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RESEARCH ARTICLE

Gravity modeling

A technique for extracting gravity anomalies originating from sediments deposited on folded oceanic crust

DA Tantrigoda[1*], MMPM Fernando[1] and SA Samaranayake[2]
[1] *Department of Physics, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda.*
[2] *Department of Physical Sciences, Faculty of Applied Sciences, Rajarata University of Sri Lanka, Mihinthale.*

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Abstract: Negative gravity anomalies observed over sediments accumulated on folded oceanic crust are usually caused by two negative density contrasts. The first is the contrast between low-density sediments lying on folded high-density oceanic crust and the second is the contrast between low-density oceanic crust immersed into the high-density upper mantle. Because the anomaly is caused by two regions with different densities, modeling it is not straightforward. Most standard methods only allow for modeling bodies with a single density contrast. This paper describes a Fourier technique to separate the anomaly caused by the sediment distribution facilitating its modeling using a standard method. It is assumed that the oceanic crust over the region under consideration has a constant thickness and that the densities of sediments, oceanic crust, and upper mantle are constant. The technique was tested with artificially generated negative gravity anomalies for a hypothetical case and found to work satisfactorily. Even though the two-dimensional version of the technique is described here for the sake of convenience, it can readily be extended to the three-dimensional case.

Keywords: Fourier transforms, gravity anomaly, inverse method, oceanic crust, sediments, upper mantle.

INTRODUCTION

Folding is one of the phenomena responsible for the Earth's present outward appearance with large-scale folding being a key mechanism of lithospheric deformation (McAdoo and Sandwell, 1985, Cloetingh et al., 2002, Munoz-Martin et al., 2010, Xie et al., 2024). Such folds can be seen in both continental and oceanic regions generally filled with sediments that create negative gravity anomalies. In continental regions, the negative anomaly is due to the density contrast between low density sediments and relatively high-density continental crust. However, in oceanic regions the anomaly is caused by two independent density contrasts (Altınoğlu et al., 2023). The first is the density contrast between sediments and folded oceanic crust, while the second is the density contrast between low-density oceanic crust folded into the upper mantle replacing the upper mantle material (Liu et al., 1982). This second component is also negative, but usually smaller than the first. When modeling this anomaly, it is necessary to consider that both source regions and the model will have two density contrasts. Most standard inversion techniques can only model gravity anomalies caused by a single density contrast (Talwani et al., 1959, Parker, 1973, Nagendra et al., 1996, Chakravarthi et al., 2002). Therefore, these methods cannot directly model gravity anomalies due to folded oceanic crust filled with sediments. This paper describes a method to separate the anomaly caused by the sediments from the total observed anomaly, making it easier to interpret using standard inversion techniques.

* Corresponding author (dhammika@tantrigoda.net; https://orcid.org/0000-0002-9046-1999)

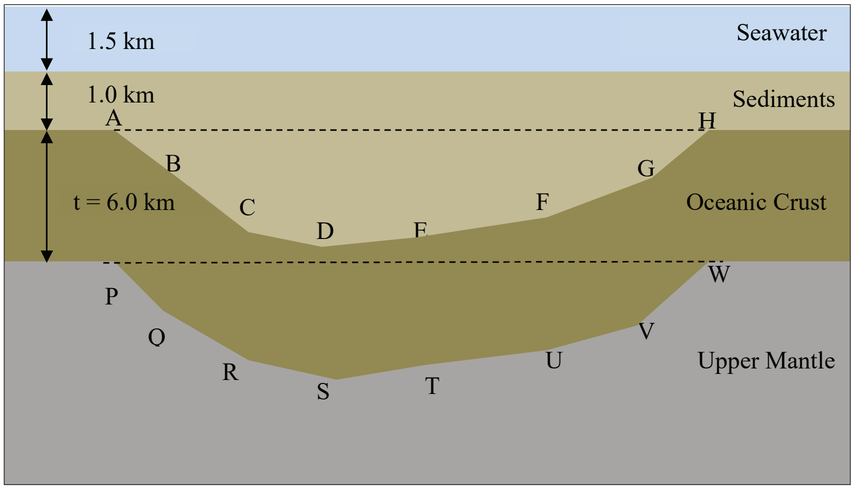

Figure 1: Sediments lying on folded oceanic crust.

METERIALS AND METHODS

Figure 1 shows a folded region of oceanic crust of thickness *t* filled with low density sediments. We assume that sediments lying above those trapped in the fold form a horizontal infinite slab. This slab and the water column above it, which also usually takes the form of an infinite slab, create a constant anomaly over and around the basin without contributing to the observed anomaly. Therefore, it is not necessary to consider these factors in the modelling process.

Let us consider a two-dimensional Cartesian coordinate system with the X-axis along the sea level and the Z-axis pointing vertically downward. Let $\Delta g_1(x,0)$ and $\Delta g_2(x,0)$ be the anomalies caused by the closed regions ABCDEFGHA and PQRSTUVWP (Figure 1), respectively, at sea level. The anomaly $\Delta g_1(x,0)$ is caused due to the density contrast between sediments and the oceanic crust while anomaly $\Delta g_2(x,0)$ is caused due to the density contrast between oceanic crust and the upper mantle material. If $\Delta g(x,0)$ is the total anomaly observed at sea level, then,

$$\Delta g(x,0) = \Delta g_1(x,0) + \Delta g_2(x,0) \qquad ...(1)$$

Since we assume that the oceanic crust has a constant thickness, both ABCDEFGHA and PQRSTUVWP have the same geometry. If both regions have the same density contrast, then the gravity anomaly produced by ABCDEFGHA at a height *t* above the sea level is equal to the gravity anomaly produced by PQRSTUVWP at sea level. This means that the anomaly $\Delta g_2(x,0)$ would be equal to the anomaly $\Delta g_1(x,0)$ upward continued by a height *t* $(\Delta g_1(x,t))$ provided both bodies have the same density contrast. However, the body ABCDEFGHA has a density contrast of $(\rho_c - \rho_s)$ while the body PQRSTUVWP has a density contrast of $(\rho_m - \rho_c)$, where ρ_s, ρ_c and ρ_m are densities of sediments, oceanic crust, and upper mantle, respectively. Therefore, the anomaly $\Delta g_2(x,0)$ can be written as,

$$\Delta g_2(x,0) = \left(\frac{\rho_m - \rho_c}{\rho_c - \rho_s}\right) \Delta g_1(x,t) \qquad ...(2)$$

Since Δg, Δg_1 and Δg_2 satisfy the Laplace's equation in Cartesian coordinates,

$$\Delta g(x,0) = \sum_k F(k)\, Exp(-ikx) \qquad ...(3)$$

$$\Delta g_1(x,0) = \sum_k F_1(k)\, Exp(-ikx) \qquad ...(4)$$

$$\Delta g_1(x,t) = \sum_k F_1(k)\, Exp(-ikx) Exp(-kt) \qquad ...(5)$$

where, *F(k)* and $F_1(k)$ are complex Fourier coefficients, *k* denotes the wave number and $\Delta g_1(x,t)$ is the anomaly $\Delta g_1(x,0)$ upward continued by a height ***t*.**

Substituting for $\Delta g_1(x,t)$ from (5) in (2),

$$\Delta g_2(x,0) = \left(\frac{\rho_m - \rho_c}{\rho_c - \rho_s}\right) \sum_k F_1(k) Exp(-ikx) Exp(-kt) \qquad ...(6)$$

Substituting for Δg, Δg_1 and Δg_2 from (3), (4) and (6) in (1) and rearranging terms,

$$F_1(k) = \frac{F(k)}{1+\left(\frac{\rho_m-\rho_c}{\rho_c-\rho_s}\right)Exp(-kt)} \quad ...(7)$$

Using the above relationship, $F_1(k)$ can be calculated for all k values as $F(k)$ is the Fourier coefficients of the observed anomaly, which is a known quantity. The inverse Fourier transform of $F_1(k)$ will give the component of the gravity anomaly due to the sediments filled in the folded oceanic crust.

Testing of the method

Gravity anomaly due to the two-dimensional structure shown in Figure 1 was calculated using the method described by Talwani et al., (1959). This was performed by calculating the anomaly caused by the density contrast between sediments and oceanic crust and that due to the density contrast between the oceanic crust and upper mantle separately, and then adding them together. Density values used were 2300 kgm^{-3}, 2900 kgm^{-3} and 3300 kgm^{-3} for sediments, oceanic crust and the upper mantle, respectively (Bott, 1971; Woollard, 1959).

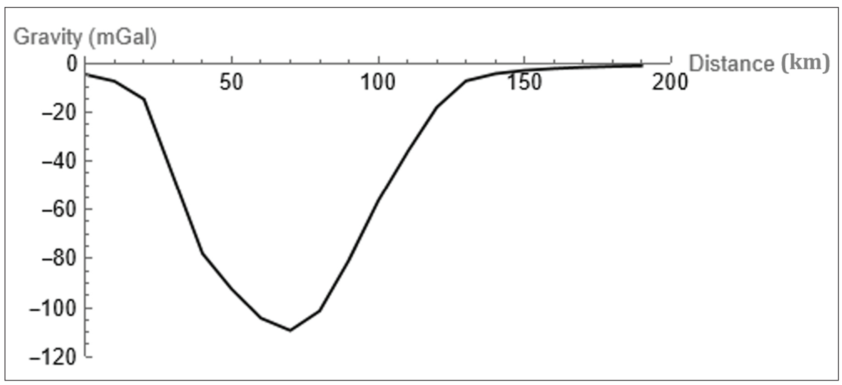

Figure 2: Directly calculated gravity anomaly due to the two source regions

The total anomaly directly calculated from the two source regions is shown in Figure 2. The anomaly attributed to the sediments in the folded oceanic crust was determined by extracting it from the total anomaly using the method described here (Figure 3). This anomaly was then compared with the directly calculated anomaly attributed to the same body with the results given in Figure 4. It is evident that these two anomalies are remarkably close to each other and the root mean square difference between two anomalies is 0.99 mGal**.**

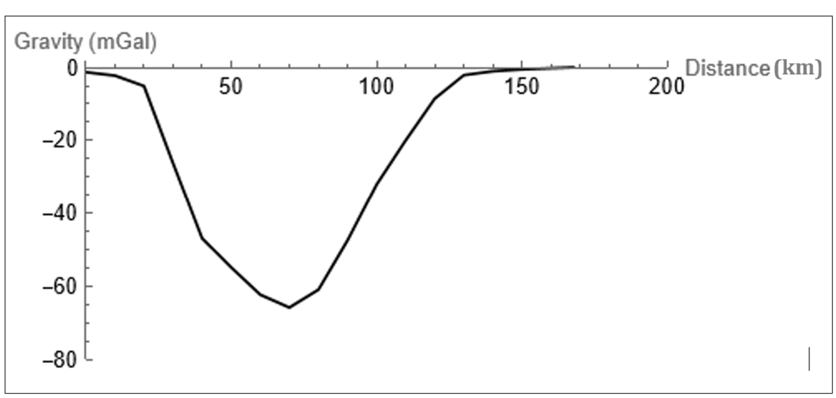

Figure 3: The anomaly due to the sediments in the folded oceanic crust, extracted from the method described in this paper

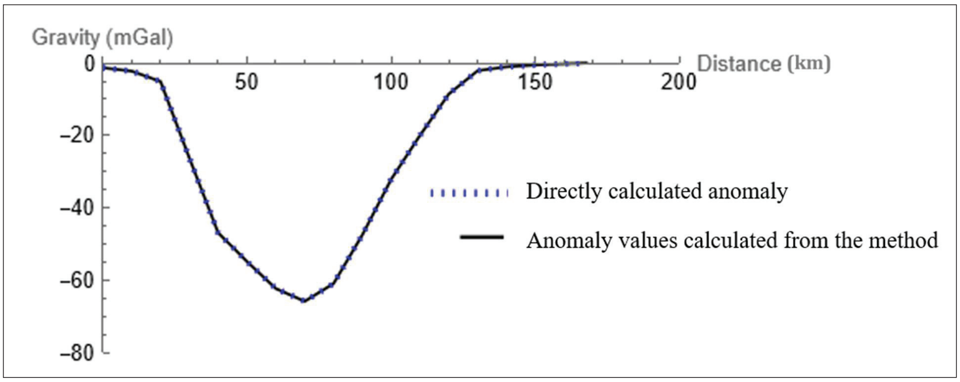

Figure 4: Comparison of gravity anomalies due to sediments obtained using the new technique with directly calculated anomaly due to the same body

Extension to the three-dimensional case

The above method can easily be extended to anomalies caused by three-dimensional sedimentary basins formed as a result of the accumulation of sediments in folded oceanic crust partly immersed in the upper mantle. Let $\Delta g(x,y,0)$ be the gravity anomaly measured over a rectangular region over the basin at sea level and $\Delta g_1(x,y,0)$ be the anomaly due to the sediments trapped in the basin over the same region. Let $F(k_x,k_y)$ and $F_1(k_x,k_y)$ be their Fourier transforms and symbols k_x and k_y denote wave numbers corresponding to x and y directions. Following a series of steps similar to those followed in the two-dimensional case, it can be shown that,

$$F_1(k_x,k_y) = \frac{F(k_x,k_y)}{1+\left(\frac{\rho_m-\rho_c}{\rho_c-\rho_s}\right) Exp\left\{-\left({k_x}^2+{k_y}^2\right)^{1/2} t\right\}} \quad ...[8]$$

It is possible to extract the Fourier transform of the gravity anomaly $\Delta g_1(x,y,0)$ starting from the Fourier transform of the observed anomaly using the above equation and hence the anomaly due to the sediments.

RESULTS AND DISCUSSION

A method for extracting the component of the gravity anomaly caused by sediments lying on folded oceanic crust is presented. This method utilises the fact that two regions contributing to the anomaly (Figure 1) have the same geometry, which is a direct result of assuming the oceanic crust has a constant thickness. A test conducted with a gravity anomaly due to a known structure demonstrates that the method works satisfactorily.

An important assumption made in the method's formulation is that the thickness of oceanic crust is constant. Normally, a thickness of 6 km is assumed as the average value in calculations related to oceanic regions. To determine the impact of varying crust thickness from this value, a test was conducted in the frequency domain. Let $F_t(k)$ be the Fourier transform of the gravity anomaly due to the sediments extracted using equation (7) when the thickness of oceanic crust is 't' while $F_6(k)$ is the Fourier transform of the gravity anomaly due to the same sediments extracted using the same equation assuming the thickness of the oceanic crust is 6 km. The fractional error caused due to this assumption can be written using (7) as,

$$\frac{F_t(k)-F_6(k)}{F_t(k)} = 1 - \frac{1+\left(\frac{\rho_m-\rho_c}{\rho_c-\rho_s}\right) Exp(-kt)}{1+\left(\frac{\rho_m-\rho_c}{\rho_c-\rho_s}\right) Exp(-k6)} \quad ...[9]$$

The above fractional error and hence the percentage error were calculated for the Fourier coefficients for an anomaly that extends over a range of 200 km sampled at 10 km intervals with the thickness values of t equal to 1, 2, 3…….10 km. These calculations show that the Fourier coefficients can be calculated satisfactorily when the actual thickness t is in the range of 4 to 9 km. It was also noted that the highest error, amounting to 11%, occurs when the thickness t is 4 km for the k value corresponding to 20 km. For all the other coefficients, the error is less when t lies in the above range. Additionally, it was observed that the error is significantly lower for small k values corresponding to long wavelengths. Therefore, the assumption that the thickness of oceanic crust is 6 km had a noticeable effect only on the low wavelength features rather than the long wavelength features. The overall shape determined by long and intermediate level features is not affected much by this assumption. This illustrates that using 6 km as the thickness of the oceanic crust does not lead to a serious error, and the proposed method generally provides satisfactory results.

In this method, it was also assumed that the thickness of sediments lying above the sediments trapped in the folded oceanic crust is of constant thickness and does not contribute to the observed anomaly. However, it is possible for these sediments to take the shape of a small-angled wedge, which can generate a gravity anomaly. In such a situation, the anomaly due to the wedged shaped sediments could be removed and the method can be still used.

CONCLUSION

Based on the results of several tests conducted, it can be generally concluded that the method described in this paper works satisfactorily. This method may also have useful applications in the interpretation of gravity anomalies caused by folded layered structures with approximately parallel sides in continental areas.

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