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The limitation of the gravity inversion method based on the Parker-Oldenburg algorithm in determination of the basement topography

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Abstract This short communication discusses a 2013 publication by Oruç et al. (2013) who presented a structural interpretation map of the Erzurum Basin in eastern Turkey using curvature gradient tensor, and inferred the basement topography using gravity inversion method. In our comment, we show the limitation of the gravity data they used and the flawed approach in determining the basement topography. The gravity data were not filtered to remove deeper sources, which subsequently resulted in two interfaces, the Moho and the interface between crystalline basement and sedimentary sequences. Multi-interface gravity data are not ideal for a single interface determination in the inversion, as shown from our discussion. Finally, we applied the approach used by Oruç et al. (2013) in the Lower Shire Basin, Southern Malawi to determine the effect of the inversion in a similar environment. The results showed that even in areas where basement is exposed, deeper basement values of greater than 3 km are resolved. Thus, the limitation of this approach is not specific to Erzurum Basin in Turkey, but also true to other sedimentary basins.

Keywords: *Structural interpretation; Gravity anomalies; Parker-Oldenburg Equation; Erzurum Basin; Shire Basin*.

1. Introduction

In 2013, Oruç et al. (2013) presented a structural interpretation map of the Erzurum Basin in eastern Turkey using curvature gradient tensor. They computed the basement topography of the Erzurum Basin by inverting gravity data. The Parker-Oldenburg equation (Parker, 1973; Oldenburg, 1974) was used as implemented in 3DINVER.M (Gómez-Ortiz & Agarwal, 2005) to image the basement-sedimentary interface. In this short communication, we discuss the limitations of the Parker-

Oldenburg algorithm, as implemented in 3DINVER.M, and as used by Oruç et al. (2013), in determining the basement topography. In a sedimentary environment, the basement topography is the boundary between the sedimentary layers and the underlying basement rocks. The density and material differences between these two layers across an interface create a density contrast. This difference or contrast is utilised to model the topography, with Moho depth being the most modeled interface using gravity data (e.g., Chisenga et al., 2020; Chisenga et al., 2019; Chisenga & Yan, 2019), which creates a region of density contrasts resulting in identification of the major boundaries in the subsurface.

In this communication, we first address the limitation of the use of gravity data and the Parker-Oldenburg algorithm, and then identify the flaws in the approach, as applied by Oruç et al. (2013), in basement topography modelling. To achieve these, we apply the inversion approach of Oruç et al., (2013) to a region in the East African Rift Systems (EARS), called the Lower Shire Basin in Southern Malawi. Chisenga et al. (2019) re-interpreted the structural setting of the Lower Shire River Basin using high-resolution airborne gravity data. In their work, they initially used the same approach as Oruç et al., (2013) to resolve the basement topography of the Lower Shire Basin. However, they noticed that the algorithm had some limitations in Sedimentary Basin modeling, which subsequently made them remove the results from their work before publishing. It is with this background that we discuss these limitations to avoid future usage of this approach by other researchers.

2. Oruç et al. (2013) inversion Approach

Oruç et al. (2013) computed the basement undulation/topography using the Parker-Oldenburg equation. They constrained the middle depth of the basement as 6 km, based on the geological insight from Pelin et al. (1980) and Şaroğlu and Güner (1981). They used a density contrast of 0.4g/cm^3, based on density values of basement crystalline rocks (~ 2.8 g/cm^3) and volcano-sedimentary sequences (~ 2.4 g/cm^3). The smallest and greater cut-off frequency parameters were chosen as 0.011 and 0.020 km^{-1}, respectively. The quality of the results was ascertained based on the similarities/fit between calculated gravity anomaly from forward-modeling of basement topography and the input gravity anomaly data, as shown in Figure 11 of Oruç et al. (2013).

The limitation in the Oruç et al. (2013) approach for the computation of the basement topography starts from the choice of data. They used Bouguer gravity anomaly with station spacing of 0.5 km and accuracy of 0.01 mGal acquired by the Turkish Petroleum Company (TPAO). Bouguer gravity data contains both long and short wavelength signal with signal overlaps. Short wavelength signals are due to sedimentary bodies, near surface rocks and intra-crustal structures while long wavelength bodies denote deep-seated bodies, which include lower crust and mantle sources. Oruç et al. (2013) did not preprocess their data before inversion to only allow signal of interest in the modeling. This is clear from the comparison of Figure 6 and Figure 11a of Oruç et al. (2013). Both these figures indicate the same gravity values from -186 mGal to over -95 mGal. With a resolution of 0.5 km, high frequency signals from the gravity data are included in the inversion.

Another problem arises due to the number of interfaces in the earth crust that the gravity data can resolve. Gravity is a versatile geophysical technique that measures bulk property of any subsurface information. Thus, the interface between the upper mantle and lower crust, called the Moho, as well as the interface between crystalline basement and sedimentary sequences are both presented in the gravity data. The question is: which interface did the Parker-Oldenburg inversion approach located in the Oruç et al. (2013) paper measure? Moho depth studies that use the

Parker-Oldenburg inversion eliminate this multi-interface scenario by applying a sediment correction procedure; such that only the Moho remains and the interface between the basement crystalline rocks and sedimentary sequences is eliminated (e.g., Van der Meijde et al., 2013).

We also noticed that they included a high cut filter in the inversion to limit the high frequencies in the inversion. The smallest and greater cut-off frequency parameters that they chose are 0.011 and 0.020 km^{-1}, respectively, representing data with wavelength of 90 km and 50 km. The High-Cut Filter is calculated using Eq. (1)

$$\mathrm{HCF}(k) = \frac{1}{2}\left[1 + \cos\left(\frac{k - 2\pi \mathrm{WH}}{2(\mathrm{SH} - \mathrm{WH})}\right)\right] \text{……Equation (1)}$$

Where HCF (*k*) is a high-cut filter, *k* is the wavelength in kilometers; WH is the smallest cut-off frequency and SH is a greater cut-off frequency. The problem with this approach is that this eliminates high frequency signals in the gravity data, which might remove the sedimentary sequences and in some instances the basement topography. Also, if this filter worked in their approach, the input gravity and output gravity data due to interface topography are not supposed to be the same as is the case in Figure 6 and Figure11a of Oruç et al. (2013). The calculated gravity data may be devoid of high frequency data and only show regional anomaly. This may mean that the high cut filter did not yield desirable results. Oruç et al. (2013) claimed that "The inversion process is iterated until a satisfactory agreement between observed and calculated gravity is obtained. Figure 11 shows a reasonably good agreement between the observed (Figure 11a) and calculated (Figure 11b) anomalies from basement undulation (Figure 11c)". We should point out here that the agreement between the two kinds of gravity data does not mean the produced model fits the basin structural architecture. This conclusion is wrong because the inversions were constrained and, prior information was based on "geological insight by Pelin et al. (1980) and Şaroğlu and Güner (1981)" which did not have constraints on the Basin depth. Others who have used this approach constrain their results to seismic data (e.g., Van der Meijde et al., 2013), in Oruç et al. (2013) case, drill hole data would have sufficed.

Oruç et al. (2013) concluded on the 3D basement topography mapping that the inferred basement configuration shows a general depression of the basement in their northern part of the study area. Based on their results, the configuration also illustrated thick sediments which are volcano-sedimentary sequence that consists of andesitic-basaltic volcanic rocks and marine sedimentary clastics. Further, they concluded that the gravity anomalies arise principally from variations in basement topography. Thus, one can easily conclude that gravity anomalies are correlated with basement topography. A major uplift of Erzurum-Horasan-Pasinler basin is placed at the northeastern of their study area and the bedrock topography shallowed southwards and northwards, and reached 3.45 km. The most significant feature of the map was the ENE–WSW trending basement depression bounded by NW-SW lineament. In general, it was noted that the boundaries between uplifts and grabens in the basement undulation had been generated by evolution of fault zones from structural disorder towards geometrical simplicity. Basement topographic high was associated with the anticlines and roughly NW-striking basement trough plunges into the series of basins. Their conclusion is correct based on their results but to some extent, we have a question. The depth to basement is between 3.5 km to 9 km, as shown in Figure 11c of Oruç et al. (2013) for the entire study area, as shown in Figure 5 for this study. Legend of the simplified geological map of eastern Turkey in Figure 5 indicates the presence of strike-slip basin fill and Oligocene-Quaternary volcano-sedimentary cover sequence as the geological units of the study area. We assume that the other unnamed unit, in grey color, corresponds to basement rocks exposed to the surface. If the assumption is true then why is it that the whole area, including the exposed basement, shows depth of not less than 3.5 km? If the inversion is correct, the northern and northeastern parts of the study area should indicate a depth to basement of close to zero. It should be noted that the inversion is influenced by the mean depth values, in Oruç et al. (2013) case, the value was 6 km, in which the inversion results undulates on, i.e. added or subtracted based on the gravity anomaly. In such cases, a zero km depth is highly unlikely to be found when no constraints are used. Also, a lack of control points, in form of drilled basement, may have caused exposed basement to appear to be 3 km deep, since no prior information is available to constrain the model.

3. Application of Oruç et al. (2013) Approach to Lower Shire Basin

The Lower Shire Basin occupies the southern-end of the Malawi Rift, which was developed during the Karoo times and re-activated during the Cenozoic time due to the rifting associated with the EARS (e.g. Castaing, 1991). It is situated near the southern-end of Malawi between latitudes 15°30’S and 16°45’S and longitudes 34°15’E and 35°15’E. The area has a full coverage of the Bouguer gravity anomaly data obtained from the Malawi Geological Survey Department (Bates and Mechennef, 2013a, 2013b). The data is part of the country-wide airborne geophysical survey results conducted by Sanders Geophysics Limited (SGL), on behalf of the Malawi Government.

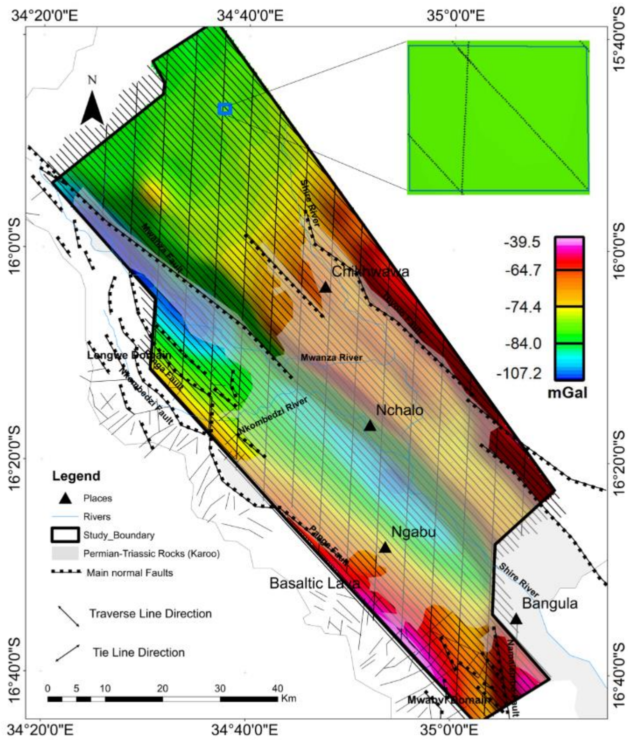

Figure 1: The gravity survey results showing the Bouguer anomaly map in the background, main existing faults, extent of alluvium deposition and data collection points with direction of traverse lines and control lines

The reliability of Parker-Oldenburg equation as implemented in 3DINVER.M as used by Oruç et al. (2013) is doubtful in basement topography mapping, as has been shown in section 2. Nevertheless, we would like to demonstrate that the approach is of limited use by applying it in the similar environment in the Lower Shire Basin.

We took the approach of Oruç et al. (2013) to compute the basement topography of Lower Shire Basin. Lower Shire basin is a Karroo sedimentary basin within the African Rift System in the Southern Malawi Rift (Castaing, 1991; Chisenga et al., 2019; Dulanya, 2017). The area is similar to the Erzurum Basin in Turkey with some visible gravity anomaly due to sedimentary basin environment and exposure of basement geology in the northern part of the study area. Thus, we compare the depth of exposed basement rocks in these two areas and the effect of both filtered and unfiltered gravity data on the basement topography.

We replicated the inversion process for Lower Shire basin. The middle depth of the basement was constrained to 4.2 km based on geological estimate from Castaing (1990). The rest of the parameters were maintained to those discussed in paragraph 1 of section 2, as used by Oruç et al. (2013). We inverted the gravity data twice. Firstly, we used the Bouguer anomaly map that is shown in Figure 2A. We also produced the calculated gravity anomaly, as shown in Figure 2B, based on the forward modeling of basement topography, as shown in Figure 2C. Second inversion used the filtered gravity anomaly data, as shown in Figure 2D. The study area is a three-layer model with two interfaces, (1) the Moho and (2) the interface that separates the basement rocks from the Karoo sedimentary rocks. An 800 km Butterworth high-pass filter was applied to Bouguer anomaly to remove the signals from the upper mantle and the Moho. This step produced a two-layer model with signal from the crystalline basement and the sedimentary layers. Then the 800 km filtered data was further filtered with a 50 km Butterworth low pass filter, since the inversion is unstable at high frequencies. The filtered data was used for inversion procedure. Then, we also produced the calculated gravity anomaly, as shown in Figure 2E, from forward modeling of the basement topography, as shown in figure 2F.

Our results confirmed the limitations of the Oruç et al. (2013) approach. Firstly, fitness or lack thereof between input gravity data and calculated data due to basement topography does not indicate that the results obtained represent the physical basin model. Despite the good fit between these two gravity data, the northern part of the Lower Shire Basin shows a depth of at least 3.5 km. This is so even though the geological information in the Lower Shire Basin indicates basement rocks exposure in the northern part (Figure 2A and 2B). Comparing the gravity anomaly and the spatial location of the basin in Lower Shire region, the low gravity is situated in the basin environment (Chisenga et al., 2019). There is even a deeper undulated in the basin areas with low gravity values compared to the basement rocks. However, the basement topography model which was produced is not reliable in such environment as it is clear that it does not fit the geological information of the area.

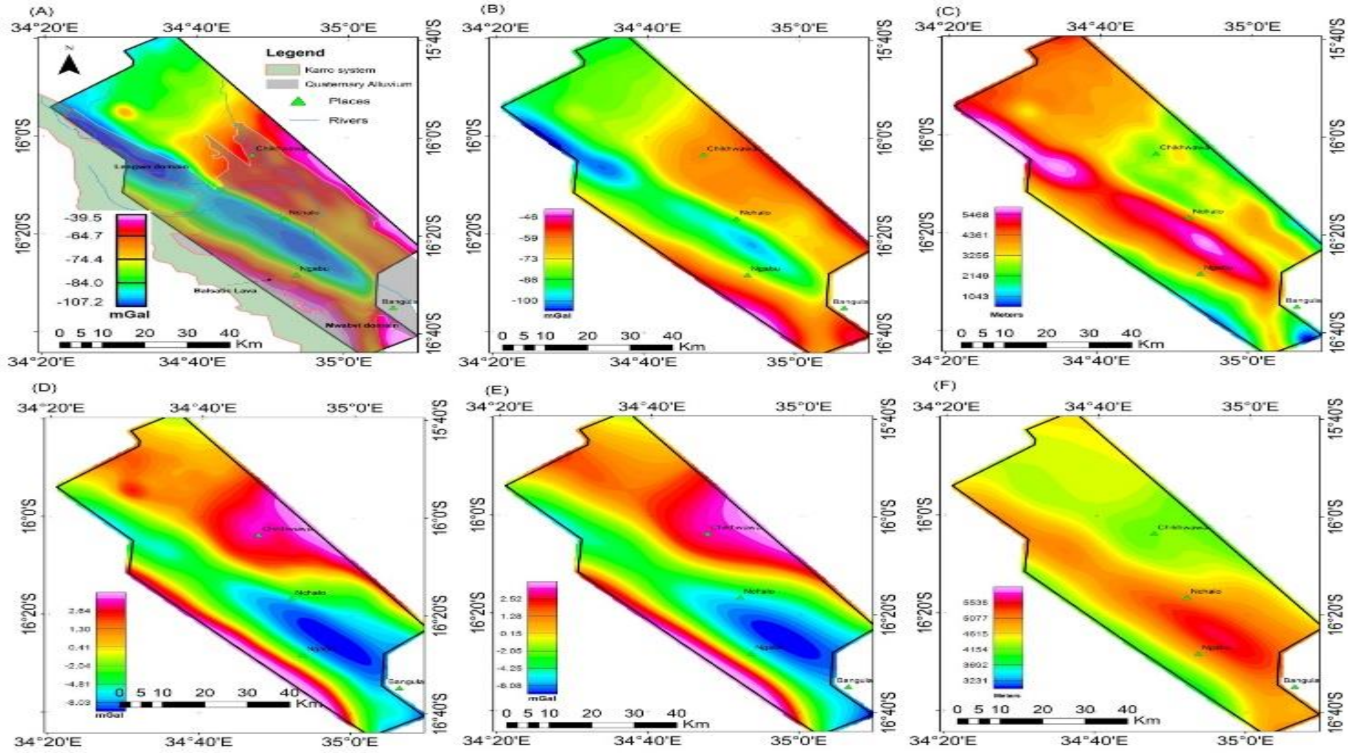

Figure 2: Gravity inversion based on Oruç et al., (2013) approach: (A) Bouguer anomaly Map of Lower Shire Basin (M Bates & Mechennef, 2013a, 2013b), also showing is the extent of quaternary and Karroo deposition. In the northern part, the Precambrian basement rocks are exposed (B) Calculated gravity anomaly based on basement topography shown in Figure 2C; (C) Basement topography based on gravity anomaly shown in Figure 2A; (D) Filtered Bouguer anomaly of Figure 2A; (E) Calculated gravity anomaly based on basement topography shown in Figure 2F; (F) Basement topography based on gravity anomaly shown in Figure 2D.

4. Conclusions

Gravity data complement the geological techniques and other geophysical techniques in basin modeling. However, a careful analysis of gravity data is needed to provide valuable insights into the basin structural architecture. Firstly, there is a need to understand the level and type of analysis on the gravity data, which may include removing unsuitable gravity signal based on the geological information of the area. Then, the choice of a suitable method is required. There are a lot of methodologies that are used for basin modeling including basement topography mapping. A careful choice of the method is required before any implementation is done. However, the Parker-Oldenburg algorithm as implemented in 3DINVER.M, and as used by Oruç et al., (2013) should not be used for basement topography mapping in its present state.

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6. Author contribution

Chikondi Chisenga: synthesizing, analysis, processing and discussion, **Emmanuel Chinkaka**: editing and discussion

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8. Declaration of conflict of interest

The authors do not have any issues that will result in conflict of interest

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