

Integrated gold prospectivity mapping in Um Garayat, Egypt

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Abstract: The gold mining sector necessitates the adoption of efficient, fast and contemporary technologies for gold exploration that accurately describe the structural setup, shear zones, faults, and other related geological features associated with mineralisation. In this work, a survey utilising land magnetics, induced polarisation (IP), transient electromagnetic (TEM), and electrical resistivity tomography (ERT) was utilised to map and primarily characterise potential gold ore deposits in Um Garayat, South Eastern Desert, Egypt. Potential polymetallic exploration in the region is also well-known. It includes Au, Ag, Cu, Zn, Pb, and Mo. Field geology, remote sensing, and geophysical investigations have been conducted in the vicinity of the ancient gold mine to investigate the distribution of the mineralised ore deposits in the Um Garayat region vertically and horizontally. To validate results, field geologic studies were conducted across numerous traverses guided by remote sensing. The results of this investigation demonstrate that low resistivity and high chargeability were indicative of ore deposit regions in the geophysical data. The subsurface magnetic susceptibility distribution validates the area's complexity. According to an integrated interpretation of the collected results, the new possible potential ore deposits are associated with hydrothermally altered zones associated with fracture zones and faults present in the form of zones of varying thicknesses. In Um Garayat, recently discovered mineral occurrences are governed by the major faults and the enrichment of hydrothermal fluids along these fault zones.

Key words: Um Garayat, South Eastern Desert, hydrothermal alteration zones, geoelectric, transient electromagnetic method, land magnetic

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1. Introduction

Geophysical techniques have provided valuable insights into subsurface mineralisation over the past few decades. There are several reasons why these methods have become so important in mineral exploration. Each method must primarily require a distinct physical characteristic, including but not limited to resistivity, conductivity, chargeability, density, magnetic susceptibility, or acoustic properties. This variety considers a complete comprehension of the subsurface by incorporating different informational collections for examination. Second, geophysical methods are relatively low-cost, non-intrusive, and simple to implement. Finally, they are suitable for exploration because they can cover both small and large areas in a relatively short time. The Um Garayat (UG) gold mine area is a highly prospective mineralised zone situated in the central part of the Wadi Allaqi major shear zone, located in the southwestern region of the Eastern Desert in Egypt. This central shear zone is home to approximately 17 occurrences of gold.

The Ancient Egyptians were able to extract visible and accessible surface gold from quartz veins at the underground deposits, reaching depths of around 30 metres. However, they were unable to exploit the disseminated gold found within extensive iron-copper-sulfide deposits and their alteration zones in the metavolcanic rocks, as reported by *Kusky and Ramadan (2002)*. Between 1901 and 2020, the Egyptian Geological Survey and Mining Authority (EGSMA), together with various companies and authorities, undertook prospecting and exploration efforts (*EGSMA, 1992*). The highest concentrations of gold were identified at depths ranging from 30 to 40 metres below the surface, with the richest quartz veins yielding between 7.75 and 155.5 grams per ton (*Sabet et al., 1983*). Additionally, *Oweiss and Khalid (1991)* documented gold content grades reaching up to 7.2 grams per ton in the primary lode and alteration zones, while *El-Kazzaz (1996)* found gold concentrations in quartz veins up to 6.98 parts per million. In the core mining region, the revealed mineralised zone exhibits a trend extending from the northwest to the northeast in proximity to the shaft. This orientation aligns with the regional structural patterns observed in the underground area and the Allaqi shear zone, which predominantly trend northwest, accompanied by secondary trends directed north, northeast, and east (*Marten, 1986*).

The mineralised zone is characterised by two rich sites: gold at the shaft area and copper-gold at the southern adits area. This study aims to identify the potential surface and subsurface mineralisation zones, particularly gold, and to assist in mapping the associated structural and lithological features. This initiative is driven by a lack of information regarding the relationship between the subsurface distribution of geophysical properties, such as electrical resistivity and magnetic susceptibilities, and gold mineralisation, especially in the high-potential gold mineralisation zone of UG. The current investigation focuses on the geophysical exploration of mineral deposits and hydrothermal alteration zones. It targets the subsurface distribution of mineral deposits around the old gold mine and Wadi tributaries, and their relationship to structural elements in the study area (Fig. 1).

Spatial prediction of natural mineral resources is essential for efficient exploration and management of these resources. Such predictions can be derived from a range of factors that affect the occurrence of minerals in geologically favourable settings. Therefore, assessing the potential for mineralisation is inherently a spatial issue that can be addressed by considering various variables. To increase the dimensionality of these parameters, and to include the third dimension (the depth), the present workflow utilises electric resistivity tomography ERT, transient electromagnetic (TEM), induced polarisation (IP), and land magnetic exploration measurements along selected profiles. In the primary phase of this study, extensive reconnaissance aeromagnetic interpretation was carried out by the same crew (*Gobashy et al., 2023*).

In summary, the results of these previous studies suggest that the UG region is characterised by a variety of rock types, including Nile alluvium, wadi alluvium, wind-blown sands, and additional superficial deposits that date from the Pleistocene to the Quaternary periods (*El-Ramly, 1973; Hunting Geology and Geophysics Ltd., 1967*). The Old Gold Mine at UG is situated at the edges or contacts of various magnetised bodies, as confirmed by structural elements that align with reduced-to-pole (RTP), analytic signal (AS), normalised source strength (NSS), and tilt angle (TA) maps. The most prevalent direction for these contacts is NE–SW. Aeromagnetic interpretations also highlight NW–SE and W–E regional trends. The interpreted magnetic trends are N35E and N40W, with a dextral fault type, and the W–E trend.

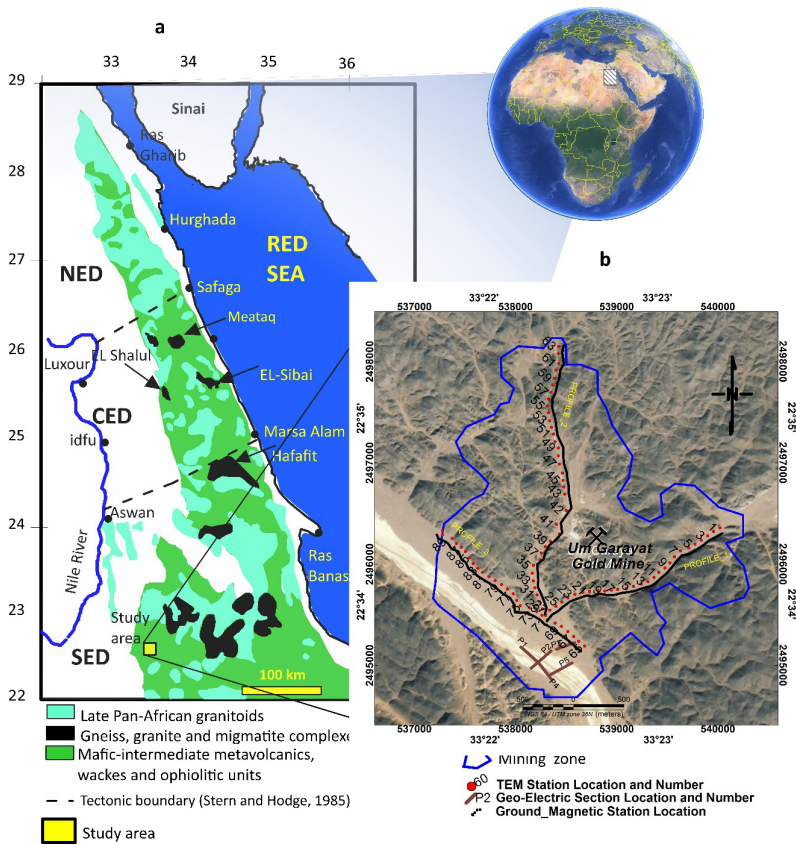


Fig. 1. a) A location map of the study area and the Nubian Shield. b) A Google Earth map of the Um Garayat region, indicating the locations of geophysical surveys. This area is situated in the Southeastern Desert of Egypt.

The transient electromagnetic method (TEM), in particular, has become increasingly popular for geophysical exploration of groundwater, mineral exploration, and general geological mapping purposes (Nabighian, 1979; Masoud et al., 2014). Using this method, it is possible to measure the electrical resistivity of subsurface layers to a depth of several hundred metres.

The TEM method is particularly effective for mineral investigations. According to Maxwell’s equations, it operates on the principle that a time-varying magnetic field, known as the primary field, induces an electrical current in the surrounding conductive materials, such as the ground. The

resulting electrical and magnetic fields, referred to as secondary fields, influence the electrical conductivity of the subsurface layers. Conversely, DC electric resistivity was employed to assess subsurface resistivity and the distribution of mineral targets (*Ali et al., 2023*). Induced polarisation (IP) is an appropriate geophysical technique for identifying semi-conductive or conductive minerals within a matrix of high electrical resistivity, such as host rocks (*Ali et al., 2020*). Because of this, IP tomography is especially helpful in locating and defining sulphide deposits. By measuring resistivity and chargeability, we can accurately distinguish between the mineral deposit composition of rocks (*Pelton et al., 1978*). Similarly, geological structures and other subsurface geological features essential to mineral exploration can be found using magnetic data. It can also identify supra-basement features, determine the thickness of the sedimentary cover, and map out potential sites for buried igneous deposits.

Magnetic methods have proven effective in the exploration of oil and the assessment of geothermal and groundwater resources. Common applications include basin modelling, analysis of seafloor structural geometry (*Hamouda et al., 2021*), Geological hazard assessment (*Arafa et al., 2021*), examination of tectonic structures, and the identification of intra-basement faults and uplifts (*Abdelazeem et al., 2013; 2021; Al-Garni and Gobashy, 2010; El-Sawy et al., 2018*). Additionally, these methods are applicable in mineral exploration (*Abdelwahed et al., 2024; EldougDoug et al., 2023; Abdelhalim et al., 2020; Abdelazeem et al., 2019; Abdelrahman et al., 2019; Groves et al., 1984; Gobashy et al., 2022; Gobashy et al., 2021; Rehman et al., 2019*), as they can effectively reveal subsurface concentrations of mineralised zones through magnetic susceptibilities, including gold, thereby enhancing opportunities for gold exploration and providing a three-dimensional perspective to the exploration process.

To validate the findings related to the aeromagnetic and radiometric signatures indicative of gold distribution and mineralised zones within the study area (*Gobashy et al., 2024*), a comprehensive approach has been undertaken. This includes the establishment of five geoelectric sections, the execution of ninety transient electromagnetic measurements (TEM) soundings, and the implementation of an extensive land magnetic survey across an area of approximately $3 \times 3 \text{ km}^2$ surrounding the historical underground gold mine in the current phase of the investigation. Additionally, remote

sensing techniques have been employed and integrated with the gathered results. It is important to note that while interpreting favourable mineral exploration zones, the results from remote sensing are primarily reflective of the rock surface (in the centimetre range), whereas the interpretations from land magnetic and electrical resistivity tomography (ERT) pertain to medium to deep depths, particularly in areas exhibiting high chargeability and low resistivity. Conversely, the TEM interpretation results are associated with deeper geological layers.

2. Topography and geologic setting

The geomorphological characteristics of the study area reveal a range of topographic features, from low to moderate and high elevations (Fig. 2). The landscape is marked by both steep and gentle slopes, showcasing highly

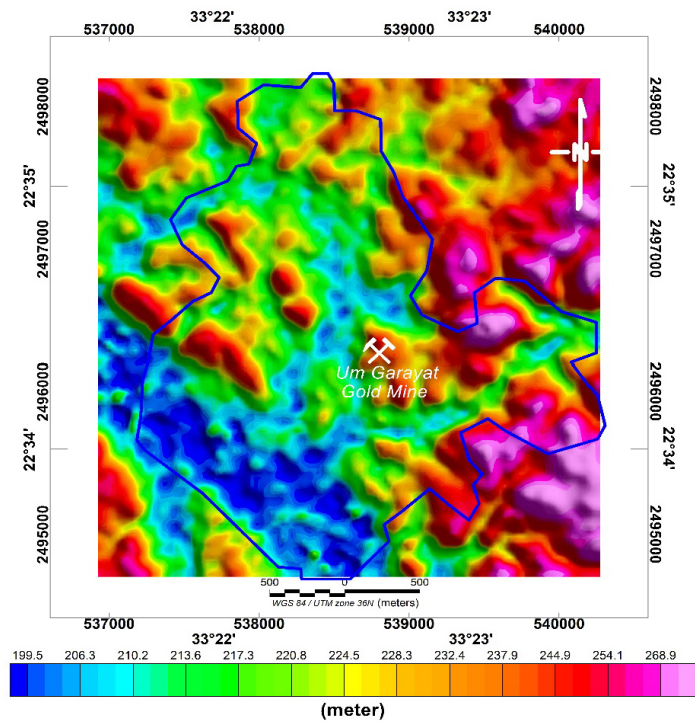


Fig. 2. A 30 m resolution DEM of the study area (NASA JPL, 2013).

weathered surfaces. The region is frequently dotted with wind-blown sand terrains, dunes, and playa deposits. The wadis align with the predominant structural trends, and the primary drainage pattern is dendritic, with flow directed northward. Notable wadis in the vicinity include UG and Allaqi, alongside prominent mountains such as Gebel UG, which rises to 250 metres. The topography of the region exhibits a range of elevation changes from 185 to 300 metres above sea level, indicating a generally low-relief topography. Accessibility is facilitated by the Aswan Asphaltic Road. The exposed geological formations at the UG gold mine site consist of Neoproterozoic metavolcanic, metagabbro rocks, and metasedimentary rocks. The metasedimentary rocks feature metamudstone and graphite schist, with many quartz veins and veinlets creating a stockwork that traverses the graphite schist. The metavolcanic rocks include meta-andesitic tuffs, meta-andesite, meta-rhyolitic tuffs, and meta-rhyolites (Fig. 3).

Andesitic, dioritic, and trachytic dykes, along with various quartz veins, veinlets, and lenses, have intruded these rocks. The petrography of these

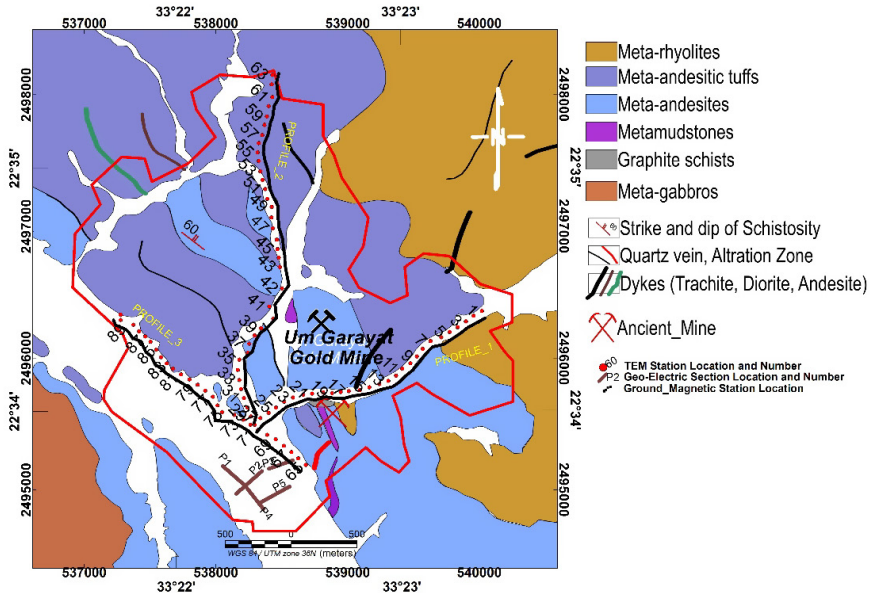


Fig. 3. Geologic map of the study area, guided by (Oweiss and Khalid, 1991). Redrawn using (Geosoft Oasis Montaj, 2015a). The map shows the locations of the measured TEM stations, land magnetic stations, and ERT profiles P1 to P5.

rocks was examined by *Sabet et al. (1983)*, *Oweiss and Khalid (1991)*, and *Ivanov (1988)*. Generally, the Wadi Allaqi volcanics consist of intermediate to mafic rock types, including basaltic andesite, andesite, and dacite. From a geochemical standpoint, the rocks display an intermediate composition, transitioning from low-K tholeiite to calc-alkaline, which suggests a continental arc or margin setting. The volcanic materials have experienced low-grade metamorphism characteristic of the greenschist facies, further influenced by considerable hydrothermal alterations (*El-Nisr, 1997*). Geologically, the UG mineralisation is restricted to a network of quartz veins, veinlets, lenses, and the corresponding hydrothermal alteration zones of the wall rock. This system of auriferous quartz veins trends from northwest to north-northeast, with a steep dip toward the east, extending approximately 4 km in parallel zones that vary in thickness, reaching up to 1.8 m (*Sabet et al., 1983; Ivanov, 1988*).

The mineralisation process began with the intrusion of andesite–granodiorite porphyry in a subvolcanic environment. The parent magma, which exhibited an intermediate to acidic composition, was particularly rich in volatile components. The adjacent country rocks experienced regional propylitisation, aligning with the greenschist metamorphic facies (*Beane and Titley, 1981*). This propylitisation resulted in the complete alteration of mafic minerals into chlorite, magnetite, hematite, pyrite, sphene, rutile, calcite, epidote, and anatase, stemming from the auto-hydration of the later magmatic phase. This transformation suggests a magma composition that was high in H₂O and CO₂ but low in sulfur. The hydrothermal activity progressed through three distinct phases. The first phase was marked by high-temperature silicification I and pyrophyllitization, which involved the leaching of alkalis and the formation of quartz lenses containing apatite, tourmaline, and calcite, alongside minor occurrences of pyrite, pyrrhotite, and chalcopyrite within milky quartz veins. This was succeeded by alkali metasomatism, characterised by extensive sericitisation. The second phase saw the development of silicification II and significant pyritisation, resulting in large metasomatic quartz bodies and further sericitisation, which included abundant orthoclase, albite, and minimal hydrobiotite. Small amounts of native gold, Au-tellurides, and proustite were detected within quartz veins situated in the southern adits region. The third phase, referred to as low-temperature silicification III, was distinguished by quartz veins abundant in

native gold, Au-tellurides, silver minerals, and a limited presence of pyrite, along with the development of calcite and pyrophyllite. This phase also witnessed alunitization and kaolinitization, with their precipitation extending into the supergene stage.

During this supergene stage, covellite and chalcocite were formed, while nearly all sulfides, especially pyrite, underwent a transformation into widespread limonite (*Ivanov, 1988*). Additionally, impregnations of chalcopyrite, covellite, chalcocite, and pyrite were noted in areas adjacent to the auriferous zones. *Oweis and Khalid (1991)* carried out a detailed geochemical exploration of gold deposits at the ancient UG mine, including placer deposits and tailings left by previous miners. They reported that the gold content in silicification, limonitization and listvenite zones, accompanied by mineralised quartz, reached up to 7.2 g/t. Gold placer deposits have been recorded at concentrations up to 7 grams per ton, with an estimated total of 128 kilograms of gold anticipated to be found in the ancient tailings. The gold mineralisation observed in the southeastern desert is primarily associated with a quartz vein system that formed concurrently with granite-related tectonic activity along the original deformation shear zone, as documented by *El-Kazzaz and Taylor (2001)*. Furthermore, they emphasised that the metamorphic source of the gold-bearing fluids was characterised by the formation of veins along fractures within brittle-ductile shear zones. This indicates that the mineralising fluids were associated with the processes of deformation and metamorphism, rather than originating from an epithermal environment.

3. Remote sensing

Recent developments in space technology have established remote sensing (RS) as a powerful instrument for mineral exploration (*Bachri et al., 2019*). The increasing availability of observation satellites, which provide multi-temporal imagery with enhanced spatial and spectral resolutions, enables geoscientists to conduct spectral analyses that reveal valuable insights into the composition of rocks and minerals (*Mbianya et al., 2021*).

Mineral exploration has greatly benefited from ASTER satellite imagery, which includes nine spectral bands spanning the Visible Near Infra-Red (VNIR) and Short Wave Infra-Red (SWIR) regions. The advent of spectro-

photometers has revolutionised the field, providing the most advanced tools for acquiring accurate and comprehensive spectral data concerning rocks and minerals (Fowler *et al.*, 2020; Ghoneim *et al.*, 2021). Given that lineaments serve as potential pathways in mineral exploration, their mapping is employed as supplementary information to identify hydrothermal alterations associated with hydrothermal solutions (Mbianya *et al.*, 2021; Hung *et al.*, 2005). Consequently, the automatic detection of lineaments is facilitated through remote sensing data. With the Eastern Desert of Egypt being rich in minerals and ores (Salem *et al.*, 2014; Hassan *et al.*, 2017), the objective of the current remote sensing study is to pinpoint promising mineralisation sites in underground formations and to integrate these findings with existing TEM and magnetic data, ultimately producing a perspective map that highlights areas with a high likelihood of mineralisation.

4. RS Methodology

The lithological units and potentially mineralised alteration zones within the UG area and its vicinity have been identified by combining remote sensing data with field investigations, which serves as the methodological foundation for the current objectives of the study. Initially, previous research materials, including geological and topographic maps as well as reports pertinent to the area under examination, were collected. Subsequently, satellite data from the ASTER program was obtained from the USGS website (<https://earthexplorer.usgs.gov>, last accessed in August 2024).

The lithological units and zones of mineralised alteration in the underground area were delineated by employing ASTER satellite data processed with ENVI 5.3. The data underwent preprocessing to rectify errors, which also encompassed the mapping of alteration minerals, including iron oxides, pyrite, chlorite, and kaolinite. From ALLOSPALSAR DEM data, lineaments have been extracted to determine possible regions of mineralisation. The final lithological and alteration mapping data were validated by field research and GPS validation locations. Figure 4 demonstrates the workflow for the remote sensing analysis. In other words, the mineral exploration process involves different stages, starting with remote sensing data analysis and filters to make the first location choice; this is followed by airborne geophysics, if possible, then detailed ground geophysics in locations which

permit acquisition, and finally drilling, geochemical analysis, and evaluation estimates. This is a plausible workflow for the procedure of mining exploration.

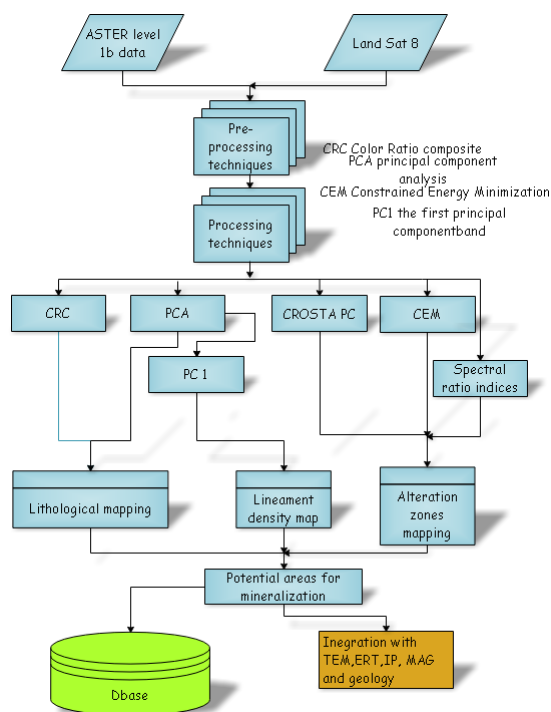


Fig. 4. The workflow followed to develop the processing sequence of the remote sensing analysis used in this study.

5. Lithological mapping

5.1. Colour ratio composites (CRC)

To extract relevant information from satellite data, this study used two main colour ratio composites. The first was the RGB composite of the ASTER ratio (4/7, 3/4, and 2/1), which is comparable to Landsat TM's Abram's ratio (Fig. 5a). The second was the RGB equivalent of the ASTER ratio composite (4/7, 4/1, and 2/3*4/3) for Landsat TM (Fig. 5b) (Sultan *et al.*, 1986). The findings made it possible to distinguish between several rock types in the research area.

5.2. Principal component analysis (PCA)

ASTER Principal Component Analysis (PCA) is a method employed to decrease the dimensionality of data sets, separate noise components, and yield

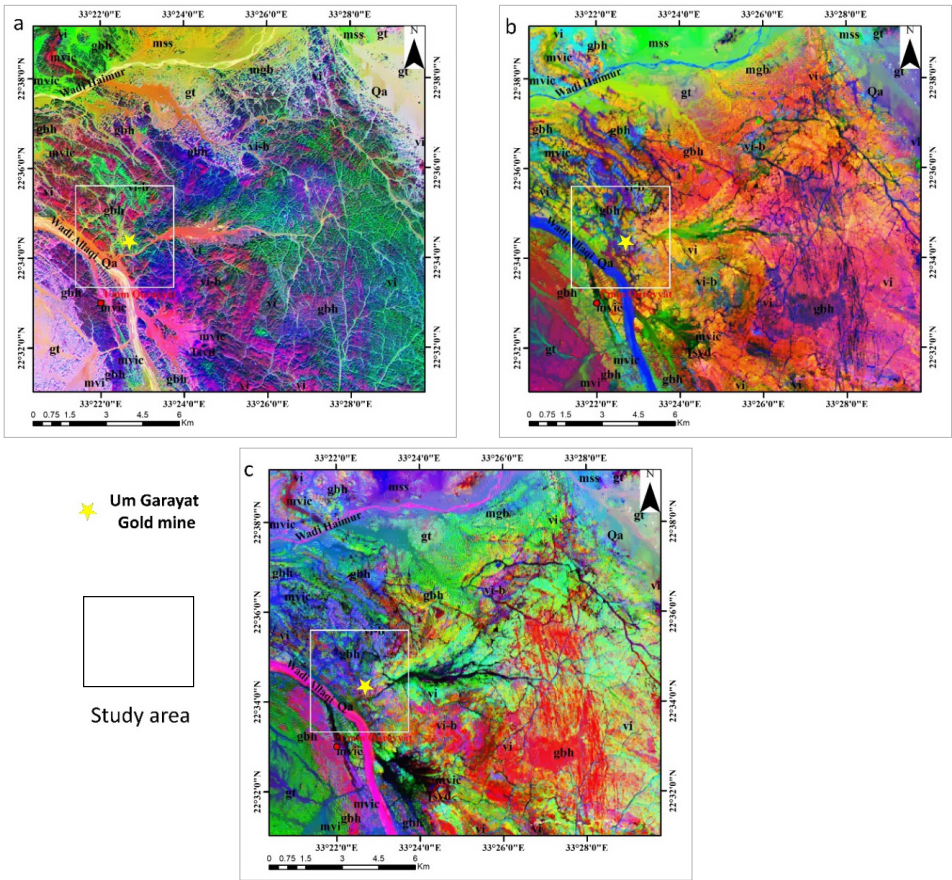


Fig. 5. a) the ASTER band ratio represented in RGB format using bands 4/7, 3/4, and 2/1 for the UG area indicated by the white box and its surrounding regions; b) the ASTER band ratio in RGB format utilising bands 4/7, 4/1, and the product of 2/3 and 4/3, as modified from the work of *Sultan et al. (1986)*; and c) the ASTER Principal Component Analysis displayed in RGB format with components PC5, PC4, and PC2. (gbbh): Gabbro-dolerite, (gt): Tonalite-granodiorite, (mgb): Coarse-grained hornblende + biotite quartz diorite, (mss): Sericite-metasedimentary schist (Umm Ashirah), mvi: Chlorite-rich intermediate volcanic schist, (mvic): Chlorite-rich intermediate volcanic schist, (Qa) Wadi deposits, (Tsvd): Altered dacitic subvolcanic with pyrite gold.

uncorrelated output bands (*Schowengerdt, 2007*). For improved differentiation between ophiolitic (gabbros and metabasalt) and metavolcanic rocks, three bands (PC5, PC4, and PC2) were chosen. To discern minute variations among the rock units under investigation, the ASTER PC combinations PC5, PC4, and PC2 were employed in this investigation. Rock units were successfully distinguished using the lithological mapping technique, which also revealed variations in tone and colour. The results demonstrated the effectiveness of Aster data and methodologies in delineating lithological units within analogous arid and semi-arid regions, showing a strong correlation with existing geological maps (Fig. 5c).

6. Alteration mapping using ASTER data

6.1. Preprocessing of the ASTER level 1T satellite image data

The preprocessing of satellite imagery was conducted to extract surface reflectance data and to achieve geometric registration. Various methodologies were utilised, including Spectral Ratio Indices (SRI), Crósta Principal Component Analysis (CPCA), and Constrained Energy Minimisation (CEM), which effectively identify zones associated with mineralisation through the detection of specific alteration minerals. In arid and semi-arid environments, these processing methods have proven to be highly effective for the mapping of lithology and alteration (e.g., *Abrams et al., 1983; Ghoneim et al., 2021; Crósta et al., 2003; Ninomiya, 2003; Van der Meer et al., 2012; Ghoneim et al., 2022*).

6.2. Spectral Ratio Indices (SRI)

Hydrothermal alteration minerals can be identified through geological mapping techniques that utilise band ratios and spectral ratio indices, as noted by *Abou El-Magd et al. (2015)*. Additionally, other ratio indices, including the OHI and KLI proposed by *Ninomiya (2003)*, as well as the Iron Oxides Index introduced by *Hewson et al. (2001)*, have been suggested for similar applications. The supplementary material includes Table S1, which presents the ratio indices of various alteration minerals derived from Aster imagery. The results reveal a correlation between iron oxides, kaolinite, and the Biotite-epidote-chlorite-amphibole index with felsic rocks, particu-

larly in the highlighted regions. Field observations further substantiate the presence of alteration zones within these specified areas (Fig. 6a).

6.3. Constrained Energy Minimisation (CEM)

One highly effective mapping strategy is the CEM technique, which minimises the influence of all other features by categorising them as unknown backgrounds, while enhancing the response of the target spectrum. By utilising the ASTER VNIR-SWIR surface reflectance data, we successfully identified the distribution of six alteration minerals, such as alunite, kaolinite, and montmorillonite, among others (Fig. 6b). This technique requires two essential inputs: the reference spectra obtained from the spectral analysis of the alteration minerals and the surface reflectance data sourced from satellite imagery.

6.4. Crósta Principal Components Analysis (CPCA)

Principal Component Analysis (PCA) serves as a method for eliminating redundancy and noise within datasets, leading to the generation of uncorrelated spectral bands (Crósta *et al.*, 2003). The Crósta approach focuses on analysing eigenvectors to discern the contributions of the original bands, thereby selecting particular principal components that effectively showcase the desired features. This methodology was applied in the context of mineral exploration utilising Landsat 8 data. In the case of iron oxide minerals, band-2 exhibited a positive eigenvalue of 0.41855, while band-3 displayed a negative loading of -0.74426 , which signifies a high contrast and effective enhancement for ferric iron detection.

The present work emphasises the significance of hydroxyl-bearing minerals by utilising OLI bands 6, 7, 5, and 4, which exhibit a strong spectral sensitivity to hydroxyls. Principal Component Analysis (PCA) 3 was selected to effectively showcase various hydroxyls, carbonates, and clay minerals, demonstrating a clear representation of these components. To delineate mineralised areas in gold mining, both the F + H image and Crósta's alteration false-composite image were employed. The Crósta image illustrates zones influenced by hydroxyl and iron oxides, utilising white, creamy, and bright tones to indicate the most probable mineralised regions, characterised by the highest Digital Number (DN) values. In contrast, yellow-brown

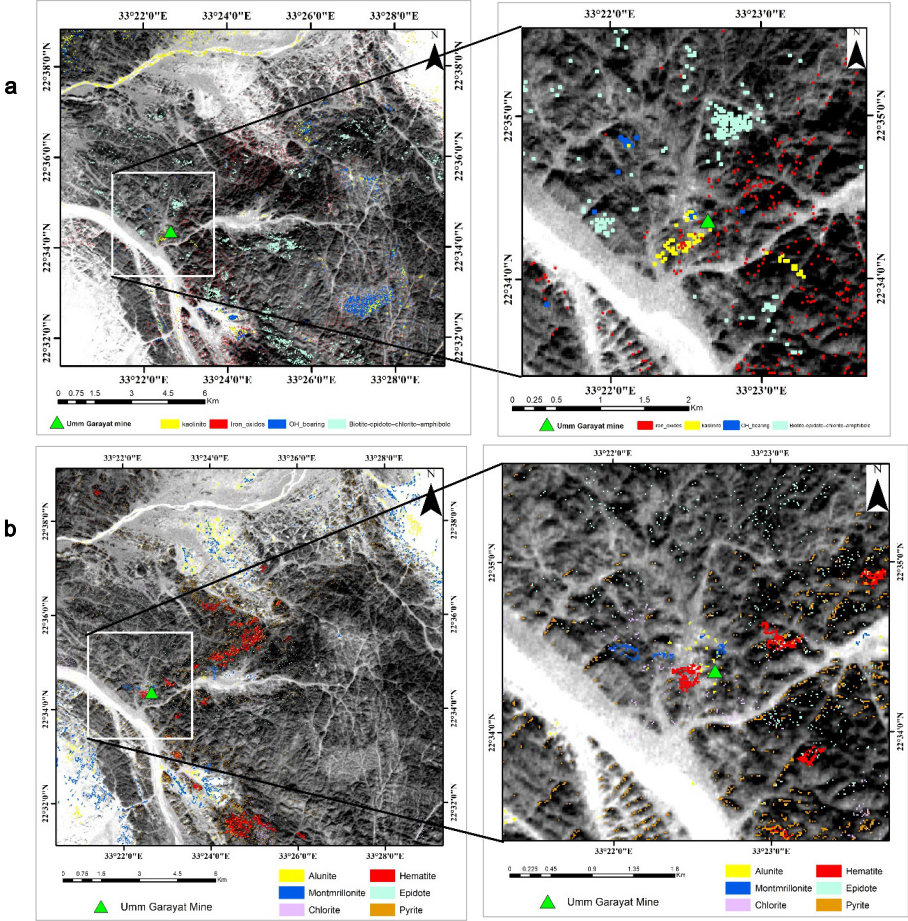


Fig. 6. a) Alteration of minerals distribution over the UG and its surroundings using the spectral ratio indices method. The right figure is a zoom-in on the UG mine area. b) Alteration of mineral distribution over the study area using the CEM technique overlying ASTER band 3. The right figure is a zoom-in on the UG mine area.

shades were applied to highlight areas rich in hydroxyls, while blue and cyan tones were used to signify zones abundant in iron oxides. The Crósta method exhibited a strong correlation with the band-ratio technique, revealing that gold mining activities were located over the identified alteration zones, thereby validating the efficacy of these methodologies and uncovering new potential sites for mineralisation (Fig. 7a).

6.5. Automatic lineament extraction

The initial Principal Component band (PC1) is recognised as the most effective for the automatic extraction of lineaments, as noted by *Burdick and Speirer (1980)* and *Baumgartner et al. (1999)*, with its accuracy significantly influenced by the spatial resolution of the imagery. The process of automatic lineament extraction was evaluated using the LINE module in PCI Geomatica, which employs techniques such as edge detection, thresholding, and linear processing, utilising ASTER VNIR-SWIR spectral bands alongside Principal Component bands. Lineaments are further examined using linear density maps, derived from the count of lines per unit area or their total length, as described by *Zakir et al. (1999)*. In this study, we employed ArcGIS 10.3 to compute lineament density automatically. The resulting map was incorporated into a lineament contour map, where increased densities suggest a greater potential for mineralisation in the associated rocks (Fig. 7b). By analysing the overlap between regions of high lineament density and significant alterations, we can identify the most promising areas for mineralisation. Subsequently, the final alteration map was combined with a lithological map obtained through remote sensing, highlighting regions with the highest likelihood of mineralisation (Fig. 7c).

7. Geophysical methodology and data acquisition

Four geophysical exploration techniques—electric resistivity, electromagnetic, induced polarisation (IP), and land magnetic surveys—have been employed to identify mineralised zones and assess the characteristics of ore deposits, including their size, depth, and thickness, within the underground (UG) region. The subsequent paragraphs will provide a concise overview of the methods utilised, the data sets collected, the instruments used for measurement, and the analysis of the data obtained.

To achieve an acceptable resolution for both shallow and deep layers, electric resistivity and induced polarisation-derived chargeability imaging data were collected along five profiles (P1 to P5, as illustrated in Fig. 3) utilising a dipole-dipole configuration with electrode spacings of 5, 10, 15, and 20 metres, and a total profile length of 155 metres. The Syscal-R2 instrument is used for the resistivity measurements. Subsurface structures

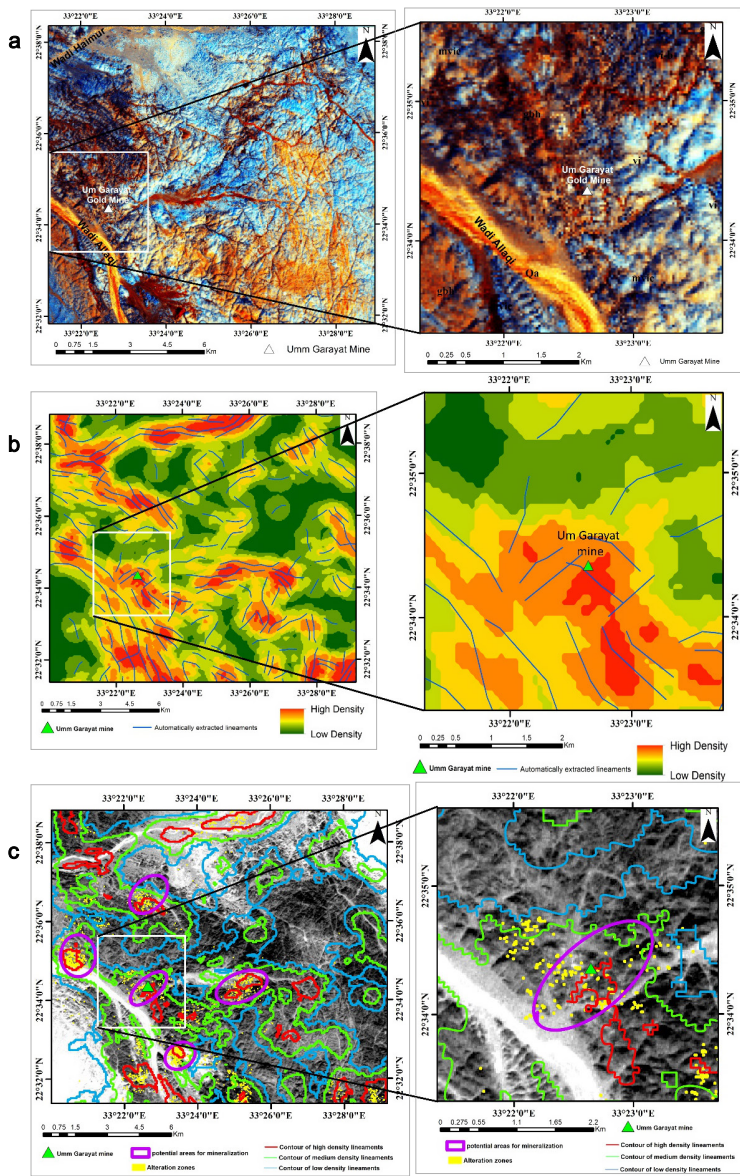


Fig. 7. a) Crósta alteration image of H, H + Fe, and Fe. The right figure is a zoom-in to the UG mine area, b) Lineament density map. The right panel is a zoom-in on the UG mine area, and c) Expected potential locations for gold mineralisation and alteration zones.

are delineated using electrical resistivity measurements at the surface, employing the tomographic inversion technique known as electrical resistivity tomography (ERT). This technique is based on the concept that various materials display distinct electrical resistivities (ER). By introducing electrical current into the ground through two current electrodes, designated A and B, and subsequently measuring the potential difference between two potential electrodes, labelled M and N, it becomes possible to create a map of the subsurface electrical resistivity distribution. The information gathered from these electrical resistivity surveys is referred to as apparent resistivity ρ_a , which indicates the heterogeneous and anisotropic characteristics of the subsurface environment. The determination of apparent resistivity can be executed using Eq. (1):

$$\rho_a = g \frac{V}{I}, \quad (1)$$

where, V = potential difference; I = applied current; ρ_a = apparent resistivity of the medium; g = geometrical factor that depends on the electrode array.

When two electrodes are disconnected from a direct current source, a phenomenon known as induced polarisation (IP) takes place, characterised by a gradual decline in voltage until it ultimately reaches zero. This observation indicates that the rocks possess an inherent charge. In the context of IP surveys, a configuration involving two electrodes for injecting electrical current and two non-polarisable electrodes for measuring the resultant difference in electrical potential is employed. The quantification of this phenomenon can be achieved through the analysis of voltage decay in various domains, including the time domain, frequency domain-induced polarisation, or spectral-induced polarisation. In the time domain IP method, the chargeability value obtained from IP measurements is calculated by integrating the decay curve of the IP response. Chargeability is defined as the ratio of the primary voltage, which exists under steady-state conditions during current injection, to the secondary voltage (*Madsen, 2019*), as represented in Eq. (2):

$$M = \frac{V_{IP}}{V_{DC}}, \quad (2)$$

where, M = chargeability; V_{IP} = secondary potential; V_{DC} = initial potential.

The transient electromagnetic (TEM) technique, also referred to as time-domain electromagnetic (TDEM) or pulse electromagnetic (PEM), is a widely utilised non-invasive geophysical approach for acquiring data on subsurface resistivity and conductivity. Comprehensive information regarding the theoretical framework and various applications of TDEM can be found in the works of *Nabighian (1979)*, *Massoud et al. (2014)*, *McNeill (1990)*, *Ward and Hohmann (1987)*, and *Pellerin and Alumbaugh (1997)*. TEM data were gathered at designated stations along three profiles, as illustrated in Fig. 3, which encompass Wadi UG and its adjacent areas, with the arrangement based on the elevation of the ground surface. The measurements were taken with a station-to-station spacing of 5 to 20 metres, ensuring sufficient proximity to identify minor anomalies. Additionally, the positions, elevations, and timing of the measurements were meticulously recorded using GPS technology.

The TEM technique functions based on the principles of electromagnetic induction. When direct current (DC) flows through a closed loop situated on the ground surface, it creates a magnetic field referred to as the primary field. Upon the abrupt cessation of DC, eddy currents are generated within the conductors located beneath the surface. The variations in these currents, along with the surrounding magnetic field—referred to as the secondary field—are indicative of the electrical conductivity of the underlying geological layers. The fundamental terminology and concepts are illustrated in Fig. 8. For ground-based systems, typical measurement parameters include an on-time of 1 to 20 milliseconds, a turn-off ramp of 1 to 30 microseconds, and an off-time of 1 to 20 milliseconds for data acquisition. The waveform produced is commonly identified as a square waveform. Data is collected within decay-time windows, often termed gates, which are structured with logarithmically increasing widths to enhance the signal-to-noise (S/N) ratio, particularly during later time intervals.

The recorded impulse response indicates that the induced electromotive force is directly related to the time derivative of the magnetic flux passing through the coil. Following this, the impulse response, denoted as db/dt , is depicted for different resistivities in a half-space configuration.

Electromagnetic noise can arise from a variety of sources, including natural phenomena such as lightning, as well as artificial sources like power supply cables and other electrical installations. To enhance the transmit-

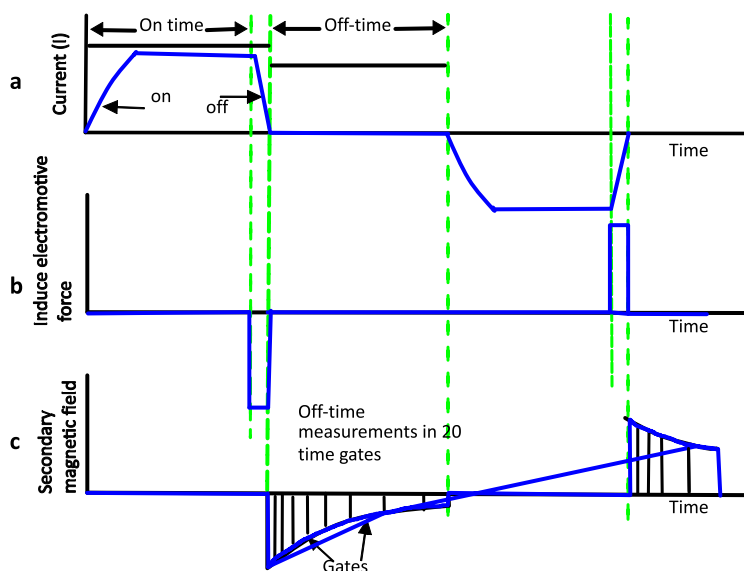


Fig. 8. The essential terminology and concepts related to the TEM method: a) the current flows through the transmitter loop; b) the electromotive force generated within the ground is a critical aspect; c) the secondary magnetic field, which is captured by the receiver coil, plays a significant role. In the graphical representations illustrating the induced electromotive force and the secondary magnetic field, it is assumed that the receiver coil is located at the centre of the transmitter loop, as modified from the work of *Massoud et al. (2014)*.

ted moment and increase decay times, it is beneficial to repeat and stack measurements, which helps to reduce background noise and improve the signal-to-noise ratio. An effective transient electromagnetic (TEM) survey may involve the collection of between 1,000 and 10,000 individual transients. In this study, the SIROTEM MK3 instrument (*Geo Instruments, 1998*) was employed to gather time-domain electromagnetic (TDEM) data across 90 stations, utilising a single loop with side lengths of 25 metres. The TEM data points were strategically placed along three profiles in areas where further electrical resistivity (ER) data could not be obtained due to inadequate electrode-to-ground contact.

To create a sustainable prospecting opportunity map, it is essential to combine findings from remote sensing (RS), induced polarisation (IP), electromagnetic (ER), and transient electromagnetic (TEM) methods with mag-

netic exploration data of mineral deposits and the magnetic characteristics associated with hydrothermal alteration zones.

On the other hand, magnetic methods have emerged as a fundamental approach in the field of mineral exploration and the identification of structural features. Numerous researchers have utilised magnetic and various geophysical techniques to facilitate mineral exploration, as evidenced by the works of *Abdelazeem et al. (2013)*, *Groves et al. (1984)*, *Rehman et al. (2019)*, *Salem et al. (2014)*, *Gobashy et al. (2020)*, and *Mekkawi et al. (2021)*.

The land magnetic profiles are recorded along the same lines as the TEM stations, employing the GEM Overhauser Magnetometer system (<https://www.gemsys.ca/rugged-overhauser-magnetometer/>, last seen 27 October 2024). Measurements were conducted along the designated profiles with a station interval ranging from 5 to 20 metres, determined by the topographical conditions. This spacing was strategically selected to account for potential source anomalies. The data acquisition involved two magnetometers: one stationed at a fixed base and the other traversing the measurement locations. A GPS device was utilised to log the coordinates, elevation, and timing of measurements whenever feasible; however, in areas with challenging terrain where GPS signals were unavailable, manual measurements were employed.

8. Data processing and analysis

TEM data were processed through inversion utilising one-dimensional earth models provided by *Zond Geophysical Software (2020)*. A range of parameters, such as the quantity and thickness of geological strata, was examined to determine the most precise model that reduced error, attained optimal fitting, and closely corresponded with the geological data. These individual models were subsequently compiled to create three geo-resistivity cross-sections along designated profiles (1, 2, and 3), with their respective locations illustrated in Fig. 3. Examples of the resulting models can be found in Fig. S1 within the supplementary material, while the final cross-sections are presented in Fig. 9a to e.

The acquired ER/IP field data underwent processing and inversion through the RES2DINV software (*Loke, 2010*). The resistivity and chargeability sections derived from this data inversion are depicted in Fig. 9.

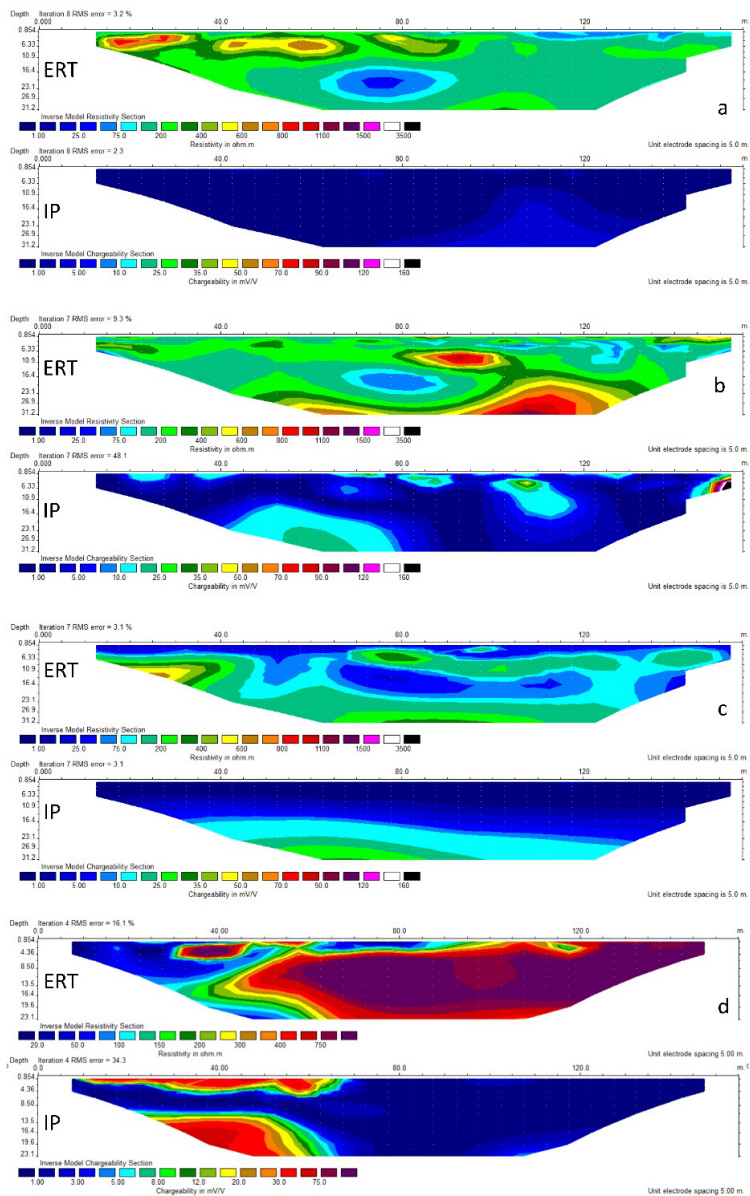


Fig. 9. Inverted geoelectric sections for profiles P1 to P5 (a to e, respectively). The upper panel represents the electric resistivity tomography, and the lower panel represents the IP inversion results.

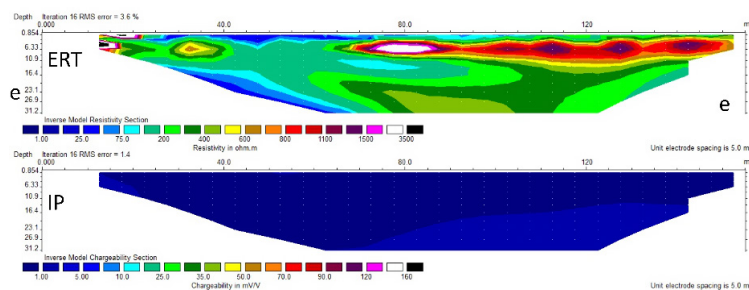


Fig. 9. Continuation from the previous page.

9. Data interpretation

9.1. Magnetic measurements

Basement rocks are considered the main contributors to magnetic sources, leading to local magnetic disturbances, or short-wavelength anomalies, that overlay the regional magnetic field characterised by long-wavelength anomalies within the RTP anomaly. These disturbances are likely associated with fault structures in the basement, as evidenced by variations in magnetic relief between adjacent magnetic highs and lows, which suggest differences in concentration. Areas exhibiting significant horizontal magnetic gradients are presumed to correspond to the locations of fault planes.

Gobashy et al. (2023) conducted a comprehensive land magnetic survey within the designated study area, revealing that shallow magnetic sources typically exhibit an average depth of approximately 20 metres, while intermediate magnetic sources are found at an average depth of around 70 metres. In the current study, only those profiles that overlap with the Transient Electromagnetic (TEM) survey are utilised for comparative analysis with the geoelectric and TEM findings. To efficiently identify the mineralised zones characterised by high magnetic susceptibility, the 2D analytical signal technique, as described by *Roest et al. (1992)*, was employed. The peaks of the analytic signal are generally situated above the causative magnetic contacts, such as dykes and veins, as noted by *Roest et al. (1992)*.

Tilt derivative (TDR) anomalies are particularly beneficial as they exhibit a zero value at or near fault lines or contacts, thereby facilitating the identification of these geological features. Consequently, magnetic anomaly

profiles, which are derived from ground-measured data and processed using Reduced to Pole (RTP), TDR, and Analytical Signal (AS) methods, have been illustrated in the upper section of Figs. 10, S2, and S3 found in the supplementary material. These profiles serve as a valuable resource for detecting fault locations, specifically at inflexion points of RTP, zero values of TDR, and peak values of AS. For detailed methodologies regarding TDR calculations, readers are directed to the work of *Salem et al. (2008)*. The generation of RTP, AS, and TDR maps was accomplished utilising Oasis Montaj software version 8.4 (*Geosoft Oasis Montaj, 2015b*).

9.2. Geoelectric cross-sections

Five measured geoelectric sections are shown in Fig. 3. Geoelectric profiles 2, 3 and 5 are directed NE–SW perpendicular to the wadi direction, while profiles 1 and 4 are directed NW–SE along the wadi pattern, all with flat topography, 155 m in length and reaching up to 22 m depth of investigation. As shown in Fig. 9, the upper panel shows the resistivity inverted section as interpreted from the VES's measurements, while the lower panel shows the chargeability inverted section as interpreted from the Induced polarisation (IP) measurements. The resistivity measurements across the profiles exhibit a range from approximately 20 to 1000 Ohm.m, while the chargeability values fluctuate between 1 and 100 mV/V. Geologically, the wadi includes Nile alluvium, wadi alluvium, wind-blown sands, and a range of other superficial deposits that originate from the Pleistocene to the Quaternary period, as noted by *El-Ramly (1973)* and *Hunting Geology and Geophysics Ltd. (1967)*. The measured geoelectric sections show three zones, a wadi deposits layer of moderate to high resistivity values (300 to 900 Ohm.m) that is underlain by a moderate to low resistivity layer of (Dry alluvium) (50 to 200 Ohm.m) that may contain groundwater or surface water (Wet alluvium) that lower its overall resistivity to (10 Ohm.m) and a very high resistivity zone (> 1500 Ohm.m) characterises basement rock.

Mineral ore deposits may be detected through the examination of ground zones that display characteristics of low resistivity coupled with elevated chargeability values. Interpreted geoelectric sections show that chargeable zones appear at profiles 3 (30 mV/V) and 4 (75 mV/V). Both profiles pass with a fault plane interpreted from ground magnetic measurements, as seen on the remote sensing-derived lineament map and confirmed by site geology.

The mineralised zone is recognised at a depth of 10 m. It extends deeper, as TEM's interpreted low-resistivity zone can be detected at depths of approximately 70 to 100 m. This is observed especially at fault zones. Not all interpreted geoelectric sections show mineralised zones; this may be due to the shallow investigation depth of the measured profiles and the thick sedimentary section to the basement rock in wadies.

9.3. TEM data

TEM VESs are measured for field complications in flat wadi areas. Inverted TEM data results were used to construct three geo-electromagnetic resistivity sections.

Geo-electromagnetic resistivity profiles are directed (NE–SW with an overall length of about 2000 m) (no. 1), (S–N of about 2700 m length) (no. 2) and (SE–NW of 1850 m length) (no. 3) along the wadi pattern, approximately as shown in Fig. 3. A maximum investigation depth of 100m to the last interpreted layer is considered. 10 layers were distinguished of 700, 500, 200, 50, 3, 0.9, 10, 250, 2500, and 6000 Ohm.m as an average resistivity from top to bottom. Interpreted TEM geo-electromagnetic sections show a sedimentary section of 60 to 90 m thickness and depth to the basement rock surface.

Integrated magnetic and TEM interpretation results show some indicated faults as the mentioned criteria (regarding the surface of last high resistivity bed “Basement assumed”) at or between stations (5/7), (24/26), (33/34), (42/43), (46/47), (57/59), (64) and (67/69), (29/30), (53/54), (70) and (79/80) as seen in the lower panel of Figs. 10 (and S2, and S3 in the supplementary material). Not all TEM-recorded faults or variation zones are associated with magnetic anomalies, and not all magnetic anomalies are associated with TEM-recorded faults.

Some facts should be stated to understand the complex situation of integrated interpretation of geophysical data, and could explain the statement “Not all TEM-recorded faults or variation zones are associated with magnetic anomalies, and not all magnetic anomalies are associated with TEM-recorded faults or variation zones.”, as follows:

A clear TEM-interpreted low resistivity zone with a deep depth relative to basement surface is not reflected on ground geomagnetic profile measurement could be due to many reasons as the case at station TEM-VES(25), as

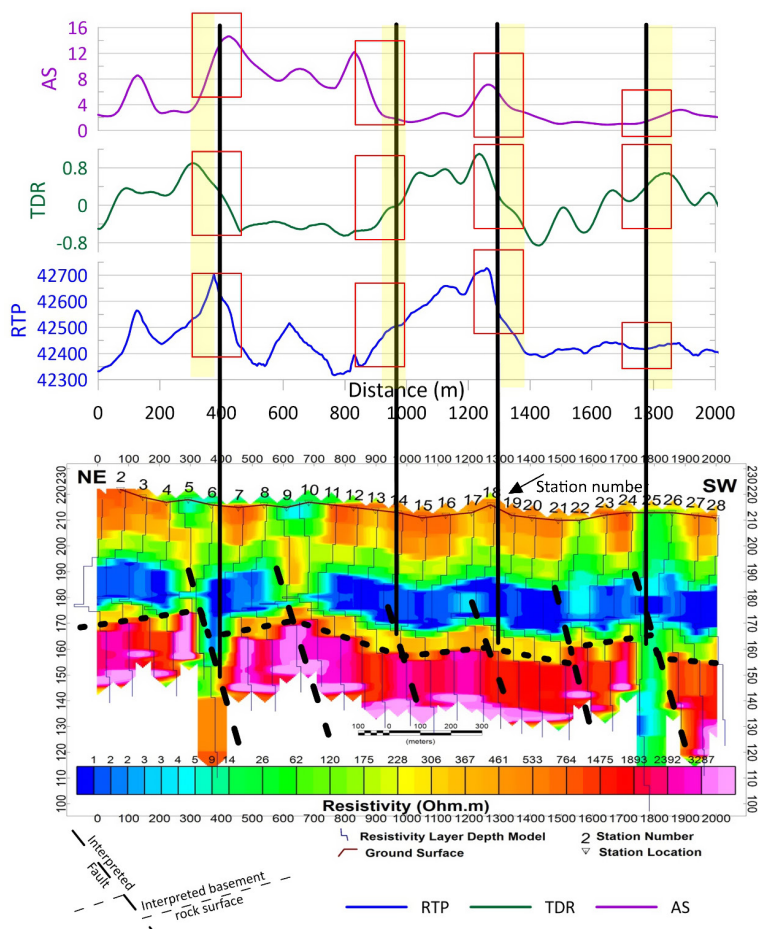


Fig. 10. Constructed geoelectric section no. 1 (lower panel) from inverted TEM measurements, the vertical scale is exaggerated; the upper panel shows the magnetic RTP signal, TDR, and AS. Red boxes mark the anomalies that show possible mineralisation.

the TEM low resistivity zone is associated with a fault that is not reflected on measured magnetic profile because the magnetic profile is not perpendicular but parallel to the anomaly and pass with the flank of the low part, also we should take into account that magnetic measurements made in the exposed basement is very sensitive to small distances of exposed magnetic source rock as governed by the inverse square law of distance for the magnetic field.

In addition to the fact that TEM-interpreted resistivity results are apparent (averaged) measurements and represent a projected circle of a cone that is proportional to the depth, which means at a depth of 50 to 70 m, the resistivity is of a circle with its centre below the TEM VES. However, its radius may be approximately 50 m.

A measured TMI field at earth's surface usually has less than 10 m and may reach a sub-meter station separation which is a very detailed profiling compared to a TEM VES station separation of 25 m in our case in addition to the uniform smooth apparent effect increase with depth, so TMI profile may be smoothed or averaged to be utilised in integration with TEM VES results, in addition to other parameters of TMI interpretation as width and amplitude of magnetic anomaly that should be taken into account in qualitative interpretation.

A lot of TMI small anomalies are not due to faults but may be due to a change in concentration or presence of a small magnetic dyke, especially a vertical one within the host rock or a change in elevation of the same rock surface, these cases will not be reflected in TEM interpretation results as it is small in size, at shallow depth, at the surface and there is no fracture no thermal solution and no mineralisation enrichment.

- TEM (VES18) represents an example of TEM VES of no low resistivity zone at depth with a recorded magnetic anomaly, where the magnetic profile crosses the magnetic anomaly at an oblique angle (not perpendicular), and this causes the change of the anomaly shape and calculated TDR and AS.
- In the case of an inferred fault, usually, the thermal solutions do not invade the whole fault plane with the same intensity but instead prefer the easiest passage to reach the surface, and as a consequence, the mineralisation distribution along the fault plane is not uniform or the same (i.e. a clear magnetic anomaly but no Low resistivity anomalous zone as TEM-VES 66).
- The advantage of TEM VES is to show the low-resistivity zone at depth, and it is the interpreter's responsibility to interpret this low-resistivity zone as mineralisation or another type of zone.
- Mineralisation location might be associated with the edge of a magnetic step model or a downthrown instead of maxima of TMI anomaly, which

may explain the offset of a magnetic anomaly with respect to TEM VES low resistivity anomaly, as TEM-VES 68, 82 and 87.

- For all the above-mentioned possible reasons, it is preferred that magnetic and TEM interpretation be carried out on a 2D map constructed on a regular grid rather than on a profile to explore the direction of strike and dip direction of structures.

As integrated interpretation results show, there is a good correlation between the thickest conductive zone ($< 100 \text{ Ohm.m}$) interpreted from TEM and magnetic faults allocated and interpreted from detailed magnetic profiles of high RTP, positive TDR and AS peak values, low basement surface and moderate interpreted resistivity values, which are a favourable place for target (mineralised zone) deposits.

Excluding the areas within the Wadi that are covered by sediments, it is evident that approximately 90% of the mineralisation indicated by TEM is situated at the interfaces of various rock units or types. This observation highlights the intricate relationship between the diversity of rock types and mineralisation, as illustrated in Fig. 11c.

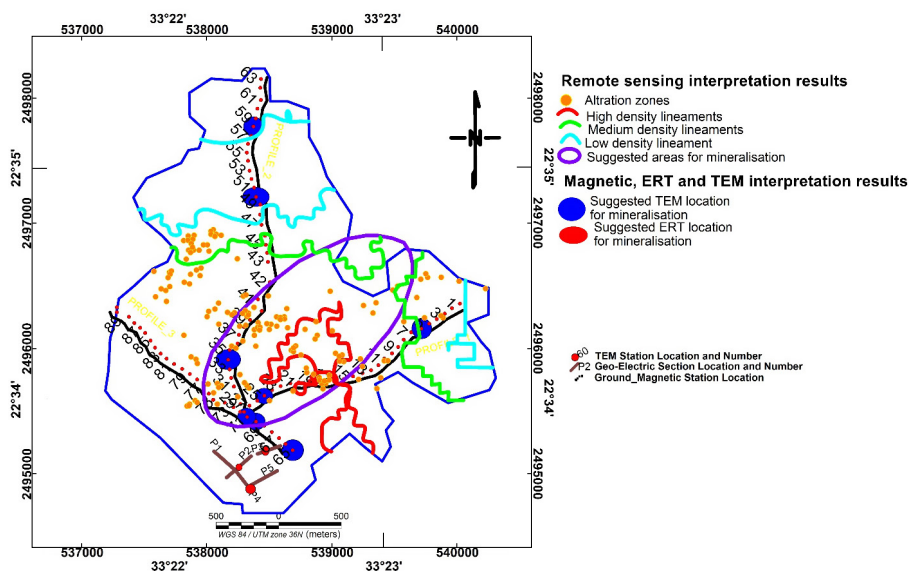


Fig. 11a. Suggested mineralisation zones in relation to RS interpretation, ERT profiles, TEM-VESs, magnetic locations and results in the study area.

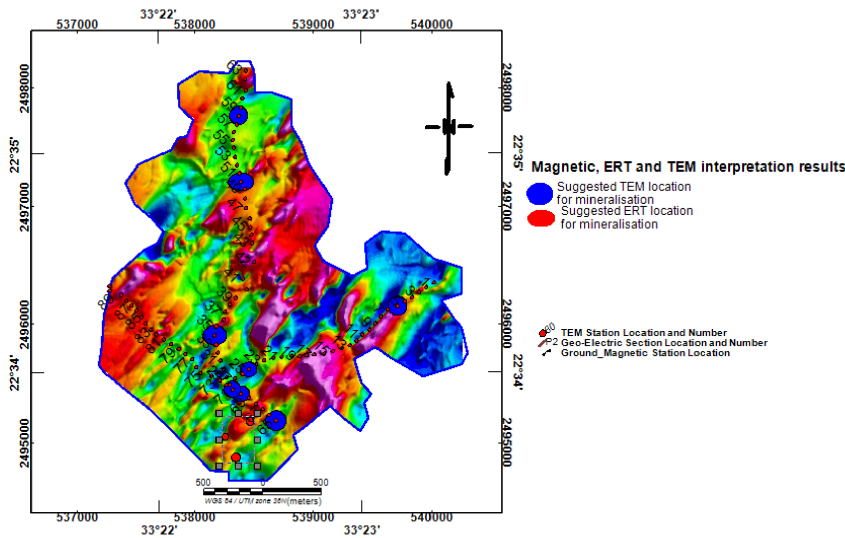


Fig. 11b. Suggested mineralisation zones and TEM stations, superimposed on the ground magnetic RTP map, *after (Gobashy et al., 2023)*, in the study area.

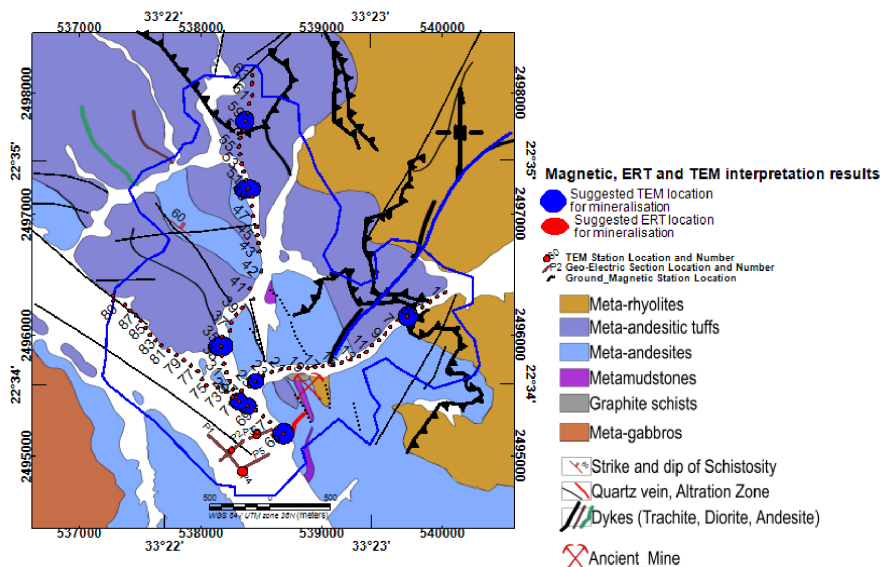


Fig. 11c. Suggested mineralisation zones and TEM-VES stations, and superimposed on the geologic map (*Geosoft Oasis Montaj, 2015a*) in the area of study.

Furthermore, there is a strong correlation between the locations suggested by ERT and the RTP magnetic anomalies, as depicted in Fig. 11b. The findings of this study are encapsulated in Fig. 11a, which outlines the potential sites of mineralisation derived from a comprehensive interpretation of the data.

Therefore, comparing all these results is not practically reasonable, but as shown in Fig. 7 remote sensing alteration zones and high lineament density (which are probable alteration zones) are distributed along large portions of the study area, suggesting ERT and TEM may coincide or not with remote sensing results (as they are at different depth ranges) but all confirm that the area is favourable for mineralisation and may need deep detailed ground study specially helicopter or drone EM exploration. Field geology validated the proposed location for mineralisation in the area.

10. Conclusions

- Mineral deposits in the South Eastern Desert are intricately associated with shear and fault zones, typically found in areas where both early and late geological structures overlap.
- For UG mineralisation, the depth of the mineralised zone ranges from 10 m to 70 m, and the width ranges from 8 m to 260 m.
- There is a good correlation between the thickest low-resistivity zone interpreted from TEM (VES no. 6, 25, 34, 43, 47, 64, and 69) and land magnetic fault traces allocated and interpreted from the magnetic RTP signal. Detailed measurements show that favourable locations for the target (mineralised zone) deposits are generally associated with high magnetic anomalies and moderate interpreted resistivity values.
- In the UG area, the mineralisation sources are associated with a deep fault or alteration zone that permits hydrothermal solutions to transport different minerals to a new location.
- The present work enhances the comprehension of gold metallogeny within the Arabian Nubian Shield and advocates for a reconnaissance and assay initiative, backed by the industry, aimed at identifying untapped resources in Egypt's Eastern Desert region.

Statements and declarations

Authors' contributions. MMG contributed to the conceptualization of the research, prepared the manuscript and supervised the data processing. SAS and MMM supervised the analysis and interpretation of the EM and ERT data. SAS, MMM, and MHK revised the manuscript. MME contributed to the acquisition, processing and analysis of the data under the supervision of MMG and SAS. AN supervised the analysis and processing of RS data. All authors have read and agreed to the published version of the manuscript.

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Data availability. The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Competing interests. The authors declare no competing interests.

Additional information. Correspondence and requests for materials should be addressed to MMG.

Statement on the use of AI. The AI was used only to improve the language style in several paragraphs.

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