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Original article

Mapping subsurface structural lineaments using the edge filters of gravity data

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ABSTRACT

The subsurface structures can be extracted from geophysical studies. This study deals with the detection of lineaments from gravity data that are related to the boundaries of the subsurface structures. The methods used in this study such as the horizontal gradient, total gradient, enhanced horizontal gradient, and improved logistic are tested on synthetic model prior to application to real gravity data. The results indicate that the improved logistic filter can be an effective method for boundary detection of gravity data. © 2021 The Author(s). Published by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

A significant goal in the analysis of potential field data is to define the source location, which assists in its geological understanding. The edges are useful in mapping the source boundaries for different applications such as mineral and oil exploration, environmental and engineering problems, and crustal studies (Sun et al., 2016; Eldosouky et al., 2020a, b, c; Pham, 2020; Eldosouky and Saada, 2020; Sehsah and Eldosouky, 2020; Dwivedi and Chamoli, 2021). The lateral boundaries of the sources have a definitive role in interpreting and enhancing potential data and the constraining of depth models. These are important in understanding the structural frames and geology (Kafadar, 2017; Oksum et al., 2019; Sehsah et al., 2019; Melouah and Pham, 2021; Pham et al., 2021c, d, e, f). To date, a variety of approaches have been directed on detecting edges to assist source definitions of magnetic or grav-

ity data (Oliveira et al., 2017; Eldosouky and Elkhateeb, 2018; Kha et al., 2018; Eldosouky, 2019; Pham et al., 2019; Pham et al., 2020a; Pham et al., 2021a; Pham et al., 2021b; Oksum et al., 2021).

Edge detection consists of the use of filters that aim at distinguishing points in a gridded data at which the physical property (density or magnetization) sharply changes or has discontinuities. These points are arranged into an assortment of curved line fragments named edges. Edge detection is crucial in machine and computer vision, image analysis, and lineaments detection (Umbaugh, 2010; Pham, 2021).

The earliest filters such as the horizontal gradient (HG) (Grauch and Cordell, 1985), the total gradient (TG) (Roest et al., 1992), and the tilt angle (TA) (Miller and Singh, 1994) provide valuable insight on source locations, but are usually not able to sharply identify the edges. A considerable number of modern approaches have been proposed to improve edge delineation. To image shallow structures and mineral targets of the basement, Verduzco et al. (2004) propose employing the horizontal gradient of the tilt angle. Wijns et al. (2005) suggest the theta-map technique to map edges for the structural analysis (Eldosouky and Mohamed, 2021). Theta map and tilt angles are related to each other, and to the horizontal tilt angle (TDX) filter by Cooper and Cowan (2006) (see also Cooper and Cowan, 2008). Ferreira et al. (2013) suggested using the tilt angle of the horizontal gradient (TAHG), a second-order filter such

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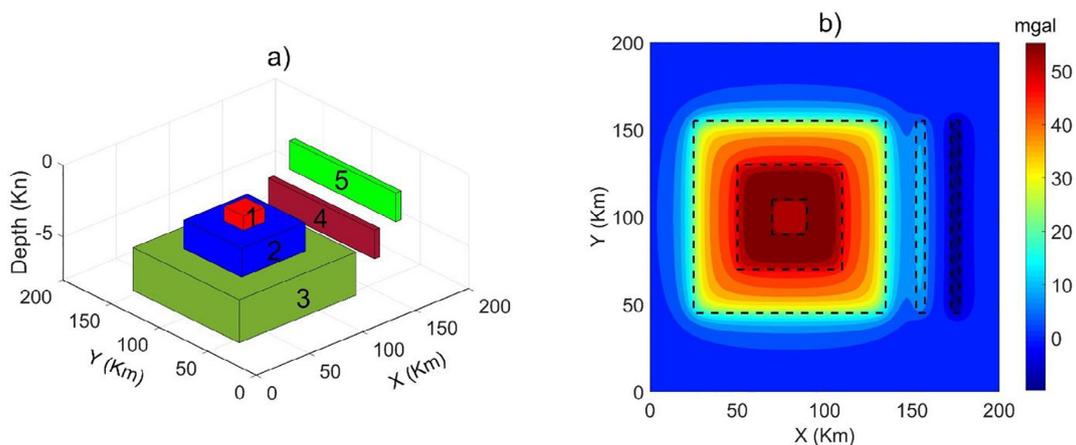


Fig. 1. (a) 3D view of the density model, (b) gravity anomalies of the model. The dashed lines show the true edges of the prismatic sources.

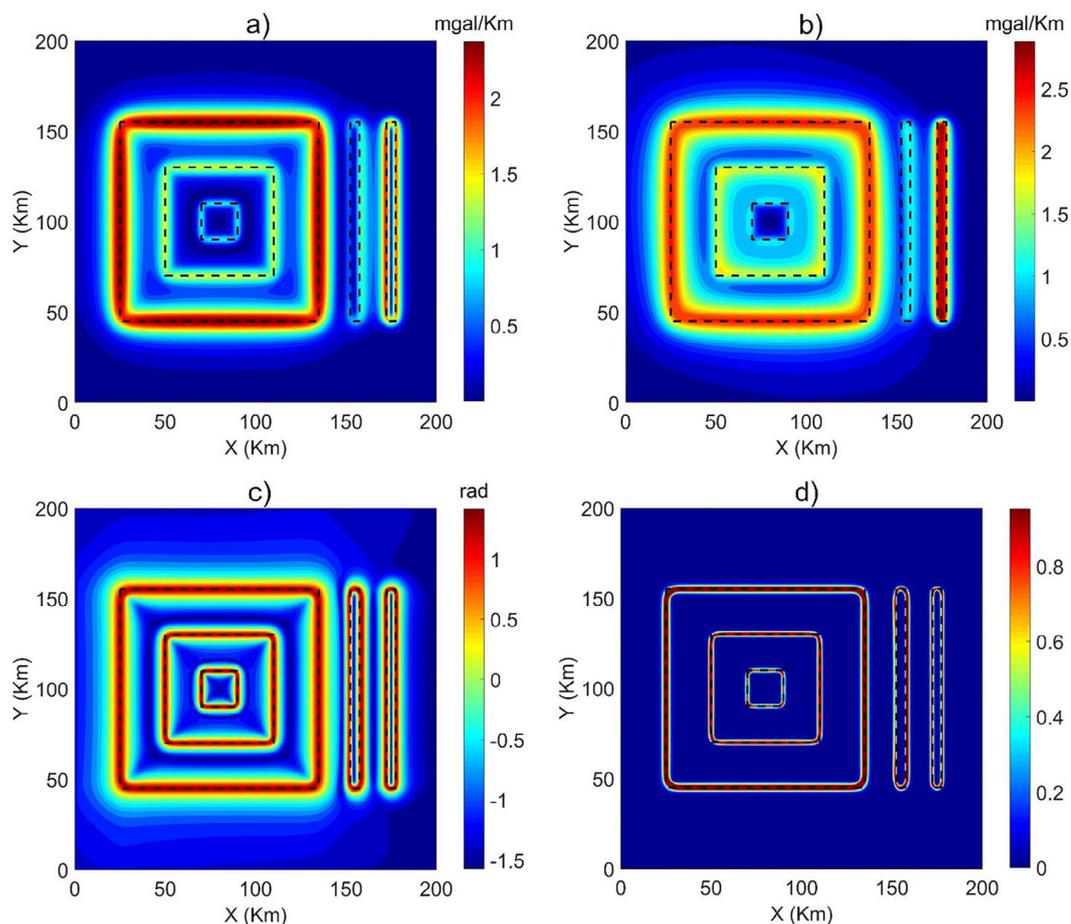


Fig. 2. (a) Horizontal gradient, (b) total gradient, (c) enhanced horizontal gradient, (d) improved logistic. The dashed lines show the true edges of the prismatic sources.

as the one proposed by Verduzco et al. (2004) that is able to delineate both shallow and deep sources. Recently, Pham et al. (2020b) have proposed an enhanced filter for determining the edges of potential sources that give more sharp delineation for the lineaments, called the improved logistic filter (IL).

South Vietnam is located in the southern part of the Indochina block, and there is a lack of studies on subsurface structures of this area. The structures in South Vietnam are obscured by sedimentary

rocks (Nong et al, 2021). However, analysis of the gravity data allowed for mapping of these subsurface geology structures.

In this context, we estimate the effectiveness of HG (Cordell and Grauch, 1985), TG (Roest et al, 1992), TAHG (Ferreira et al, 2013), and IL (Pham et al, 2020b) techniques through a synthetic density model. These techniques are also applied to real gravity data for accurate deciphering of main structural lineaments of South Vietnam.

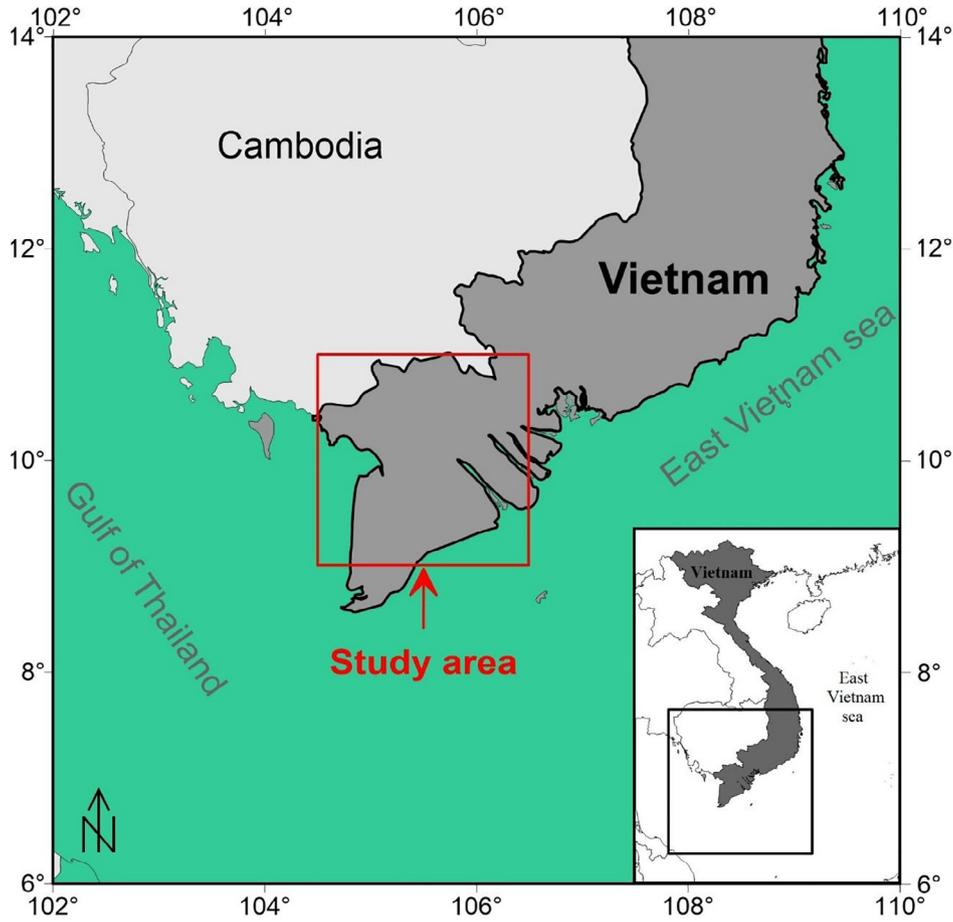


Fig. 3. Location of the study area.

2. Methods

Cordell and Grauch (1985) introduced the horizontal gradient (HG) that tends to generate maximum values positioned over the source frames. The HG filter is given by:

$$HG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2}, \quad (1)$$

where F is the magnetic or gravity anomaly.

Roest et al. (1992) suggested using the maximum values of the total gradient (TG) to outline the lateral boundaries. The TG is given by:

$$TG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2 + \left(\frac{\partial F}{\partial z}\right)^2}. \quad (2)$$

To simultaneously reveal the edges of the sources from various depths, Ferreira et al. (2013) suggested employing the TA of the horizontal gradient that is given by:

$$TAHG = \operatorname{atan} \frac{\frac{\partial HG}{\partial z}}{\sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2}}. \quad (3)$$

Pham et al. (2020) introduced the improved logistic (IL) filter that is given by:

$$IL = \frac{1}{1 + \exp[-p(R_{HG} - 1) + 1]}, \quad (4)$$

where R_{HG} is the ratio of the vertical gradient to the horizontal gradient of the HG, and given by

$$R_{HG} = \frac{\frac{\partial HG}{\partial z}}{\sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2}}. \quad (5)$$

and the positive constant p is set by the interpreter. In general, the estimation of p is between 2 and 5 which allow the most trustworthy results (Pham et al., 2020b).

3. Synthetic model

Initially, the effectiveness of the above methods is estimated with synthetic model that includes five prismatic sources (Fig. 1a) with excess densities of the bodies as -0.2 g/cm^3 (body1), 0.2 g/cm^3 (body 2), 0.4 g/cm^3 (body 3), 0.3 g/cm^3 (body 4), and -0.3 g/cm^3 (body 5). The gravity anomaly of the sources was computed at 201×201 grid nodes with 1 km spacing, as shown in Fig. 1b. The results of the chosen edge detection methods are shown in Fig. 2. Fig. 2a shows the HG map. As it can be seen, the HG method does not produce clear edges for the bodies 1, 2 and 4. Fig. 2b shows the TG map. We can see that the TG method is less effective in determining the edges of the bodies 1 and 2, and it cannot extract the edges of the thin bodies 4 and 5. Fig. 2c shows the TAHG map. Clearly, the TAHG method allows for a clearer estimation of the edges compared to the HG and TG methods. Although the TAHG method shows a balanced image for the source edges, the detected edges have a low resolution. Fig. 2d shows the IL map. We can see that the IL method brings a balanced image for

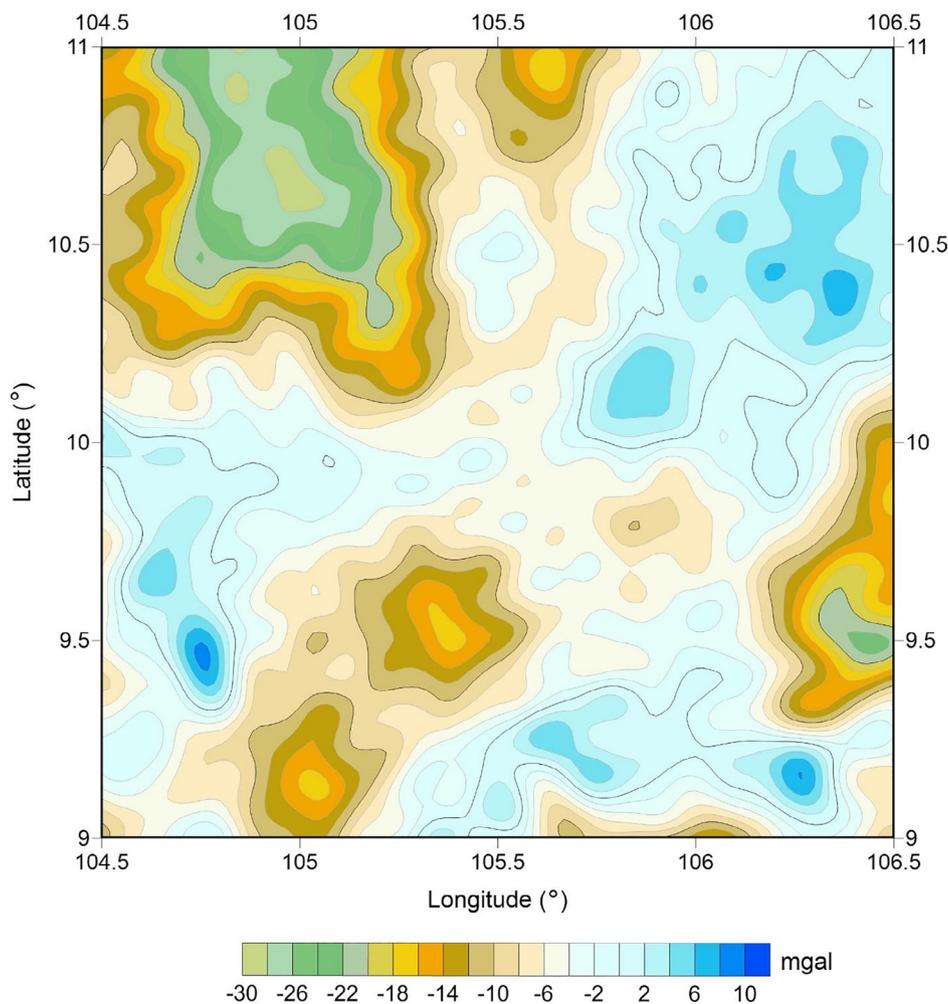


Fig. 4. (a) Bouguer gravity map of the study area.

the detected edges, and it provides an edge map with a higher resolution compared to other methods.

4. Real application

The study area is a part of South Vietnam (Fig. 3), which is located in the southern part of the Indochina block. South Vietnam lies in a junction region between the Philippine, Eurasian, and Indian-Australian plates (Metcalfe, 2017). The structures in South Vietnam are obscured by Neogene-Quaternary sediments (Nong et al, 2021). There is a lack of studies on subsurface structures in South Vietnam. Interpretation of the gravity data allowed for detecting the subsurface structures of this area.

The real gravity data used in this study were obtained from the global gravity field model EIGEN6C4. The EIGEN6C4 data has a high resolution, and its error is significantly lower than the EGM2008 and EIGEN6C3 (Pal et al, 2016). This data is obtained by a combination of GRACE, LAGEOS, GOCE, and DTU10 data. Fig. 4 depicts the Bouguer gravity map after the application of corrections to free-air gravity anomaly data of the model EIGEN6C4.

Here, transformation have been applied to the gravity data in (Fig. 4) to compute the horizontal gradient, total gradient, enhanced horizontal gradient, and improved logistic functions. Fig. 5a depicts the HG of the gravity data. Since the HG filter depends on the burial depth of the density structures, it cannot

generate a balanced image for the lineaments of the subsurface structures. Fig. 5b depicts the TG of the gravity data. Like the HG filter, the TG method does not produce a balanced image for source edges. In addition, as shown in the synthetic model, this method tends to produce the peaks over the center of structures. Thus, it is impossible to give the true lineaments of the subsurface structures. Fig. 5c presents the lineaments detected by the TAHG method. We can see that this method is more effective in producing a clearer estimation of the lineaments than the HG and TG methods. Fig. 5d presents the lineaments determined by the IL method. Similar to the TAHG method, the IL method is a balanced detector, and therefore the detected boundaries are clearer than those obtained from the HG and TG methods. However, it is worth noting that the IL method generates a map of lineaments with higher resolution compared to the TAHG and other methods.

5. Discussions

It is well known that the short wavelength lineaments are mostly associated with shallower depth whereas the longer wavelength lineaments are mostly related to deep interior inside the Earth. While the HG and TG filters are dominated by the short wavelength lineaments (Fig. 5a and b), the TAHG and IL methods can delineate both the longer to smaller wavelengths structural and tectonic boundaries in the form of lineaments (Fig. 5c and

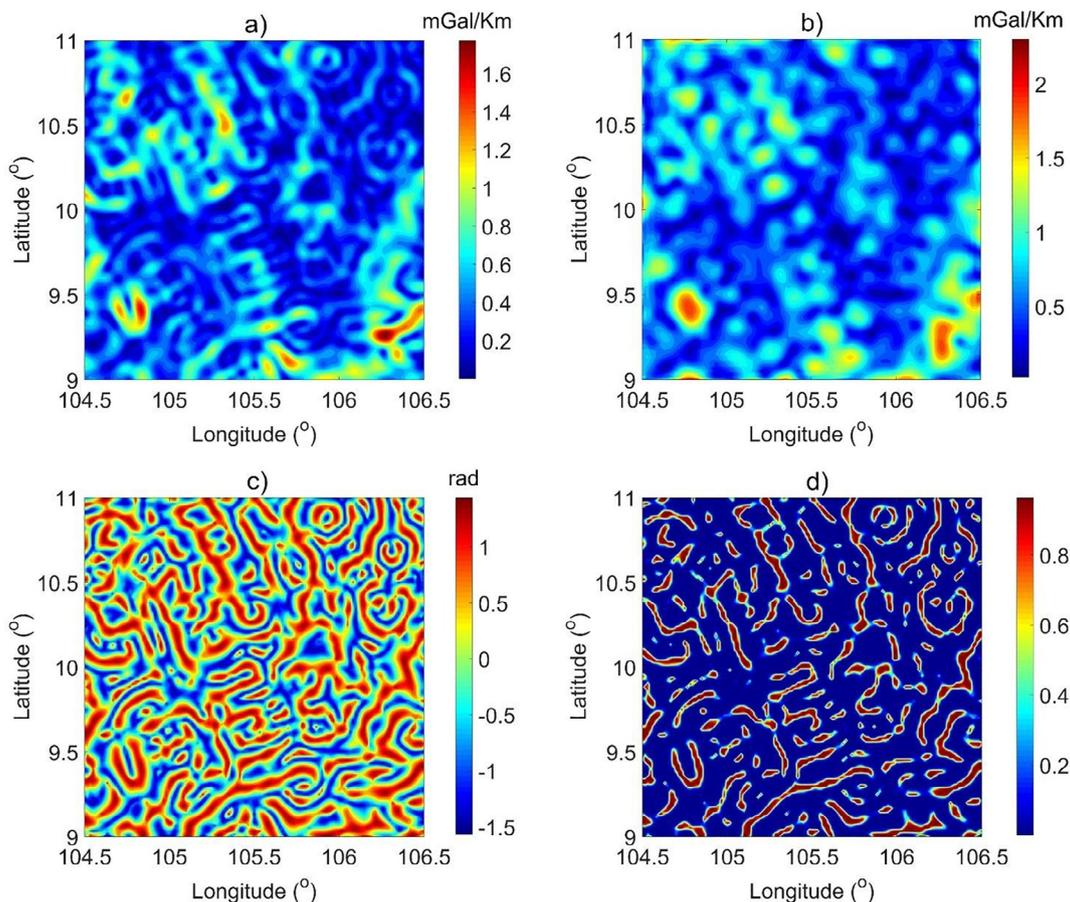


Fig. 5. (a) Horizontal gradient, (b) Total gradient, (c) Enhanced horizontal gradient, (d) Improved logistic.

d). The TAHG and IL maps indicate that several trends exist in the data, with the NW–SE and NE–SW trends being dominant (Fig. 5c and d). The obtained result also reveals circular-shaped lineaments anomaly in the Northeast region. Although the TAHG and IL filters are more effective in enhancing the gravity lineaments than the HG and TG methods, the IL generates the sharper lineaments. On the other hand, the IL peaks demonstrate the existence of many density lineaments that are obscured by Neogene-Quaternary sediments. The boundaries estimated by the IL filter are marked to locate the lineaments. Fig. 6 presents the lineaments extracted by the IL map. Fig. 7 shows the rose diagram of these lineaments. This diagram presents some main trends with the dominated lineament trends in NW–SE and NE–SW directions. The obtained results illustrate the usefulness of the IL filter for gravity field interpretation. This method equalizes the amplitudes of the anomalies due to the density structures located at different depths, making the most of the information existed in observed field data, and for qualitative studies. Although the IL filter is a good and appreciated filter, the lineaments of subsurface structures in South Viet-

nam need further investigation to verify that these lineaments are or are not faults.

6. Conclusions

Initially, the effectiveness of the horizontal gradient, total gradient, enhanced horizontal gradient, and improved logistic filters are tested with a synthetic gravity model. Findings show that all the edges have been estimated well using both HG, TAHG, and IL techniques. However, the edges on the IL map are more prominent than those detected by the other techniques. Further, gravity data from South Vietnam have been interpreted to extract the lineaments of the subsurface structures. The obtained results show the existence of several trends in the data, with the NW–SE and NE–SW trends being dominant. These lineaments help to increase scientific knowledge in South Vietnam, which can be used to further study within geology aims in this area. These results also indicate that the IL technique is an effective detector for lineaments detection in gravity data.

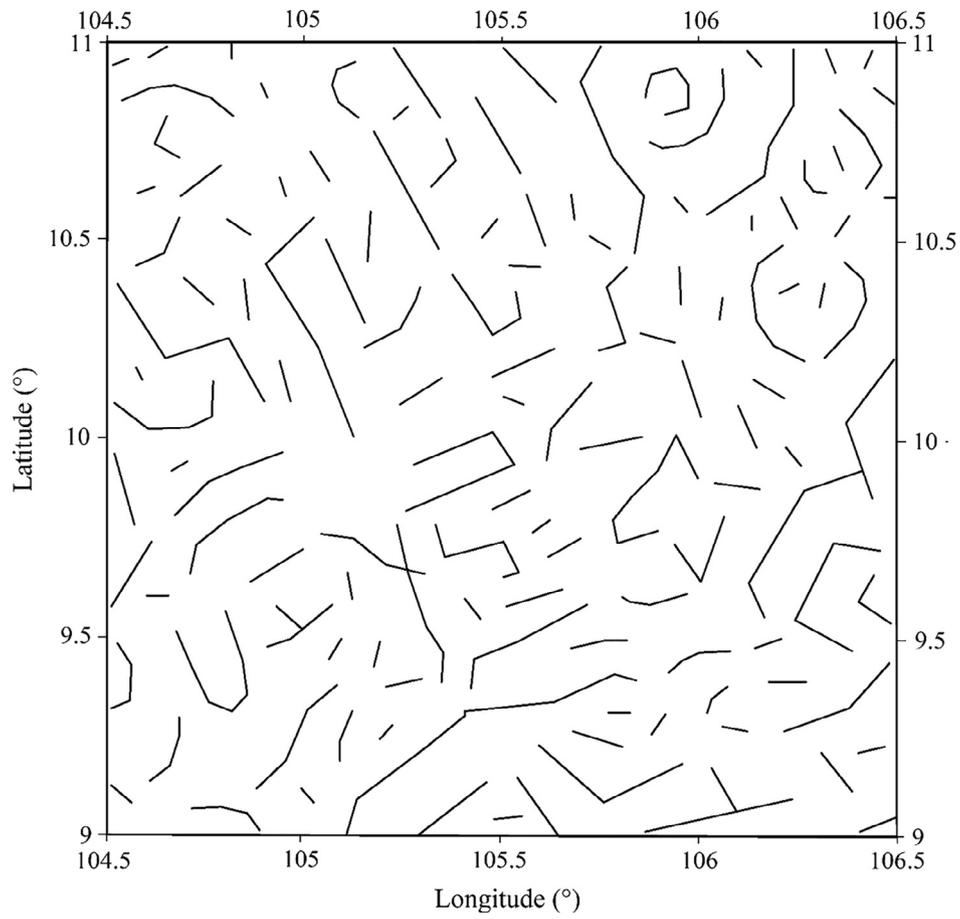


Fig. 6. The lineaments extracted from the improved logistic map of the gravity data.

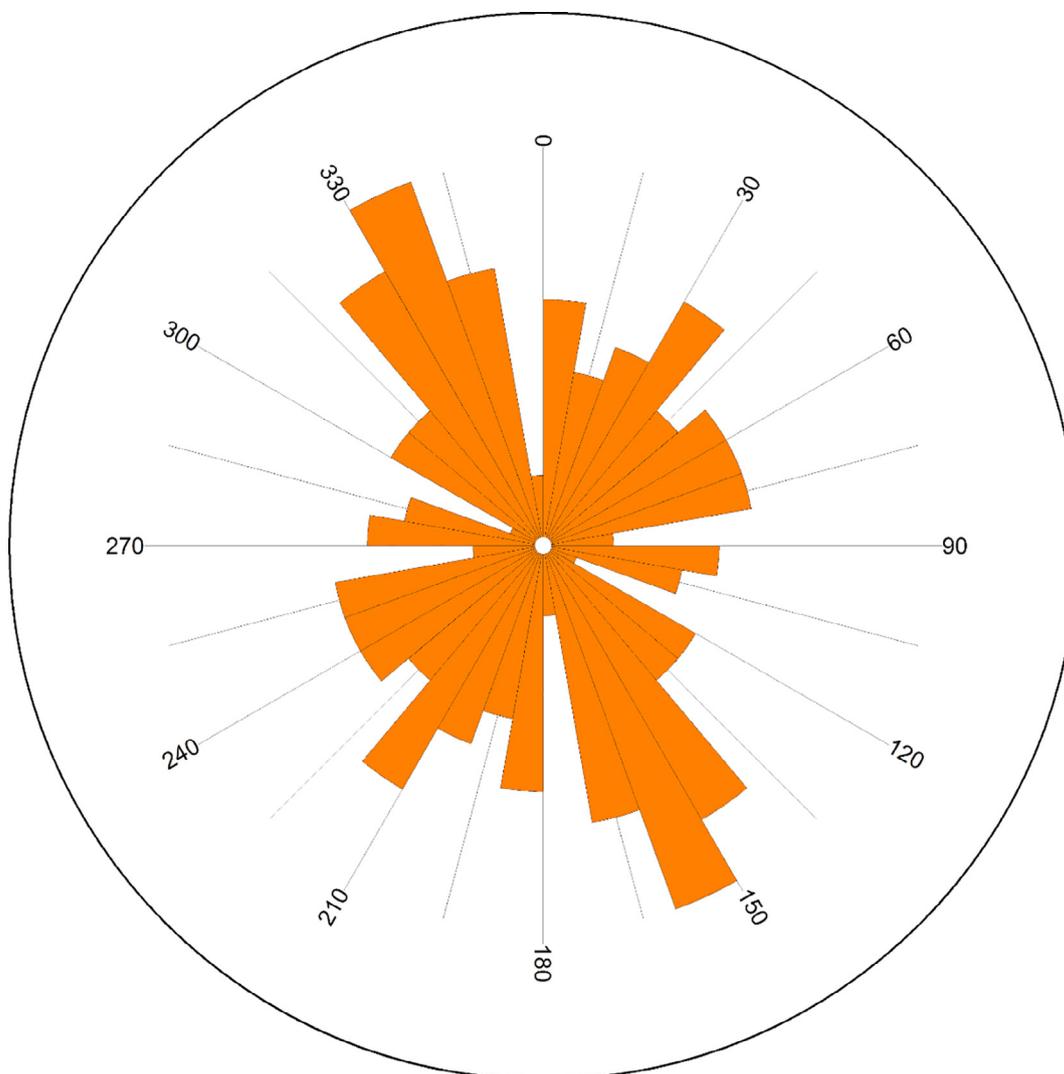


Fig. 7. Rose diagram of the lineaments in Fig. 6.

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.2021.101594>.

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