed line. The bathymetric isolines for water depths 200 m, 1000 m and 3000 m are shown. These isolines define the principal features that define the basin. B) Basement depth from gravity inversion: coloured relief map of the basement model.

Conclusions

We have developed a tool for the study of the flexural rigidity or elastic thickness of the crust, and demonstrated its usefulness. Flexural rigidity is a required parameter when the crustal vertical response to loading or unloading is to be calculated, such as during the loading or unloading of a sedimentary basin. We show as an example our results from the South China Sea. There, an isostatic model and a rough sediment thickness model were used to constrain crustal thickness in order to separate the gravity signal due to the Moho from that generated by the basement undulations. It was then possible to formulate a detailed model of the basement. In this specific case the model revealed tectonic features that are not seen in the bathymetry, being wholly concealed by the overlying sedimentary infill.

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References

Andersen, O. B. and Knudsen, P. [2001] Global marine gravity field from the ERS1 and Geosat geodetic mission altimetry. Journal of Geophysical Research, Vol. 103 , No. C4, p. 8129 (97JC02198).

Braitenberg, C. and Zadro, M. [1999] Iterative 3D gravity inversion with integration of seismologic data. Boll. Geof. Teor. Appl., Vol. 40, N°. 3/4, 469-476.

Braitenberg, C., Ebbing, J. and Götze, H.-J. [2002] Inverse modeling of elastic thickness by convolution method - The Eastern Alps as a case example, Earth Planet. Sci. Lett., 202, 387-404.

Braitenberg C., Wienecke, S. and Wang, Y. [2006] Basement structures from satellite-derived gravity field: South China Sea ridge. Journal of Geophysical Research, Vol.111, B05.

Ebbing, J., Braitenberg, C., Bjørnseth H.M., Fichler, C. and Skilbrei, J.R. [2006] Basement Characterisation by Regional Isostatic Methods in the Barents Sea. EAGE/EAGO/SEG Conference, Saint Petersburg.

Ebbing, J., Braitenberg, C. and Wienecke, S. [2007] Insights into the lithospheric structure and the tectonic setting of the Barents Sea region by isostatic considerations. Submitted to GJI.

Förste, C., Flechtner, F., Schmidt, R., König, R., Meyer, U., Stubenvoll, R., Rothacher, M., Barthelmes, F., Neumayer, H., Biancale, R.. Bruinsma, S., Lemoine, J.-M. and Loyer, S. [2006] A mean global gravity field model from the combination of satellite mission and altimetry/gravimetry surface data – Eigen-GL04C. Geophysical Research Abstracts, Vol. 8, 03462.

Hwang, C., E.-C. Kao, and B. Parsons [1998] Global derivation of marine gravity anomalies from Seasat, Geosat, ERS-1 and TOPEX/POSEIDON altimeter data. Geophys. J. Int., 134, 449-459.

Oldenburg, D. W. [1974] The Inversion and Interpretation of Gravity Anomalies. Geophysics 39, 526-536.

Parker, R. L. [1972] The Rapid Calculation of Potential Anomalies. Geophys. J. R. Astr. Soc. 31, 447-455.

Sclater, J.G. and Christie, P.A.F. [1980] Continental stretching: an explanation of the post Mid-Cretaceous subsidence of the central North Sea basin. J. Geophys. Res., 85, 3711-3739.

Watts, A.B. [2001] Isostasy and Flexure of the Lithosphere, Cambridge University Press, Cambridge, 2001, 458 pp.

Wienecke, S., Braitenberg, C. and Götze, H.J. [2007] A new analytical solution for the differential equation of the 4th order estimating the flexural rigidity in the Central Andes (15°- 33° S). in editorial process, Geophys. J. Int.