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Geophysical survey of the Khachovi gold-polymetallic ore occurrence (Adjara-Trialeti folded zone, Georgia)

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Abstract. This article presents the findings of a geophysical survey conducted on the Khachkovi gold-polymetallic occurrence in Georgia. The study aimed to evaluate the geological prospects through comprehensive investigations. Three methods – electrometry, magnetometry, and gamma spectrometry – were employed in the survey, covering approximately 3.5 square kilometres. Analysis of the survey data revealed high magnetic field anomalies and variations in the gravity field, indicating gabbro-diorite intrusive bodies at depth. The Khachkovi occurrence was structurally associated with faults, fractured zones, and hydrothermally altered zones. Electrically conductive minerals within the hydrothermally altered zones were confirmed through induced polarization values and anomalous potassium content. The study area exhibited low potassium, thorium, and uranium levels, potentially due to Quaternary sediments and weak alterations. Hydrothermally altered sulfide mineral-containing zones were primarily linked to fault zones, intrusive bodies, and brecciated zones. The surface hydrothermally altered zone consisted mainly of pyrite-bearing rocks. The geophysical survey provided valuable insights into the geological characteristics and prospects of the Khachkovi gold-polymetallic occurrence, offering guidance for further exploration activities. These findings contribute to understanding the mineralization potential and future mining efforts.

Keywords: *hydrothermally altered zones; geological prospects; mineralization potential; gabbro-diorite intrusive bodies; exploration activities*

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INTRODUCTION

The Gujareti-Khachkovi ore field is in the central part of the Adjara-Trialeti ridge (Bluashvili, Mindiashvili 2021). Administratively, the Khachkovi gold-polymetallic occurrence is located to the north of the village of Khachkoi in Tsalka Municipality, within the gorge of the Khachkovi River. The target area is highland, with absolute altitudes ranging from 1900 to 2400 meters.

From a geological standpoint, the mentioned occurrence is situated in the central part of the Adjara-Trialeti zone (Fig. 1), within the territory of the Gujareti-Khachkovi ore field (Gamkrelidze 1986). Although the study of the Khachkovi gold-polymetallic occurrence has a long history, there is currently no consensus or general agreement among geologists regarding its prospects. To assess the prospects of the Khachkovi gold-polymetallic occurrence comprehensively, it is advisable to conduct complex geological-geophysical and geochemical studies (Dentith, Mudge 2014).

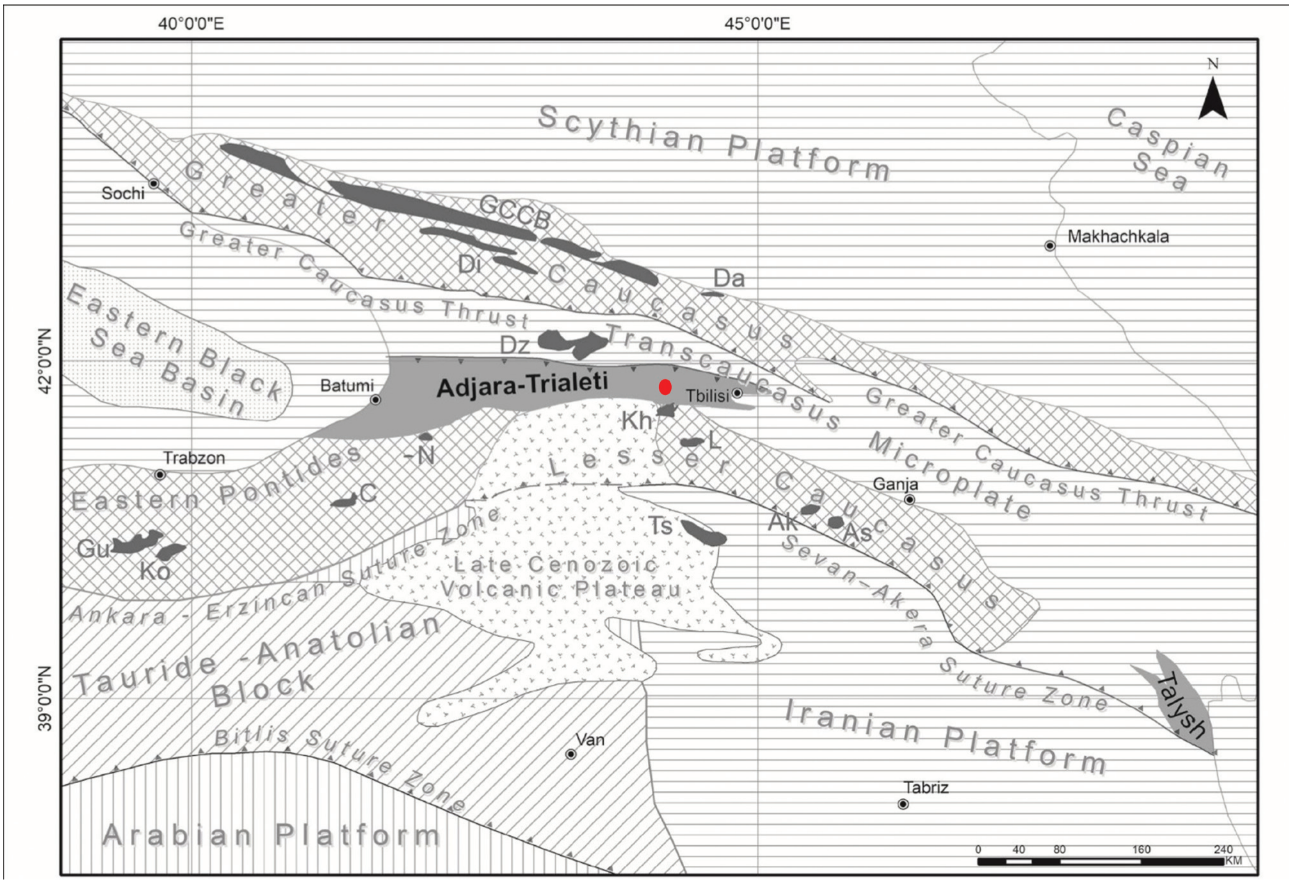

Fig. 1 Simplified schematic geological map of the Arabian–Eurasian collision segment of the Alpine–Himalayan orogenic belt (adapted after Philip *et al*. 1989; Yilmaz *et al*. 2000; Gamkrelidze 2003; Moritz *et al*. 2016; Okay, Topuz 2017)

In light of the information mentioned above, a complex geophysical survey was conducted on the Khachkovi gold-polymetallic occurrence of the Gujareti-Khachkovi ore field, aimed at addressing specific objectives:

- Geo-mapping: Differentiation of the rocks based on their electrical and magnetic characteristics, as well as the content of potassium, thorium, and uranium, and identification of potential faults and intrusive bodies (including covered intrusions) (Menke 2012).
- Study of geoelectric sections at a depth of 130–150 meters to identify zones of induced polarization and anomalous values of potassium content and establish their association with potential hydrothermally altered zones and the gold-polymetallic occurrence.

The geophysical survey was conducted using the following methods: electrometry (electrical tomography-dipole-dipole scheme), magnetometry, and gamma spectrometry (Reynolds 1997). Based on the research data, electrical tomography (induced polarization, specific electrical resistivity) sections were developed, along with a magnetic field map (measured – TMI and pole counted – RTP), a map indicating the content of potassium, thorium, and uranium, an F = K * U / Th parameter map, and a map of geophysical survey results (Dobrin, Savit 1988). The geophysical survey standing points' coordinates were determined using a satellite navigation device, GPS, in the coordinate system "WGS-84".

GEOLOGICAL BACKGROUND

In the construction of the Khachkovi ore occurrence, middle Eocene volcanogenic-sedimentary deposits, andesite flows, andesite, diabase and diabase-porphyry dykes, and gabbro diorite minor intrusive take part (Fig. 2). The major part of the area (about 75%) is occupied by medium-fragmented tuff breccia and tuff conglomerates. Andesite flows (sheets) crop out mainly on the watersheds in the northern and eastern parts of the area. Khachkovi area is characterized by a sharply increased development of dykes among which age, petrochemistry, and rate of hydrothermal alteration are distinguished with two series due to distribution features. Younger dykes that cross-cut middle Eocene andesite flows, and diabase-porphyries represent gabbro-diabase minor intrusive. They have mainly sub-meridional (NE) and, rarely, sub-latitudinal strikes. Their distribution as dyke belts and areal swarms is typical. The diabase dykes belt width

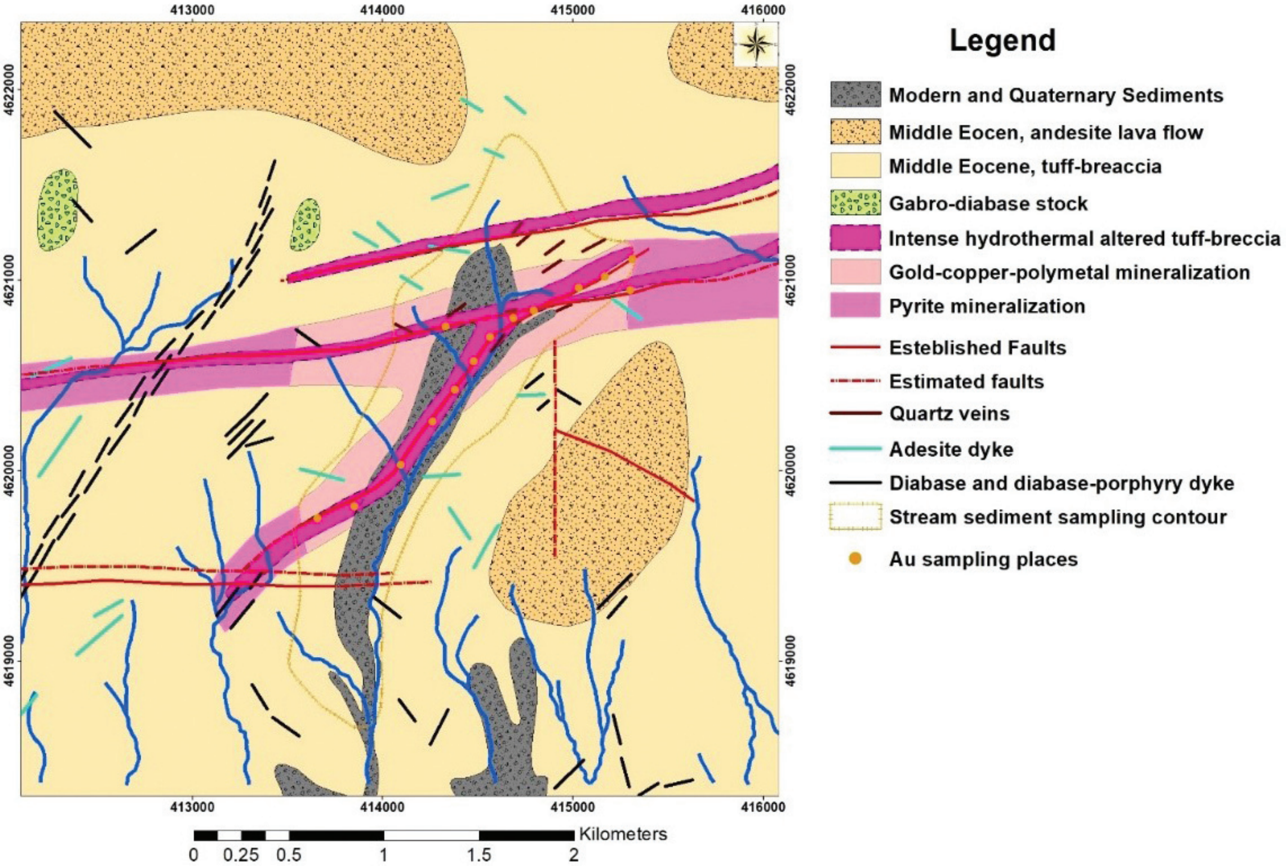

Fig. 2 Geological map of Khachkovi gold-polymetallic occurrence (after Tskhelishvili 1992, with additions by the authors)

is 50–60 m, and thickness of some dykes is 1–4 m. Diabase and diabase porphyry dykes are the freshest formations in the area and are not influenced by hydrothermal alteration. Older dykes-andesite dykes are less widespread. They are mainly stretched in a sublatitudinal direction, though there are some dykes in other directions. They are thicker than diabase dykes (from 2.5 to 35 m) and more separated spatially from each other, but at the same time, they are relatively wider than diabase dykes (from 2.5 to 35 m). Andesite dykes are altered and significantly strongly altered within the mineralized zone areas. In our opinion, these dykes are the roots of andesite flows. They even correspond to these flows by their composition.

The alteration character in dykes (porphyritic, silica, sericite, overprinted pyrite alteration) is similar to the alteration observed in andesite flows from mineralized zone wall rocks (contacts), but in the latter the alteration is weaker and becomes less in the lateral direction from the connection and the way-up section. Dykes and flows of andesites are pre-mineralization formations. Andesite flows usually serve as screens for mineralization, and hydrothermal mineralization dies in them.

SURVEY OBJECTIVES, METHOD, AND VOLUME

The geophysical survey was conducted using electrometry, magnetometry, and gamma spectrometry. The main objectives of the geophysical survey conducted on the Khachkovi gold-olymetallic occurrence of the Gujareti-Khachkovi ore field were as follows:

- Geo-mapping: Differentiation of the rocks according to the electrical and magnetic characteristics, potassium, thorium, and uranium contents, and separation of possible faults and intrusive bodies (including covered intrusions).
- Study of geoelectric section at a depth of 130–150 meters (Loke *et al*. 2013; Mosaad *et al*. 2020; Capa-Camacho *et al*. 2022).
- Identification of induced polarization zones and areas with anomalous values of potassium and determination of their association with the possible presence of hydrothermally altered zones and gold-polymetallic mineralization (Han *et al.* 2016; Ohioma *et al.* 2017).

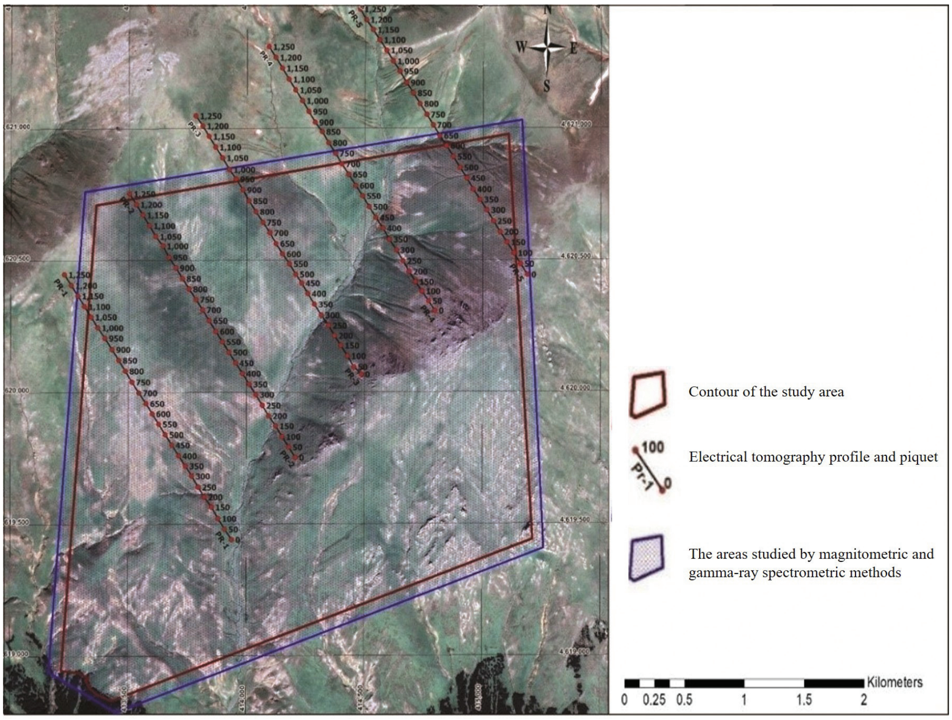

Fig. 3 Layout plan of the electrical tomography profiles and the area studied by the magnetometry and gamma spectrometry methods

In the research conducted using the electrical tomography method, a dipole-dipole modification was employed. The measurements were carried out with a device using feeder distances of AB = 50 meters and receiver distances of MN = 50 meters. The measurement level was set at 8, with a measurement step of 50 meters. The specific measuring device used for this purpose was the "ARES-2." During the electrical tomography study, precise measurements of polarization and specific electrical resistivity values were taken. The survey encompassed five profiles oriented in north-western directions (3200). Each profile had a length of 1250 meters, resulting in a total combined length of 6250 meters for all the surveyed profiles. The layout of these profiles is illustrated in the survey documentation (Fig. 3).

The area of 3,5 square kilometres was studied by the method of magnetometry. The distance between the examined profiles is about 90–110 meters, while between the measured points it is 8.0–13 meters. Profiles have north-western orientations (3200). In the magnetometry research process, magnetic field variations were observed. The measuring device used was "GSM-19TG" (Martin *et al.* 2009).

The area of 3.5 square kilometres was studied by gamma spectrometry. The distance between the researched profiles is 90–110 meters, and the direction of the profiles is north-western (3200). Gamma field recording was performed in continuous mode. The measuring instrument used was "RS-125" (Sukadana *et al.* 2021).

Geophysical survey data was processed by using the computer programs "Res2Dinv", "Mapinfo", "Encom Discover", and "Surfer".

RESULTS OF THE GEOPHYSICAL SURVEY

A comprehensive analysis of existing historical geophysical and geological data, combined with the geophysical survey conducted on the Khachkovi gold-polymetallic occurrence in the Gujareti-Khachkovi ore field, enables us to determine the following:

The geophysical fields observed in the Adjara-Trialeti zone, particularly in the Khachkovi gold-polymetallic occurrence of the Gujareti-Khachkovi ore field, exhibit variability in a wide range of values due to the diverse physical properties of existing rocks and the complex geological structure of the area. The anomalous magnetic field map (Fig. 4), derived from the aeromagnetic survey data, shows that the Khachkovi gold-polymetallic occurrence site is situated within a high-value anomalous magnetic field zone oriented towards the east, which coincides spatially with the distribution of high-value gravity fields. According to the geological-geophysical research data, these high (anomalous) magnetic and gravity field values can be attributed to gabbro-diorite intrusive bodies at depth.

Small outcrops of these intrusions can be observed on the surface near the Khachkovi gold-polymetallic occurrence. The geophysical survey suggests that the potential intrusive bodies at depth to the south of the occurrence are enclosed by deep faults oriented to-

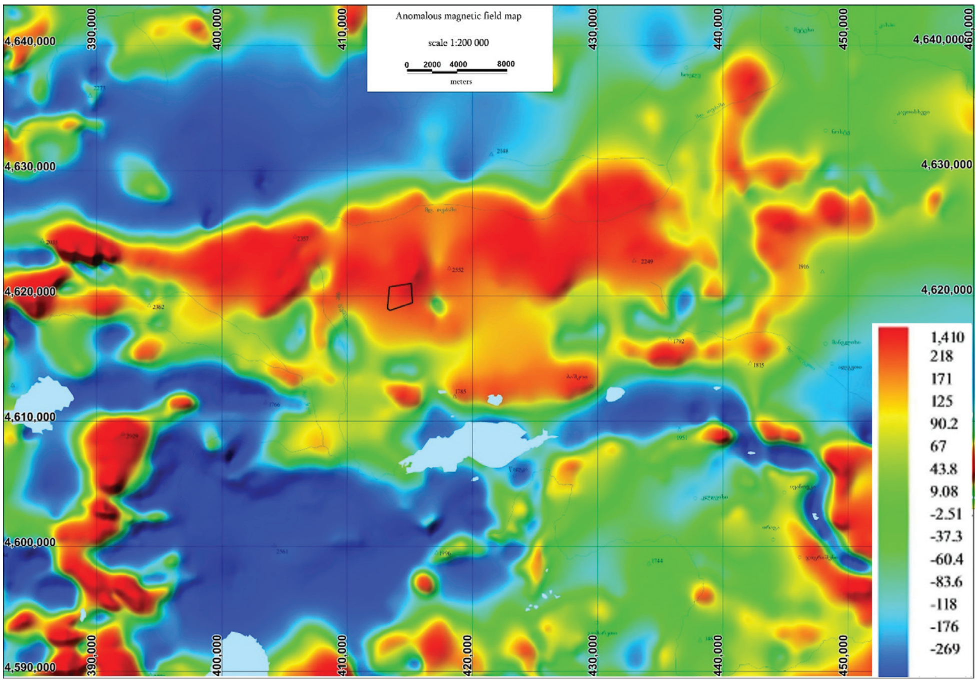

Fig. 4 Anomalous magnetic field map built on aeromagnetic survey data, indicating the contour of the study area

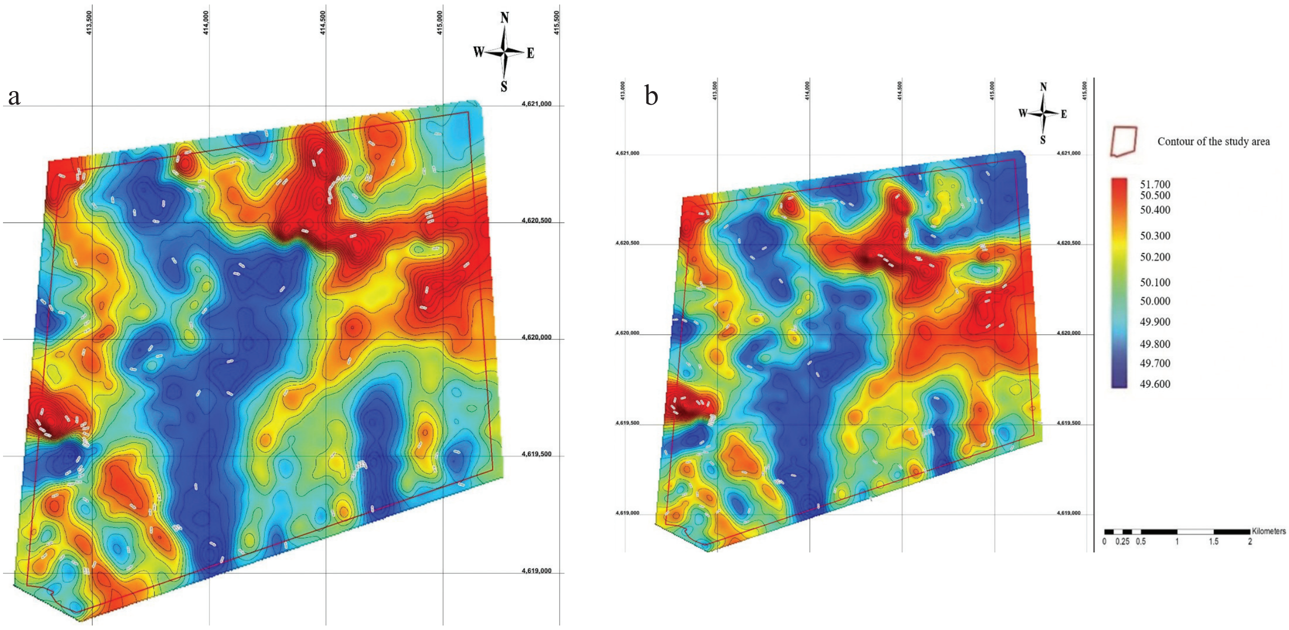

Fig. 5 Magnetic field maps: (a) measured – TMI, (b) pole counted – RTP

wards the east. Conversely, the intrusive bodies are bordered by the Arjevani-Bakuriani sub-latitudinal regional upthrust on the northern side (Mindiashvili, Bluashvili 2022).

In the west and east directions of the mentioned occurrence, possible intrusive bodies at depth have been segmented into separate blocks due to near-meridional fault structures. The Khachkovi gold-sulfide occurrence is situated within one of these segmented blocks (Blakely 1996; Hinze *et al.* 2013).

The Khachkovi gold occurrence (gold-polymetallic, gold-quartz-baryte, etc.) is believed to have a genetic association with diorite magmatism (Okrostsvaridze *et al.* 2021; Mindiashvili *et al.* 2023). Furthermore, it shows structural connections with the conjugated structures formed by the Arjevani-Bakuriani regional faults resulting in fractured and brecciated zones (Bluashvili *et al.* 2020).

Based on the surface magnetometry survey (Fig. 5), the presence of an anomalous zone with high magnetic field values (> 50,300 nT) in the Khachkovi gold-polymetallic occurrence is attributed to the existence of magmatic bodies, including covered magmatic bodies, as indicated by geological-geophysical data. Most of these magmatic bodies are characterized by andesite coverings and intrusions of gabbro-

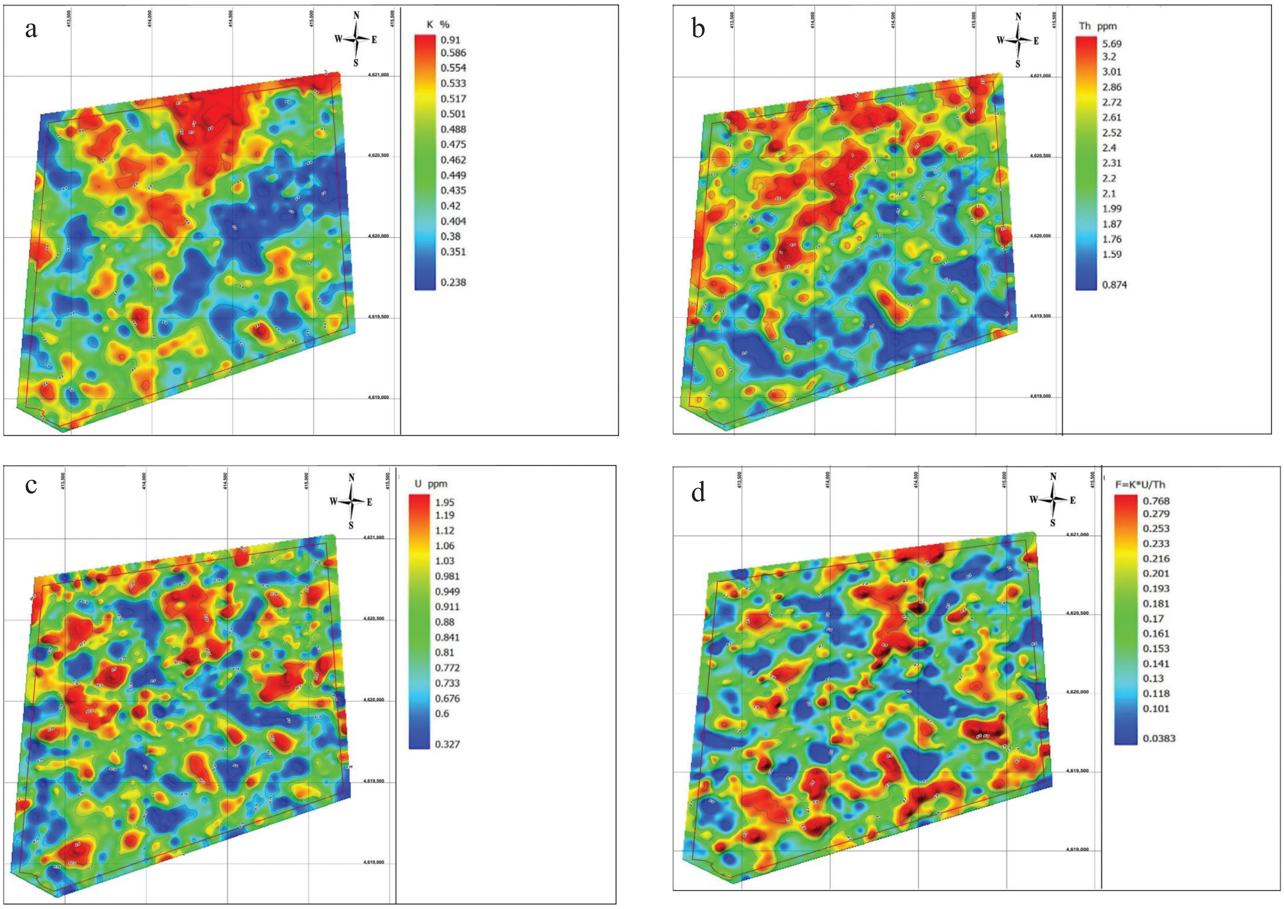

Fig. 6 Maps of gamma spectrometry: (a) map of potassium content, (b) map of thorium content, (c) map of uranium content, (d) F = K*U / Th parameter map

diorite. It is expected that dioritic intrusions (diorite porphyrites, quartz diorites) would be found at depths where the anomalous zone with high magnetic field values (> 50,300 nT) spatially aligns with the area displaying elevated (> 1,300 ohms) values of specific electrical resistivity.

Upon analyzing the maps derived from the geophysical survey data, the hydrothermally altered zones containing sulfide (electrically conductive) minerals are strongly characterized by high polarization values (> 25 mV/V). The elevated and anomalous induced polarization values are attributed to electrically conductive (sulfide) minerals within these hydrothermally altered zones. Based on the findings from the surface geological survey, it is generally observed that hydrothermally altered zones contain pyrite minerals (with rare occurrences of chalcopyrite and sphalerite minerals). It is important to note that the mere presence of pyrite minerals can manifest high polarization values.

The analysis of potassium (K), thorium (Th), and uranium (U) content, as well as the F K*U / Th parameter maps derived from the gamma spectrometry study (Fig. 6) reveal that high anomalous values of the gamma field are not observed in the study area.

However, there are slightly elevated potassium content values (0.7–0.8%), primarily concentrated in the northern part of the study area. Interestingly, this zone of potassium content coincides spatially with the induced polarization anomaly detected in the electrical tomography profiles: Profile-3 piquet 350–550, piquet 750–1000, and Profile-4 piquet 200–4 and 500–650. The presence of this induced polarization anomaly is caused by the existence of a hydrothermally altered sulfide (electrically conductive) mineral-containing zone (Fig. 7).

The low values of potassium (K), thorium (Th), and uranium (U) in the study area could be attributed to two factors: First, the presence of relatively thick quaternary sediments (more than 1–2 meters) may mask or dilute the concentration of these elements in the subsurface. Second, the hydrothermally altered zones on the surface are not exhibiting significant changes in terms of their geochemical characteristics. Considering the geological data, the second reason appears to be more plausible.

According to the geological-geophysical research data, two zones containing hydrothermally altered sulfide minerals have been identified in the Khachkovi deposit area. One of these zones extends in the northeast direction, while the other extends towards the northern direction (north-western). The shape and spreading direction of these hydrothermally altered, sulfidic (electrically conductive) mineral-containing zones are significantly influenced by the existing fault (fracture) zones. The anomalous hydrothermally altered sulfidic zones with electrically conductive minerals are predominantly found near the fault (fracture) zones, intrusive bodies, and brecciated zones at their contact areas.

According to the geological survey data, the zones containing hydrothermally altered sulfide minerals observed at the surface in the Khachkovi occurrence are not characterized by high intensity of alteration. Geological research conducted (Arevadze 1970; Bluashvili *et al.* 2020; Narozauli, Gagnidze 2001; Tskhelishvili 1992) indicates that the surface hydrothermally altered zone is primarily composed of rocks containing pyrites (with occasional occurrences of chalcopyrite and sphalerite minerals), along with relatively few quartz and barite veins found in the zone. The geological survey data aligns well with the findings of the geophysical survey.

Specifically, due to the pyritization of the hydrothermally altered zone, the induced polarization data showed high values in the zone (Fig. 8). The low intensity of hydrothermal alteration observed on the surface is attributed to the low values of potassium (K), thorium (Th), and uranium (U) contents in the gamma fields of the study area.

The hydrothermally altered sulfide (electrically conductive) mineral-containing zone in the northeast direction is spatially aligned with the same strike faults (fractures), possibly covered diorite bodies, and the brecciated zone in its contact areas. In its southwest part, this zone is delineated by the fault of the northern direction, which is observed in the vicinity of Profile-1 of the electrical tomography. According to the geophysical survey, the hydrothermally altered zone in the northeast direction, which contains sulfide (electrically conductive) minerals, extends through the study area but is not delineated.

It should be noted that the gold-containing zone is

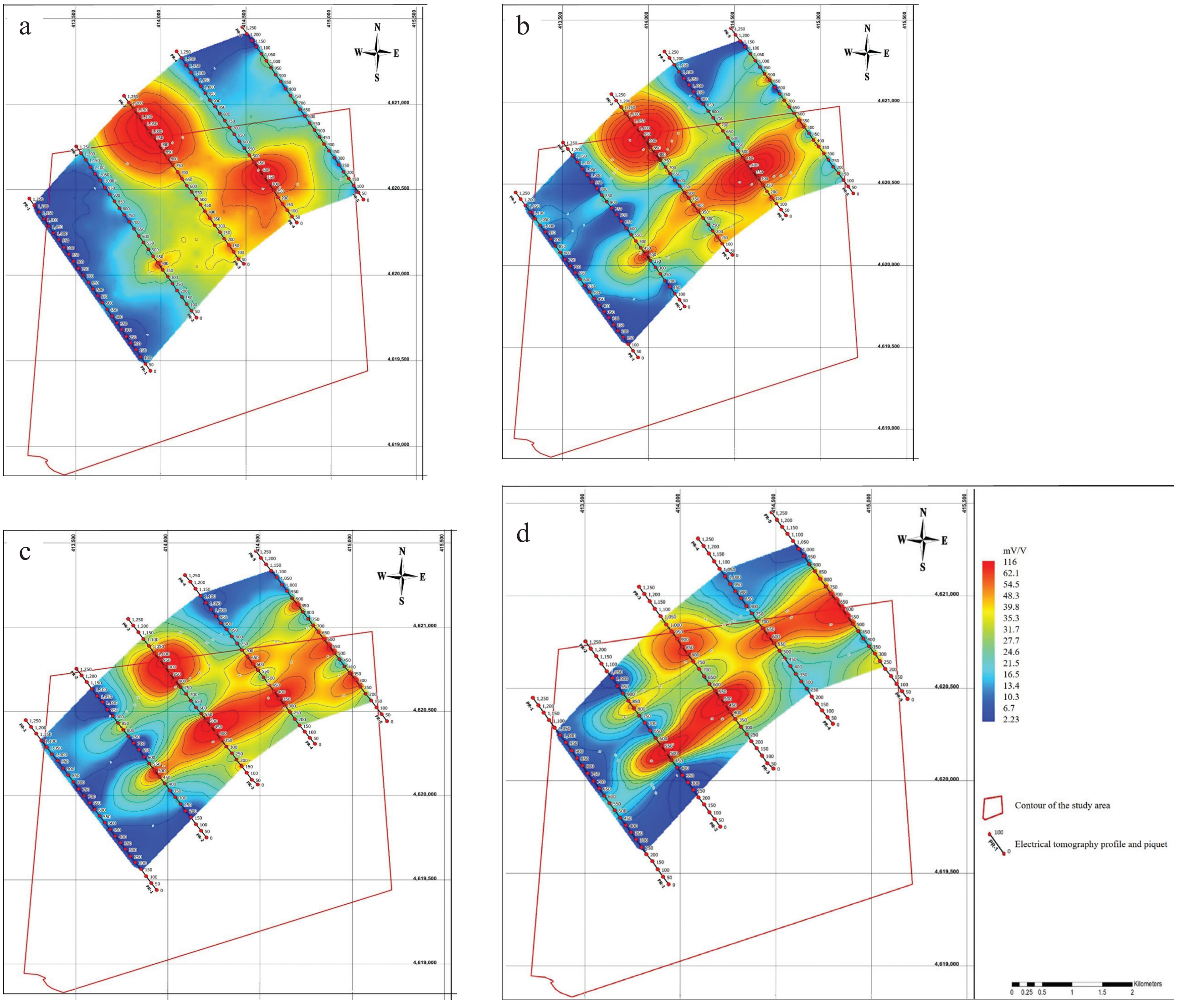

Fig. 7 Induced polarization maps: (a) depth of 25 meters from the surface, (b) depth of 55 meters from the surface, (c) depth of 100 meters from the surface, (d) depth of 150 meters from the surface

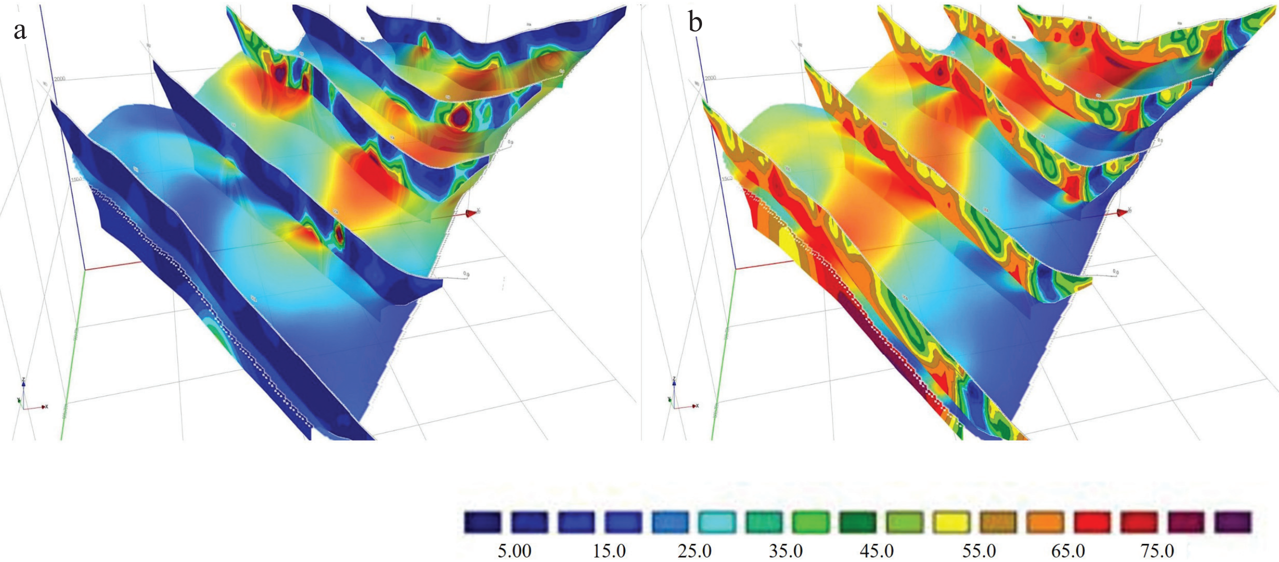

Fig. 8 Electrical tomography sections (induced polarization), with an induced polarization map (built for a depth of 100 meters) (a). Electrical tomography sections (specific electrical resistivity) (b)

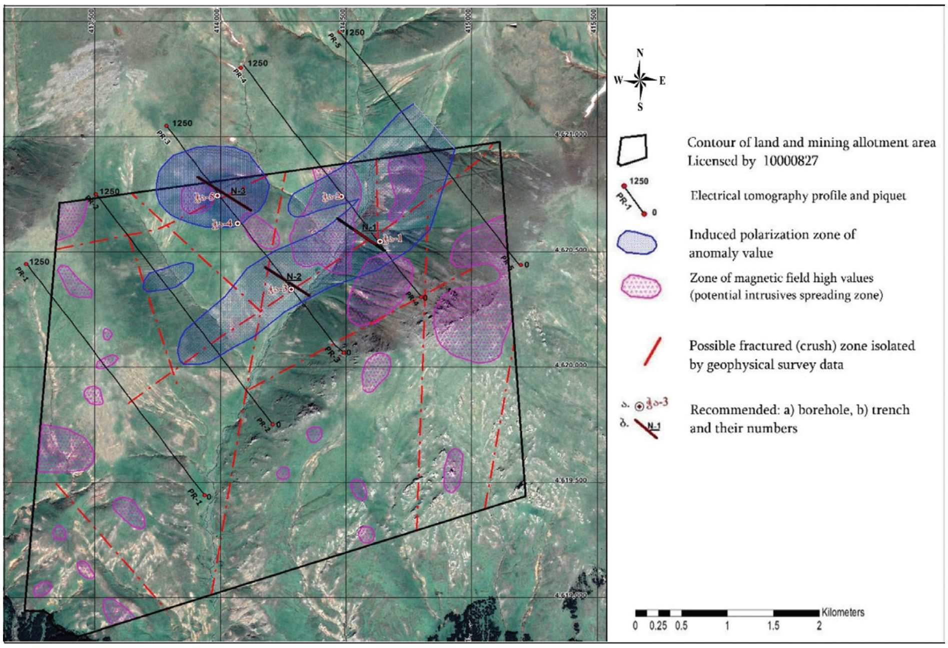

Fig. 9 Results of the geophysical survey, recommended boreholes and trenches

Table 1 Recommended boreholes

##	Pr No	Pk No	X	Y	Recomm. borehole No	Azimuth	Inclination angle	Depth, m
1	PR-4	300	414636	4620544	1	300–320^0	60^0	150–200
2	PR-4	550	414483	4620738	2	300–320^0	60^0	150–200
3	PR-3	355	414283	4620338	3	300–320^0	60^0	150–200
4	PR-3	735	414068	4620623	4	300–320^0	60^0	150–200
5	PR-3	875	413989	4620744	5	300–320^0	65^0	150–200

Table 2 Recommended trenches

Trench No	Profile No	Trench head coordinates		Trench end coordinates		Trench length, m
		X	Y	X	Y	
1	4	414655	4620505	414468	4620645	240
2	3	414354	4620309	414178	4620434	230
3	3	414122	4620681	413909	4620823	240

situated within the hydrothermally altered area in the north-eastern direction (Profile-4, piquet 400–700). The approximate dimensions of this hydrothermally altered sulfide (electrically conductive) zone in the northeast order are about 1400 meters long and 150–350 meters wide.

The hydrothermally altered zone containing sulfide (electrically conductive) minerals and having a north (more north-western) orientation is identified by high induced polarization values (Profile-3, piquet 750–1170). The anomalous polarization zone spatially coincides with a potassium 0.7% content zone and partly with the high importance of the magnetic field zone. This complex anomaly can be attributed to a deep-seated intrusive body whose contact zone with tuff-breccias is hydrothermally altered and contains sulfide (electrically conductive) minerals. The anomaly has an isometric shape, measuring about 420 × 420 metresistivity) sections, we can observe that the polarization anomaly zones (Profile-4; Profile-3, piquet 300–600; Profile-4, piquet 300–500; Profile-5, piquet 500–650) isolated for revealing sulfide mineral-containing rocks are almost vertical, suggesting that the angleers.

Based on the analysis of the electrical tomography (polarization, specific electrical of inclination of the sulfide zone causing the anomaly is close to the vertical. The anomalous zones of high polarization values are not well-defined at depth, indicating that the hydrothermally altered sulfide (electrically conductive) mineral-containing zones extend even below 150 meters, and their spreading area increases at depth.

The recommended boreholes and trenches layout to test the identified anomalous zones is shown on the geophysical survey results map (Fig. 9) and Tables No 1 and No 2.

DISCUSSION

The geophysical survey on the Khachkovi gold-polymetallic occurrence of the Gujareti-Khachkovi ore field aimed to achieve several objectives. These objectives included geological mapping, studying geoelectric sections, identifying induced polarization zones and anomalous potassium values, and establishing their association with hydrothermally altered zones and gold-polymetallic mineralization (Telford *et al.* 1990). The survey utilized three geophysical methods: electrometry (electrical tomography-dipole-dipole scheme), magnetometry, and gamma spectrometry (Sharma 1997). The measurements were carried out on multiple profiles and points within a 3.5 square kilometre area. The geophysical data were processed using various computer programs. The geophysical survey results provided valuable information about the geological features and mineralization potential of the Khachkovi gold-polymetallic occurrence. The data revealed the presence of gabbro-diorite intrusive bodies at depth, which were responsible for the anomalous magnetic and gravity field values observed in the area. These intrusions were surrounded by faults and regional upthrusts, indicating a complex geological structure. The geophysical survey also identified hydrothermally altered zones containing sulfide minerals. These zones exhibited high values of induced polarization, indicating the presence of electrically conductive minerals. The analysis of potassium, thorium, and uranium content, as well as the F = K*U / Th parameter showed slight anomalies in the potassium content and low values of other elements. This suggests the presence of Quaternary sediments and relatively low-intensity hydrothermal alterations in the study area (Lorenzo 2014; Pirajno 2009). The spatial distribution of the hydrothermally altered zones was influenced by fault zones, intrusive bodies, and breccia zones in contact areas. The geological survey data supported the findings of the geophysical survey, confirming the presence of pyrite and occasional quartz and barite veins in the hydrothermally altered zone. Overall, the geophysical survey provided valuable insights into the geological and mineralogical characteristics of the Khachkovi gold-polymetallic occurrence. The data can serve as a basis for further exploration and assessment of the occurrence prospectively. The maps and sections generated from the survey data are valuable tools for understanding the subsurface features and planning future exploration activities, such as drilling and trenching (Kearney *et al*. 2002).

CONCLUSIONS

Based on the analysis of the data obtained from the geophysical survey, the following results can be summarized:

Hydrothermally altered zones of the north-eastern and northern (more north-western) orientations containing sulfide (electrically conductive) minerals were identified and mapped. Surface geological observations revealed the presence of pyrite minerals (with occasional chalcopyrite and sphalerite minerals) within these zones, along with limited occurrences of quartz and barite veins.

The dimensions of the anomalous zones caused by the hydrothermally altered sulfide (electrically conductive) mineral-containing zones were determined, along with their distribution in depth, angle of inclination, and orientation.

The geophysical survey data also identified and mapped covered intrusive bodies.

Additionally, fault (fracture) zones were isolated and contoured using the geophysical survey results.

These findings offer valuable insights into the geological characteristics and prospects of the Khachkovi gold occurrence, facilitating further exploration and enhancing our understanding of the mineralization potential in the area. To validate the data obtained from the geophysical survey, it is advisable to employ geological methods to verify the anomaly zones identified as a result of the geophysical survey. This verification should encompass surface and in-depth assessments to ascertain the presence of gold content in the specified zones. Such comprehensive validation will enhance the reliability and accuracy of the survey results, aiding in making informed decisions for potential mining and exploration activities.

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