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Original article

Reinterpreting aeromagnetic data of the Agadir Melloul region (Morocco) for delineating structural lineaments: A new look

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ABSTRACT

Aeromagnetic data of the Agadir Melloul region (Morocco) has been previously interpreted to delineate structural lineaments using the tilt angle method. In this study, we show the limitations of the tilt angle method in extracting the boundaries of magnetic sources and reinterpret aeromagnetic data of the Agadir Melloul region using the improved logistic method. Initially, the tilt angle and improved logistic methods are tested on 3D synthetic magnetic models where the results obtained from the improved logistic method show improvements in the delineation of the actual edges of sources compared to the tilt angle method. Then, aeromagnetic data from the Agadir Melloul region has been enhanced by the improved logistic method for delineating structural features. The obtained result provides a new look at the structural lineaments of the study area.

1. Introduction

The Agadir Melloul region is within the southeastern portion of the Igherm region which is known as one of the important mining areas containing some world-renowned ore deposits. These deposits consist of a variety of metallic minerals including valuable metals such as silver, copper, and cobalt. The major metal in the area is copper with over 200 mines. Interpretation of magnetic data to identify lineaments has been used for a long time to study structural controls of mineralization in many ore deposits. Information of such structural features can help in optimizing the choice of areas for exploration by targeting more precisely structures related to metallogenic deposits (e.g., Abia et al., 2020; Echogdali et al., 2021; Ouchchen et al., 2021, Ouchchen et al., 2022).

Subsurface geology can be investigated using potential field surveys based on measuring the variations in both gravity and magnetic fields arising from density/susceptibility differences between subsurface rocks (Ekinci et al., 2013; Duong et al., 2021; Long et al., 2021; Hang et al., 2019; Ghomsi et al., 2022a, b; Pham et al., 2022a, b; Ekwok et al., 2022). Locating the edges of transformed anomalies provides an effective perspective to detect lateral changes of subsurface structures (e.g., Hang et al., 2017; Kha et al., 2018; Oksum et al., 2019, 2021; Sehsah and Eldosouky, 2022; Eldosouky et al., 2020a, 2021a, 2022a,c; Saada et al., 2021a,b). Information on the edges of potential field sources has an important role in estimating potential mineral deposits (Elkhateeb and Abdellatif, 2018; Pham, 2020, 2021; Shebl et al., 2021; Elkhateeb et al., 2021). Many different interpretation methods have been

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introduced to estimate the edges of the causative sources from potential field data (Eldosouky et al., 2020b, c, 2020d; Melouah et al., 2021). Cordell and Grauch (1985) introduced the gradient amplitude method that is based on the first-order horizontal derivatives of potential field data. Roest et al. (1992) suggested using the total gradient method that is formed through a combination of the first-order vertical and horizontal derivatives of the field. To improve the resolution of the edges, Fedi and Florio (2001) and Beiki (2010) have developed the modified versions of the horizontal gradient and total gradient methods. One of the disadvantages of these methods is that the obtained results are dominated by the signals due to the shallow sources, therefore, it becomes difficult to identify deep geological structures (Dung and Minh, 2017; Pham et al., 2018a, Pham et al., 2020a, Pham et al., 2020b, Pham et al., 2021a, Pham et al., 2021b, Pham et al., 2021c). Some authors have developed balanced methods to detect the edges of the shallow and deep sources at the same time. Miller and Singh (1994) introduced the tilt angle method that normalizes the vertical gradient by the gradient amplitude. Wijns et al. (2005) introduced the theta map method that uses the gradient amplitude to normalize the total gradient. Although these balanced methods are effective in estimating all edges of sources located at different depths, they can produce secondary edges and complicate the delineating of real geological structures (Pham et al., 2021d, e,f,g; Prasad et al., 2022; Eldosouky et al., 2022b). To solve this problem, Pham et al. (2018b), Pham et al. (2019), Pham et al. (2020c) introduced the logistic filters that are based on the gradients of the gradient amplitude or total gradient.

Ouchchen et al. (2021) interpreted aeromagnetic data of the Agadir Melloul region to estimated structural lineaments using the tilt angle method. Using synthetic magnetic data, we review the effectiveness of the tilt angle method. We found that this method produces artifacts around sources. In addition, we reinterpreted aeromagnetic data of the Agadir Melloul region using the improved logistic filter. The obtained result from this filter provides a new look at the structural features of the area.

2. Geological setting

The Agadir Melloul region is part of the Central Moroccan anti-Atlas at the northern margin of the West African Craton (Fig. 1a). The studied sector is located at the western end of the Agadir Melloul inlier (Fig. 1b). Eburnean-metamorphosed metasedimentary rocks include mica-schists and orthogneiss, and multiple plutons of granitoids (e.g., Choubert, 1963; Choubert and Faure Muret, 1973; Hafid, 1992). The base is covered by a Neoproterozoic blanket (Choubert and Faure Muret, 1973) subdivided into three large groups: i) a group of Cryogenic age (Taghdout Group) represented by quartzites and limestones injected with veins, or even packed in small massifs of dolerites or micro-gabbros; ii) a terrigenous sedimentary ensemble (Tiddiline Group) attributed to the Lower Ediacaran and iii) a volcano-sedimentary ensemble (Ouarzazate Group) attributed to the Upper Ediacaran (Kouyaté et al., 2013) (Fig. 1c). The major phase of the Pan-African orogeny that structured the first set is dated to 685 ± 15 Ma (Rb/Sr, Clauer, 1974). It is a compressive ductile strain of NW-SE direction (Oudra et al., 2005). It generates synschistous isoclinal folds and overlapping and declining tectonic accidents (Leblanc, 1975; Hassenforder, 1987). The late Pan-African phase is essentially extensional and results in i) the tilting of the blocks of the Ouarzazate Group, ii) the impressive dislocation of quartzites from the Taghdout group, and iii) the establishment of mafic lavas (Kouyaté et al., 2013).

The late-Neoproterozoic (Adoudounien) Cambrian cover outcrops on the Neoproterozoic sites. It began with the volcano-sedimentary and siliciclastic deposits of the “Base Series”, evolving into increasingly carbonate content deposits of dolomite from the addition of “Lower Limestone”, topped by purplish-red pelites interspersed with carbonate beds of the “Lie de vin Series”, followed by carbonate deposits from “Upper Limestone” (e.g., Choubert, 1963; Algouti et al., 2001; Benssaou and Hamoumi, 2001, 2003; Benssaou et al., 2017). Hercynian tectonics, linked to the reactivation of deep faults in the basement, is responsible for the structuring of these terrains and the development of folds with a large radius of curvature and submeridian deformation corridor (Chèvremont et al., 2013) (Fig. 1c).

In the Mesozoic, veins of dolerites vertically cut both the Precambrian substratum and its folded Paleozoic cover (Choubert, 1963; Leblanc, 1975), and are linked to the contemporary Triassic extension associated with the opening of the Atlantic ocean (Ait Brahim et al., 2002; Youbi et al., 2013) (Fig. 3c).

The Neogene inversion reactivates the old basement accidents. The resulting uplift took place in two episodes: (i) in the first episode, the anti-Atlas underwent kilometer-scale vertical movements that bring the Precambrian basement back to subsurface conditions causing it to cool to temperatures <60 °C in the Lower Cretaceous (133 Ma) (Sebti et al., 2009); and (ii) in the second episode dated Neogene, the chain of the Anti Atlas underwent an exhumation responsible for the rejuvenation of these reliefs. This last uplift is the result of a combined effect between atlas compressions and an asthenospheric rise (Missenard et al., 2006).

3. Methods

The tilt angle method was introduced by Miller and Singh (1994). It is known as the first phase-based filter and is given by:

$$TDR = atan\frac{\frac{\partial F}{\partial z}}{\sqrt{\left(\frac{\partial F}{\partial x}\right)^2+\left(\frac{\partial F}{\partial y}\right)^2}}. \quad (1)$$

where $\left(\frac{\partial F}{\partial x}\right), \left(\frac{\partial F}{\partial y}\right), \left(\frac{\partial F}{\partial z}\right)$ are the gradients of potential field data F.

Since the tilt angle method uses the ratio of the gradients, it can equalize the amplitude of different anomalies. The method uses the zero value to extract the lateral boundaries of the sources.

Pham et al. (2018b) introduced a new method based on the logistic function of the total gradient for determining the source edges. To improve the effectiveness of this method for thin sources, Pham et al. (2020c) suggested using an improved logistic filter that is given by:

$$IL = \frac{1}{1+exp[-p(R_{THG}-1)+1]}, \quad (2)$$

where R_{THG} is the ratio of the gradients to the total horizontal gradient, and given by.

$$R_{THG} = \frac{\frac{\partial THG}{\partial z}}{\sqrt{\left(\frac{\partial THG}{\partial x}\right)^2+\left(\frac{\partial THG}{\partial y}\right)^2}}. \quad (3)$$

with

$$THG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2+\left(\frac{\partial F}{\partial y}\right)^2} \quad (4)$$

and the constant p is set by the interpreter. In general, an estimation of p between 2 and 5 will bring the best results (Pham et al., 2020c). The peaks of the IL can be used to extract the source edges.

The Euler deconvolution method is used to estimate the depth and location of the potential field sources. This method was developed by Thompson (1982) and has been applied to magnetic data along with profiles. Reid et al. (1990) extended the Euler deconvo-

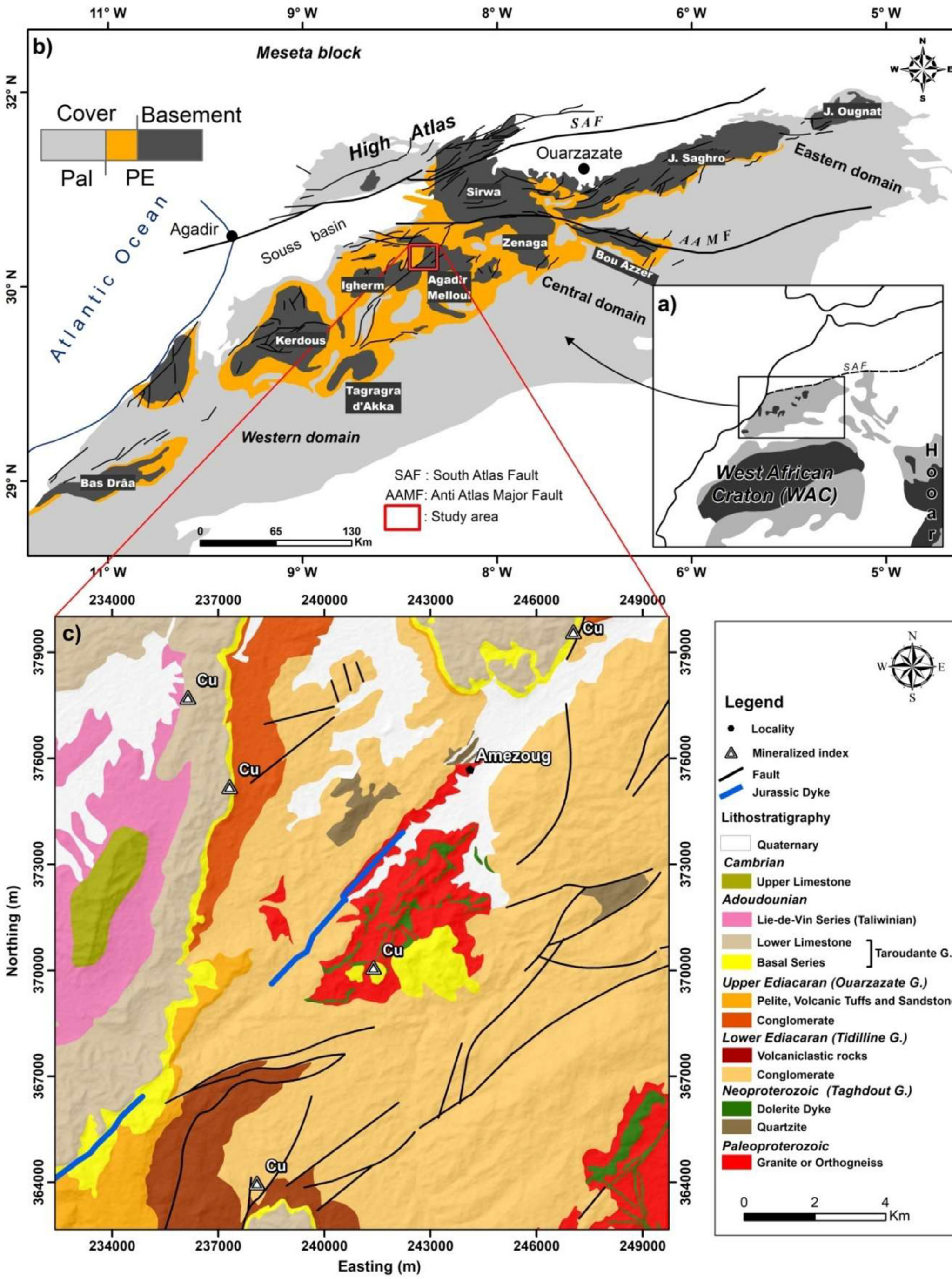

Fig. 1. (a) Location map of the anti-Atlas, (b) General geological map of the anti-Atlas and location of the study area (modified from Gasquet et al., 2008), (c) Geological map of the study area (modified from Ouchchen et al., 2021).

lution method for interpreting gridded data. The 3-D equation of Euler deconvolution is defined by Reid et al. (1990) as:

$$(x - x_0)\frac{\partial F}{\partial x} + (y - y_0)\frac{\partial F}{\partial y} + (z - z_0)\frac{\partial F}{\partial z} = N(B - F) \quad (5)$$

where (x_0, y_0, z_0) is the location of the magnetic source, B is the regional value and N indicates the structural index and relates to the geometry of the source.

4. Synthetic examples

In this section, the efficiency of the tilt angle and improved logistic methods are compared. In this context, these methods were applied to two synthetic magnetic models. The 3D view of the first model is shown in Fig. 2a. This synthetic model consists of three prismatic sources with the parameters given in Table 1. Fig. 2b shows the synthetic magnetic data of the model with the true boundaries of the sources are shown by the dashed lines. Fig. 2c shows the result obtained from applying the tilt angle method. Although the source edges can be detected by the zero contours, the tilt angle method produces a false zero contour

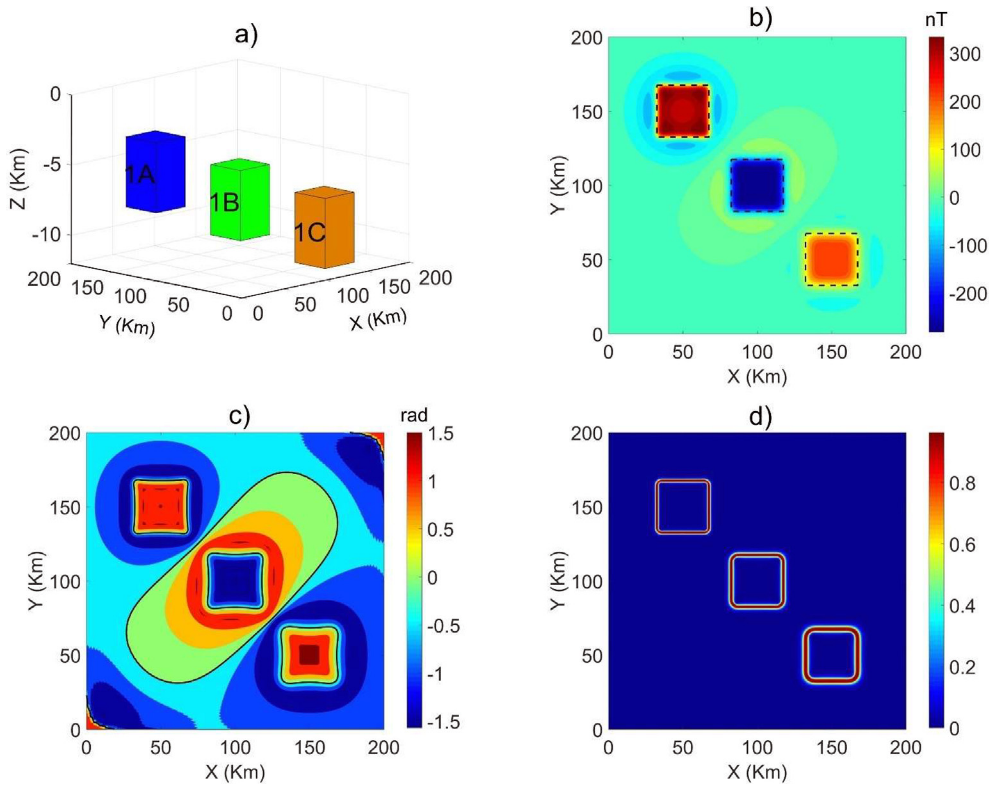

Fig. 2. (a) 3D view of the first model, (b) magnetic anomalies of the model, (c) tilt angle, (d) improved logistic.

Table 1
The parameters of the first model.

Parameters / Prism ID	1A	1B	1C
Center coordinates (km; km)	50; 150	100; 100	150; 50
Width (direction x) (km)	35	35	35
Length (direction y) (km)	35	35	35
Depth of top (km)	3	5	7
Depth of bottom (km)	8	10	12
Declination (°)	0	0	0
Inclination (°)	90	90	90
Magnetization (A/m)	2	−2	2

around the source 1B. Fig. 2c shows the edges detected by the improved logistic method. Clearly, this method is more effective in producing a clear image of the edges than the tilt angle method. In addition, the improved logistic method does not bring any false information to the edge map.

In the second synthetic example, a more complex model consisting of three prismatic sources was used to estimate the effectiveness of the methods. The 3D view of the second synthetic model, whose parameters are given in Table 2, is shown in Fig. 3a. The synthetic anomaly of the model is shown in Fig. 3b where the true boundaries of the sources are shown by the dashed lines. Fig. 3c shows the tilt angle of data in Fig. 3b. We can see that the tilt angle method produces false edges around sources 2A and 2B. Fig. 3d shows the edges determined by the improved logistic method of data in Fig. 3b. As can be observed from this figure, the improved logistic method produces a result with high resolution avoiding bringing false edges around the sources.

Table 2
The parameters of the second model.

Parameters / Prism ID	2A	2B	2C
Center coordinates (km; km)	100; 100	100; 100	100; 100
Width (direction x) (km)	20	60	100
Length (direction y) (km)	20	60	100
Depth of top (km)	3	5	8
Depth of bottom (km)	5	8	12
Declination (°)	0	0	0
Inclination (°)	90	90	90
Magnetization (A/m)	2	2	2

5. Application to aeromagnetic data of the Agadir Melloul region

5.1. Data

The high-resolution aeromagnetic data used in this note were acquired by the Canadian company "Géoterrx-Dighem" in 1998 on behalf of the Ministry of Energy, Mines, and Sustainable Development (Rabat, Morocco). Data were collected with a flight altitude of ~30 m, line spacing of ~500 m, and a flight orientation of ~N15°. The data were corrected and leveled by the base station. The international geomagnetic reference field (IGRF) was subsequently subtracted from the corrected total field. The values of the magnetic anomaly thus obtained were interpolated on a grid with 125 m resolution (Fig. 4a). The magnetic anomaly data was reduced to the pole (RTP) using a magnetic tilt of 41.1° and a declination of −4.3°, to reposition the anomalies from their causal sources (Baranov and Naudy, 1964). The RTP signature of the studied area contains anomalies of different amplitudes (Fig. 4b).

5.2. Results

Similar to the study of Ouchchen et al. (2021), we have applied the tilt angle method to the RTP data of the Agadir Melloul region for mapping of magnetic lineaments affecting the area. Fig. 4c shows the results of the tilt angle method applied to the RTP

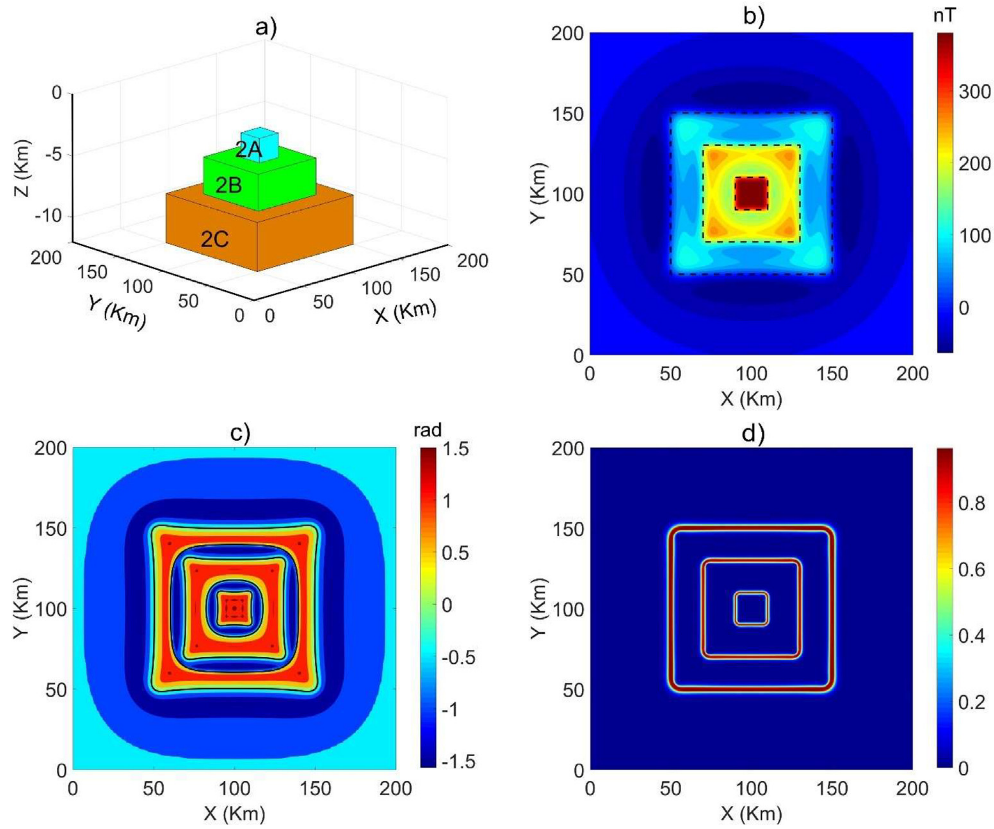

Fig. 3. (a) 3D view of the second model, (b) magnetic anomalies of the model, (c) tilt angle, (d) improved logistic.

map. The zero-crossing of the tilt angle is used to outline the boundaries of geologic structures. We can see that the zero-crossing of the tilt angle map indicates that there are several different trends in the data with NE-SW trend being dominant (Fig. 4c). Apart from the tilt angle method, the improved logistic method has also been applied to the RTP data of the study area to map structural lineaments. Fig. 4d depicts the result obtained from applying the improved logistic method to the RTP map. The peaks of the improved logistic function are used for mapping geological features. As can be seen from Fig. 4d, the improved logistic map also reveals geological structures with a predominant NE-SW trending lineament. The depths of magnetic sources in the Agadir Melloul region are computed by the Euler deconvolution method. The Euler deconvolution was performed using a 10×10 grid window which lies on the range of sizes that are typically used, and a structural index of 0 to locate and determine the contact depth. The Euler depth solutions are shown in Fig. 6. The histogram of the Euler solutions is shown in Fig. 7. We can see that the calculated depth solutions range from 20 to 650 m.

5.3. Discussion

In general, the Agadir Melloul region is characterized by a weak magnetic signal (Ouchchen et al., 2021). The negative anomalies detected are associated either with the Precambrian basement formations (conglomerates, pelites, and ignimbrite rocks) or with the non-magnetic sedimentary formations of the cover (the lower series, lower limestones, and the Lie de vin series). In addition, the strong magnetic signal oriented northeast coincides with the doleritic dyke of the Jurassic age, vertically cutting the sector. On the other hand, magnetic data can help in mapping linear systems linked to regional tectonic events and therefore provide a better understanding of the structure of the study area (Archibald et al., 1999; Austin and Blenkinsop, 2009; Salem et al., 2008; Henson et al., 2010). The cause of these lineaments could be the edges of the magnetic bodies, lithological and structural changes, faults, folds, and lateral variations in the magnetization contrast of the basement (Milligan and Gunn, 1997).

Ouchchen et al. (2021) used the tilt angle method for the mapping of magnetic lineaments affecting the region. As can be seen from Fig. 4c, the method can equalize the amplitudes of large and small anomalies, but many adjacent boundaries obtained from this method are connected, making it difficult to detect the geological structures. The obtained result in Fig. 4d shows that the improved logistic method is effective in detecting a wide range of magnetic structures in the Agadir Melloul region. Moreover, it is worth noting that the improved logistic method provides results with higher resolution compared to the tilt angle method. For comparison, Fig. 5 shows the magnetic structures extracted from the tilt angle and improved logistic maps. As can be observed from this figure, many magnetic structures can be detected by both methods. However, the tilt angle method produces more boundaries than the improved logistic method. As shown in the synthetic examples, these additional boundaries in the tilt angle map are artifacts, which are connected to other edges, complicating the geological interpretation. The theoretical examples also showed that the improved logistic method allows for a more accurate estimation of the source edges compared to the tilt angle method. The mapping lineaments in the improved logistic map are oriented NE-SW and E-W. As elucidated in section 2, the geological history of the study area is characterized by the succession of several orogenies; Eburnean, Pan-African, Hercynian, and Alpine. Each of these orogenies was a long-term work in which geological events generated varied geodynamic contexts (oceanic expansion, subduction,

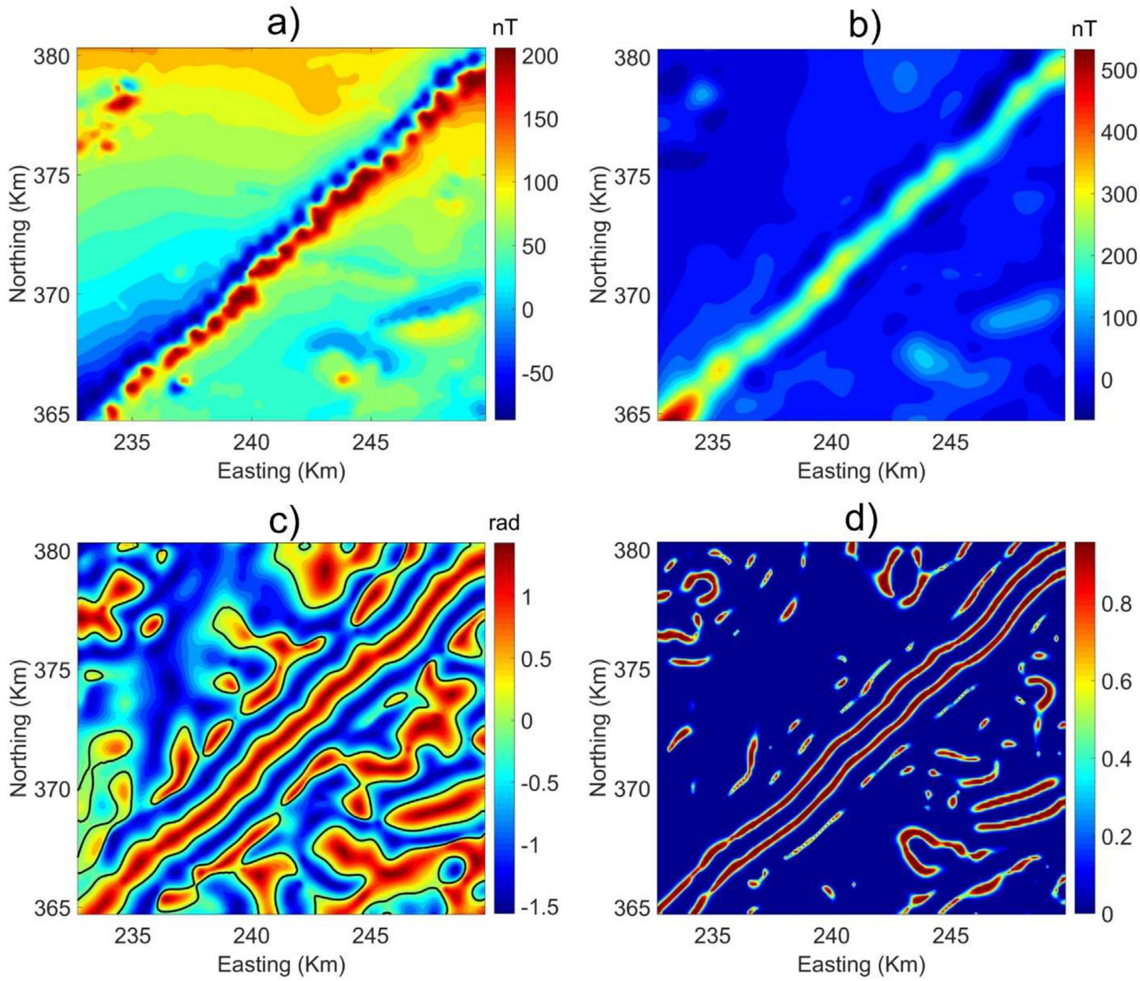

Fig. 4. (a) Aeromagnetic map, (b) RTP aeromagnetic map, (c) tilt angle, (d) improved logistic.

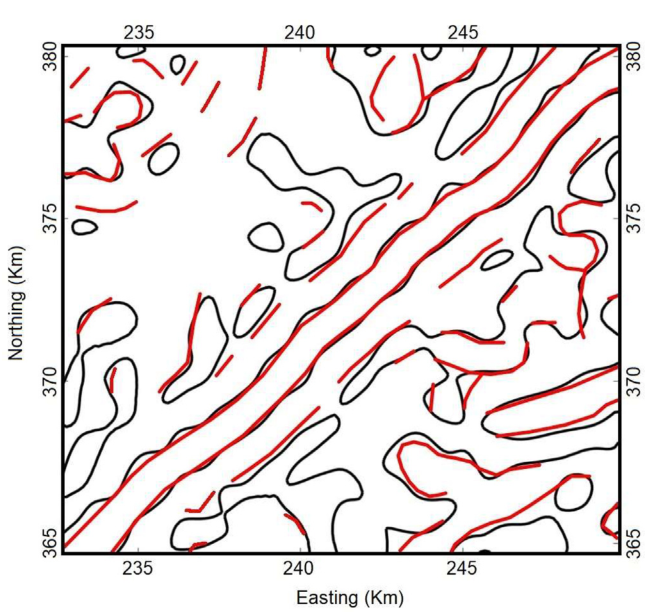

Fig. 5. Magnetic lineaments (red lines) detected by the improved logistic method and magnetic lineaments (black lines) determined by the tilt angle method.

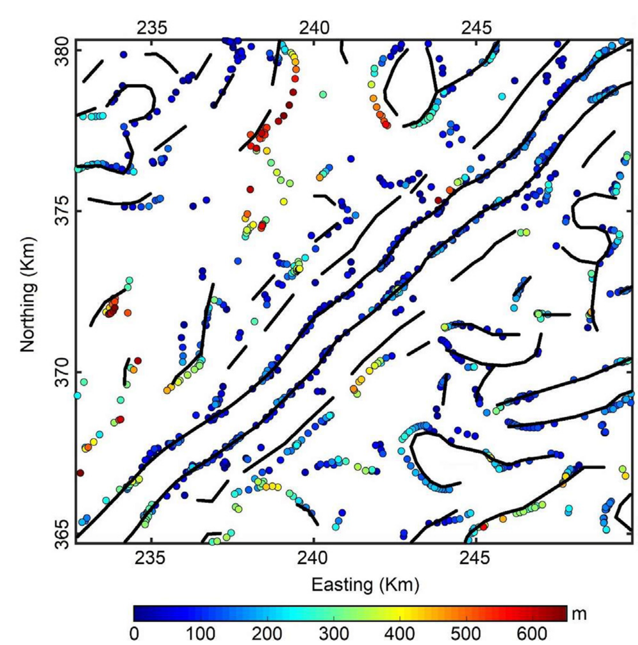

Fig. 6. Depths obtained from the Euler deconvolution method. The black lines show magnetic lineaments detected by the improved logistic method.

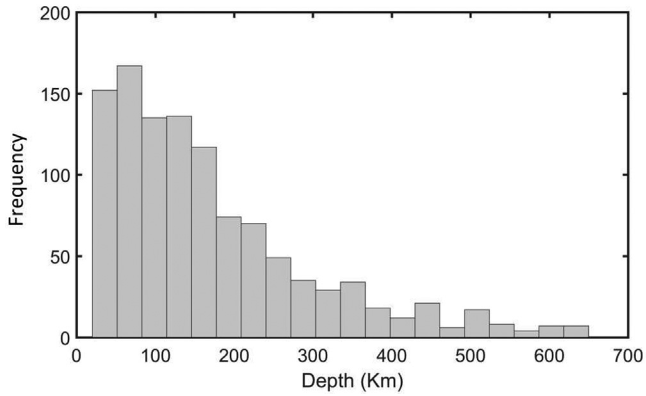

Fig. 7. Histogram of the Euler solutions.

active margins, island arcs, rifts, metamorphic orogenic roots, distensive sedimentary basins, etc.). Consequently, these lineaments can be directed by different tectonic events. In the basement area, these lineaments may correspond to overlapping and stall-overlapping accidents of the major Pan-African phase (for a summary see Gasquet et al., 2008). But these accidents can be replayed as normal faults trending NNE-SSW to NE-SW affecting the Ouarzazate Group during the late to post-orogenic event (Oudra et al., 2005). In the area of the cover, they can be interpreted as geological structures previously described at the level of the Anti Atlas as the result of a regional shortening relating to the Hercynian Orogeny of major NW-SE direction (e.g., Hassenforder, 1987; Belfoul et al., 2001, Faik, et al., 2001; Caritg et al., 2004; Helg et al. 2004; Burkhard et al., 2006; Soulaimani and Burkhard, 2008). According to these authors, the folded and brittle geological structures have a NE-SW orientation. However, other orientations (—e.g. E-W and N-S) have been highlighted on the buttonhole borders. From the Trias and to the opening of the central Atlantic, the anti-Atlas is subject to a NNW-SSE extension (Robert-Charrue and Burkhard, 2008) with the establishment of the magmatic of the CAMP (Province Magmatic Central Atlantic) represented basic veins of NE-SW direction. The latter is well expressed in the study area by a mega dolerite vein.

On the other hand, the lineaments mapped near the basement/-cover contact which hosts copper mineralization in stratiform clusters (e.g., Tizert copper deposit; Oummouch et al., 2017), deserve to be explored more, because they are defined as a guide to exploring for new copper deposits. For another comparison, the lineaments extracted from the improved logistic map are plotted on the Euler solutions map to measure the degree of similarity between them (Fig. 6). Most of the magnetic sources are found to be located in a depth range of 20 m to 250 m, with major trends of the Euler solutions being NE-SW and E-W. These trends match reasonably with the result from the improved logistic method. It is also noted that the use of the improved logistic method produces more continuous lineaments compared to the Euler deconvolution. Consequently, the improved logistic method can enhance magnetic data, which shows the boundaries of magnetization sources with higher resolution and permits a more precise interpretation of magnetic data than the tilt angle method. The improved logistic map brings a new look at the structural lineaments in the Agadir Melloul area.

6. Conclusions

We aimed to reinterpret the aeromagnetic dataset of the Agadir Melloul area. First, we compared the performances of the tilt angle and improved logistic methods through two synthetic models. The synthetic examples demonstrated that the improved logistic method can detect all edges with higher precision compared to the tilt angle method. In addition, the improved logistic method brings higher resolution edge maps without any false information. The result obtained from the application of the improved logistic method to aeromagnetic data of the Agadir Melloul area was found to be in good agreement with some structural lineaments in the tilt angle map. This result also helps to remove false information in the tilt angle map, so it brings a new look at the structural lineaments in the Agadir Melloul area.

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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Data and materials availability

All data needed to evaluate the conclusions in the paper are presented in the paper.

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