Mapping of gold mineralization using an integrated interpretation of geological and geophysical data—a case study from West Baranes, South Eastern Desert, Egypt

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Abstract
The current study is mainly devoted to the integration, analysis, and interpretation of the available geologic, remote sensing, and potential field data (mainly magnetic) to delineate the subsurface geologic structural elements controlling the western part of Baranes, South Eastern Desert, Egypt, and its relation to the southwestern desert structural regime. Additionally, to detect potential mineralization zones for future mining plans in the study area. The Western part of Baranes has not had enough geomorphological mapping, consequently, potential discoveries of mineralization zones are very low. So, in this paper, an attempt is initiated to better understand the evolution of the geomorphology and structural regime of the region and construct a digital geological map and structural patterns showing the possible locations of mineralization zones based on the previous knowledge from similar potential sites and focus on the future economic importance of the region. To achieve this purpose, processed Landsat-8 images successfully revealed the lithological contacts and fault zones helping in distinguishing between the different rock units; moreover, the aeromagnetic data available in the area is used and several filters are applied including reduction to the pole, Euler homogeneity equation, analytic Signal (AS), and advanced grid filtering are sequentially used aiming to detect the possible subsurface distribution of mineralization zones from the integrated interpretation of magnetic susceptibilities and available geologic and remote sensing data.

Keywords Mapping of gold mineralization · Magnetic exploration, Landsat ETM · Eastern desert · Normalized source strength · Gold mineralization

Introduction
Shear /fracture zones have played a significant role in the formation of several large gold resources across the world. Major dominating shear zones govern the majority of large gold resources. (Roberts 1987; Hodgson 1986; Groves et al. 1984), even though they are hosted in detail by contrasting fluid pressure; this fluid migration and gold deposition system may be caused by subsidiary brittle-ductile fault fractures and/or a temperature regime between the first and second-order structures (Eisenlohr et al. 1989). The majority of these deposits are located mostly in Archean shields (Zimbabwe (Foster 1988); Canada: Sigma mine (Robert and Brown 1986); Red Lake (Andrews et al. 1986); Western Australia: Golden Mile area (Groves and Phillips 1987; Groves et al. 1984, 1987)). Similar deposits also occur in more recent terranes, e.g., schists of the Mesozoic age of New Zealand (Brathwaite 1988), and Hercynian basement of France (Bonnemaison and Marcoux 1987; 1990), and...
Similarly, the Arabian–Nubian Shield (ANS) is the world’s principal block of Neoproterozoic crust. Tectonic events during the Pan-African Orogeny include the rifting of Rodinia and the subsequent assembly of Gondwana (850–590 Ma) (Johnson and Woldehaimanot 2003; Stern 1994). There are several shear-associated deposits in the shield that are significant sources of both precious and basic metals (Au, Ag, Cu, Zn, and Pb) on a global scale (Johnson et al. 2017). Gold occurrences, in particular, may be found all across the Nubian shield (NS), with hundreds of locations in the Eastern Desert of Egypt, characterized by trenches, adits, and dumps, as well as placer gold workings in alluvium (Klemm et al. 2001). Known as orogenic gold, the bulk of these ancient mines were situated on quartz-carbonate veins that contained gold in metamorphic terranes. In Egypt, such veins are now being mined.

The investigated area (Western part of Baranes) is situated in the southern portion of the eastern desert of Egypt (SED). It constitutes part of the Nubian shield, the Egyptian western limb of the ANS as shown in Fig. 1. Unfortunately, gold discoveries are very few in this area, although it is surrounded by many potential gold discoveries. This may be related to the very few intensive integrated studies and geomorphological mapping in the area. Moreover, the Precambrian basement of Egypt is studied extensively in several locations including Sinai, the northeastern desert (NED), the central-eastern desert (CED), and the SED. Both NED and CED attain much attention from geophysical studies. This may be in part close to the urbanization, or to the old activities of mining and exploration since the Pharos time. On the other hand, the SED received less attention, and research is required to comprehend the geochronological structure and better define the primary characteristics of the SED crust. The SED may reflect a very much similar infrastructure-superstructure relationship similar to those of the CED, but the SED shows older units than the CED (Stern 2018, 2017). It shows that the SED has been exposed to a higher degree than the CED and has been significantly less affected by the main Najd shearing. In other words, the challenges in unravelling tectonic structures can make it difficult to grasp the geometry of ore bodies, resulting in uncertainties or errors in mineral exploration, mine design, ore deposit appraisal, and even mineral exploitation. As a result, a variety of geophysical methods are needed to determine the kind, size, and shape of these structures. Among these very critical structural elements are the shear zones, fractures, and faults.

Several authors have investigated geologically, areas close to west Baranes such as Abdelsalam and Stern (1996). El-Shimi (2005) and Elkhateeb and Eldosouky (2016) studied the Wadi Allaqi area and all used aeromagnetic analysis on discovering the Wadi Allaqi area’s potential mineralization zones. Recently, El Gamal et al. 2013 studied Garara graben to estimate the structural evolution of the area. On other hand, the El-Nom borehole (Mahmoud and Essa 2007) -drilled in the Gebel Abraq area SE Aswan City- shows the geologic stratigraphic of the area. Studies confirm that the sedimentary cover might be reached about 2300 m. It is dominated mainly by consolidated sandstones, amorphous sandstone with silty-sized quartz grains, siltstones, and black shale. All these subsurface rock units represented the period from Berrisian to Cenomanian.

Magnetic surveys have been widely used as an economic geophysical tool in geologic mapping applications, especially aeromagnetic surveys. Land and aeromagnetic surveys are passive measurements of the ambient magnetic field. It is used as a reconnaissance tool so it has many applications in different fields in geology including geologic mapping of prospective areas with buried igneous bodies that are frequently associated with mineralization. Determination of supra-basement features, determining the thickness of sedimentary cover (Abdelazeem et al. 2021), identification of intra-basement faults and uplifts, basin modeling, structure geometry (Al-Garni and Gobashy 2010; Abdelazeem et al. 2014; Balkaya et al. 2017; El-Sawi et al. 2018), study of the tectonic structure, hydrocarbon exploration, modeling groundwater, and geothermal resources (Al-Garni et al. 2006; Gobashy et al. 2021a, b) allow a visualization of the geological structure of the upper crust, particularly the spatial geometry of lithologic units and address the presence of folds and faults, helps to locate buried objects (drums, pipes, and unexploded ordnance) (Abdelazeem and Gobashy 2016), and in mineral exploration (Groves et al. 1984; Al-Garni and Gobashy 2010; El-Sawy et al. 2018; Abdelazeem et al. 2019; Abdelrahman and Gobashy 2019; Rehman et al. 2019; Aboelkhair et al. 2020, and Abdelhalim et al. 2020, Gobashy et al. 2021a, 2021b, and Gobashy et al. 2021b).

In the present study, available aeromagnetic data were processed, reduced to the pole (RTP), and different filters, e.g., normalized source strength (NSS), analytic signal (AS), Euler Deconvolution, and tilt angle are applied to achieve possible zones of gold mineralization and help in mapping structural and lithological features in the study area. Moreover, many grid analysis techniques are used to delineate probable gold deposits and identify geological discontinues (dykes, faults, and shear zones) which act as a conduit for mineralizing fluids. The above technique will be tested in the West Baranes area.

The Landsat Thematic Mapper (TM), on the other hand, is widely used to outline structural lineaments, construct geological maps, and identify lithological units of the Eastern Desert (ED) basement complex. This saves fieldwork labor and yields worthwhile findings quickly (Sultan et al. 1986). Gad and Kusky (2006) used enhanced TM imagery with band processing and field observations to distinguish mineral assemblages from country rocks in the Eastern
Desert, and Gobashy et al. 2021b combined remote sensing and land sat TM imagery for locating gold mineralization zones in the Barramyia district, ED. Suture lines and shear zones have also been traced at various scales.

The West Baranes area is poorly mapped and studied although it contains some areas such as Gebel Abraq and Wadi Garara that may represent a possible potential zone for mineralization, especially for gold opportunities. Thus, this
study aims to construct a new updated geomorphological map of the area and try to detect new locations for mineralization based on interpretations and integration of geophysical aeromagnetic data, geological features of the area, and Landsat ETM satellite images (remote sensing techniques including band combination, principal component analysis, and supervised classification).

**Geology and location of the study area**

The area under study is located West of Baranis, east of Aswan city and near Gebel Abraq district, South Eastern Desert, Egypt, between latitudes 22° 59’ 55” to 23° 43’ N and longitudes 33° 48’ - 35° 00’ E (Fig. 1). The location of the area gives it the advantage of being a part of the Neoproterozoic Arabian-Nubian Shield and passing through the western extension of Allaqi-Heiani-Gerf-Onib-Sol Hamid-Yanbu suture (Stern 1994; Abdelsalam and Stern 1996).

Geologically, the area is dominated by Nubian sandstone formation, unconformably overlying the Precambrian basement rocks. The Nubian formation is of Upper Cretaceous age and composed of bedded to massive cross-bedded sandstone and is overlain by claystone of El-Quseir variegated shale. (Abd El Kader 2001). The region’s geologic outcrops display a broad variety of stratigraphic rock units (sedimentary, metamorphic, and igneous), ranging in age from the Precambrian to the Quaternary. The area is mostly composed of Precambrian rocks in the north, east, and southwest. The upper Cretaceous Nubian sandstone dominates the sedimentary cover in the study area (Fig. 2), which is located above the Precambrian unconformity, and quaternary deposits fill the area’s wadis. Aged Neoproterozoic, the Eastern Desert’s crystalline basement structure is located in the Arabian Nubian Shield’s northwest corner (ANS). The Neoproterozoic basement seen elsewhere in the ANS is fully represented in the Egyptian ED. The distribution of structural lineaments in the area shows that the main trends are NW, ENE, EW, and NNW. This is confirmed by the rose diagram as shown in Fig. 2. The trends could be assigned to structural complexes which related to phases of tectonism as follows:

- NW-trending is mainly related to the second structural complex of the Western Allaqi–Heiani suture: a central nappe, called the central allochthon, in which the early SW-verging structures were afterwards deformed by steeply inclined folds that trended to the northwest. Additionally, in the Oligocene age, the red sea rift activated in the NW direction as a rejuvenation of the old preserved trend in the deep basement complex.
- ENE-trending is the main trend that formed the Phanerozoic structures of Egypt. The motions between the African Plate and the neighbouring plates have been linked to four deformations. These periods include the Tethyan rifting (NE-SW to ENE-WSW), Cretaceous-Early Tertiary rifting (NW–SE to WNW–ESE), and Late Cretaceous-Tertiary inversion of the Tethyan basins, and ongoing compressional deformation of other regions up to the present.

In general, the area under study tectonically was affected by the Allaqi-Heiani suture which considers being the western extension of the Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture that represents one of arc–arc sutures in the Arabian–Nubian Shield. It extends for more than 250 km from the N-trending Hamisana Shear Zone in the east to Lake Nasser in the west. The map in Fig. 2 shows the general structural lineaments of the area that tends to be in the directions NW–SE and NE-SW.

Furthermore, the area lies in the Pan African Arabian Nubian Shield (PANS) composed of foreland sediments (Nubian Sandstone formation) represented by the Khart-Wadi Hodein Shear Zone (KHSZ) is an NW-oriented transcurrent shear zone covering about 186 km in the SED of Egypt, and exhibiting a sinistral sense of shear (Hamimi et al. 2019).

**Methodology**

To achieve the purpose of this study, integrated geology, remote sensing (RS), and aeromagnetic are used. The filters applied to magnetic data are generated using the GeoSoft Oasis Montaje standard edition software. The spectral reflectance of rock and mineral assemblages was characterized using the integration of remote sensing methods with field-based mapping of rocks connected to gold resources. Images from the Landsat-8 Operational Land Imager (OLI), released by (https://earthexplorer.usgs.gov), were utilized in this investigation.

Initially, row 43 was processed with 11 bands or channels and accessed using path 174. Band combination, principle component analysis (PCA), and supervised classification were the modules employed to improve picture visualization and rock discrimination. Band combinations have lately been employed, as previously noted, to identify lithological units
of the basement complex in the West Baranes region, Eastern Desert, as part of the RSH (Gad and Kusky 2006, 2007).

The principal component analysis (PCA) technique, in particular, is an enhancement tool used usually in geological mapping to recognize the lithological content (Abrams et al. 1983; Tangestani and Moore 2001, Abdelmalik et al. 2004, and Abdelhalim 2013). It is used as an enhancement tool for geological applications (Santisteban and Munoz 1978), and land-cover change detection (Lodwick 1979; Singh 1986). The principal component analysis (PCA) technique is commonly used for compressing the size of the data set by reducing the number of dimensions which helps in highlight the significant information from the data table, make an easy description of the data set, analyze the structure of the observations and the variables, and as an image compressor.

To achieve the study goals, remote sensing techniques are used which effectuate the best visualization to distinguish various rock units in the area. Magnetically, several filters

Fig. 2 Detailed geologic map of the study area (modified after Conoco, 1983)
are applied to the total magnetic intensity map available from the Egyptian General Petroleum Corporation (EGPC 1983). Table 1 displays the survey parameters. In the following sections, we summarize the methodology and advantages of each filter.

**The reduced-to-pole filter**

The reduced-to-pole filter (RTP) is applied to the total magnetic intensity (TMI) data to minimize the effect of skewness of the geomagnetic field. The RTP is calculated from the total magnetic anomaly map on a regular grid (IGRF free). The used inclination and declination of the field are (I = 35.2309° and D = 4.1710°) at the latitude of 24 degrees N and longitude of 35 degrees E. These RTP values are later used in magnetic interpretation and depth estimation in the frequency domain.

**Derivative filters**

Extracting valuable information from the magnetic field data requires the application of special filters to enhance desired signals resulting from the magnetized sources. Among these filters or grid-based operations are the derivatives of the field. This includes vertical and horizontal derivatives in their simple form. Most of the advanced filtering techniques are depending on vertical and horizontal (first, second, and third) derivatives of the magnetic anomalies or both of them to delineate qualitatively features of the source bodies such as edges and centers including enhancement of the low magnetic anomalies. The vertical derivatives enhance the high-frequency components at the expense of the long-wavelength ones. The horizontal derivatives, on the other hand, are effective edge detector, it is used in defining the position of edges of the source bodies and it is less sensitive to the variations in the depth of the sources. The three first-order derivative components \( \left( \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z} \right) \), the three second-order diagonal components \( \left( \frac{\partial^2 T}{\partial x^2}, \frac{\partial^2 T}{\partial y^2}, \frac{\partial^2 T}{\partial z^2} \right) \), and the off-diagonal components \( \left( \frac{\partial^2 T}{\partial x \partial y}, \frac{\partial^2 T}{\partial x \partial z}, \frac{\partial^2 T}{\partial y \partial z} \right) \) are calculated for the West Baranes area. Linear features are posted on the maps. Several trends can be obtained through rose diagrams and used for further processing.

**The analytic signal**

The analytic signal filter (AS) is applied to detect lineation and track magnetic discontinuities in the study area. The horizontal and vertical magnetic tensor diagonal elements are combined to provide the analytical signal or total gradient. The shape of the analytical signal over the causative body relies on its positions (horizontal coordinate and depth), but not on the direction of its magnetization. The amplitude of the analytic signal is simply calculated as given in Nabighian (1972, 1984).

**The tilt angle filter**

Another well-liked improvement using an output provided by the tilt filter (Miller and Singh 1994; Verduzco et al. 2004; Salem et al. 2007; Gobashy et al. 2021a, b). The degree of amplification of this filter varies depending on the local amplitude of the field gradients, and the filter output does not preserve any amplitude information.

**The normalized source strength filter**

In essence, the normalized source strength (NSS), which is obtained from the magnetic gradient tensor, is an effective edge detection filter (MGT). For a significant class of sources, it is not strongly reliant on magnetization direction and is just marginally so. Its maximum occurs precisely above the causal magnetic source, and it is proportional to the intensity of the source. This feature is essential in mineral exploration where the magnetic contacts are the target for mineralization zones. The angle between the magnetization and displacement vectors for massive sources that are well represented by a dipole may be calculated using the eigenvalues. In a diagonalized form, the magnetic gradient tensor \( \Gamma \) is given as:

\[
\Gamma = V^T A V
\]

where \( V = [v_1, v_2, v_3] \) represent the eigenvectors and \( A = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \) represent the eigenvalues. Following Beiki

### Table 1

Aeromagnetic survey specifications, Eastern desert, Area II, Egypt. (Egyptian general petroleum corporation, Aero service, 1983, 1984a, b. Interpretation report, airborne gamma-ray spectrometer, and magnetometer survey of the eastern desert of Egypt)

| Parameter                  | Value                                  |
|----------------------------|----------------------------------------|
| Magnetometer               | Varian VIW 2321G4 Single-Cell Cesium Vapor |
| Altitude                   | 120 m (394 feet) (Terrain Clearance)   |
| Average total Altitude     | 42, 425 gamma                           |
| Magnetic field intensity:  |                                        |
| Flight line spacing:       | Traverse = 1.0 KMS, Tie = 10.0 KMS     |
| Flight line direction      | Traverse = 45°/225, Tie = 135°/315°    |
| Declination                | 1.9° East                               |
| Inclination                | 32.8° North                             |

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et al. 2012, the normalized magnetic moment $\mu$ (or the normalized source strength, NSS) and the angle between the displacement vector and magnetic moment vector $\varphi$ are given by:

$$\mu = \sqrt{-\lambda_2^2 - \lambda_1\lambda_3}$$

(2)

And

$$\varphi = \cos^{-1}\left(\frac{\lambda_2}{\mu}\right); 0 \leq \varphi \leq 180^\circ$$

(3)

where the intermediate eigenvalue is $\lambda_2$, with the smallest absolute value. When comparing the NSS with the AS, the $\mu$ can provide more reliable information about the source geometry when geologic bodies carry remanent magnetization (Beiki et al. 2012). The normalized source strength transformation map, and the two complementary maps $\lambda_2$ and $\varphi$ are calculated for the west Baranes area. A specially designed Matlab function is used for this analysis.

**The Source Parameter Imaging**

The Source Parameter Imaging (SPI™) approach estimates magnetic depths by extending a complex analytical signal. This methodology, also known as the local wavenumber method, was developed by Thomson and Smith in 1997 and is a profile or grid-based method for measuring magnetic source depths. The approach relies on the link between source depth and the observed field’s local wavenumber \( k \), which may be estimated using horizontal and vertical gradients for every location within a grid of data.

**The (CET) grid analysis**

The texture of an image is analyzed by the CET (Centre for Exploration Targeting) grid analysis technology to find regions of structural complexity and consequently, to determine the favorability of a gold deposit occurrence. To find crossings, junctions, or contacts, and changes in direction in the strike, this approach first finds magnetic discontinuities, then identifies locations of discontinuity, and analyses structural relationships. It facilitates picking the areas that are perceived to be prospective (Holden et al. 2008, 2010). Thus, the technique includes the following steps: texture analysis (Holden et al. 2008), texture ridge detection (Kovesi 1997), and thinning of texture ridges (Lam et al. 1992).

**Euler deconvolution**

To quantitatively determine the depth of the causative source of the magnetic anomalies, a semi-automatic Euler deconvolution procedure (Reid et al. 1990) was applied to the RTP data. Results are clustered or non-clustered solutions represented as colored circles. The color scale represents the different depths.

**Magnetic tomography**

A detailed analysis of the subsurface distribution of magnetic susceptibilities is carried out along two selected profiles to reveal the distribution of different rock units and its relation to surface and subsurface structural elements and shear zones dominated in the area. This is performed through modelling the subsurface assuming the 2D half-space is divided into a large number of blocky cells each of unknown magnetic susceptibility. The proposed model is then inverted using regularized focused inversion (Portniaguine and Zhdanov 1999) and a threshold value is assumed which stops inversion when achieved. The available surface magnetic susceptibilities are used as constraints to control inversion. The resulting tomographic model indicates the possible distribution of the subsurface susceptibilities and when interpreted and correlated with the surface geology, the magnetic signature of mineralized zones could be extracted. The two proposed profiles are selected based on the contact occurrence density of the study area.

**Results and discussion**

Remarkable discrimination between the basement complex and sedimentary cover from the sand sheets resulted from the Landsat enhanced thematic mapper (ETM+) image (7, 4, 2) in the RGB map for the study as shown in (Fig. 3a). Moreover, the contact and overlap between Phanerozoic and Proterozoic rocks fairly delineated and could be enhanced. Further analysis using supervised classification implementing all the available geological maps of the previous works in the area, resulted in a new geological map produced with a classification of distinguished nineteen rock units in the study area (Fig. 3b). These are shown in Table 2.

Based on the geologic outcrops in the area, the PCA, supervised classification, and nomenclature of the Conoco geological map (1987) of the area, a geological map has been produced (Fig. 1). Analysis shows that the Precambrian rocks cover the northern, eastern, and southwestern parts of the area, it is characterized by the presence of granitoid group with its two main types (older and younger granites). Moreover, the so-called Intrusive metagabbro to metadiorite complex in Conoco geologic map meets the
sandstone, not basalt.

stones which refined in the map to assign as a Nubian eruptions in the study area, there are some black sand- and sand sheets (Fig. 4a). Because of some volcanicity

strata (Said 1990). The present study confirms that most composed of hard yellowish-brown well-joined sandstone in age from Jurassic to Upper Cretaceous and is mainly the Precambrian unconformably. This sandstone ranges

graben as a part of Hodien basin. The upper Cretaceous Nubia sandstone dominated mainly the sedimentary cover at the study area (Fig. 4b) which lies above the Precambrian unconformably. This sandstone ranges in age from Jurassic to Upper Cretaceous and is mainly composed of hard yellowish-brown well-joined sandstone strata (Said 1990). The present study confirms that most of the sedimentary cover is Upper Cretaceous Nubia sandstone succession consisting of sandstones, siltstones, and shale (Fig. 4b). Consequently, the Nubia sandstones are arranged from oldest to youngest units in the area as follows: Abu Aggag Formation, Timsah Formation, Umm Brammily Formation, overlayed by Quaternary deposits and sand sheets (Fig. 4a). Because of some volcanicity eruptions in the study area, there are some black sandstones which refined in the map to assign as a Nubian sandstone, not basalt.

On the other hand, qualitative interpretation of the total magnetic intensity map (TMI) (Fig. 5a) divides the study area into zones of different magnetic intensities based on the different rock types in the area. Zone A represents high magnetic anomalies (> 42,450 nT) concentrated at the NE, SE, and SW corners of the area. Corresponding to Gabal Abraq (A1), Wadi Figo and Gabal Kalat metasediments (A2), and Gabal Nasya calc-Alcaline tectonized granitic rocks (A3). It is composed mainly of metasediments, metamorphosed shelf sediments, and volcanogenic rocks, partly including pyroclastics The intermediate magnetic anomalies (42,300 to < 42450nT) correspond to Gabal Mulgata and Umm Bara- mil formation (B1), Gabal Tarabti and Abu Aggag Forma- tion (B2), and Gabal Musrar and Abu Aggag Formation (B3). Finally, the low magnetic anomalies (<42300nT) cor- respond to tectonized granitic rocks close to Wadi Garara (C1), and Gabal Amreit and Temsah formation (C2) represent- ing the sedimentary cover on the area.

The reduced-to-pole magnetic anomaly map (Fig. 5b) addresses more clearly the locations of the anomalies associated with their source bodies. Several lineaments can be detected. The rose diagram indicates a dominant NW–SE, representing the Najd fault system and the structural complex of the Western Allaqi–Heiani suture trend. The E-W trend represents the south of the Migif-Hafafit gnéissic terrane and Allaqi-Heiani-Gerf-Onib ophiolite belt, and the ENE trend representing the Phanerozoic structures of Egypt. Quantitative interpretation of the reduced-to-pole data is performed using selected digital filters. Derivative filter critical analysis (Fig. 6) indicates dominant NW–SE, E-W, and ENE trends, similar to the RTP map.

The superior advantage of the analytic signal filter is shown in Fig. 7a. Clear and resolved peaks are detected over the magnetic contacts in the area (pink color); these trends track precisely the known surface rock units as detected from the surface geologic mapping.

The tilt angle (Fig. 7b) shows also clear NW–SE and NE-SW trends of the detected lineaments. The estimated depths of magnetic sources range from 215 to 3100 m. The zero-contour line in the map indicates the magnetic contacts all over the study area. Euler deconvolution (Fig. 7c) extracted depths ranging from zero (exposed rocks) to about 1000 m below sea level. This is characteristic of Euler analysis, where it may be attributed to shallow sources.

The normalized source strength (NSS) filter (Fig. 8a, b, c), on the other hand, is similar to the AS filter; however, the resolution is greatly improved where the full magnetic gradient tensor is used in the transformation. In the AS filter, only the diagonal gradients are used. Figure 8a and b shows the λ2 map, and the φ maps respectively. Both maps are intermediate steps in calculating the NSS (µ) map. The φ map can be used to extract the direction of magnetization of selected structures when compared with the maxima of the µ map. The µ map contains the general magnetic texture as the RTP and AS maps. However, finer detailed and resolved anomalies could be observed and detected. The peaks of the µ signal (Fig. 8c) shown on the map as circles provided the possible locations of source magnetization (Clark, 2012a, b, 2014). In general, the maps produced by using the conventional Euler deconvolution, AS, tilt angle, and normalized source transformation approaches to RTP data show a decent grouping of solutions in a linear and curved form, showing the nature of possible rock unit interactions and representing the diverse geometries of the causative sources in the area.

µ map (Fig. 8a) accentuates the variation in the magnetization of the magnetic sources in the study area and highlights discontinuities and anomaly texture that are related to faults, dyke, intrusive bodies, and shear zones.

The entropy (Fig. 9a) provides a measure of the textual information within a specified window in the dataset. It measures the statistical randomness of neighbourhood data. Contoured values indicate the amount of randomness exhibited by the texture in the neighbourhood centered about each cell. Regions exhibiting high statistical randomness are considered high in entropy (pink color) whereas regions of little randomness have low entropy (blue color). The high entropy sites are concentrated overlying the surface sand
sheets, east Gabl Abraq, Gabal Shiqaqat foliated quartzite, and tectonized granites. While the low entropy is represented at the Northeastern corner of the area at Wadi Garara, and Wadi Anid quaternary deposits. This indicates a possible underlying shearing or fracture zone with possible magnetization at the central zone of the area. An estimation of the regional variance in the data is given by the standard deviation (Fig. 9b).

It determines the standard deviation of the data values within the nearby neighbourhoods at each place in the grid. Significant features frequently differ significantly from the background signal. This is recognized at the same localities of the entropy variations. The phase symmetry (Fig. 9c) detects line-like features by identifying axes of symmetry which is closely related to the periodicity of its spatial frequency. The map clearly shows the linear and curvilinear features in the area, which are in close agreement with the results of Euler and Tilt angle filters. The skeletonization (or line thinning) (Fig. 9d) is a morphological operation that takes a binary grid and skeletonizes each foreground object by iteratively eroding its boundary cells until the object is only 1 cell wide. This process improves the resolution of the detected lineaments from the previous step. Finally, the contact occurrence density (Fig. 9e) generates a heat map that highlights the high density of structural contacts, which include junctions and intersections of different structures and locations where structures have significant orientation changes. Similarly, the orientation entropy (OE) map

| Weathered diorite | Metamorphic rocks |
| Weathered calc-alkaline | Metagabbro |
| Um barmil formation | Intermediate volcanic |
| Timsah formation | Granitoid |
| Serpentinites | Gabbro |
| Sand sheets | Diocritic rocks |
| Quaternary deposits formations | Basalt |
| Ophiolitic Metagabbro | Aluvial deposits |
| Metavolcanics | Abu Aggag formation |
| Metasediments | |

Fig. 4 (a) Sand sheets due NW of the study area towards Nasser Lake due west. (b) Nubia sandstone
Fig. 9f indicates areas of potential structural complexity. Figure 10 also shows the possible localities of mineralization zones (marked as black stars) as posted on the metallogenic map of Egypt (modified after the Metallogenic map of Egypt, metallic and non-metallic deposits, 1988). The area surrounding the study area is presented to show the distribution of different distributions of metallic and nonmetallic deposits close to the west Baranes area.
Fig. 6  First- and second-order gradients of the RTP map, West Quseir. Solid straight lines indicate faults or contacts, and bounded zones indicate high-frequency magnetic zones.
Fig. 7 Analytic signal map of the study area. Solid circles indicate clustered massive contacts bodies. Solid lines indicate linear features/contacts (a), tilt angle solutions (b), and Euler deconvolution analysis (c).
Fig. 8 The normalized source analysis. λ2 map (a), φ map (b), and the normalized source strength (μ) map (c). The pink color on (c) indicates strong magnetic contacts. Circles indicate peaks of the highest anomalies.
Fig. 9 CET analysis. Entropy as a measure of statistical randomness of a neighbourhood data (a), standard deviation: an estimate of the local variation in the data (b), phase symmetry and line-like features map (c), skeletonization and edge enhancement (d), a heat map that highlights high density of structural contacts (e), and orientation entropy (OE) indicating areas of potential structural complexity (f).
Fig. 10 Opportunity map for mineralization occurrences in the study area superimposed on the metallogenic map of Egypt (modified after Metallogenic map of Egypt, metallic and non-metallic deposits, 1988), and magnetic tomographic sections AA' (a), and BB' (b)
The 2D magnetic susceptibility tomography, on the other hand (Fig. 10a, b), reveals that the overall picture of the magnetic field of the two profiles is compatible with the detailed geological mapping and structural framework of the area. The sheared metavolcanics show gradational lithologic contact against quartz-carbonate rocks and are in structural contact against other rock units in most cases. The proposed locations of gold mineralizations (a1, a2, ab3, a4 for profile AA”, and b1, b2, ab3, b4, and b5 for profile BB”) are associated with faults and magnetic contacts between high and low-magnetic susceptibility rocks.

Conclusions

A wealth of geologic, structural, remote sensing, and filtered magnetic data became available for the area of West Baranes. Rock units are classified into nineteen different rock units. The basement is highly differentiated, using the Landsat enhanced thematic mapper (ETM +) image. Moreover, the contact and overlap between Phanerozoic and Proterozoic rocks are fairly delineated and could be enhanced. Supervised classification resulted in a new geological map produced with a classification of distinguished nineteen rock units. Study confirms that most of the sedimentary cover is Upper Cretaceous Nubia sandstone succession consisting of sandstones, siltstones, and shale. The Phanerozoic successions affected by the inherited Proterozoic tectonism such as the presence of the southern Hodien shear zone and northern Khodaa shear zone (Fig. 1), built up the Grara garben as a part of Hodien basin. Magnetic grid analysis using Euler deconvolution and tilt angle delineated the NW–SE dominant trend, representing the Najd fault system and the structural complex of the Western Allaqi–Heiani suture trend, the E–W trend representing the south of the Migif-Hafait gneissic terrane and Allaqi-Heiani-Gerf-Onib ophiolite belt, and the ENE trend representing the Phanerozoic structures of Egypt. The depths to magnetic sources in the area range from surface features to sources at about 3150 m. Most of these sources are associated with the fracture zones/ shear zones in the area. The AS and normalized source strength results agree in addressing the exact location of magnetic contacts/faults that agrees well with the Euler, derivatives, and SPI depth maps. The CET grid analysis and the heat map (Fig. 9e) determine accurately the best probable locations for mineralization (Fig. 10). This is generally associated with the locations of the high density of structural contacts and areas of potential structural complexity (OE) map. The magnetic tomographic inversion confirms the association between magnetic contacts/faults and proposed gold mineralization zones.

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Declarations

Competing interests The authors declare no competing interests.

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