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Original article

Application of the improved parabola-based method in delineating lineaments of subsurface structures: A case study

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ABSTRACT

Identification of lateral boundaries for the subsurface structures is a popular topic in many applications of geoscience. For this purpose, many edge detection and enhancement methods have been introduced to determine the lineaments of subsurface structures. In this study, the improved parabola-based method has been applied to reveal the lineaments of subsurface structures of Nam Dinh province. The obtained results have shown that there are NW–SE trending structures in this region and most of the lineaments are in the depth range of 2 km to 8 km. These results provide a new perspective to help us better understand the structural framework and tectonic settings of the study area.

1. Introduction

The gravity method is one of the oldest methods used in geophysics exploration (Elhussein, 2021). The gravity exploration programs began from the first and third of the 20th Century and continues to this day as a small but significant element in several exploration areas (Nabighian et al., 2005). Interpreting the gravity anomalies can bring information on the depths and edges of the subsurface structures (Kafadar, 2017; Kafadar, 2019; Pham et al., 2020a; Pham et al., 2020b; Pham et al., 2021a; Pham et al., 2021b). Understanding the edges of gravity sources has an important effect on mapping the geology map. Several methods have been developed to extract the edges of the gravity data. Miller and Singh (1994), Wijns et al. (2005), Nasuti et al. (2018), Zareie and Moghadam (2019) have introduced balanced methods for extracting the boundaries of the deep and shallow structures simultaneously. However, these methods produce the secondary structures in edge maps (Eldosouky et al., 2020; Pham et al., 2021c; Pham et al., 2021d; Melouah and Pham, 2021; Oksum et al., 2021). Using the amplitude-based methods, this problem can be solved. These methods have been developed by Nabighian (1972), Cordell (1979), Fedi and Florio (2001), Beiki (2010), among others. Although the amplitude-based methods can avoid bringing false structures, they are dominated by the large-amplitude signals due to the shallow structures (Pham, 2021; Pham et al., 2021e). Some authors have developed peak locating methods to overcome this problem. The use of these methods has shown great success in determining the lateral boundaries of the subsurface structures in many areas (Paoletti et al., 2004; Nasuti et al. 2012; Tschirhart and Morris, 2014; Phillips et al., 2007; Fofie et al., 2019). The parabola-based method is the first method, developed by Blakely and Simpson (1986) to determine the peaks of the signals. Kha et al. (2018) improved the parabola-based method to bring more detail to the peak. However, both methods cannot detect all peak's locations (Pham et al., 2021f). Recently, Pham et al. (2021g) have been introduced an improved method for locating the signal peaks. The method determines the maximum locations by fitting a parabola to three successive data points.

Nam Dinh province is located in the southeastern part of the Song Hong delta, Vietnam (Fig. 1). The area is covered by Quaternary sediments, and so its deep structures are not observed on the surface. Subsurface geological structures of the area can be determined quickly and economically by assessing gravity data.

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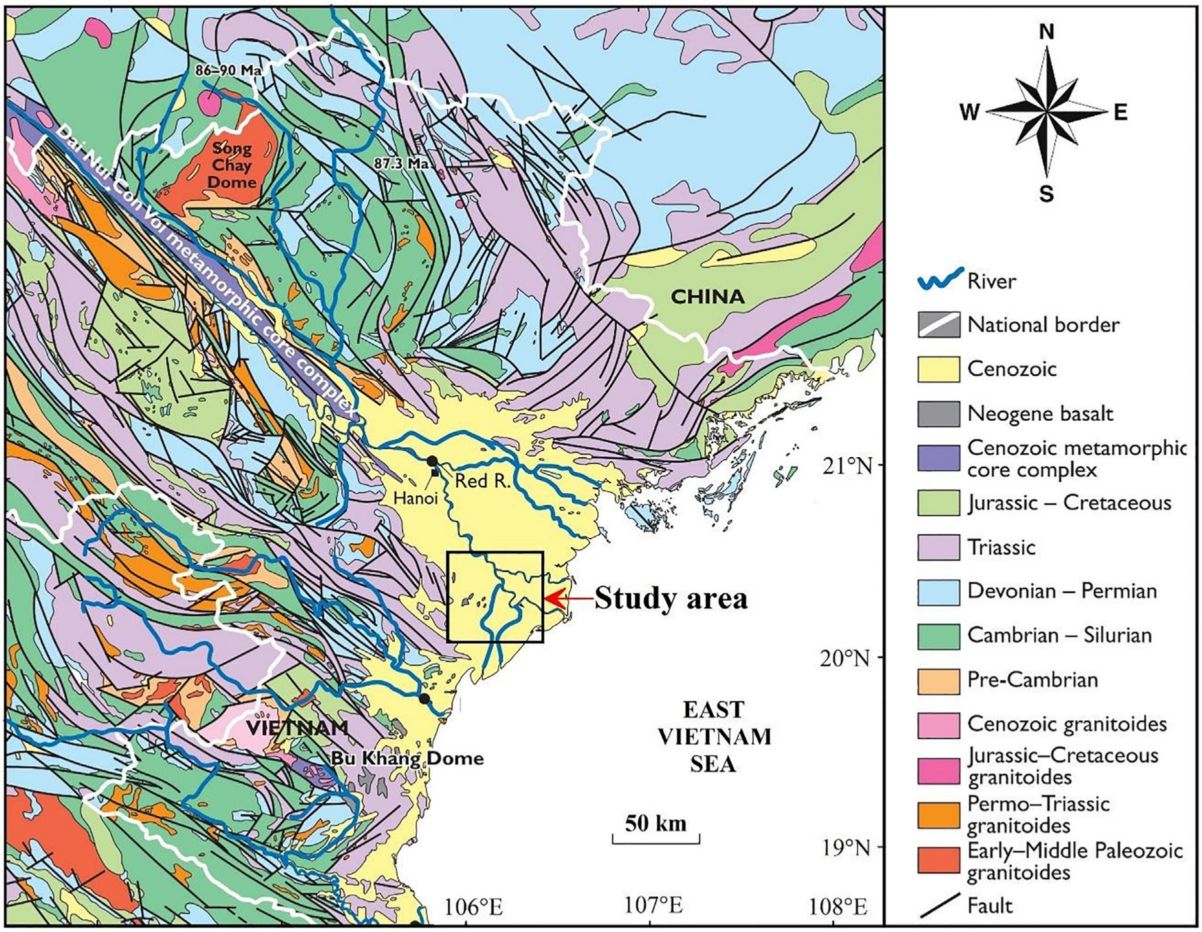

Fig 1. Location of the selected province on geological map (modified from Fyhn et al., 2019).

In this paper, we show the results of the improved parabola-based method (Pham et al., 2021g) applied to gravity data from Nam Dinh province (Vietnam) to extract lineaments. These results bring new information that is essential to improve the understanding of the structural framework and tectonic setting of the study area.

2. Geological setting

Nam Dinh province is located in the Northern region of Vietnam (Fig. 1) which is known as a significant part of the Tethyan orogenic belt, and is located between the Cenozoic Indochina and South China blocks (Hieu et al. 2012). It is bordered on the southeast by the Gulf of Tonkin, on the northwest by Ha Nam province, on the northeast by Thai Binh province, and on the southwest by Ninh Bình province. Nam Dinh province is a part of the Song Hong delta that is known as one of Asia's largest deltas (Tue et al., 2019; Pham, 2020). The delta formed during the Holocene as a result of the Red River sediment discharge into the East Vietnam sea (Tanabe et al., 2006). It is underlain by Cainozoic extensional basins (Fyhn and Phach, 2015) (Fig. 1). The location of the study area is shown in Fig. 1. This area extends from longitude 105°54′32″ to 106°26′19″ and latitude 20°6′59″ to 20°31′35″. It is covered by Quaternary sediments with a maximum thickness of 180 m (Phach et al., 2020).

3. Methodology

The improved parabola-based method is introduced by Pham et al. (2021g) for interpreting potential filed data. The method can be briefly introduced as follows:

Consider a 3 × 3 moving window consisting of a central grid point and its eight nearest neighbors in four directions (Fig. 2). If this window contains a maximum, it must satisfy at least one of the four following conditions:

$$\begin{cases} G_{i,j} > \frac{G_{i-1,j}+G_{i+1,j}}{2} \quad and \quad \left|\frac{-b}{2a}\right| \le d, \\ G_{i,j} > \frac{G_{i,j-1}+G_{i,j+1}}{2} \quad and \quad \left|\frac{-b}{2a}\right| \le d, \\ G_{i,j} > \frac{G_{i-1,j-1}+G_{i+1,j+1}}{2} \quad and \quad \left|\frac{-b}{2a}\right| \le d, \\ G_{i,j} > \frac{G_{i+1,j-1}+G_{i-1,j+1}}{2} \quad and \quad \left|\frac{-b}{2a}\right| \le d. \end{cases} \quad (1)$$

A counter N is increased by one for each satisfied inequality. For each condition met, the value and location of the peak are found by fitting a quadratic polynomial moving within three consecutive data points. For the condition given below:

$$G_{i,j} > \frac{G_{i-1,j} + G_{i+1,j}}{2} \quad (2)$$

the value of the peak is calculated by:

$$G_{max} = ax_{max}^2 + bx_{max} + G_{i,j}, \quad (3)$$

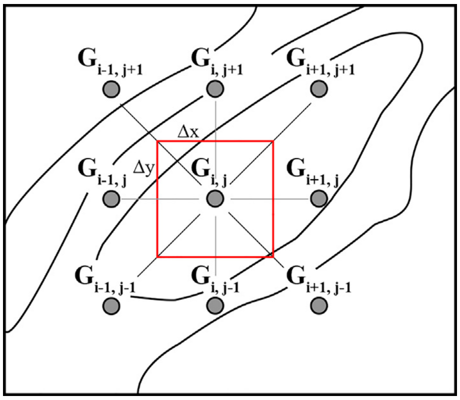

Fig 2. Schematic representation of locations of grid points. Curved lines display contours of the data (modified from Blakely and Simpson, 1986; Pham et al., 2021g).

where

$$a = \frac{1}{2d^2}\left(G_{i-1,j} - 2G_{i,j} + G_{i+1,j}\right),\quad b = \frac{1}{2d}\left(G_{i+1,j} - G_{i-1,j}\right), \tag{4}$$

d is the grid intersections distance and the peak location is given by:

$$x_{max} = -\frac{b}{2a} \tag{5}$$

If number of satisfying inequality N is greater than 1, the location of the largest G_{max} located inside the central grid cell (the box of size Δx × Δy) is assigned as a maximum of the window. If N is equal to 1, an acceptance criterion that is based on the curvature of the parabola at the maximum location and the maximum of the data are considered. The criterion is given by:

$$k = \frac{\frac{2a}{\left[1+(2ax_{max}+b)^2\right]^{3/2}}}{max(G)} \text{ or } k = \frac{2a}{max(G)}. \tag{6}$$

The acceptance criteria k is decided by the researcher. In general, $k \leq -0.04$ will yield the best results. The flow diagram used to detect the maximum locations is shown in Fig. 3 (Pham et al., 2021g).

Fig. 4a shows the 3D view of synthetic model that includes two prisms with the geometric and density parameters are presented in Table 1. Fig. 4b shows gravity anomalies of the model. Fig. 4c shows the gradient amplitude of the data in Fig. 4b. The maximum locations of the gradient amplitude are fully detected by the improved parabola-based method (Fig. 4d). The method brings all the information on the source edge locations.

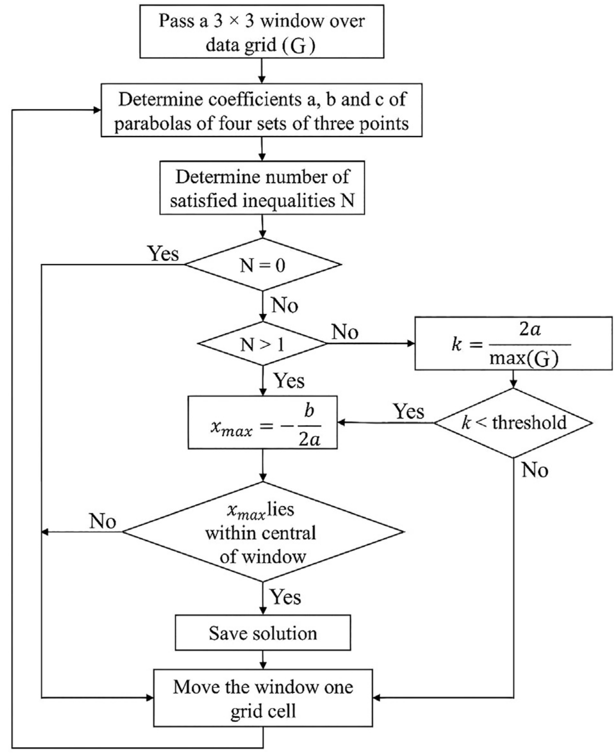

Fig 3. The flow chart of improved parabola-based method (Pham et al., 2021g).

4. Results and discussion

The gravity data used for extracting subsurface structures of this area were collected in 2011 by Department of Geology and Minerals of Vietnam (DGMV, 2011) (Fig. 5). In order to reduce the effect of high frequencies, an upward continuation of 1 km to the gravity data of Nam Dinh province was applied. Fig. 6a shows the upward continued Bouguer gravity map of the area. The data varies from −17 to 16 mgal with the appearance of a dominant NW–SE anomaly trend in the map. Fig. 6b shows the horizontal amplitude map of the gravity data. This map shows the presence of a dominant NW–SE structural trend, but it does not yield sharpened responses at the geological contacts. For this reason, the use of the peak locations of the horizontal amplitude brings a better estimation of lateral boundaries of the geological bodies than itself. Using the improved parabola-based method, the maximum locations of the horizontal amplitude are detected and shown in Fig. 6c. These maximum locations show subsurface structures of the study area. Fig. 6d shows the superposition of these locations on a gray-scale horizontal amplitude map. Obviously, this method can determine all peak locations of the amplitude of the horizontal gradient, and thus can be seen that most of the extracted structures are NW–SE trending lineaments. These trending lineaments are parallel to the structural trend in the Song Hong fault zone and the Red River basin (Fyhn and Phach, 2015). The results demonstrate the existence of many lineaments which are not outlined by geological mapping alone. For comparison, Fig. 7 displays the results obtained from CURVGRAV-GUI software that was developed by Kafadar (2017) using the curvature method (Phillips et al., 2007). Here, the curvature method has been applied to the gravity in Fig. 6a to detect gravity lineaments and to estimate their depth. The obtained result shows a major trend in NW–SE direction, and most of the lineaments are found to be located in the depth range of 2 km to 8 km. It is obvious that our result is in agreement with the lineaments estimated by the curvature method. Although the curvature method produces some new lineaments that are not determined by the improved parabola-based method, these lineaments may be false information, as pointed out by Pham et al. (2021f) and Pham et al. (2021g). The existence of the NW–SE trending lineaments in Fig. 6c and 7 indicates that the Red River basin appears to extend farther southeast beyond the border of the study area as the results reported by Phach et al. (2020). The obtained results can bring some references for further study within geology aims in Nam Dinh province. Also, these results suggest that the improved parabola-based method is a useful tool for delineating the lateral boundaries of the subsurface structures from gravity data.

5. Conclusions

The improved parabola-based method has been applied to gravity dataset from Nam Dinh province (Vietnam) to detect linea-

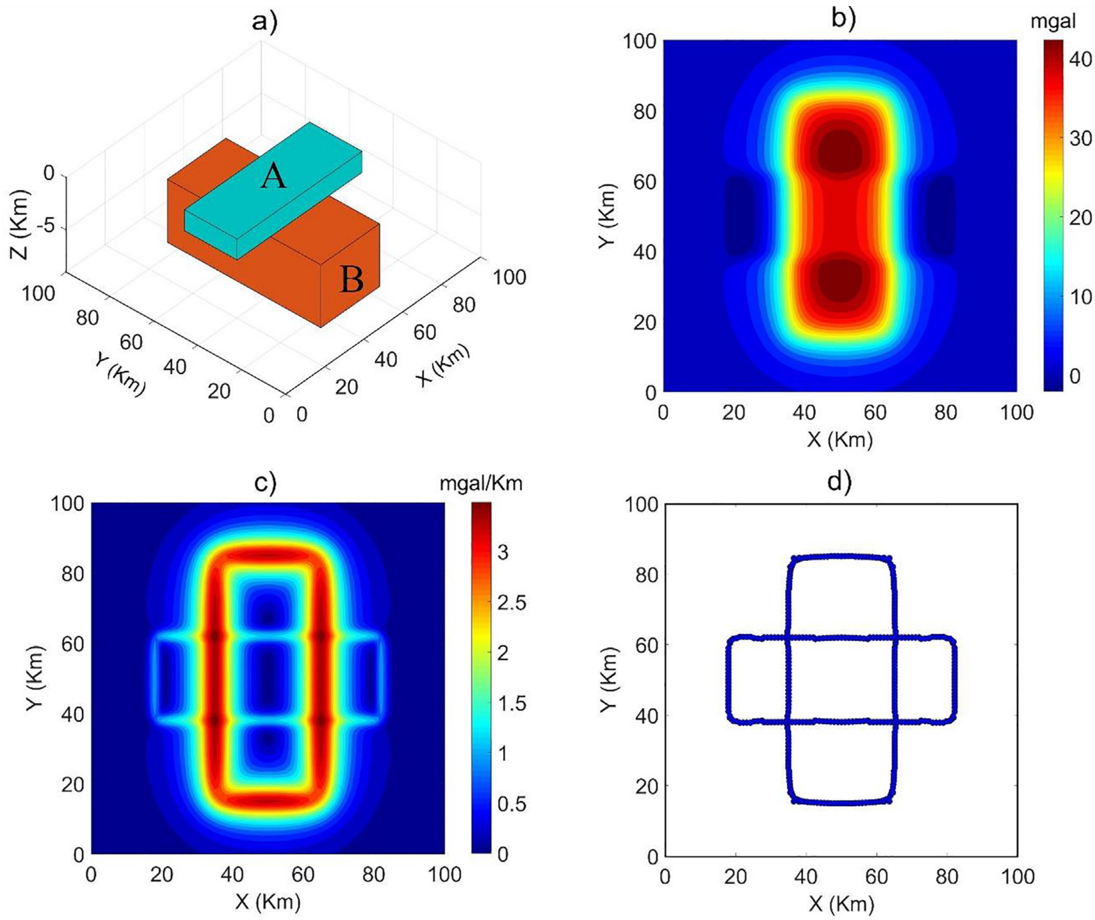

Fig 4. (a) 3D view of the gravity model, (b) gravity anomaly, (c) horizontal amplitude, (d) the peaks of horizontal amplitude obtained from the improved parabola-based method.

Table 1
Geometric and density parameters of the synthetic model.

Parameters/Model label	A	B
x-coordinates of center (km)	50	50
y-coordinates of center (km)	50	50
Width (km)	12	15
Length (km)	32	35
Depth of top (km)	1	3
Depth of bottom (km)	3	9
Density contrast (g/cm^3)	−0.1	0.25

ments of subsurface structures in the area. We have detected the maximum locations of the gradient amplitude of gravity data, which deal with lineaments of subsurface density structures. This study finds new information on the lineaments of subsurface structures of the study area. The structures in Nam Dinh are characterized by northwest-southeast tectonic trends, and most of the lineaments are found to be located in the depth range of 2 km to 8 km. The results determined by the improved parabola-based method can bring some references for further studies. The

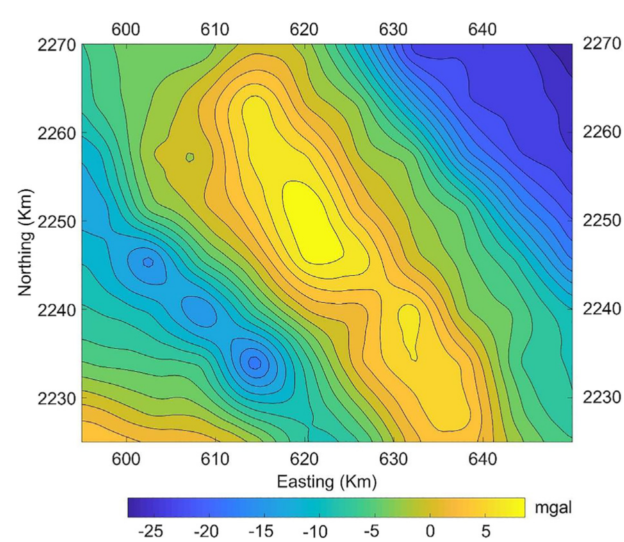

Fig 5. (a) Bouguer gravity map of Nam Dinh province.

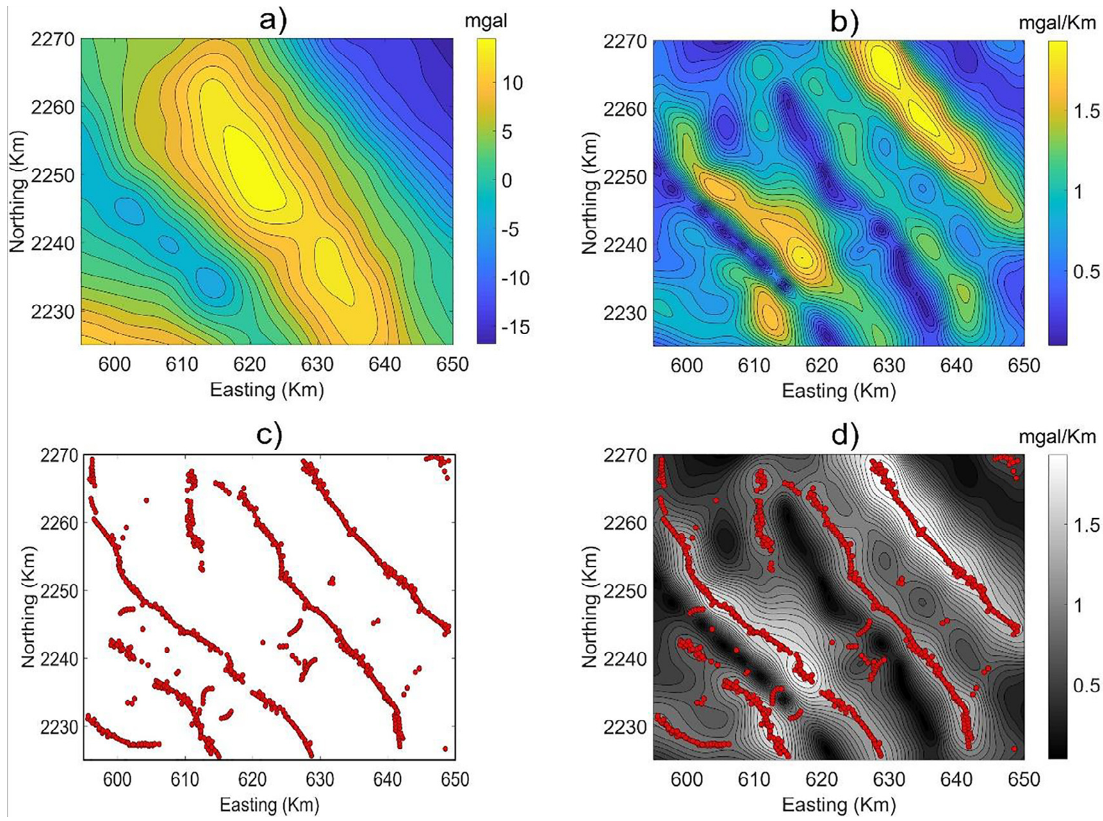

Fig 6. (a) Upward-continued Bouguer gravity map of the study province, (b) horizontal amplitude of data in Fig. 6a, (c) maximum locations of horizontal amplitude obtained from the improved parabola-based method, (d) maximum locations superimposed on gray-scale horizontal amplitude map.

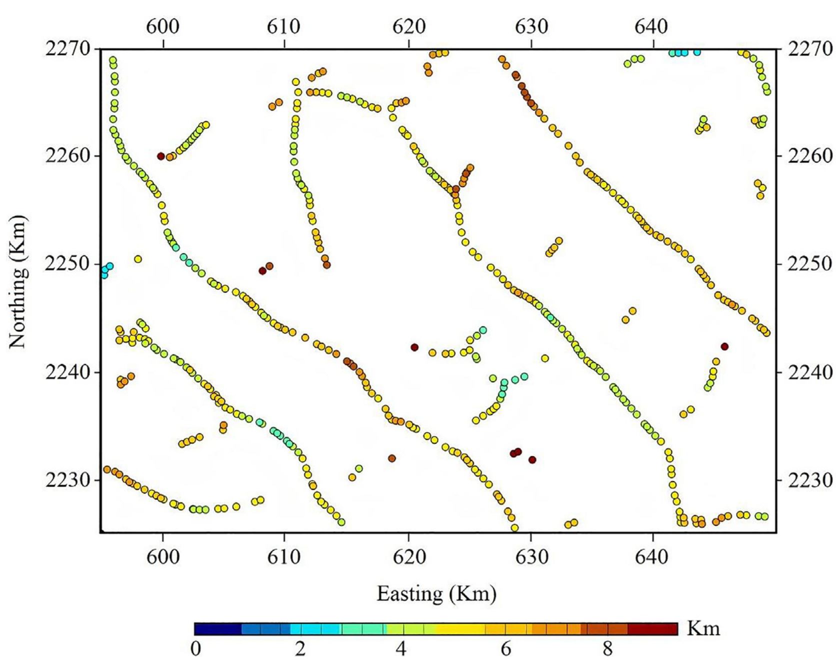

Fig 7. Maximum locations and depths obtained from the curvature method.

improved parabola-based method thus offers great promise for rapid mapping of subsurface structures without the assumptions on density contrasts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2021.101585.

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