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Review

Uncertainties in crustal thickness models for data sparse environments: A review for South America and Africa

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ABSTRACT

With the recently available high resolution gravity data from the GOCE satellite a whole range of crustal thickness models have been derived. The added value of GOCE is that it provides data globally, including regions that are poorly covered by seismological studies, like large parts of Africa and South America. Potentially these models can provide new insight in crustal structure for these data poor regions. We compare different models of crustal thickness for South America and Africa and attempt to assess the quality of different modelling techniques and the impact of different data sources. We introduce one new global crustal thickness model based on gravity data, DMM-1, and use seven additional, recently published, continental or global crustal thickness models based on gravity or seismological data. All models use different modelling techniques, and either gravity (four models) or seismological data (four models). We will show that significant differences exist between the models but that these cannot be directly related to the used data. Choices made in the selection and parametrization of the various modelling techniques have more impact than using different data sources including data sources of supposed higher quality. The significant differences, up to 28 km, between models can have a major influence on geodynamical analysis for the two continents. We propose that future work should focus on developing a standard for modelling in data sparse environments, and expanding seismological efforts in those regions that are most different between the shown models to verify the actual crustal thickness. Furthermore, the contribution and inclusion of (satellite) gravity data in crustal thickness models should be further explored.

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1. Identifying the gap

In the recently published special issue in Tectonophysics on 100 years of Moho (Thybo et al., 2013) a wide overview is given of the history of crustal thickness observations. Since probing the crust with controlled source studies since 1850 (Prodehl et al., 2013) it took around 60 years before the actual crust–mantle boundary was observed by Mohorovičić (1910). Only since the 1980s passive seismics have been more widely applied in detection of the crust–mantle boundary (Prodehl et al., 2013). Since then a massive number of (temporary) seismic networks have been operated. The networks focussed primarily on scientifically interesting regions (active tectonics and earthquake risks in combination with dense population). Parts of Europe and North America have been extensively covered by dense seismic arrays providing unprecedented resolution for tomographic and crustal modelling studies. But for many regions in the world this coverage is not homogeneous and despite 160 years of probing the crust (Thybo et al., 2013) there are still white spots in the worlds' crustal thickness map. For a broad variety of reasons (accessibility, safety, scientific interest, finances) there are numerous regions for which no crustal thickness estimates are available. Most of these regions are in Africa, South and Central America, and parts of Asia.

The crustal structure of these regions is among the least understood of the Earth's continental areas. Variations in basic but fundamental parameters such as crustal thickness are still poorly constrained over large portions of these continents. Estimates of crustal thickness for these areas have been traditionally scarce or, at best, unevenly distributed. To the best of our knowledge, only a handful of seismic models provide crustal thickness information on a continental scale for the South American (e.g. Laske et al., 2013; Assumpção et al., 2013b; Lloyd et al., 2010; Feng et al., 2004, 2007) and the African continent (e.g. Laske et al., 2013; Pasyanos and Nyblade, 2007), and these models are largely based on seismic datasets gathered from uneven distribution of seismic experiments throughout the continents. This uneven data coverage has resulted in large lateral variations in resolution (see an example of Africa regions with low path coverage in Begg et al., 2009) and significant trade-off's between well-resolved and poorly resolved portions of the continent. Consequently, knowledge on tectonic and geodynamic processes and their relationships with and influences on crustal thickness and upper mantle structure is limited.

2. How to fill the gaps?

There are many different ways these white spots in our crustal thickness knowledge can be filled. Seismological networks and deep seismic surveys are the most traditional but require massive investments to provide homogeneous cover. Not only many instruments would be needed but also the logistics to reach certain places and to secure safety would be very expensive. The largest white spots in Africa are in the densely forested Congo basin and the difficult accessible Sahara. The safety situation in many of the countries in these regions is such that it is not possible to install a high density network of seismometers. Similar inaccessibility holds for large parts of the basins west of the Andes, including the Amazon basin. An alternative source of information should be sought in a technique that does not require intensive field campaigns and has a good spatial coverage. Gravity surveying has always been indicated as such source. Variations in the Earth gravity field are a result of four main factors (van der Meijde et al., 2015). The first two are the Earth's shape, rotation, and topography. The fourth factor is due to inhomogeneous composition of the Earth's interior. Vertically there are several discontinuities at different depths (e.g. crust–mantle boundary) that are irregular, but also within the different layers the mass distribution is inhomogeneous. These variations, both in depth and lateral, contribute to the gravity signal and can be modelled. However, inversions, or analysis, of gravity models are normally highly non-unique and this is one of the main challenges for any inversion attempt.

2.1. Satellite gravity

With the launch of the Gravity field and Ocean Circulation Explorer (GOCE) (Floberghagen et al., 2011; Drinkwater et al., 2003) in 2009 the Earth science related efforts in gravity got another boost (van der Meijde et al., 2015). After the time-lapse and long-wavelength studies from Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) a new sensor was available for determination of the Earth's gravity field and geoid with high accuracy and spatial resolution. Equipped with a three-axes gradiometer and flying at an altitude of 260 km and less GOCE provided (the GOCE mission ended on 13.11.2013) the most detailed measurements of Earth's gravity from space ever by acquiring gravity gradients, i.e. the three-dimensional second derivatives of the gravitational potential. For solid Earth sciences GOCE data have made a unique contribution and provides insights that would not have been possible otherwise. Research has largely focussed on those areas where GOCE really made a difference because of the lack of terrestrial and airborne gravimetry data, like in Africa and South America. The primary application of GOCE data in those, and other, areas is crustal studies, such as recovery of Moho or intra-crustal discontinuities (van der Meijde et al., 2015).

Gravity models are based on either satellite measurements alone or on a combination of satellite, airborne, and ground-based gravity measurements, often combined with altimetry data for oceanic regions. Up to now, four releases (R1 to R4) of GOCE gravity field models have been computed in the frame of the ESA project "GOCE High-Level Processing Facility" (HPF). In the frame of GOCE HPF, three different methods and processing philosophies are applied for gravity field modelling: the direct approach (DIR; Bruinsma et al., 2010), the time-wise approach (TIM; Pail