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Interpretation of gravity and magnetic data with geological constraints for 3D structure of the Thuringian Basin, Germany

Ilya Prutkin [a,*], Peter Vajda [b], Thomas Jahr [a], Florian Bleibinhaus [a], Pavel Novák [c], Robert Tenzer [c,d]

[a] Institute of Earth Sciences, Jena University, Burgweg 11, 07749 Jena, Germany
[b] Geophysical Institute, Slovak Academy of Sciences, Dubravska cesta 9, 845 28 Bratislava, Slovakia
[c] NTIS – New Technologies for the Information Society, Faculty of Applied Sciences, University of West Bohemia, Technická 8, Plzeň, Czech Republic
[d] School of Geodesy and Geomatics, Wuhan University, Wuhan, China

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ABSTRACT

We apply a novel method for the separation of potential field sources and their 3D inversion at the regional study area of Thuringian Basin in central Germany. The gravity and magnetic data are separated into long, medium and short wavelengths and then inverted separately. The main goal is to study uniqueness of the solution and its stability in all numerical steps of the interpretation process and to demonstrate, how geological constraints can diminish the degree of non-uniqueness by the interpretation of the gravity and magnetic anomalies. Our numerical experiments with medium wavelengths reveal that if we explain negative anomalies with the topography of near-surface layers, the obtained solution is not supported by borehole data. These negative anomalies are thus explained by restricted bodies (granitic intrusions) at the depths from 4 down to 10 km. These bodies are located above a density interface with topography at the depth of approximately 10 km. The 3D inversion of magnetic data (at short wavelengths) allows investigating a detailed structure of the upper boundary of the crystalline basement: two uplifts in the depths between 2.0 and 0.7 km are found. By using the residual negative anomalies we further study the salt tectonics, showing that the geometry of a salt pillow with a thickness of approximately 200 m closely agrees with borehole data.

1. Introduction

Our investigation is carried out under the framework of the project INFLUINS (Integrated Fluid Dynamics in Sedimentary Basins), which is devoted to studies of relationship between the near-surface and deeper fluids and material flows. The project links geology, hydrogeology, mineralogy, geophysics, basin analysis, remote sensing and other geoscience topics. A geophysical investigation is necessary in order to explain the internal structure of the Thuringian Basin, and to develop a joint 3D model of its underground using seismic, gravimetric, magnetic and borehole measurements. In our study we use mainly gravity and magnetic data. A detailed structural model forms an essential boundary condition for models of fluid transport, one of the central goals of the project INFLUINS.

Our new method for the 3D potential field data inversion has been tested on a local and isolated gravity anomaly by Prutkin et al. (2011). For this anomaly, we primarily focused on a wide variety of admissible solutions, which generate the same field. By interpreting the gravity and magnetic anomalies for the Thuringian Basin, we deal with a larger geographic area. Both, the gravity and magnetic data are inverted, taking into consideration the fact that they represent a complex composition of various signals. In our study, we try to consider all available geological information to obtain a unique solution.

First, we separate the sources into the deep, intermediate and shallow components by applying successively the upward and downward continuation procedures. All components are inverted separately. Here we deal for the first time with a problem of low frequencies, meaning that deep masses generate long wavelengths, but the converse implication is not necessarily true. Here we demonstrate how this problem can be solved by using additional geological information.

For intermediate wavelengths, we begin with the three largest negative gravity anomalies, which are correlated with the negative magnetic anomalies. From each anomaly, we remove a model of the regional field. We then approximate the resulting residual anomaly by the field of several 3D line segments and subtract their effects. The residual field is inverted for 3D topography of a contact surface. We apply our inversion algorithms to transform segments into three restricted bodies, which are interpreted geologically as granitic intrusions. Finally, we combine all objects and obtain a 3D model of the main intermediate sources.

Among shallow sources, there are two main gravity anomalies, which are correlated with the magnetic ones. We transform magnetic data to so-called pseudo-gravity and compare it with measured gravity.

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* Corresponding author.
E-mail address: Ilya.Prutkin@gmx.de (I. Prutkin).

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Their high spatial correlation indicates that both, the gravity and magnetic anomalies are likely related to the same source. We then invert the anomalies for the 3D topography of density interface, which is interpreted as an uplift of the crystalline basement. For several local areas, we invert negative gravity anomalies for the geometry of salt deposits. This interpretation is supported by drilling data from existing boreholes.

2. Separation of sources in depth and the problem of low frequencies

We use the Bouguer anomaly data in gravity modelling and the total magnetic intensity anomaly in our magnetic investigation. Both fields are represented by gridded data for the whole area of Thuringia with the grid resolution of 500 m. The regional geological model of the study area is provided by the Thuringian State Agency for Environment and Geology (TLUG).

We begin with a separation of sources in the gravity and magnetic anomalies into shallow (above 5 km), intermediate (between 5 and 20 km) and deep ones (below 20 km). For this purpose, we apply our algorithm based on applying the subsequent upward and downward continuation procedures (cf. Prutkin and Casten, 2009). The main goal of the algorithm is to extract the component of the field, which is harmonic above the prescribed depth h. We can treat this function as an effect of the half-space below the depth h. If such components are found for two values of the depth h_1 and h_2, $h_1 < h_2$, we can obtain the signal of sources located in the horizontal layer between the given depths h_1 and h_2. It is important to note that we deal with the depth to singularities of the corresponding component as a harmonic function. For instance, an effect of smooth undulations of a density interface can be harmonic down to great depths.

Here we face a problem, which we call the problem of long wavelengths. We describe the problem in the following way. High-frequency components decrease faster, therefore, if we have a signal generated by deep objects, long wavelengths prevail. Equivalently, if we observe short wavelengths, they should be generated by shallow objects. However, the converse implication does not hold, meaning that if we observe long wavelengths, we cannot assert that they are caused by deep sources. An example of an ambiguity in the interpretation of long wavelengths is the above-mentioned smooth topography of a density interface.

The field of deep sources is shown in Fig. 1a. We calculated the gravitational effect of the TLUG geological model. Then, we separated it in a similar way into the short, medium and long wavelengths. The long wavelengths are shown in Fig. 1b. We obtained another example of the ambiguity in their interpretation: a low-frequency anomaly occurs, although it is caused by density heterogeneities in near-surface layers. After subtracting this field from the given data (i.e., long wavelengths) we observe an increasing gravity signal from the south-west to the north-east (Fig. 1c), which can be explained by a known Moho topography. Eventually, we interpret the low-frequency component of the given gravity such that it includes a long-wavelength effect of the basin structure and the effect of Moho.

Medium wavelengths of the measured gravity values are shown in Fig. 2 (left). The negative anomalies are explained in the next section by granitic intrusions located at the depth of several kilometres. We deal again with the problem of the ambiguity in the interpretation of long wavelengths, meaning that the same anomalies can be attributed to undulations of topography in shallow layers. To discriminate sources of these anomalies, we performed the following investigations: For the area of the northern negative anomaly, we inverted the anomaly for topography of two density interfaces: between Muschelkalk (Middle Triassic shell-bearing limestone) and Buntsandstein (Lower Triassic bunter sandstone) and between Buntsandstein and Zechstein (Permian rocks); the anomaly is shared in equal parts (inversion algorithm is described in the next section). Then, we took a profile through existing boreholes and compared topography of density interfaces found by the inversion and their positions according to information from the boreholes. Since the first and the third layers have higher mass density than the second one, the negative anomaly is explained by thinning of the first layer and by a depression of the second density interface. However, these undulations are not supported by data from the boreholes, see Fig. 2 (right). In this case, sources of low-frequency anomalies cannot be shifted upward, because this would contradict available geological information.

3. Interpretation of medium wavelengths

We begin processing of intermediate wavelengths of gravity with three negative anomalies outlined with dashed lines in Fig. 2 (left). For each area, we reduced anomalies for a model of the regional field by applying again the upward and downward continuation procedures.

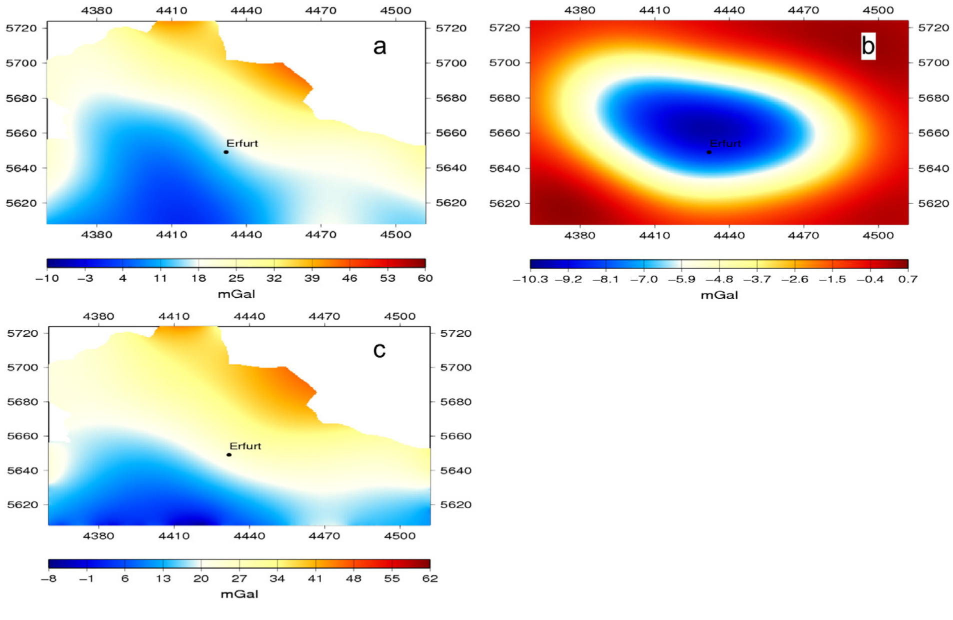

Fig. 1. Long wavelengths and their interpretation: a – the low-frequency part of observed gravity, b – the same for the effect of the geological model, c – the residual field (effect of Moho). Gauss-Krüger coordinates are used (in km).