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A regional background model for the Arabian Peninsula from modeling satellite gravity gradients and their invariants

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ABSTRACT

Gravity gradients of the GOCE (Gravity field and steady state Ocean Circulation Explorer) mission are available and provide free available data with global homogeneous coverage. The spatial resolution is about 80 km which makes it possible to construct regional models of large or remote areas. We study the benefit of using this data for compiling a 3D regional density model of the lithosphere with emphasis on the crustal structure for the Arabian Peninsula. We keep the data at satellite level to avoid noise amplification. The initial density model was set up with only a few seismic constraints and modified by forward modeling. Forward models benefits from the use of the full gravity gradient tensor and the invariants. The misfits between the measured and calculated field are more easily recognized in the gravity gradient tensor than in the gravity field alone. Different shape and location of anomalies are visible in the different components. Hence, modeling is better controlled as geometries which fit one component do not necessarily fit all other components. Regional models are important for a general understanding of any area and as a background for local interpretations. Here, we explain how to construct density models from satellite gravity gradients and show the advantage of such an approach by comparison to earlier studies based on either seismic or gravity data.

1. Introduction

The estimation of lithospheric and crustal thickness is of major interest to understand the geological evolution of an area. The Arabian Peninsula is located between the rift system under the Red Sea, the convergence zone of the Eurasian plate and the spreading axis of the Gulf of Aden. The occurrence of a cratonic area bounded by active rift systems leads to large variations in crustal and lithospheric thickness. Initial investigations of the lithospheric structures were already conducted 30 years ago (e.g. Gettings et al., 1986; Mechie et al., 1986; Mooney et al., 1985). The seismic studies of the area were limited and could only explain parts of the area. The GOCE satellite mission measured gravity gradients in an altitude of 255 km (later 225 km) from 2009 to 2013 and provide a homogeneous coverage with gravity gradients at a spatial resolution of 80 km (Ebbing et al., 2013; Bouman et al., 2015). Gravity gradients are sensitive to major density boundaries like the crust mantle boundary (Moho) itself and intra-crustal density changes. Compared to vertical gravity, gradients provide information about variations in the gravity field in horizontal and vertical direction. In addition, they are less sensitive to long wavelength trends. The expected large variations of Moho and LAB depth make the Arabian Peninsula a perfect case study to set up a lithospheric model with help of satellite gravity gradients.

The study area consists of the Arabian shield and platform. It is bounded by the Red Sea in the West, the convergence zone of the Eurasian plate to the North and East and the Gulf of Aden spreading axis in the South. Thus, the investigation area comprises passive rifting geology, an active spreading center and a cratonic area. The Arabian plate originated 25 Ma by the rifting of North Africa and the resulting spreading axis in the Red Sea (Stern and Johnson, 2010). The Western part of the Arabian Peninsula is called the Arabian shield which exposes 50% plutonic and 50% volcanic and sedimentary rocks (Gettings et al., 1986). The shield is a cratonic area where Precambrian basement crops out. In the Eastern part of the Arabian Peninsula the basement is deepening with a maximum depth of 14 km as an almost linear trend running from South West to North East covered with Phanerozoic sediments (Konert et al., 2001). In contrast, the Western part exhibits basement outcrops. The deepening of the basement correlates with the crustal thickness. Several authors investigated the crustal thickness based on teleseismic receiver functions and seismic refraction profiles (e.g. Mooney et al., 1985; Mechie et al., 1986; Al-Damegh et al., 2005; Hansen et al., 2007) (See an overview in Fig. 1). All authors interpret a shallower Moho under the Arabian Shield between 25–40 km depth and 40–53 km under the Arabian platform. The seismic refraction profile interpreted by Mooney et al., 1985 is a 1000 km profile mainly covering the Arabian shield. Only few teleseismic stations are located on the Arabian platform

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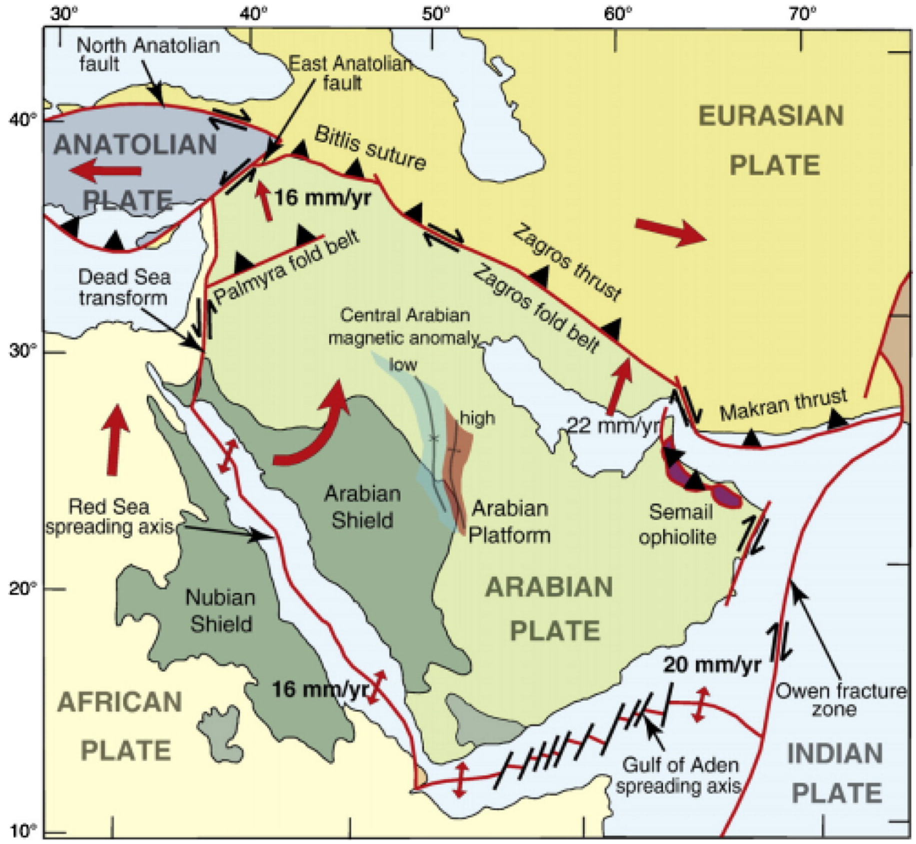

Fig. 1. Tectonic overview from Stern and Johnson (2010).

constraining the crustal thickness (cf. Al-Damegh et al., 2005; Hansen et al., 2007). Therefore, the regional geological structures are homogeneous, but large uncertainties remain in the crustal thickness and depth to the lithosphere-asthenosphere boundary.

1.1. Previous gravity based studies

Mechie et al., 2013 presented three different Moho depths, based on the inversion of combined (satellite and terrestrial) gravity data, terrestrial data alone and seismological measurements. The gravity field was EIGEN-6C (Förste et al., 2011) sampled on a 0.5° × 0.5° grid. The inversion was conducted with a simple Bouguer gravity anomaly and an unconstrained two-layer model (Parker, 1973). The final Moho (Mechie et al., 2013) comprises depths of about 25 km under the Red

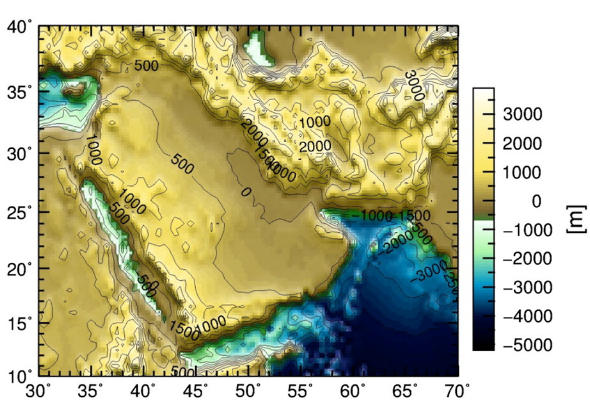

Fig. 2. Topographic map of the area.

Sea Rift system and a depth of about 45 km at the Southern tip of the Arabian Peninsula. Other parts of the peninsula show a rather constant depth of 35 km. Offshore in the Arabian Sea, a Moho depth of 6 to 15 km is calculated. The other Moho maps (from seismological and terrestrial data) cover only about 50% of the Arabian Peninsula and the margins. Most data is available at the Red Sea in the Western part and the Arabian shield. These maps predict shallower crust in the Red Sea (10 km compared to 25 km) and more depth variations over the continent.

The Moho calculated from the EIGEN-6C gravity model is smoothed and underestimates depth variations in the Red Sea and the offshore parts. The reasons are the rough sampling of the gravity data (0.5° lateral resolution) and a low pass filter of 300 km wavelength. Both were used to stabilize the inversion and avoid unrealistic results (cf. Mechie et al., 2013). The filtering and the low spatial distribution of terrestrial data lead to a minor contribution of the ground gravity stations to the inversion. The second model, which will be used for comparison is derived from the GEMMA project by Reguzzoni and Sampietro, 2015 b). The GEMMA model was derived by inversion of GOCE data for Moho depth on a global scale. The starting model bases on CRUST2.0 (Laske et al., 2013) and a mantle model derived from density-depth relations. Misfits of the vertical gravity gradient of the forward calculated model are inverted for depth changes of the Moho (cf. Reguzzoni et al., 2013; Reguzzoni and Sampietro, 2015). The global error estimate is below 1 mE (1 Eötvös (E) = 10^ − 9 s^ − 2). This model is used for comparison, because it is not compiled for the Arabian Peninsula, but optimized on a global scale which differs from our local model approach.

The gravity gradients and invariants are expected to map better density contrasts that occur in horizontal and vertical direction. In our modeling approach we are able to include lateral density changes which were also included in the GEMMA model but not in the approach presented in Mechie et al. (2013). We will use both models for comparison, because the model approaches differ significantly, even if the data (satellite gravity measurements) is similar.

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