

Gold Mineral Potential Evaluation Using Integrated Aeromagnetic and Aeroradiometric Datasets in the Nong Son – Da Nang Area, Vietnam

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Abstract: *The Nong Son–Da Nang area, located in the Central Region of Vietnam, is geologically diverse and rich in various types of mineral resources, with gold mineralization being the most prominent. In this study, magnetic anomaly data and radiometric data (including gamma radiation intensity, the concentrations of potassium, thorium, and uranium) were integrated with the distribution of surface exposed gold occurrences to construct a prospectivity map of gold mineralization zones in the study area. The horizontal gradient method applied to the vertical derivative of the residual magnetic anomaly field at a depth of $h = -2600$ m, combined with magnetic anomaly field inversion, was employed to identify structural features associated with gold mineralization zones. The fault system in the area is characterized by sub-latitudinal faults (Tam Ky-Phuoc Son fault, Tra Bong-Tra My fault), sub-longitudinal faults (Poko fault), as well as secondary faults trending in the northwest - southeast and northeast - southwest directions. Based on the correlation coefficients between thorium and potassium (ranging from 0.4 to 0.6), in combination with data on surface-exposed gold mineralization points, the author has delineated 11 potential gold mineralization zones. These zones are primarily confined within the influence of major fault systems, including the Tam Ky-Phuoc Son fault in the north, the Tra Bong-Tra My fault in the south, the Poko fault in the west, and along or near the boundaries of secondary fault systems. Results from inverse magnetic anomaly field analysis along profile AB indicate that these prospective zones are predominantly located within Proterozoic metamorphic rocks, which exhibit low magnetic susceptibility values ranging from $(7 \pm 21) \times 10^{-3}$ (SI).*

Keywords: Nong Son – Da Nang; Gold mineralization; Aeromagnetic data; Aeroradiometric data; COSCAD 3D

1. Introduction

The Nong Son - Da Nang area, situated within the Kon Tum massif in central Vietnam, is geographically constrained between coordinates $X = 776,400$ m to $900,000$ m and $Y = 1,690,000$ m to $1,757,800$ m. According to synthesis reports by Nguyen et al. (2000, 2014), Nguyen et al. (2000), and Hai et al. (2014), the region hosts a wide variety of mineral resources, among which gold mineralization is particularly significant (Fig.1). Numerous ore deposits and mineral occurrences have been identified, investigated, and evaluated several of which are currently under exploitation. These mineralized zones are typically associated with geophysical anomaly fields that can be detected at the surface. Alterations in the physical properties of rocks serve as a fundamental prerequisite for delineating geological targets using integrated geophysical methods. The mineralized bodies in the study area are generally characterized by high density and low magnetic susceptibility, setting them apart distinctly from surrounding intrusive rocks, including granites, and Paleozoic to late Jurassic formations (Zhiqiang et al., 2019).

Geophysical data are considered the first step in mineral exploration. They reduce the time and cost by detecting surface occurrences of mineralizations and their subsurface extensions as well as structures (Haldar 2018). The combination between airborne geophysical data and gold mineral occurrence is widely used in mineral exploration.

Gamma-ray spectrometric data is a good tool in mapping zones related to mineralizations (Gnojek and Prichystal 1985). Besides, aeromagnetic survey is further useful in defining the boundaries of magnetic sources and structures, which are connected with mineralization (Assran et al. 2019; Hong, 2022; Phan et al., 2020; Petrov, 1997; Petrov et al., 2010).

The current study focuses on the use of airborne spectrometric, magnetic data and gold mineral occurrence, to delineate and map mineral alteration zones and structure lineaments in order to delineate the probable locations of new mineralized zones for development processes. The specific goals of this

study are as follows: (1) Prospect mapping of potential gold mineralization zones by applying processing techniques such as analysis of the K/Th ratio, alteration F-parameter, Th-K correlation coefficient; and (2) Extract surface and subsurface structural lineaments, that may control the existence of mineralizations.

2. Geology and mineralization overview

The Nong Son - Da Nang area is considered the only exposed high-grade metamorphic basement on the eastern margin of the Indochina Terrane, comprising a complex assemblage of magmatic, sedimentary, high-grade metamorphic, and reworked metamorphic rocks. The area is geologically complex (Fig.1), with the highest metamorphic grades reaching granulite facies and remnants of eclogite facies metamorphism (Bao et al., 1982; Thang, 1987a,b; Osanai et al., 2001; Nakano et al., 2013). The central and southern parts of the study area are dominated by high-grade metamorphic rocks of the Kham Duc - Nui Vu Formation. These units are structurally controlled by several major sub-latitudinal fault systems, including the Rao Quan - A Luoi, Tam Ky - Hiep Duc, and Tra Bong - Tra My faults. The northwestern part is characterized by Cambrian - Ordovician sedimentary rocks of the A Vuong Formation and Triassic sedimentary rocks of the Song Bung and Nong Son Formations. In the northern part of the area, Jurassic sedimentary sequences of the Khe Ren and Huu Canh Formations are dominant. Magmatic rocks are also widespread. The mafic Ta Vi Complex occurs as small lenticular bodies, while the Chu Lai Complex, distributed along the Tra Bong - Tra My fault, trends in an east - west direction. The northern and northwestern regions contain ultramafic rocks of the Hiep Duc Complex, appearing as small lenticular intrusions. Additionally, several magmatic complexes such as Ben Giang - Que Son and Dai Loc are exposed along the northeast - southwest trending fault systems. The southern part of the region is dominated by the Tra Bong Complex. Other complexes, including the Cha Val, Hai Van, and Deo Ca, are more sporadically distributed and occupy relatively limited areas.

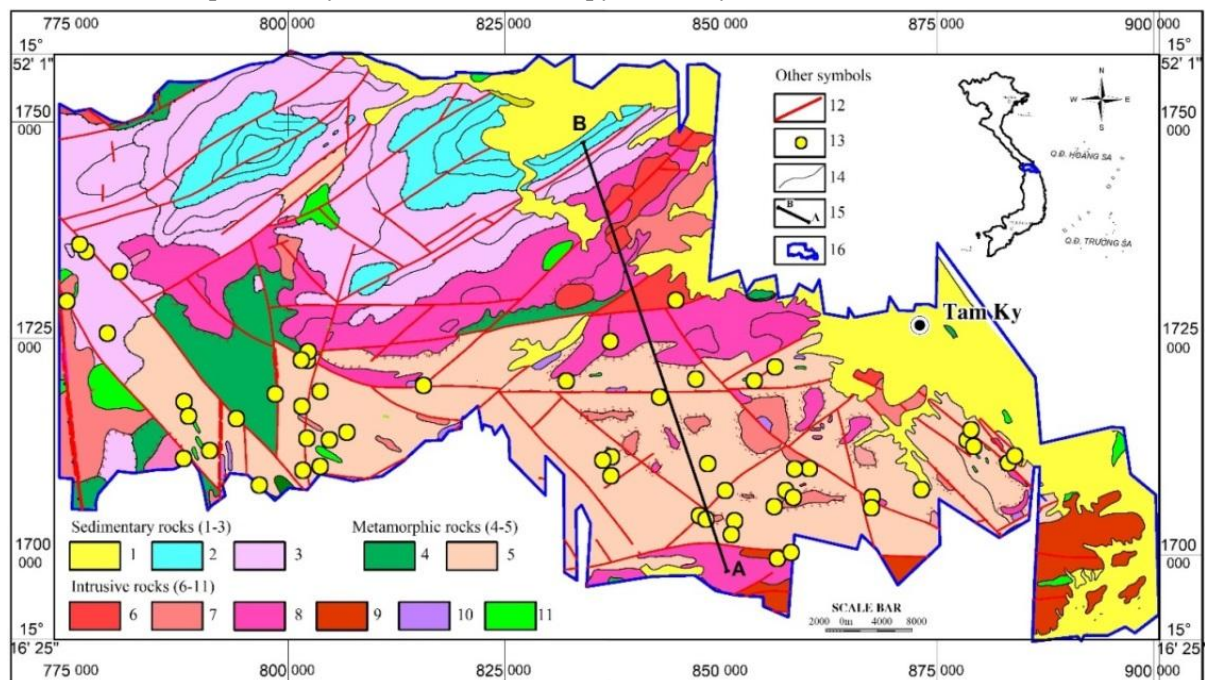


Fig. 1. Location of the study area and simplified geological-structural map of the Nong Son - Da Nang area

Sedimentary rocks (1-3): 1- Quaternary sediments and basalt; 2- Jurassic sedimentary rocks, including: Ban Co formation, Khe Ren formation, Huu Canh formation; 3- Triassic sedimentary rocks, including: Song Bung formation, Nong Son formation. Metamorphosed sedimentary rocks (4-5): 4- Cambrian-Ordovician sedimentary rocks: A Vuong formation; 5- Proterozoic metamorphosed sedimentary rocks: Kham Duc - Nui Vu formation. Intrusive Igneous rocks (6-11): 6- Cretaceous - Paleogene intrusive rocks, including: Deo Ca complex, Ba Na complex; 7- Devonian-Triassic intrusive rocks, including: Tra Bong complex, Dai Loc complex, Hai Van complex; 8- Paleozoic intrusive rocks: Ben Giang - Que Son complex; 9- Proterozoic intrusive rocks: Chu Lai complex; 10- Ultramafic rocks: Hiep Duc complex; 11- Mafic rocks: Ta Vi complex, Nui Ngoc complex, Cha Val complex. Other Features (12 - 16): 12- Faults; 13- Mineral occurrences; 14- Geological boundaries; 15- Geological - geophysical cross section (Line A-B); 16- Boundary of the study area.

3. Data and methods

3.1. Aeromagnetic data

The data was in the form of a total magnetic intensity grid with a measurement error of ± 10.5 nT (Fig.2a) (Nguyen et al.,2000, 2014; Nguyen et al., 2000), the magnetic inclination ($I = 17.5^\circ$) and declination ($D = -0.6^\circ$) were obtained based on the International Geomagnetic Reference Field (IGRF-NOAA) 2000 on software Geosoft (Geosoft, 2008; <http://www.geosoft.com>; <https://www.ncdc.noaa.gov>). To overcome undesired distortion in the shapes, sizes, and locations of magnetic anomalies, due the effect of inclination and declination of the Earth's magnetic field, Baranov (1957), Baranov and Naudy (1964) proposed a mathematical approach known as reduction to the pole (RTP) to transfer the total magnetic data anywhere into magnetic anomalies as if measured at the magnetic pole, and the results are shown in Fig. 2(b)

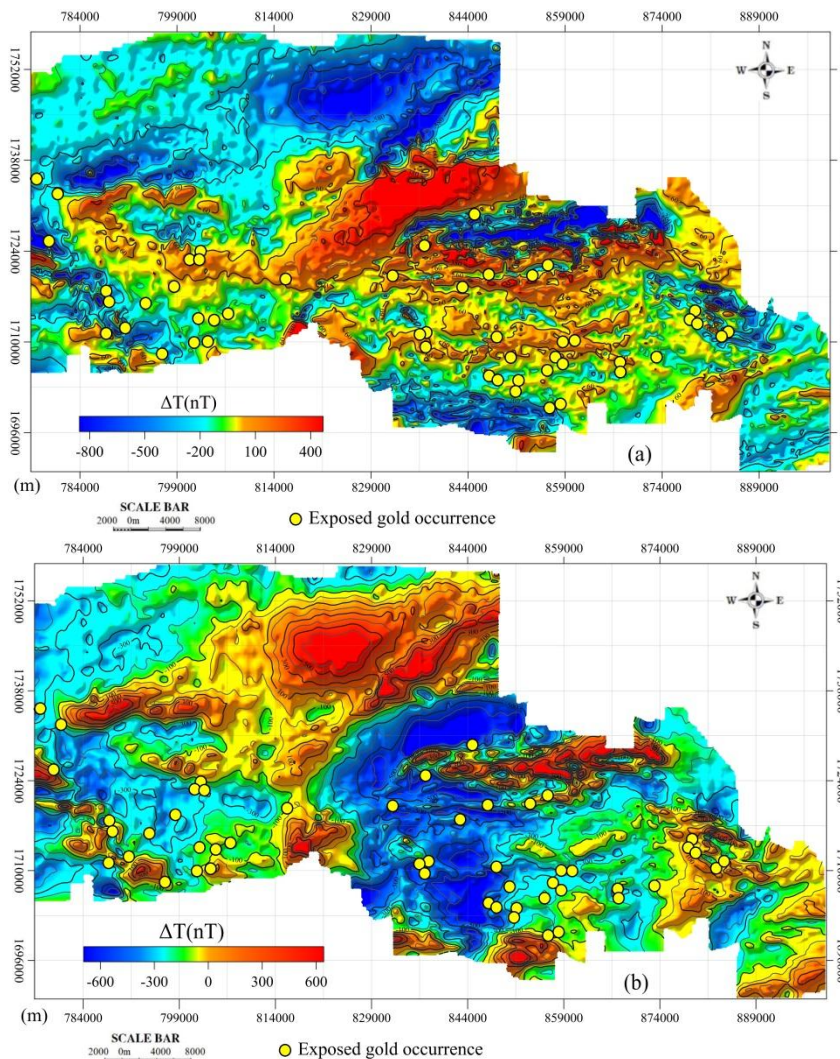


Fig.2. (a)- Aeromagnetic anomaly map; (b) - Reduction to the pole (RTP) of the aeromagnetic anomaly map of the Nong Son – Da Nang area

Observation of the magnetic anomaly field map (Fig.2b) indicates that the magnetic field in the study area exhibits an amplitude range from -700 nT to 600 nT. A prominent negative anomaly zone, with amplitudes ranging from -700 nT to -250 nT, extends in a northeast-southwest direction and divides the area into two distinct positive anomaly blocks located in the northwest and southeast, with amplitudes ranging from 150 nT to 600 nT. Additionally, several local positive magnetic anomaly zones, with amplitudes varying from 100 nT to 250 nT, are observed, primarily concentrated in the southwestern and southeastern parts of the study area.

3.2. Aeroradiometric data

Airborne gamma-ray spectrometric data were utilized to describing the distribution and intensities of radioactive elements (gamma radiation intensity, the concentrations of potassium, thorium, and uranium) over the main lithologies using qualitative interpretation of K, U, Th and gamma radiation

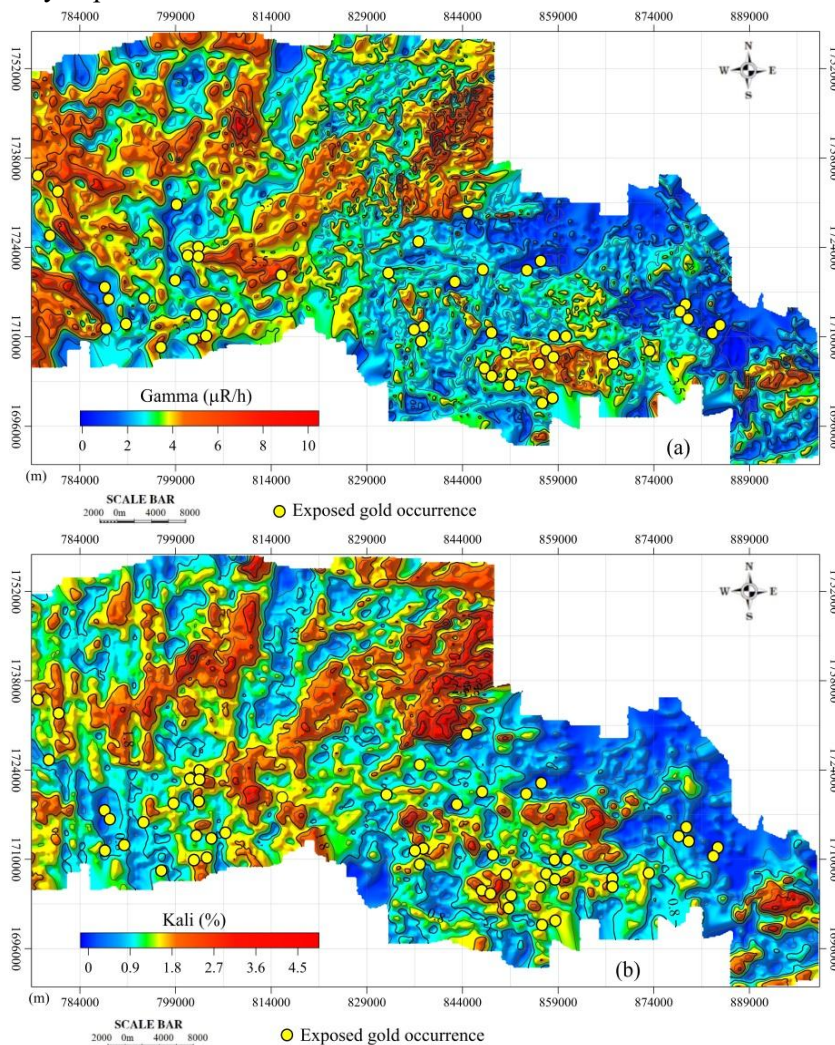
intensity composite image maps.

Observation of Fig.3(a–d) reveals a prominent northeast – southwest trending zone in the central part of the study area, characterized by high gamma ray intensity ranging from 5 $\mu\text{R/h}$ to 11 $\mu\text{R/h}$ (Fig. 3a), elevated potassium concentrations between 5 % and 12 % (Fig.3b), thorium concentrations ranging from 16 ppm to 70 ppm (Fig.3c), and uranium concentrations from 7 ppm to 20 ppm (Fig.3d). This anomaly zone is associated with intrusive rocks of the Hai Van, Deo Ca, Ba Na, and Ben Giang complexes.

In the western part of the study area, gamma intensity ranges from 4 $\mu\text{R/h}$ to 8 $\mu\text{R/h}$, potassium concentrations vary between 1.7 % and 2.5 %, thorium from 14 ppm to 20 ppm, and uranium from 7 ppm to 10 ppm. These geophysical signatures correspond to magmatic rocks of the Hai Van and Hiep Duc complexes.

The southern zone is characterized by moderate gamma-ray levels ranging from 2 $\mu\text{R/h}$ to 5 $\mu\text{R/h}$, lower potassium concentrations of 0.9 % to 1.8 %, thorium ranging from 10 ppm to 16 ppm, and uranium from 3 ppm to 8 ppm. These values are associated with intrusive rocks of the Chu Lai Complex.

The southwestern area exhibits low gamma-ray intensity (0 to 2 $\mu\text{R/h}$), low potassium content (0 to 0.9 %), thorium concentrations ranging from 0 ppm to 14 ppm, and uranium concentrations from 0 ppm to 5 ppm. This zone is predominantly associated with sedimentary rocks of the Ai Nghia Formation and undivided Quaternary deposits.



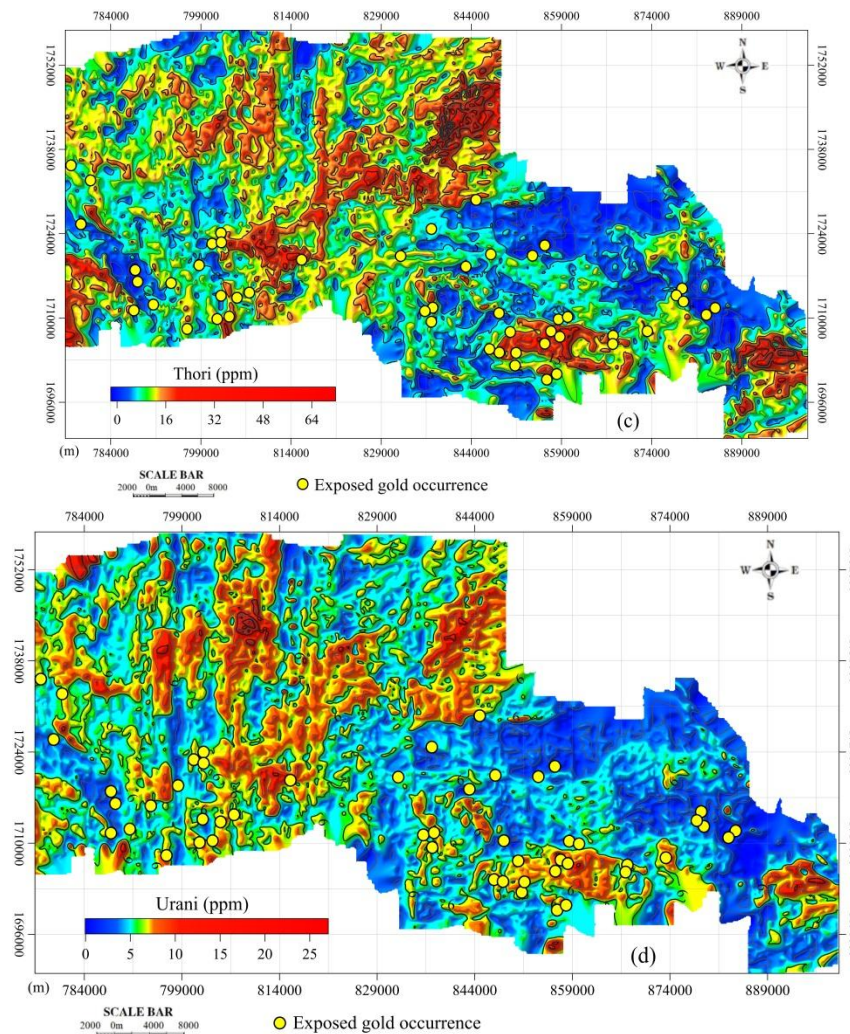


Fig. 3. (a) Contour map of gamma-ray intensity (I_γ); (b) Contour map of potassium concentration; (c) Contour map of thorium concentration; (d) Contour map of uranium concentration in the Nong Son - Da Nang area

3.3. Processing of airborne geophysical data

3.3.1. Processing of aeroradiometric data

The K/Th ratio map was constructed to determine where the relative concentrations of K relative to Th increased. Besides, the alteration F-parameter is used to delineate the mineralized alteration zones in the investigated area. The most effective parameter of the three radioelements was suggested by Efimov (1978) as a so called F-parameter (Gnojek and Prichystal 1985). It is defined as:

$$F(\%) = \frac{U}{Th/K} = \frac{K}{Th/U} = K \times \frac{U}{Th} \quad (1)$$

The F-parameter depends on two main significant relationships, the richness of uranium compared to Th/K ratio and the richness of potassium compared to Th/U ratio of the rock.

The F-parameter is very useful in identifying zones of potassium alterations associated with gold, copper and polymetallic mineralizations (Gnojek and Prichystal 1985; Abd El Nabi 2012). Efimov (1978), who determined the value of the F-parameter, showed that in common non-altered rocks, it can take values up to 1.2 or 1.3, and in altered rocks, it may be 2 or even 5, in exceptional cases 10. The F-parameter values (in %) for each rock unit were calculated, based on the F-parameter equation (1).

3.3.2. Processing of aeromagnetic

Method of maximum horizontal gradient of magnetic anomaly field vertical derivative.

The method used to determine the boundary of surface and subsurface structures, that may control the existence of mineralizations by the location of the set of horizontal gradient maxima points of the vertical derivative of the magnetic anomaly field. The horizontal gradient maximization method was first applied by Cordell (Cordell, 1979) in determining the boundary of the object according to the position of

the points with the maximum value of the horizontal gradient. This method was later developed and applied by the authors to many different regions (Blakely, 1996; Fedi and Florio, 2001; Verduzco et al., 2004; Nguyen et al., 2014).

To improve the resolution of the maximum horizontal gradient method, we apply the maximum horizontal gradient method to the vertical derivative of the magnetic anomaly field. The horizontal gradient amplitude is calculated according to the formula:

$$\text{The HD_VD} = \sqrt{\left(\frac{\partial \text{VD}}{\partial x}\right)^2 + \left(\frac{\partial \text{VD}}{\partial y}\right)^2} \quad (2)$$

Where: VD - is the vertical derivative of the magnetic anomaly field ($\text{VD} = \partial \Delta T(x, y) / \partial z$); x and y - are the directions along the Ox and Oy axes.

4. Results and Discussions

4.1. Determination of surface structural features that can control the existence of mineralization.

We calculate the horizontal gradient of the vertical derivative for the residual magnetic anomalies field at depth $h = -2600$ m (Fig.4) and get the results shown in Fig.5.

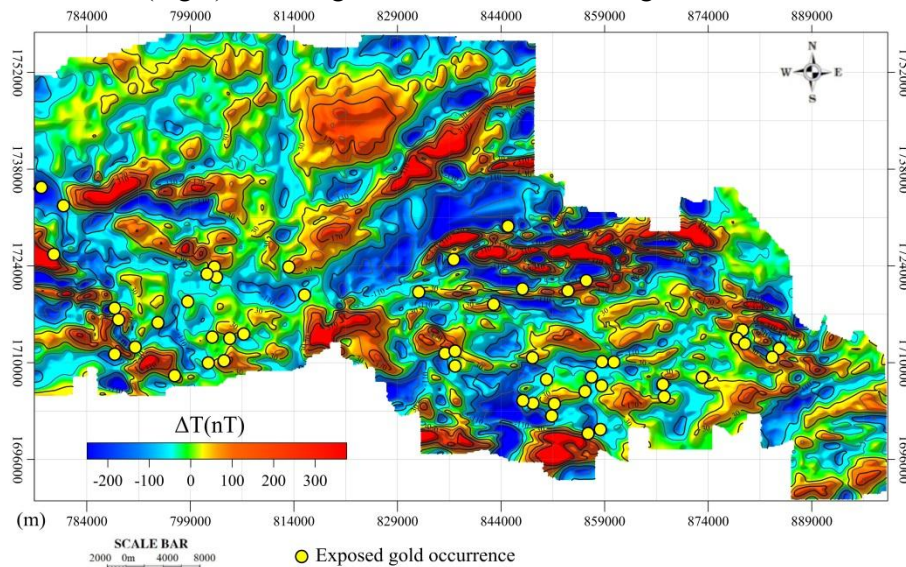


Fig.4. Residual magnetic anomaly field at depth $h = -2600$ m in the Nong Son - Da Nang area

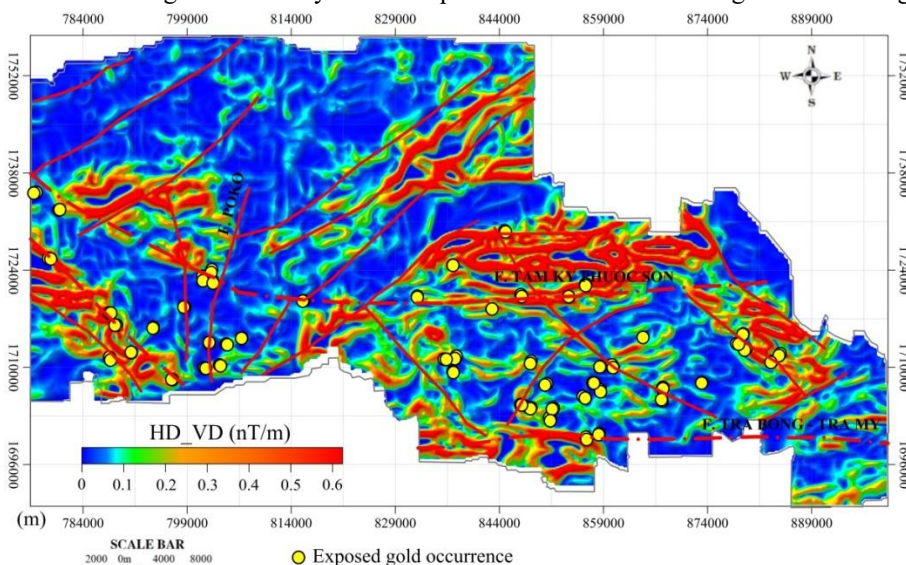


Fig. 5. Horizontal gradient of the vertical derivative for the residual magnetic anomalies field at depth $h = -2600$ m in the Nong Son - Da Nang area

Observing the horizontal gradient value of the vertical derivative of the residual magnetic anomaly (Fig.5) shows that the bands of maximum horizontal gradient values extend mainly in the sub-latitude

direction and the northeast - southwest, and northwest - southeast. Two major faults, the Tam Ky - Phuoc Son fault and the Tra Bong - Tra My fault, develop along the latitude with a maximum amplitude >0.4 nT/m. The northwestern area is characterized by fault systems in the northeast - southwest direction with amplitudes ranging from $0.05 \div 0.3$ nT/m, showing that the geological activity here is quite stable.

The southwest and southern areas are characterized by amplitudes >0.25 nT/m in the northwest - southeast direction with relatively thick density, demonstrated at this area has very complex tectonic activities and indicating that this area may have the potential of magma/mineral mass with high magnetic composition.

4.2. Inversion of magnetic anomalies field

To investigate the subsurface geological structure, the authors conducted a survey along the AB profile (as shown in Fig.1), which intersects the Tam Ky - Phuoc Son fault and the Tra Bong - Tra My fault zones. In this study, the COSCAD 3D software package (<http://www.coscad3d.ru>) was employed to perform inversion of magnetic anomaly data (Fig.2b) down to a depth of $h = -2600$ m. By integrating gamma-ray intensity data (Fig.3a) and the concentration factor F (Fig. 8), a geological - geophysical cross section was constructed along the AB profile (see Fig. 6e).

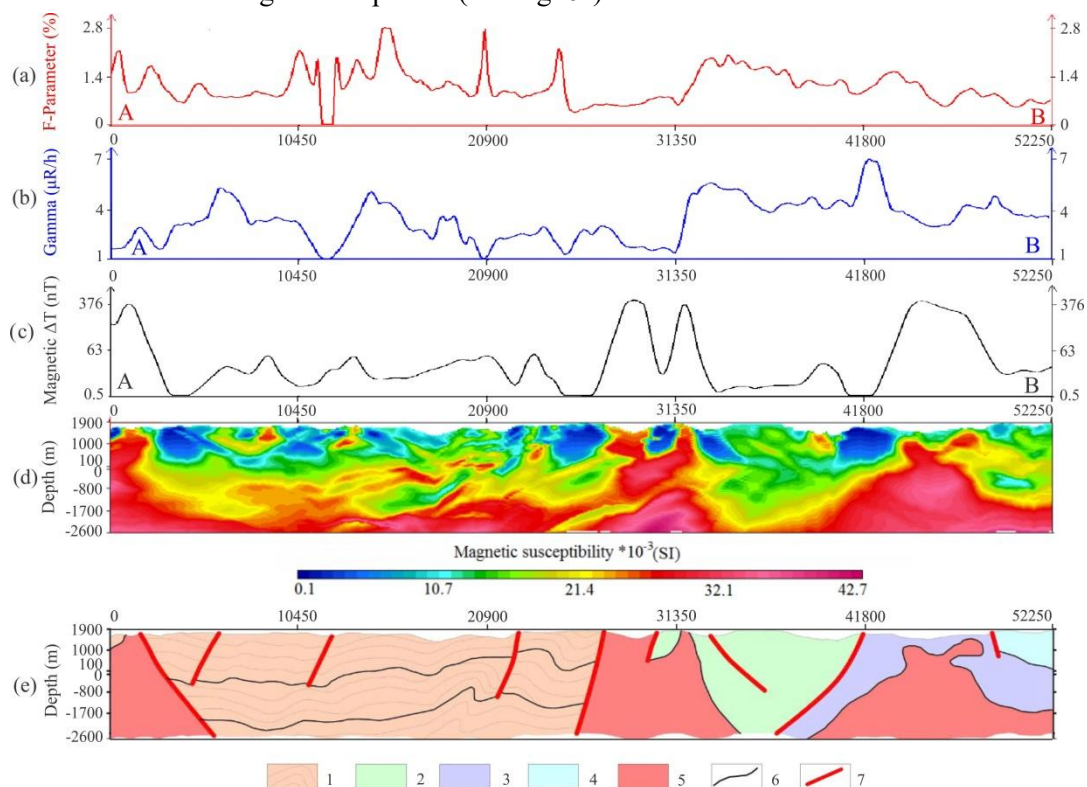


Fig. 6. Geological - geophysical cross section along profile AB as indicated in Fig.1. Fig.6(a)- Alteration F-parameter; Fig.6(b)- Gamma-ray intensity; Fig.6(c)- Magnetic anomaly field (ΔT); Fig.6(d) Inversion result of magnetic anomaly data; Fig.6(e)- Geological interpretation based on the inversion model in Fig.6(d) along profile AB

1- Proterozoic metamorphic rocks; 2- Cambrian Ordovician sedimentary rocks; 3- Triassic sedimentary rocks; 4- Jurassic sedimentary rocks; 5- Magmatic rocks; 6- Geological boundaries; 7- Faults

From the magnetic susceptibility model (Fig. 6d), in the segment from 0 to 3000 m, the susceptibility values range from $(21.4 \div 42.7) \times 10^{-3}$ (SI) and extend down to a depth of approximately $h = -2600$ m. This corresponds to a magnetic anomaly of approximately 376 nT (Fig.6c). Correlation with the geological map (Fig.1) indicates that this anomaly is associated with Paleozoic magmatic rocks (as illustrated in Fig.6e).

Continuing from point A toward point B, the alteration F-parameter (Fig.6a), gamma-ray intensity (Fig.6b), magnetic anomaly field (Fig.6c), and magnetic susceptibility (Fig.6d) all exhibit continuous variations. This reflects a complex subsurface geological structure, likely influenced by the activity of a deep-seated fault system that has fractured and altered the rocks. Furthermore, these faults may have served as conduits for the upward migration of magnetic magmatic bodies, causing varying degrees of contact metamorphism in the surrounding rocks (Fig. 6d, 6e). Correlation with the geological map (Fig.1)

suggests that this fault system corresponds to the deep Tra Bong - Tra My fault zone, which provides favorable conditions for ore formation.

Along the AB profile, from approximately 3000 m to 25000 m (Fig.6d, 6e), the magnetic susceptibility gradually increases with depth, while the magnetic anomaly curve shows complex variations ranging from 50 nT to 63 nT. In contrast, the gamma-ray intensity exhibits a significant variation from 1 $\mu\text{R/h}$ to 6 $\mu\text{R/h}$, and the concentration factor F ranges from 0 % to 2.8%. These features suggest that this zone has undergone intense compression and fracturing due to secondary fault systems. Correlation with the geological map (Fig.1) reveals that this region corresponds to Proterozoic metamorphic rocks, which represent a favorable environment for ore mineralization. The geophysical variations in magnetic susceptibility and F also suggest that, beyond the surface mineralized outcrops, gold mineralization may extend to depths of up to $h = -800$ m (Figs. 6d, 6e).

Based on the interpretation of Fig.6(a–e), the AB profile can be divided into two distinct segments separated at approximately 25000 m by the Tam Ky - Phuoc Son deep fault system. The southeastern segment (Fig.1) is primarily composed of Proterozoic metamorphosed sedimentary rocks. In contrast, the northwestern segment consists of younger sedimentary rocks ranging from Cambrian to Jurassic in age. In this section, the alteration F -parameter remains relatively stable and gradually decreases toward the end of the profile, from approximately 2.1% down to 0.7%. The abrupt increase in gamma-ray intensity and magnetic anomalies in this area likely reflects the intrusion of magmatic bodies into younger sedimentary rocks rather than an indication of strong mineralization potential in this segment.

4.3. Prospect mapping of potential gold mineralization zones

To map the prospects of potential gold mineralization zones, in the study the author used processing techniques such as analysis of the K/Th ratio (Fig.7), alteration F -parameter (Fig.8), Th-K correlation coefficient (Fig.9)

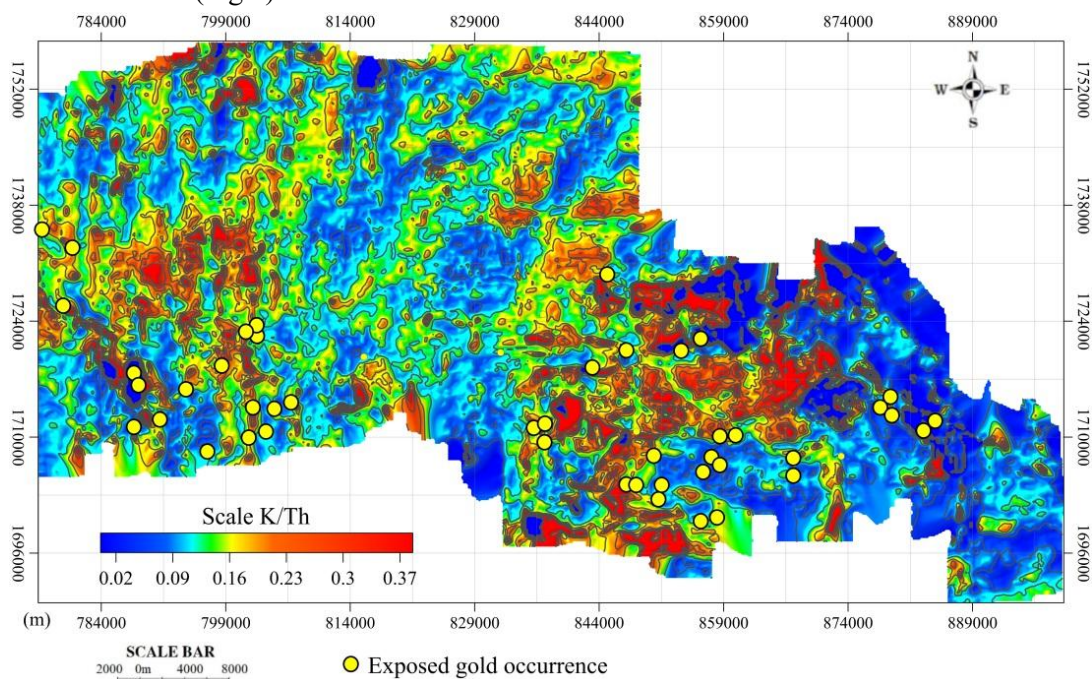


Fig.7. Potassium/Thorium ratio map of the Nong Son – Da Nang area

The results were shown on Fig. 8 as an alteration F -parameter colour map. As an illustration on Fig.1.8, values of the F -parameter, as estimated from airborne spectral gamma-ray data, vary from a minimum of 0.1 for quaternary sedimentary rocks and basalts, to a maximum of 2.7% for Paleozoic magmatic rocks including: Ben Giang - Que Son complex, showing the metasomatism of the potassic alteration associated with mineralization related to these granites.

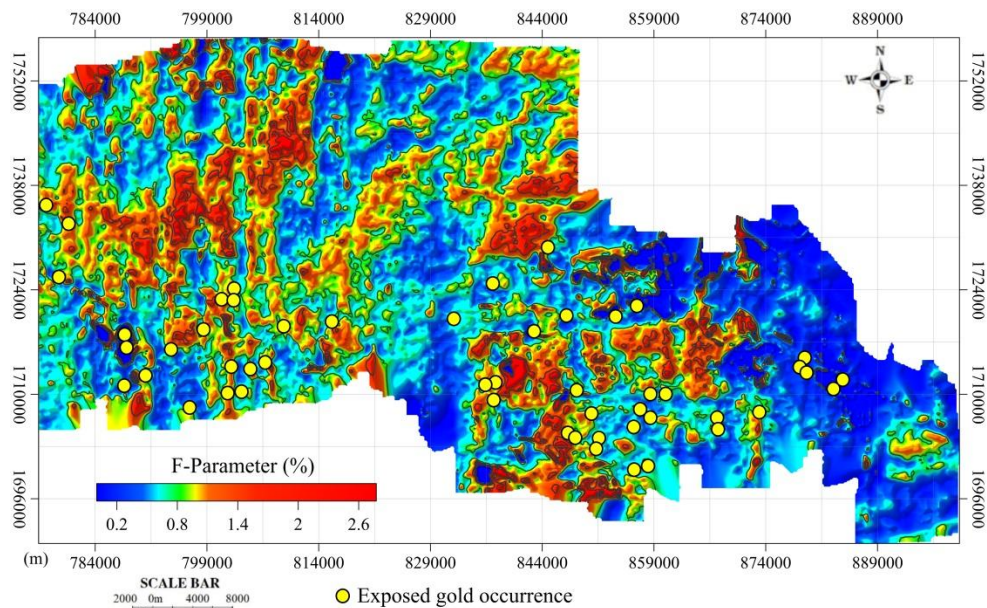


Fig.8. Alteration F-parameter maps of the Nong Son – Da Nang area

The results of the radiometric data analysis primarily reflect geological and mineralization features at shallow depths and near-surface levels. Therefore, by integrating the interpretation of radiometric anomalies, magnetic anomalies, surface-exposed gold mineralization occurrences, and the correlation between thorium (Th) and potassium (K), the authors delineated zones with potential for gold mineralization, as illustrated in Fig. 9.

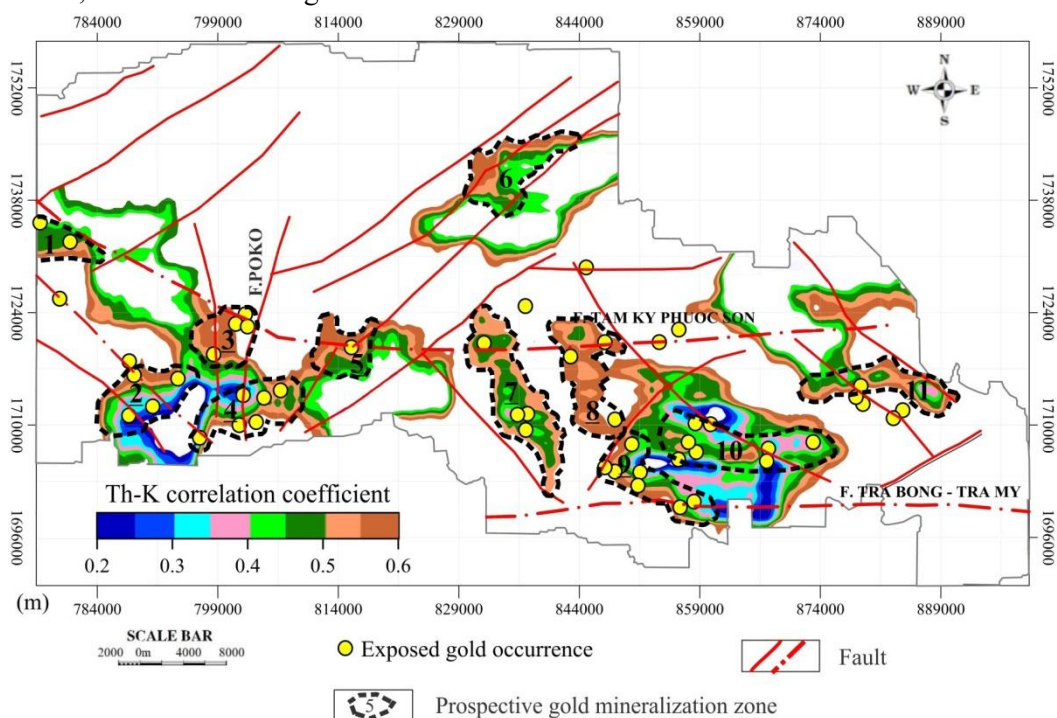


Fig. 9. Delineated prospective zones for gold mineralization in the Nong Son - Da Nang area

Due to its geochemical specialization, thorium (Th) tends to accumulate in hydrothermally altered zones associated with gold bearing geological bodies and is typically stable and immobile. In contrast, potassium (K) is more mobile. Therefore, a higher correlation coefficient between Th and K indicates a greater likelihood of gold mineralization.

The results presented in Fig. 9 show that the delineated prospective zones correspond to areas where the Th - K correlation coefficient ranges from 0.4 to 0.6. These correlation based delineations suggest that gold mineralization is predominantly controlled by major fault systems: the Tam Ky - Phuoc Son fault zone to the north, the Tra Bong - Tra My fault zone to the south, and the Poko fault to the west, as well as associated secondary fault systems.

Integration with the geological - geophysical cross section along profile AB (Figs.1 and Fig.6) indicates that these prospective zones are mainly developed within Proterozoic metamorphic rocks characterized by low magnetic susceptibility values, ranging from $(7 \div 21) \times 10^{-3}$ SI.

Based on the analysis shown in Fig. 9, the authors identified a total of eleven prospective zones. Among these, five zones (1-5) are located in the western part of the study area. These zones are mainly controlled by the Tam Ky - Phuoc Son fault system to the north and the Tra Bong - Tra My fault system to the south (northwest - southeast trending), with the Poko fault and other subsidiary faults crossing the central portion. A notable feature in this area is Prospective Zone 1, which exhibits a high Th-K correlation coefficient (0.5 to 0.6) and is hosted within Triassic sedimentary rocks.

In the eastern part, six prospective zones (6-11) have been delineated. These zones are almost entirely situated within the influence of the Tam Ky - Phuoc Son and Tra Bong - Tra My fault systems, which trend sub-latitudinally. Of particular interest is prospective zone 6, which, despite the absence of surface gold occurrences, shows a relatively high Th-K correlation (0.4 to 0.6). According to geological data (Fig. 1) and the AB cross section (Fig.6), this zone is developed within Triassic sedimentary rocks and structurally controlled by northwest - southeast trending faults.

5. Conclusions

Analysis of the results obtained from magnetic anomaly data and radiometric anomalies (gamma-ray intensity, concentrations of U, Th, and K), in conjunction with surface gold mineralization occurrences, reveals the following key findings:

- A total of 11 potential gold mineralization zones have been identified. These zones are primarily controlled by major fault systems, including the Tam Ky - Phuoc Son fault in the north, the Tra Bong - Tra My fault in the south, the Poko fault in the west, and various subsidiary fault systems along or near their margins.

- The correlation coefficient between thorium and potassium ($0.4 \div 0.6$) is closely associated with these prospective zones. Among them, ten zones show direct surface expressions of gold mineralization, while one zone (zone 6) does not exhibit surface gold occurrences but still displays a high Th-K correlation, indicating concealed mineralization potential.

- Geological and geophysical structural analysis, both at the surface and subsurface levels, indicates that the majority of prospective zones are hosted within Proterozoic metamorphic rocks, which are characterized by low magnetic susceptibility values ranging from $(7 \div 21) \times 10^{-3}$ SI.

- It is recommended to carry out detailed geochemical and ground geophysical studies at the determined alteration zones that were detected from the present study and identify the known as well as the new mineralization occurrences and determine their grades and extensions.

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