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Review Article

Gravity derived Moho for South America

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ABSTRACT

Crustal structure in South America is one of the least understood among the Earth's continental areas. Variations in crustal thickness are still poorly constrained over large portions of the continent because of scarce or unevenly distributed crustal thickness estimates throughout South America. To address this scarce and inhomogeneous data cover we explore the possibility to derive crustal thickness from satellite gravity data. In this study, we utilize the combined gravity model EIGEN-6C, which is composed of GOCE and other gravity data. The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite has a much more uniform spatial resolution than any land-based gravity or seismic survey in South America. The gravity data inversion is for a simple two-layer model with fixed density contrast over the interface, the Moho. The method is not relying on point constraint data and assumes that all of the signal is related to topography of the Moho. Model quality can therefore be assessed by a comparison with point observations on crustal thickness. We show that for the stable part of the continent 90% of our estimates are similar, within error bounds, to seismic observations. Variations occur in active orogenic zones or regions with suspected non-standard Moho density contrasts. A comparison with seismological models shows a high correlation with the most recent model. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints the gravity based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America.

Contents

1. Introduction

The crustal structure of South America is one of the least understood among the Earth's continental areas. Variations in basic but fundamental

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parameters such as crustal thickness are still poorly constrained over large portions of the continent. Estimates of crustal thickness are commonly obtained from either seismic or gravity measurements over the Earth's continents, but land-based data coverage – both seismic and gravimetric – has been traditionally scarce or, at best, unevenly distributed throughout South America. Due to restricted financial and technical means devoted to scientific purposes and local circumstances it has always been very difficult to obtain detailed information on and/or maintain networks to study the Earth's structure underneath South America. Parts of Brazil, the Andes and Venezuela have been extensively studied but the rest of the continent has been only sparsely covered with crustal thickness observations. To our knowledge, only a handful of models provide crustal thickness information on a continental scale for the South American continent (Assumpção et al., 2013–this issue; Bassin et al., 2000; Feng et al., 2004, 2007; Lloyd et al., 2010, e.g.), and these models are largely based on seismic datasets gathered from uneven distribution of seismic experiments throughout the continent. This uneven data coverage has resulted in large lateral variations in resolution and significant trade-offs between well- and poorly-resolved portions of the continent. Consequently, knowledge on South American tectonic and geodynamic processes and their relationships with and influences on crustal thickness and upper mantle structure is limited.

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite (launched on 17 March 2009) has a much more uniform spatial resolution than any land-based gravity or seismic survey in South America and an improved accuracy with respect to previous spaceborne gravimeters thanks to the inclusion of six accelerometers (three pairs in three orthogonal directions) (Drinkwater et al., 2003). This improved resolution and accuracy is of great interest for studies of the Earth especially in places where limited or inhomogeneous data is available, and provides a unique opportunity for improving our knowledge of basic crustal structure in places with scarce data coverage like South America (Assumpção et al., 2013).

In this study, we utilize the combined gravity model EIGEN-6C (Förste et al., 2011), which is composed of GOCE and other gravity data, to derive a model of crustal thickness variation for South America. First, crustal thickness is obtained after assuming a simple layer-over-half space model for the crust and lithospheric mantle and inverting sediment corrected Bouguer gravity anomalies based on EIGEN-6C with the 3D procedure of Parker and Oldenburg (Gómez-Ortiz and Agarwal, 2005; Oldenburg, 1974; Parker, 1973). To evaluate our gravity-based results, we compare our estimates to an independent compilation of point estimates on crustal thickness for South America developed by Assumpção et al. (2013). The evaluation exercise shows a good correlation between independent point observations and gravity-derived estimates of crustal thickness. Our model is then compared with independent continental-scale crustal thickness models based on the joint inversion of point observations and regional surface waves. The differences and similarities are used to comment on the applicability of using (satellite) gravity data for modeling of crustal thickness in areas where there are no point data or good surface wave coverage. Our results illustrate that models derived from (satellite) gravity data can provide first order constraints on crustal thickness. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints the gravity based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America.

2. Material and methods

2.1. Gravity data

The crustal thickness map developed in this study is based on the inversion of a global gravity model that contains gravity gradient data from the GOCE (Gravity Field and steady-state Ocean Circulation Explorer) mission (Drinkwater et al., 2003). The GOCE satellite was launched in March 2009 and was the first of a series of Earth Explorer satellites launched by the European Space Agency (ESA), as part of its Living Planet Programme, to gather information for understanding critical Earth system variables. In particular, the GOCE satellite has the goal to map our planet's gravity field in unprecedented detail. In order to counteract the attenuation effect traditionally seen in gravity data and to amplify the gravity signal, GOCE is equipped with the first spaceborne gradiometer, thus adding unique gradient data to existing worldwide gravity models, in particular at shorter wavelengths. The gradiometer contains six proof masses capable of observing detailed local changes in gravitational acceleration in three spatial dimensions with extremely high precision. Since the gravitational signal is stronger closer to the Earth, GOCE has been designed to fly in a very low orbit of approximately 250 km which is much lower than other Earth gravity observation satellites thereby improving the signal strength.

GOCE data was chosen for this research to be used in a combined model of GOCE satellite gravity data, data from previous satellite gravity missions, radar altimetry data and terrestrial data, EIGEN-6C (Förste et al., 2011). A Bouguer corrected gravity anomaly map of the Earth (Barthelmes, 2009) was downloaded from the International Centre for Global Earth Models (ICGEM). The data is based on the classical gravity anomaly. This is defined as the magnitude of the gradient of the downward continued potential on the geoid minus the magnitude of the gradient of the normal potential on the ellipsoid (Eqs. (93) and (121)–(124) of Barthelmes (2009)). A Bouguer plate correction compensates for mass related to topography that exceeds above or below the reference surface. It is modeled by a solid slab of fixed density and infinite extent from the point of observation. This is necessary to exclude the effect of surface topography contributions in the assessment of gravity signals from the Moho. The Bouguer gravity anomaly is the classical gravity anomaly minus the attraction of the Bouguer plate. At ICGEM, it is calculated by the spherical approximation of the classical gravity anomaly minus $2\pi G\rho$ H (Eqs. (107) and (126) of Barthelmes (2009)). Their topographic heights H are calculated from the spherical harmonic digital elevation model DTM2006 used up to the same maximum degree as the gravity field model. Densities used are for $H \geq 0$ (rock) is 2.67 g/cm^3 and for $H \leq 0$ (water) is 1.67 g/cm^3.

To develop the crustal thickness map presented in this study, the Bouguer anomaly map was downloaded at a grid spacing of 0.1° from the ICGEM (International Centre for Global Earth Models) website (Fig. 1). The Bouguer anomalies were then corrected for the presence of sediments. Sediments have a lower density than the bedrock. In this sediment correction the lighter sediments were replaced with more heavy bedrock material. Sediment thickness and density information was retrieved from a global sediment thickness map (Laske and Masters, 1997) (Fig. 1) and the correction was applied in a similar way as the Bouguer correction. We used a density contrast of 0.2 g/cm^3 between the sediment basin and the surrounding bedrock. This is based on the average density value of the central layer in the digital soil map of Laske and Masters (1997) which is around 0.2 g/cm^3 less than the 2.67 g/cm^3 used for rocks in the Bouguer correction.

2.2. Inversion method

Different approaches are possible for inverting gravity data for crustal thickness. The most straightforward approach is inversion for a simple two-layer model with fixed density contrast over the interface, the Moho (e.g. Oldenburg, 1974). This method is not relying on point constraint data and assumes that all of the signal is related to topography of the interface to be modeled. A 3D approach (Li and Oldenburg, 1998) is regularly used for shallow studies but not often for modeling of the Moho discontinuity (e.g. Welford et al., 2010). To overcome the non-uniqueness inherent to this approach it is possible to do a joint inversion of gravity data with a priori information on crustal structure like seismic point observations or profiles and