Gravity Field Imaging by Continued Fraction Downward Continuation: A Case Study of the Nechako Basin (Canada)

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Interpretation of gravity data plays an important role in the study of geologic structure and resource exploration in the deep part of the earth, like the lower crust, the upper mantle (Lü et al., 2013, 2019). The gravity anomaly reflects the lateral resolution of the underground mass distribution. So gravity data has the advantage of identifying the horizontal positions of the geologic structure and ore bodies. But both horizontal distributions and vertical distributions, also called depth variations, are important and interesting for interpreters and geoscientists (Hartman et al., 1971). Several gravity methods of source depth estimation have been proposed and developed. Li (2003) summarized and compared the most common classical methods, including Euler deconvolution (Thompson, 1982), Werner deconvolution (Hartman et al., 1971), analytic signal-based methods (Nabighian, 1972), local wavenumber methods (Thurston and Smith, 1997), and wavelets methods (Cooper, 2006). These methods are very useful and effective in the depth interpretation of gravity data.

With the development of airborne and satevllite techniques of gravity measurement, combined with the ground or the ship measurement, multi-height data from different ways are possible to be accessed over one area. Multi-scale methods, like imaging methods, which use the data of different levels are popular. In the study areas without multi-height data from different ways, continuation is a common and effective strategy to implement these. Because of the stability of upward continuation, many imaging methods have been proposed using upward continuation, such as DEXP, ScalFun, the reduced and multiridege Euler, summarized by Florio and Fedi (2018). As upward continuation reduces the resolution of the gravity data with the increasing of the upward height, Fedi et al. (2009) pointed out that these methods can recover the resolution that is lost with the increased altitude by combining the transformation with high order vertical differentiations. However, it is still difficult to distinguish the information with great burial depths (Zhou et al., 2021). Conversely, downward continuation enhances the resolution of gravity data (Zhang et al., 2018), so it can be used in imaging methods. However, downward continuation has an inherently unstable feature that has limited its widespread applications. Imaging methods based on downward continuation, such as the normalized total gradient method and the singular (quasi-singular) point method, usually require additional calculations which are similar to the basic normalized theory. More accurate and stable results are obtained through modified methods (Fedi and Florio, 2011). But these mainly rely on the accuracy and stability of the downward continuation method used in imaging methods. The error is very obvious when the spatial measured distance between the different geologic sources is small (Zhou et al., 2021). Although numerous methods have been presented to improve the accuracy and stability of downward continuation, they are nowhere near enough for improving the imaging of gravity data.

In this paper, we used a fourth-order method of continued fraction downward continuation to image gravity data. This downward continuation method is developed in the space domain, and for imaging the gravity data, only downward continuation calculations and a median filtering are needed from the measurement upper level to an expected maximum lower level. For general methods, the calculations of downward continuation are very sensitive to the vertical distributions of the geological sources, which leads the downward continuation to fail to go deeper than the shallow point of these sources. But the positions of singular points' horizontal and vertical distribution, which usually can be used to indicate the positions of geological sources, can be identified by the presented imaging method. So, the geologic source depths were directly obtained without any normalized calculations. First, we used two sets of model data without noise to test the imaging method by continued fraction downward continuation. Secondly, we applied the method to real airborne gravity data over the Nechako basin (Canada).

For the synthetic model, we consider three cubic prisms all sized 10 m × 10 m × 10 m with different burial depths and density contrast: the first prism's depth to the top is 15

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m and its density contrast with the background is 0.4×10^3 kg/m^2; the second one's depth to the top is 25 m and its density contrast with the background is 0.8×10^3 kg/m^2; the third one's depth to the top is 35 m and its density contrast with the background is 1.6×10^3 kg/m^2. The gravity data (Fig. 1) are calculated over a 150 × 150 grid with a 1 m in cell spacing. We downward the data from 0 m to 75 m in depth with a 1 m in depth spacing by the imaging method of continued fraction downward continuation (Fig. 2). It is evident that from the gravity data's contour map in its measurement level it is not obvious to identify these three prisms, but the values of the continued fraction downward continuation present these three cubic prisms' locations not only accurate in lateral distributions but also in depth variations though with slightly drifting off the positions for the second and third prisms. The imaging method based on the continued fraction downward continuation gives these sources' horizontal and vertical positions with the sources' rough shapes.

To illustrate the imaging method, we perform real gravity data to test and demonstrate in the Nechako basin of Canada. The Nechako basin located in the British Columbia, is the setting of a series of Jurassic–Cretaceous to Paleocene sedimentary basins which have the potential for hosting hydrocarbons (Riddell, 2011). These basins formed as a result of uplift, deformation, and erosion of North American continental rocks and amalgamated terranes. The basins are those hosting large volumes of coarse clastic sedimentary successions that were deposited at the end of the Early Cretaceous. Structure development, as well as magmatism and burial related to compression tectonics in the Middle to Late Cretaceous and transtensional regimes in the Eocene led to optimal conditions for hydrocarbon development and maturation

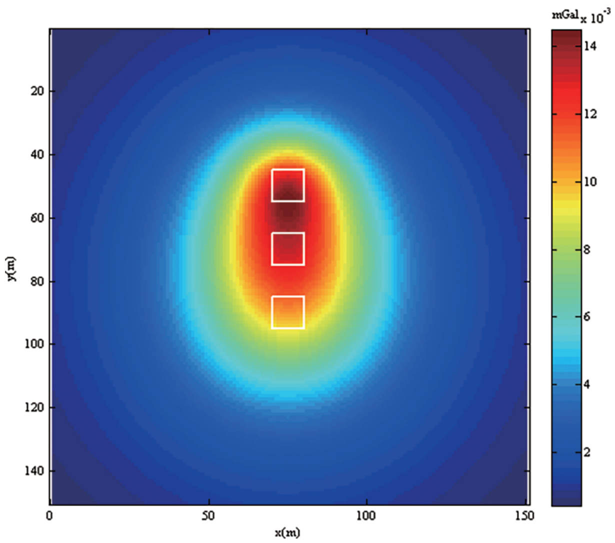

Fig. 1. Prism model.

(a) The gravity effect of three cubic prisms, which with density contrasts of 0.5×10^3 kg/m^2, 0.8×10^3 kg/m^2, and 1.5×10^3 kg/m^2, respectively are buried at depths from 15 m to 25 m, from 25 m to 35 m, from 35 m to 45 m, respectively, and along the y-axis from 45 m to 55 m, from 65 m to 75 m, from 85 m to 95 m, respectively, and along the x-axis all from 70 m to 80 m. Where the white rectangles are the horizontal location of the prisms.

(Riddell, 2010). An incomplete picture of the extent, depth, and volume of these sedimentary basins exist due to deformation and dismemberment occurring during Cretaceous to Eocene time. Additionally, due to overlying Eocene and Miocene age volcanic sequences, and the presence of significant glacial till coverage, there is minimal surface exposure of the Cretaceous and Eocene sedimentary basins of interest (Gravity and Magnetic Inversion Modeling, Nechako Basin, British Columbia Project, 2014).

The airborne gravity data (Fig. 3) used herein is measured over the Nechako Basin of Canada also used in Zhang et al., 2018. The data were acquired during a helicopter-borne gravity survey with an AIRGrav gravimeter installed in an Astar helicopter carried out by Sander Geophysics Limited in 2008. The nominal aircraft altitude is 0.15 km above the ground. Though corrections Bouguer anomaly is obtained and the precision is estimated at ±0.5 mGal. The grid point intervals of the data are 0.4 km × 0.4 km and the grid measuring point numbers 178 × 178. The order in the imaging method by continued fraction downward continuation is also fourth. Here also no filters or extension paddings are used. We downward the gravity data from 0 m to 40 km in depth with a 0.4 km in depth spacing. To display the results, the imaging results are presented in two ways: three 2D (Fig. 4) slices which are one horizontal cross-section and two vertical cross-sections, and a 3D image (Fig. 5) with values less than 200 mGal equals to NaN. Compared with gravity inversion and 3D modelling in this area (Phillips, 2011), this imaging result by continued fraction downward continuation can be a choice of identifying and modelling the distributions of the geologic sources in both lateral and

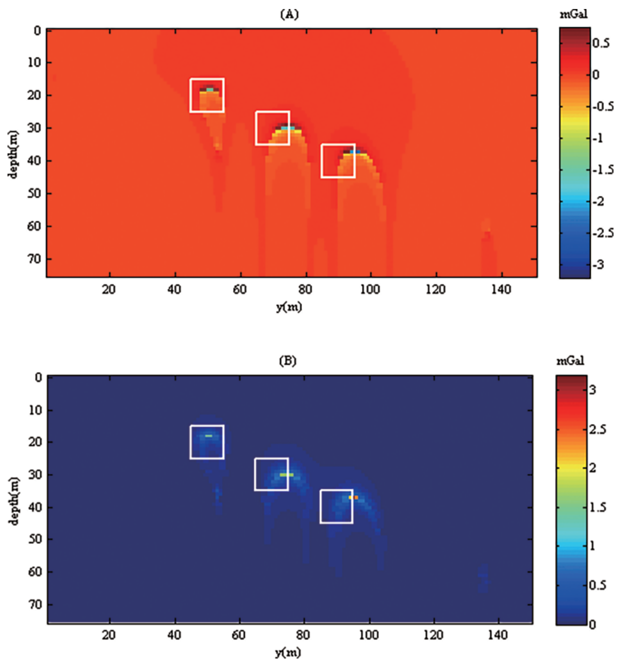

Fig. 2. Cross section intersected from the 3D results in Fig. 1.

The vertical cross section of the gravity field value after downward continuation from 0 m to 75 m for the coordinate $x = 75$ m, where the rectangles are the vertical location of the prisms. (a) imaging by the downward continuation; (b) imaging by the absolute value of downward continuation.

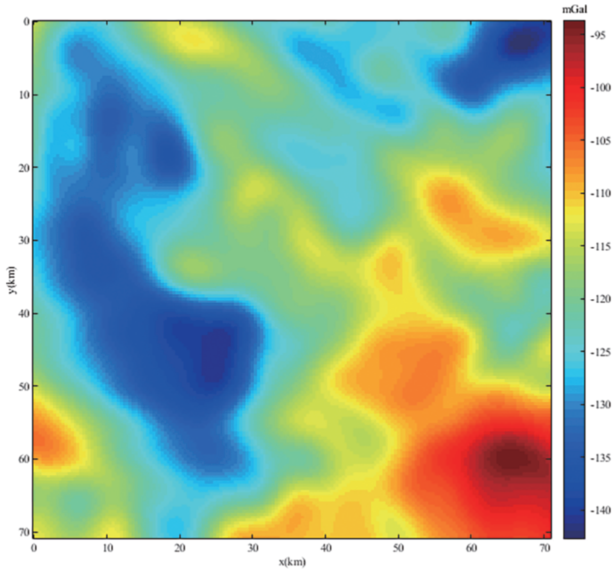

Fig. 3. Gravity anomaly over Nechako basin of Canada.
The contour map of the airborne gravity data was acquired during a helicopter-borne gravity survey with an AIRGrav gravimeter installed in an Astar helicopter carried out by Sander Geophysics Limited in 2008 over the Nechako basin of Canada. The nominal aircraft altitude is 0.15 km above the ground. The grid point intervals of the data are 0.4 km × 0.4 km and the grid measuring point numbers 178 × 178.

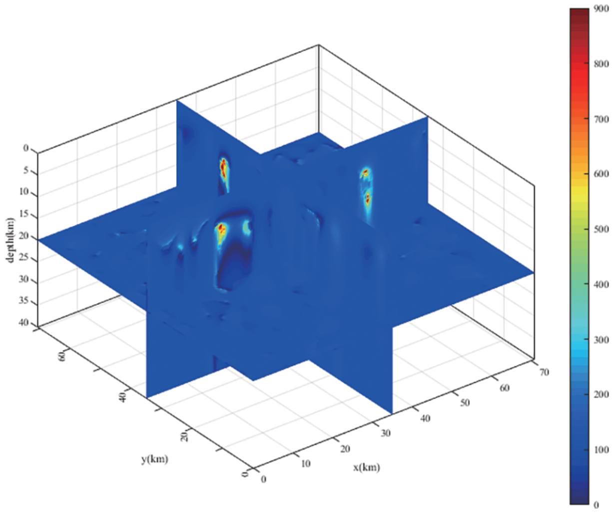

Fig. 4. Cross section intersected from the 3D imaging in Fig. 5.
The cross sections of the gravity imaging results by continued fraction downward continuation from the airborne anomaly in Fig. 5 at x = 35 km, y = 35 km, and z = 20 km.

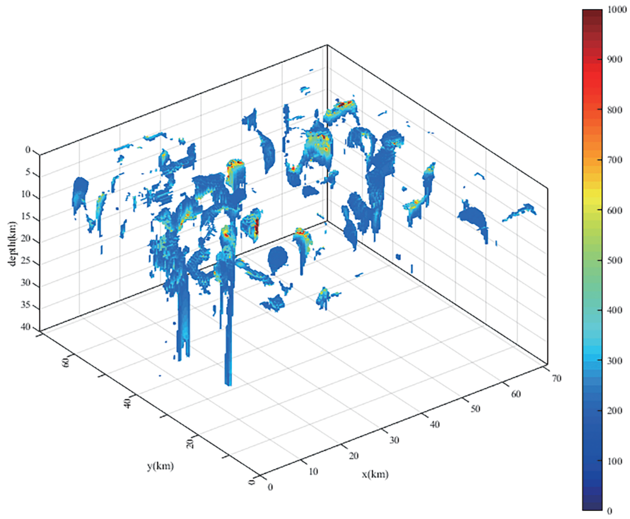

Fig. 5. The gravity imaging result.
The gravity imaging from 0 m to 40 km in depth with a 0.4 km in depth spacing, where the gravity values less than 200 mGal are set to be NaN.

depth.

It can be concluded that using continued fraction downward continuation, the gravity field can be imaged. By synthetic model and real example, we obtain reasonable results which match the data or agree with the previous results satisfactorily. Even there are several geological bodies with different burial depths in the study area, the depth estimations do not tend to be one average depth as other general methods but give reasonable imaging of gravity field. The downward continuation based on the continued fraction in the space domain can image the position of the singular-source points directly without other constraints. Only the downward continuation value needs to be calculated from the measurement level to an expected maximum depth. The downward value and its absolute value are calculated so that the maximum value indicates the source depth range. This makes the gravity imaging method by continued fraction downward continuation easy to utilize the gravity data directly and prior information for geologic modelling and interpretation.

Key words: depth estimation, downward continuation, gravity data, continued fraction

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