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Integrated Geophysical and Geochemical Characterization of Subsurface Sulfide Mineralization Over Parts of Gawuch Formation, Chitral, North Pakistan

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Abstract. A multidisciplinary approach combining geophysical and geochemical exploration techniques which have been employed in this study. The sulfide minerals characterization hosted in the Gawuch formation, Chitral, northern Pakistan. Geologically, the mineralization is observed in several forms such as disseminated, fracture filling and supergene enrichment. The geophysical survey, using the electrical self-potential (SP) method have identified five prominent circular to semi-circular, high conductive or negative (SP) anomaly closures (A, B, C, D and E). These anomalies suggest geological discontinuities or fracture zones typical of porphyry deposits, indicating the potential in which presence of a subsurface network of fractures or veins that could be promising drilling targets for sulfide mineral prospection in the area. The half-width method indicates that the anomaly sources range from near surface to around 22.48 meters deep, suggesting shallow mineralization targets. Shallow core drilling and samplings further confirmed the geophysical anomalies and yielding an average geochemical composition of Cu (7.84%), Fe (28.34%), Pb (87.2 ppm), Sb (157 ppm), Zn (446 ppm), Ag (75.5 ppm) and Au (0.14 ppm), thus confirming the presence of polymetallic sulfide deposits. The integrated geophysical, core drilling, geological and geochemical analysis has led to the interpretation that sulfide mineralization in the Gawuch formation, Chitral region is structurally controlled by NNE-SSW trending fault/fracture system and associated with diorite-granodiorite intrusion which exhibit affinities with porphyry systems, thus intimating a potential porphyry style mineralization.

Keywords: sulfide minerals, electrical self potential, anomalies, porphyry deposit, core drilling.

Introduction

The global supply of essential metals like copper, lead, antimony, iron, zinc, nickel relies heavily on the extraction of sulfide minerals, making them the most valuable ore minerals in the mining industry. Their extraction process is a crucial component of modern society, driving economic progress, technological innovation and infrastructure development. The northern regions of Pakistan have been a prime target for mineral exploration and extraction owing to their geologically complex terrain that harbors an extensive array of economically significant minerals including porphyry copper, breccia related epithermal gold deposits, placer deposits, gemstones and sulfide-rich quartz veins from hydrothermal processes (Farhan *et al*., 2023; Ali *et al*., 2021; Hussain *et al*., 2021; Anjum *et al*., 2018). Previous geological studies in the Chitral region have identified the occurrence of sulfide minerals, including lead, antimony and copper (Calkins *et al*., 1981). Additionally, geochemical analysis of chip samples have validated the occurrence of these minerals with notable traces of silver and gold and also indicate in a prospective area for mineral exploration and extraction. The geophysical physical and chemical properties of sulfide deposits, whether disseminated or massive, differ significantly from those of their host rocks, reported by (Thomas *et al*., 2000). A geophysical key signature of sulfide minerals is high electrical conductivity which attributed to the presence of mobile electrons in their crystal lattice. This conductive property is highly advantageous for advanced geophysical techniques, including self-potential (SP), induced polarization (IP) and electro-magnetic (EM) surveys, which can identify in map differences in conductivity between sulfide-rich rocks and their surrounding formations (Morgan, 2012).

The study area, Drosh-Kaldam Gol lies in Chitral, northern Pakistan which is situated at the northwestern edge of an intra-oceanic arc named as Kohistan island

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Arc (KIA) terrain, a region of significant tectonic activity and crustal deformation (Fig. 1). This terrain is sandwiched between the Indian and Karakoram landforms. Its southern and northern boundaries are defined by the Main Mantle Thrust (MMT) or Indus Suture Zone (ISZ) and the Karakoram-Kohistan Suture, which is also referred to as the Main Karakoram Thrust (MKT) or Shyoke Suture Zone (SSZ) Shown in Fig 1 and reported by (Ullah *et al*., 2022ab; Petterson, 2010; Coward *et al*., 1986; Bard *et al*., 1980; Tahirkheli and Jan, 1979). The cover sequence in this portion of the Kohistan terrain comprises meta-basalts and metasites, with interbedded carbonate rocks, including limestone and marble, belonging to the cretaceous Gawuch formation (Pudsey *et al*., 1985). These lithologies are considered as the western counter parts of the Chalt-Yasin group located in the Hunza and Yasin valleys of Gilgit Baltistan (Petterson and Windley, 1991; Tahirkheli, 1979). The Gawuch formation has been intruded by numerous early eocene age (40-45Ma) dykes and sills having diorite and granodiorite composition, which are genetically linked to the Kohistan batholith's Lowari pluton (Tahirkheli *et al*., 2012). Notably, sulfide mineralization in the Gawuch formation, Chitral region has been observed to be spatially associated with these diorites, granodiorites and accompanying quartz veins (Farhan *et al*., 2023; Tahirkheli *et al*., 2005).

A significant gap in geophysical data exists regarding the occurrences of sulfide ore mineralization in the area under investigation. This deficiency necessitates comprehensive geophysical investigations to thoroughly map the underlying geological features, such as faults, fractures, alteration zones. The primary aim is to detect anomalies that may signify the presence of subsurface sulfide mineral concentrations. By integrating the geophysical data with the geological and geochemical outcomes, a more comprehensive and precise understanding of the study area will be achieved (Brown and Patel, 2023; Smith *et al*., 2022).

The aims of this study is to conduct a comprehensive geological interpretation in area using self-potential geophysical and geochemical techniques. The objectives are as:

- Map the subsurface distribution pattern of sulfide minerals occurrences.
- Examine structural lineaments and trends and evaluate their effect on mineralization.
- Determine the depth and extent of geophysical anomalies.
- Identify drilling prospects with high economic potential for sulfide ore minerals.
- Validate geophysical interpretations through shallow borehole drilling and geochemical analysis of core and grab samples from geophysical anomalous sites.

The under utilization of geophysical techniques in the northern region of Pakistan has resulted in a significant oversight. The proposed study seeks to rectify this by introducing a novel paradigm for identifying new avenues for mineral potential zones and enhancing exploration activities in the region.

Regional and local geological setting. The northern segment of the Kohistan arc terrain is tectonically divided into three distinct units that are: Shyok suture mélange sedimentary volcanic cover sequence and Kohistan batholith (Fig. 1). The Shyok suture is a geologically complex entity that displays a range of manifestations, from a sharp fault to a wide, 4 Km zone of deformation. This zone is characterized by a melange of heterogeneous blocks, including basalts, serpentinites, marbles, sandstones, conglomerates embedded in a turbiditic slate matrix, which collectively define the Shyok mélange zone (Pudsey and Maguire, 1986). This zone serves as a significant tectonic boundary, delineating the Kohistan terrain from the Eurasian plate to the north and signifies the termination of the northern Neotethys branch, referred to as the Shyoke ocean (Tahirkheli *et al*., 2012; Khan *et al*., 1989; Bard *et al*., 1980; Tahirkheli and Jan, 1979). Within the Kohistan Arc terrain, a prominent lenticular belt is characterized by a volcano-sedimentary cover sequence lying between the northern Shyok suture and the southern Kohistan batholith. The basal unit of metabasalts, referred to as the Chalt volcanics (Petterson and Windley, 1991) which defines the sequence, succeeded by a diverse set of quartzites, limestones and turbidites, forming the Yasin group (Pudsey and Maguire, 1986; Pudsey *et al*., 1985). The Kohistan batholith is a large intrusive complex that cuts across the Shyok suture and volcano-sedimentary cover sequence, comprising a range of plutons from gabbros to granites. It constitutes the core of the Kohistan terrain and preserves a protracted magmatic history spanning 73 million years, from 102 to 29 Ma (Petterson and Windley, 1986).

The study area in Chitral (Fig. 2), encompassing the Drosh-Kaldam gol area, is located at the northwestern extremity of the Kohistan island Arc and exhibits all the three tectonic components mentioned earlier. The region's stratigraphic framework comprises cretaceous metasediments and Eocene volcanic rocks, which are

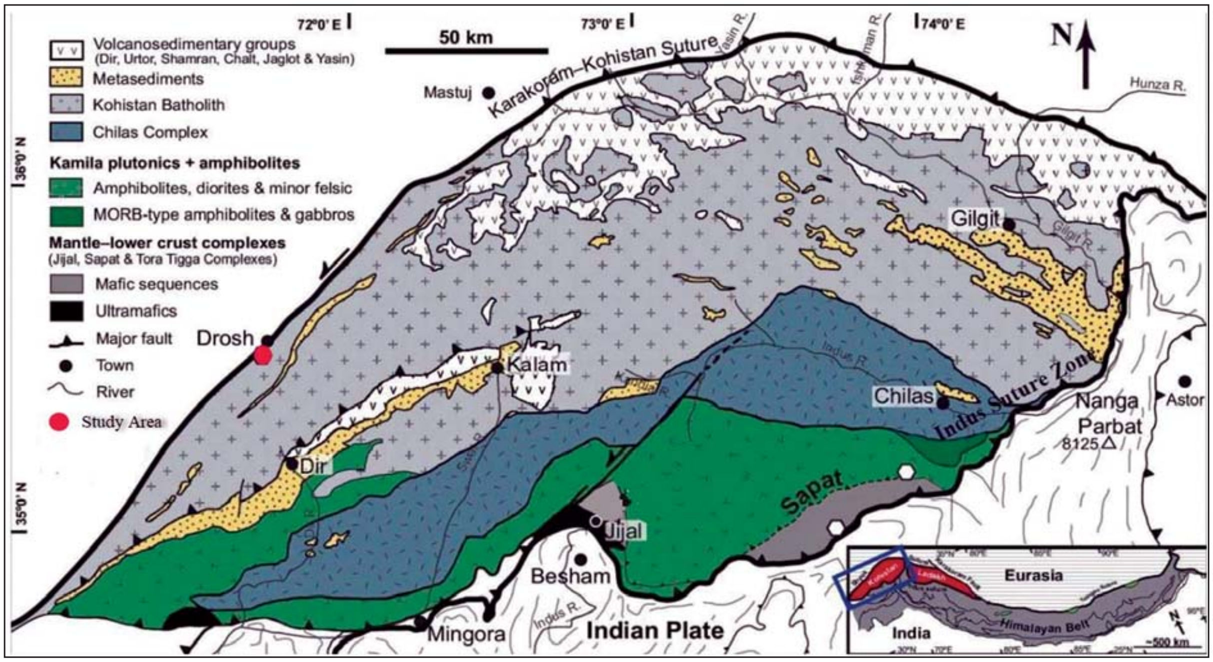

Fig. 1. Geological map of the Kohistan Island Arc, northern Pakistan, showing structural setting and location of the study area after (Ewing and Muntener, 2018).

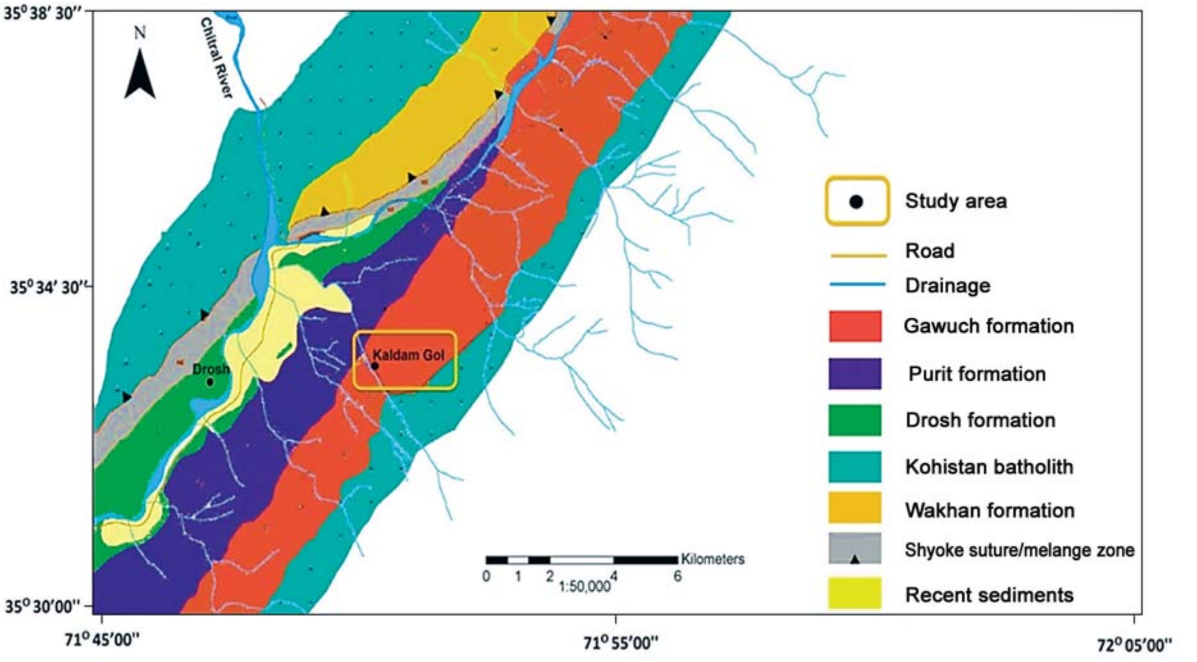

Fig. 2. Geological map showing stratigraphic units in Drosh area, Chitral, northern Pakistan, with orange rectangle depicting locality of the study area after (Rashid *et al*., 2019).

further sub divided into three distinct formations, progressing from north to south, the Drosh formation, Purit formation and Gawuch formations (Pudsey *et al*., 1985).

The Drosh formation is characterized by a sequence of andesite and dacite volcanics, exhibiting porphyritic textures with varying bed thickness, which rests atop the Purit formation. This volcanic sequence is likely a product of an eocene volcanic event, analogous to the one that occurred in Dir-Utror volcanics (Shah and Shervais, 1999). In contrast, the Purit formation has a fluvial origin, characterized by a suite of calcareous red conglomerates, shale and sandstones (Pudsey *et al*., 1985). The Gawuch formation, on the other hand, is probably marine in origin, consisting of meta volcanics, phyllites and carbonate lithologies, including limestone and marble, which have been intruded by quartz veins, granodiorite and diorite. The formation's southern contact with the Kohistan batholith's Lowari pluton is intensely sheared, with phyllites derived from Gawuch meta volcanics through mylonitization (Farhan *et al*., 2023; Tahirkheli *et al*., 2012) shows in Table 1. Sulfide mineralization in the Gawuch formation has been reported to be linked with Kohistan batholith (Farhan *et al*., 2023; Tahirkheli *et al*., 2012).

Table 1. Stratigraphic units near Drosh Kaldam Gol, Chitral (Pudsey *et al*., 1985).

Formation name	Type locality	Lithology	Thickness
Drosh formation	Drosh Gol	Andesites and dacites	1.5 km
Purit formation	Purit Gol	Red shales, sandstones and conglomerates.	1.5 km
Gawuch formation	Gawuch Gol	Metavolcanics, marble and intrusive rocks	02 km

Materials and Methods

Self potential method. Self potential, or spontaneous polarization (SP) and it is a passive method in geophysical exploration that is used to measure natural electrical potentials between two surface points on the earth, generated by hydrological or geochemical processes (Azunna and Chukhu, 2018; Godwin, 2016; Corey *et al*., 1983). This method has a rich history, dating back to 1830 when Robert Fox, first conducted SP experiments in Cornwall's tin mines, making it one of the oldest electrical geophysical exploration techniques (Soupios and Karaoulis, 2015; Burr, 1982; Fox, 1830). Later, in 1882, Carl Barus employed the same technique at Nevada's Comestock Lode. The SP method made a pioneering discovery in 1907 by detecting the first sulfide ore deposit through electrical means at Nautenen, Lapland, Sweden (Burr, 1982; Lunberg 1948). This method is highly effective in detecting large anomalous surface potentials associated with various ore bodies, including chalcopyrite, pyrite, pyrrhotite, galena, graphite, and magnetite, as well as groundwater accumulations (Azunna and Chukhu, 2018; Jinadasa and De Silva, 2009; Corey *et al*., 1983). The measured potentials, reported in millivolts (mV) which are relative to a designated 'survey base' point, which is assigned an arbitrary zero-volt potential, serving as a reference point for the measurements. In mineralized zones, SP anomalies often display a wide range of values, spanning from a few millivolts to more than one volt, with negative potentials typically recorded above the mineralized body compared to surrounding areas. These negative potentials result from sulfide oxidation or valence electron stripping (Corey *et al*., 1983).

SP Sources. There are various phenomenological sources of SP, including electro-kinetic (also known as electro-mechanical or streaming potential) which is arises from the movement of ions, fluids and electric charges (Lyklema, 1995), electrochemical potential emerges from the differential distribution of chemical species in groundwater (Stoll *et al*., 1995), thermoelectric effect induced by electric current within fluid-saturated porous media (Revil, 1999; Marshall, 1959), rapid fluid disruption is caused by heated gases that lead to the separation of electric charges (Lewicki, 2003; Johnston *et al*., 2001) and finally, oxidation and reduction reaction stemming from contaminants, plume interactions or subsurface ore body and groundwater interactions lead to redox potential (Ebrahimzadeh, 2015; Revil *et al*., 2009; Naudet *et al*., 2003). The redox potential phenomenon is a type of electrochemical process, where the conductive properties of the ore body enable oxidation reactions above the water table and reduction reactions below it. This can lead to a consistently negative self potential, typically varying from several hundred millivolts and above conductive minerals like pyrite, chalcopyrite, magnetite graphite and pyrrhotite (Sharma, 1997).

The geo-battery model, established by Sato and Mooney (1960) and it is the basis for most mineral exploration fieldwork (Fig. 3). This model is grounded in the principles of redox gradients and electronic conduction, where the ore body acts as a conducter, facilitating the flow of electric current. The ore body's upper section functions as a cathode, undergoing reduction, whereas the lower section serves as an anode, undergoing oxidation, thereby generating a measurable electric potential difference. This process generates negative SP anomalies detectable at the surface, caused by the migration of ions in the ground and electrons in the conductive ore body (Ebrahimzadeh, 2015). The SP source mechanism and its diverse range of potential applications, renders it an optimal geophysical technique for various fields, including groundwater, geothermal and volcanic systems, environmental and geotechnical engineering and mineral investigations (Roy, 2021; Minsely, 2007; Heinson *et al*., 2005; Sheffer *et al*., 2004; Revil *et al*., 2001; Corwin, 1990).

Data acquisition and analysis. The SP method is widely employed in mineral exploration for the identification of metallic sulfide ore deposits, including pyrite, chalcopyrite, galena and pyrhotite due to its advantages of being cost effective, rapid and non-invasive capabilities (Essa and Munschy, 2019; Corey *et al*., 1983). This technique is capable of identifying both massive and scattered sulfide deposits, producing distinct anomaly signatures (Parasnis, 1986). Its operational simplicity, cost-effectiveness and straight forward methodology make SP measurement an ideal option for initial exploration and reconnaissance studies, providing valuable insights into subsurface geology. The field equipment used in this study for data collection included non-polarizing electrodes, digital multimeter (UNI-T), insulated wire, connectors and clips and copper sulfate salt. Field measurements were collected using a digital multimeter, facilitated by two porous pots filled with copper sulfate solution, which established a non-polarizable connection to the ground through copper electrodes, ensuring precise data acquisition. To calibrate the base to roving pot drift voltage, pre-survey procedures involved placing filled porous pots in close proximity within a ground pit at the base station and using a meter to measure the voltage between them show in (Fig. 4a & b). If the measured voltage difference was negligible (*i.e*, approaching zero), the survey was deemed ready to proceed as outlined in the protocol (Corey *et al*., 1983).

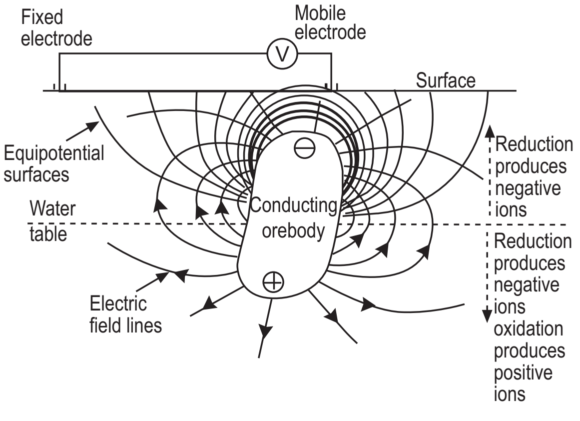

Fig. 3. Schematic illustration of the Sato-Mooney geo-battery electrochemical model of the self-potential anomaly caused by an ore body after (Azunna and Chukwu, 2018; Sato and Moony, 1960).

The area under investigation has been segmented into two separate blocks, namely Block-1 and Block-2, considering the mineralization distribution and accessibility factors of each block. block-1 is located on the right bank of the Kaldam Gol river, while block-2 is situated on the left bank, allowing for a more targeted approach to data collection and analysis (Fig. 5). Our geological field investigations in the study area have revealed a complex sulfide mineralization system, manifesting in multiple forms, including: quartz-vein hosted sulfides, sulfides concentrated along foliation planes, scattered and disseminated sulfides and supergene sulfide enrichment. The study area's treacherous terrain, marked by steep slopes and a rugged landscape, presented significant obstacles to carrying out a geophysical survey in a conventional grid pattern. To overcome this challenge, the fixed base electrode technique was utilized to gather self potential data along irregular profiles that followed dry mountain streams, foot tracks and areas with gentler slopes. This process entails securing one end of the wire to the reference or base electrode, then extending it to the first station. At this point, the mobile electrode is positioned in a shallow earth pit (Fig. 3). The difference in electric potential between the base and mobile electrodes is measured, with the polarity of the voltage difference noted in accordance and a standard convention. Throughout the entire procedure, the negative lead (black) of the multimeter remains connected to the base pot, ensuring a consistent and standardized measurement methodology. Following each voltage measurement, the roving or positive electrode is repositioned and the wire is uncoiled to the next station, with this process being repeated in a sequential manner until the wire's full length is utilized, thereby marking the completion of the survey.

Fig. 4. Field photographs showing **(a)** SP data measurement using a digital multimeter during the field work **(b)** Measurement of base to roving pot drift voltage at the base station.

To achieve optimal coverage of the area, a survey design consisting of 24 irregular profile lines was established for measuring raw SP data across the study area. It based on geological trend calculations and key features like oxidized and alteration zones and mineral extensions along the NNE-SSW trend of the Gawuch formation. Aligned perpendicular to the host rock formation, the profiles recorded 341 SP readings at intervals of 10 and 20 meters. These profiles ranged from 80 to 700 meters in length, collectively spanning a distance of 4.44 kilometers (Fig. 5). A data sheet was used to record survey details including absolute voltages, time, date, area, personnel, profile line, station number and GPS coordinates. The minimum curvature gridding appling method in Golden Surfer software longitudinal profiles, 2D and 3D maps were created to highlight SP anomaly zones. The subsequent analysis of these maps and profiles was aimed at assessing susceptibility, exploring variations and estimating anomaly depths to pinpoint prospective sulfide deposit locations.

Geochemical methods. In this study two types of samples, drill core and grab samples were collected from geophysical anomalous sites during the fieldwork, for in-depth geochemical analysis and integration with geophysical findings. The Shaw backpack core drill rig was used to extract shallow drill core samples in the field. Its compact, light weight design makes it ideal for exploring mineral deposits in challenging terrains,

Fig. 5. Satellite illustration showing self potential data sets within Block-1 and Block-2 of the study area.

such as mountainous areas or areas with limited access. Its portability user-friendly design enable quick, efficient drilling, sampling, allowing for rapid exploration and data collection. During the fieldwork, detailed records and photos were taken of rock unit interfaces and their physical characteristics. GPS coordinates were recorded to precisely geotag sample locations and reference points. The resulting core and grab samples were carefully organized, labeled and transported to the National Centre of Excellence in Geology (NCEG), University of Peshawar for detailed geochemical examination of both base and precious metals.

Atomic absorption spectroscopy (AAS) was employed at NCEG's labs to analyze the concentrations of precious metals such as gold and silver, while base metal concentrations (copper, lead, antimony, iron, zinc, manganese, nickel and cobalt) which were determined with a handheld XRF analyzer (Niton Gun). Furthermore, mineral phases were identified through X-ray diffraction (XRD) with a JDX-3552 Diffractometer at the University of Peshawar's Centralized Resource Laboratory.

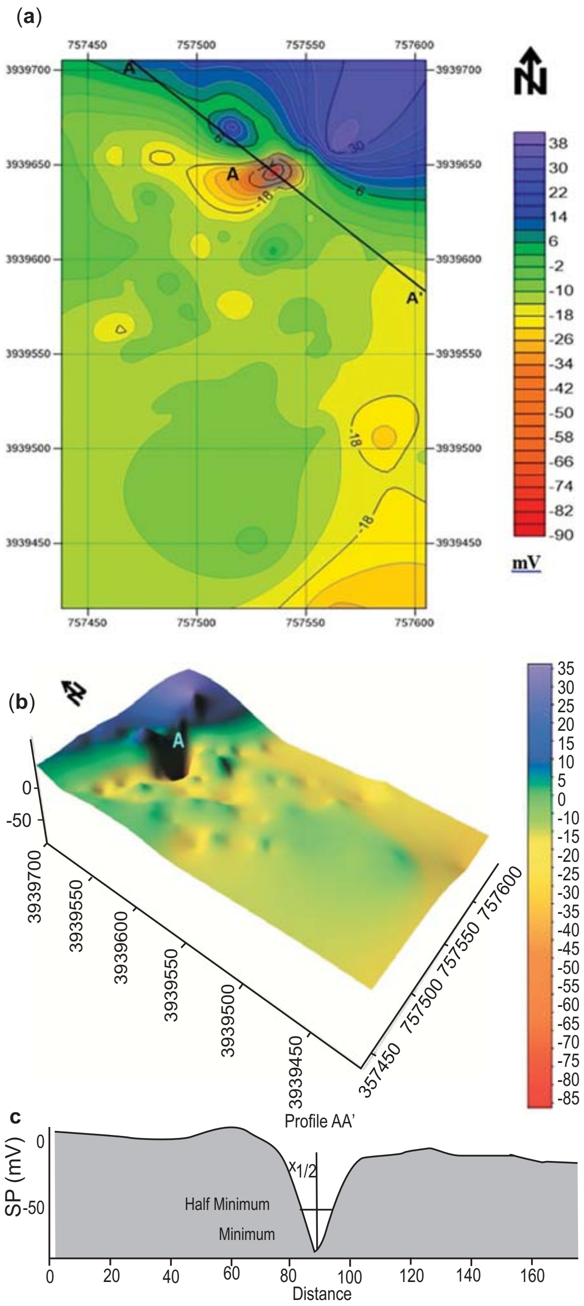

Fig. 6. Illustrations showing **(a)** 2D equipotential contour map **(b)** 3D surface distribution map of Block-1 highlighting the location of anomaly 'A' and **(c)** Longitudinal profile section AA' of anomaly "A" derived from 2D contour map for depth estimation using half width rules.

Results and Discussion

Qualitative analysis of SP data. SP data maps were qualitatively analyzed to infer subsurface geological, structural and lithological features. The SP data exhibit a wide range of values, varying from a few millivolts to -156 millivolts, indicating a non-uniform distribution of anomalies across the area, with significant heterogeneity. The 2D equi-potential contour analysis of Block-1 and Block-2 in the study area (Figs. 6a, 7a, 8a and 9a), reveals a complex spatial distribution of SP values, characterized by both negative and positive readings. The presence of conductive minerals, such as sulfides or oxides, is implied by the reddish to yellowish colour spectrum, which corresponds to negative values, while non-conductive minerals are denoted by the bluish to greenish hues, which represent positive values in the dataset (Azunna and Chuku, 2018), while the 3D surface distribution of self potential anomalies within the surveyed area is depicted in (Fig. 6b, 7b, 8b and 9b) providing a clear and intuitive visualization of the concentration and extent of conductive minerals, facilitating a better understanding of their spatial distribution. Furthermore, the visualizations reveal scattered indication of moderately negative SP values across the study area, signifying the existence of sulfide ore fragments or isolated blocks within the overburden. These scattered signatures suggest that sulfide ore is dispersed throughout the area, rather than a concentrated deposit. Analysis of the 2D equipotential and 3D surface maps revealed five prominent anomaly closures, labeled as anomaly A, B, C, D and E which is characterized by negative SP values of -95 mV, -26 mV, -156 mV, -96 mV and -103 mV, respectively, suggesting the presence of subsurface sulfide mineralization in the study area.

Quantitative analysis of SP data. The process of estimating depth involves a quantitative examination of geophysical data from targeted profiles, enabling the interpretation of anomalies and a deeper understanding of the subsurface geological structure. This analysis seeks to refine the data by eliminating extraneous signals and retaining only the geologically significant information. The depth of anomaly sources can be estimated based on the principle that depth influences anomaly shape, with shallower sources producing narrower, sharper anomalies and deeper sources producing broader, flatter ones (Abdulbariu *et al*., 2016). Golden Surfer software was used to generate longitudinal profile sections for SP anomalies in both Block-1 and Block-2, which are displayed in Fig. 6c, 7c, 8c and 9c. The half-width rule (Nettleton, 1976) was employed to approximate the depth to the center of the anomalous bodies. This method involves measuring half the width of the anomaly at the midpoint of its peak value, where the amplitude is half of the maximum or minimum show in Fig. 10 (Adeyemi *et al*., 2006; Sheriff, 1991). The depth was calculated using the following equation:

$$Z = X_{1/2}$$

where Z is representing the depth and $X_{1/2}$ is the half width at the negative maximum.

A summary of the estimated depths of the identified SP anomalies in the study area, calculated using the half-width rule is provided in Table 2.

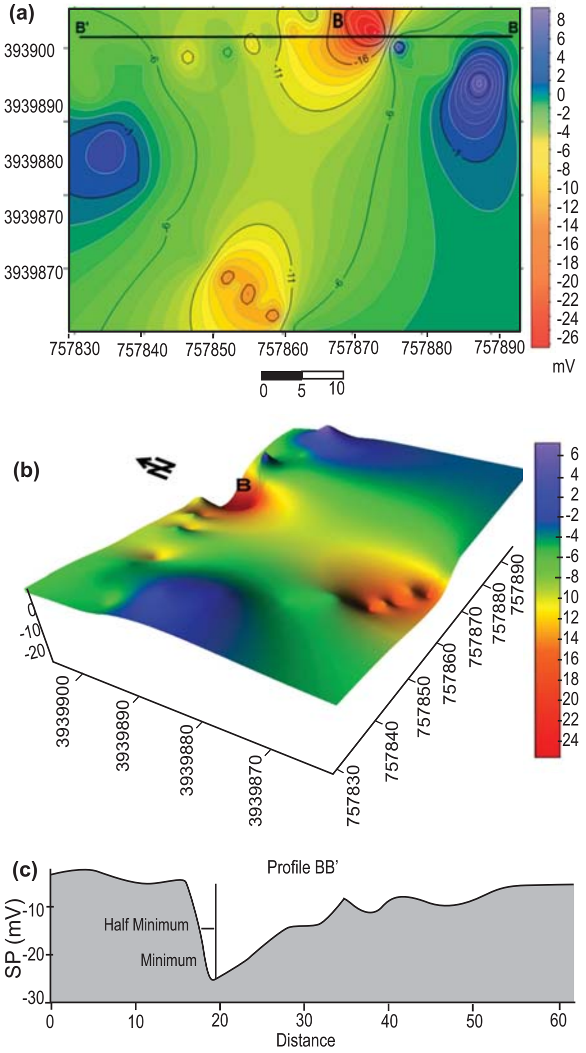

Fig. 7. Illustrations showing **(a)** 2D equipotential contour map **(b)** 3D surface distribution map of Block-1 highlighting the location of anomaly 'B' and **(c)** Longitudinal profile section BB' of anomaly "B" derived from 2D contour map for depth estimation using half width rules.

Pilot drilling and geochemical analysis. Given the successful identification of multiple sulfide mineral occurrences at shallow depths within the study area through electrical self potential surveying, it was deemed beneficial to conduct drilling and confirm for further investigate these findings. Therefore, a shallow pilot drilling was initiated, utilizing the shaw backpack portable drill rig to collect core samples from the geophysical anomalous zones (Fig. 11a). Considering their convenient locations and nearby access to the Kaldam Gol river, anomalies A and D were chosen for drill testing as they can be easily supported with a reliable water supply, facilitating efficient drilling operations. The shallow intersection of sulfide mineralization in both drill holes, within 6 feet from the surface, suggests a near-surface mineralized zone with potential for further mineralization at depth. Geochemical analysis of the core samples revealed significant concentrations of valuable metals i.e., anomaly A is characterized by high grades of copper (7.56%) and iron (23.05%), accompanied by notable levels of silver (12 ppm) and gold (0.141 ppm), while anomaly D contains copper (0.18%) and iron (5.22%)

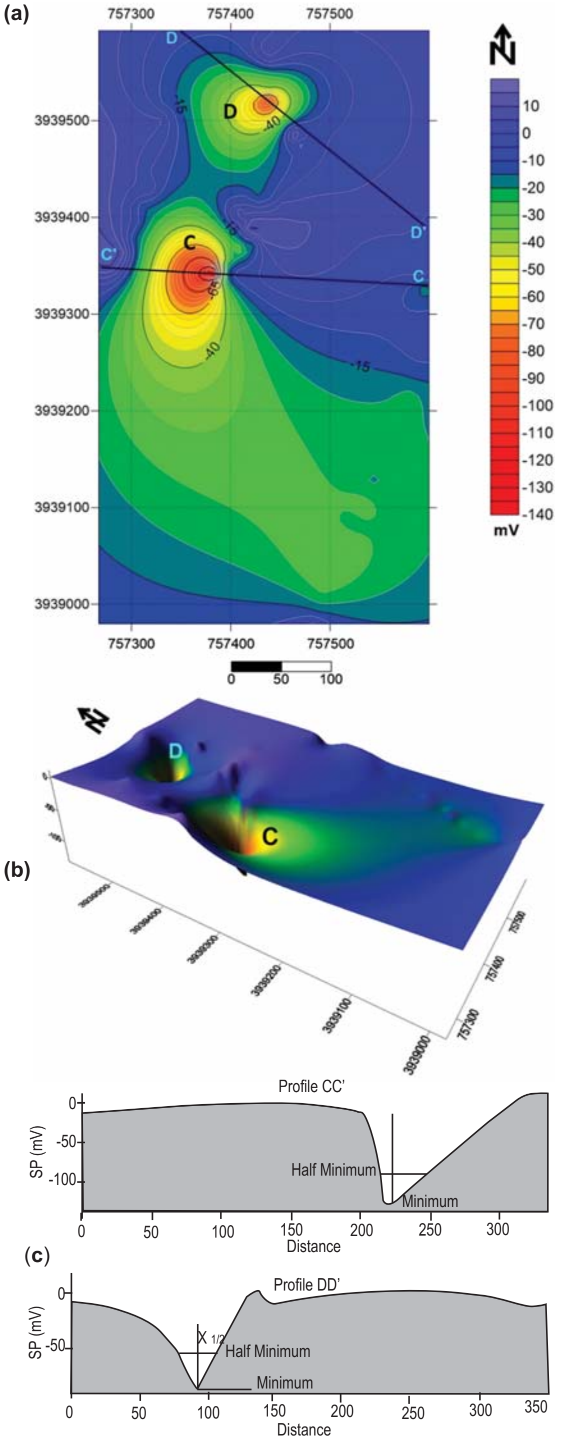

Fig. 8. Illustrations showing (**a**) 2D equipotential contour map; (**b**) 3D surface distribution map of Block-2 highlighting the locations of anomaly 'C' & 'D' and (**c**) Longitudinal profile sections CC' & DD' of anomaly "C" and anomaly "D" derived from 2D contour map for depth estimation using half width rules.

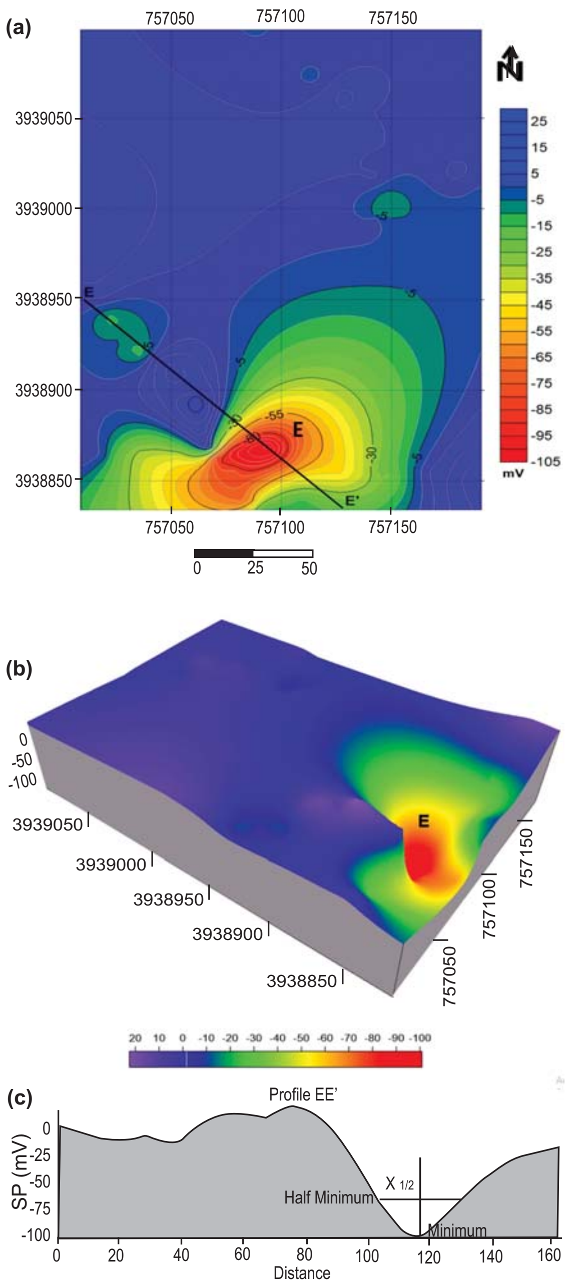

Fig. 9. Illustrations showing (**a**) 2D equipotential contour map; (**b**) 3D surface distribution map of Block-2 highlighting the location of anomaly 'E' and (**c**) Longitudinal profile section EE' of anomaly "E" derived from 2D contour map for depth estimation using half width rules.

with a notable silver content (139 ppm), indicating promising economic potential for both targets (Table 3). Moreover, XRD analysis (Fig. 12) further

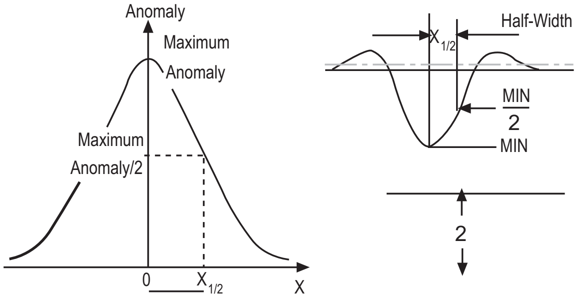

Fig. 10. Methods for estimating depth using anomaly shape and half-width calculation (Abdulbariu *et al*., 2016).

Table 2. Summary of depth estimates of the identified SP anomalies using half width rules.

Profile	Half width rule SP curve depth (m)
AA′	07.72
BB′	02.36
CC′	17.59
DD′	13.50
EE′	22.48

validated that the primary ore bodies in the study area are composed of pyrite, chalcopyrite and magnetite. These findings are in agreement with the self potential anomalies in the area, as the identified minerals exhibit strong negative SP signatures, which is a characteristic feature of these minerals.

A comprehensive, multi-disciplinary geophysical and geochemical investigation was conducted in the Gawuch formation of Drosh-Kaldam Gol area, situated at the northwestern extremity of the Kohistan Island Arc terrane in Chitral, northern Pakistan, to delineate and characterize the sulfide mineralization potential in the area. The geophysical survey employed the electrical

Fig. 11. Illustrations showing (**a**) Drilling operation within the study area using shaw portable drill rig (**b**) Collected oxidized core sample showing primary and secondary sulfide mineralization.

Table 3. Base and precious metal concentrations in the samples collected from the geophysical anomalous sites of Gawuch formation at Dosh-Kaldam Gol area, Chitral.

Sample no.	Block / Anomaly	Cu (%)	Pb (ppm)	Sb (ppm)	Fe (%)	Zn (ppm)	Mn (ppm)	Ni (ppm)	Co (ppm)	Ag (ppm)	Au (ppm)
AKC-A	Block-1/A	7.56	113	160	23.05	530	1046	29	53	12	0.141
AKG-B	Block-1/B	7.75	62	124	28.35	440	670	31	56	-	-
AKG-C	Block-2/C	10.71	130	170	38.41	430	630	36	84	-	-
AKC-D	Block-2/D	0.182	41	90	5.22	120	830	110	67	139	ND
AKG-E	Block-2/E	13	90	240	46.75	710	1003	30	65	-	-
Average values:		**7.84**	**87.2**	**156.8**	**28.35**	**446**	**835.8**	**47.2**	**65**	**75.5**	**0.141**

self potential technique, which provides simple, dependable and cost-effective means of mineral exploration especially in complex topographic environments like the one encountered in this study area. This study employed both qualitative and quantitative analysis methods to examine the self potential data. By examining contour maps, profiles, and raw field data, qualitative analysis sheds light on the subsurface geology, structural makeup and lithological features of the study area, revealing valuable insights into its geological makeup. Meanwhile, quantitative analysis delivers numerical and mathematical insights into the depth and properties of specific materials or geological formations, offering a more precise understanding of the subsurface landscape (Kassim, 2015; Adagunodo, 2013).

The study area (Block-1 and 2) exhibits a wide range of self potential (SP) anomalies, with amplitudes varying from a few mVs to potentially over -150 mVs. In Block-1, two prominent negative anomalies (A and B) stand out, aligning with the regional geological strike in a NNE-SSW direction. These anomalies are marked by closely spaced, semi-circular/elliptical contour closures and peak values of -95 and -26 mVs, respectively (Fig. 6a-b and 7a-b), while, Block-2 of the study area features three notable SP minimum anomaly closures, designated as anomalies C, D and E (Fig. 8a-b and 9a-b). Anomaly C, showcasing a prominent SP anomaly peak of -156 mV and is distinguished by its elliptical shape and NNE-SSW trending pattern, situated on the western side of the map (Fig. 8a), while, the northern region of the equi-potential contour map (Fig. 8a), reveals a lenticular

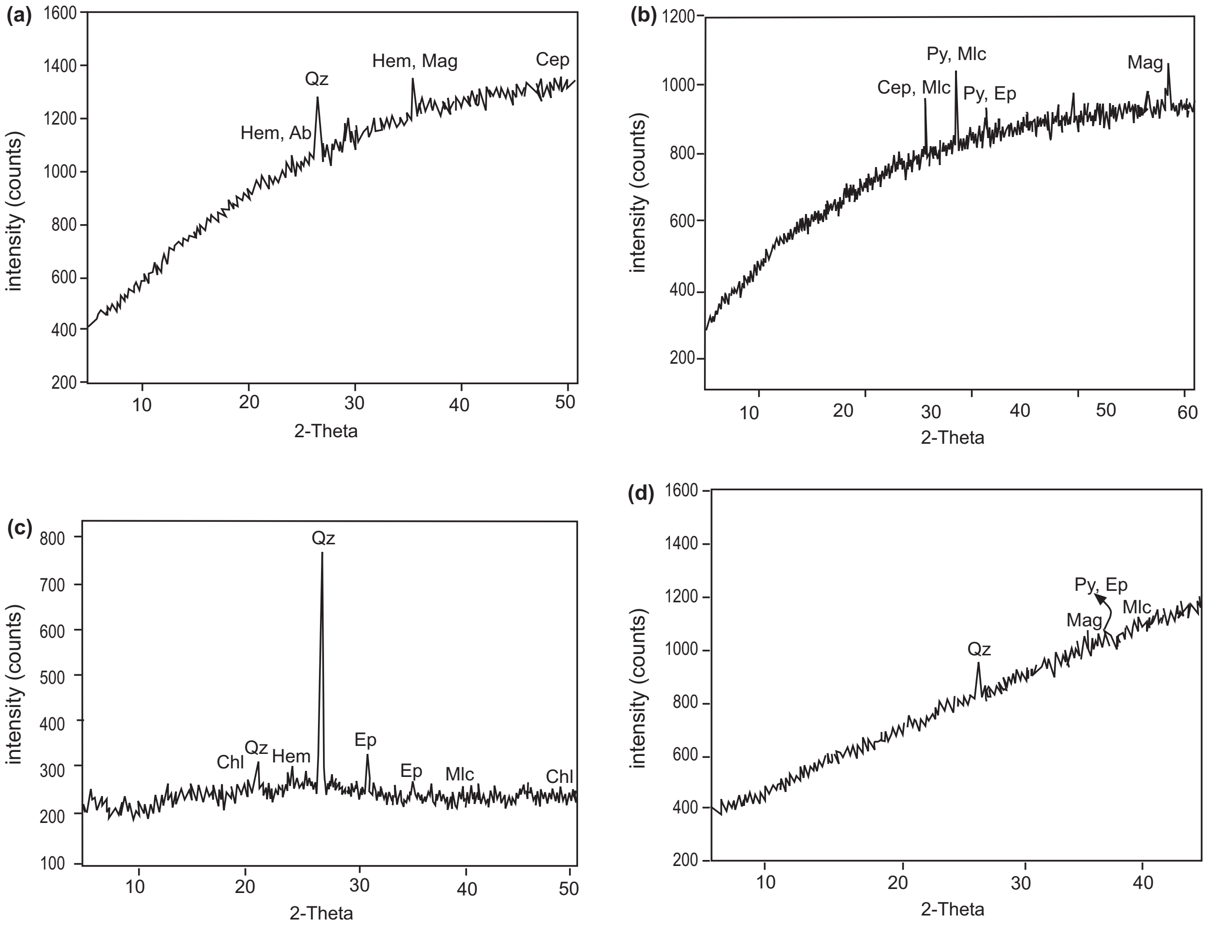

Fig. 12. X-ray diffraction patterns of the whole rock samples from the geophysically anomalous sites of Block-1 and Block-2 of the study area (**a**) Geophysical anomalous zone (anomaly A) (**b**) Geophysical anomalous zone (anomaly C) (**c**) Geophysical anomalous zone (anomaly D) and (**d**) Geophysical anomalous zone (anomaly E). Chl = Cholrite; Ep = Epidote; Ab = Albite; Qz = Quartz; Hem = Hematite; Mlc= Malachite;Mg = Magnetite; Py = Pyrite; Ccp = Chalcopyrite.

shaped anomaly with a limited extent designated as anomaly D, trending in NNE-SSW and peaking at -96 mV. Furthermore, anomaly E, situated in the southwestern part of the area, also exhibit NNE-SSW trend and marked by semi-circular/elliptical contour closures with a significant negative SP maximum of -105 mV (Fig. 9a). So, the results demonstrate that the study area exhibits a predominance of negative SP anomalies with different intensities, indicating a non-uniform distribution of SP sources. In areas with suitable geological setting, a distinct mineralogical signature is apparent. Notably, economically viable ore deposits typically do not occupy the entire volume of a deposit but rather encircled by high grade to lower grade mineralization that gradually transition into the surrounding country rock, forming a mineralogical gradient (Chukwu, 2013). It is significant to note that the self potential anomaly consistently displays a negative polarity when positioned directly above a sulfide or mineralized body, unlike the reference points located away from the mineralized zone (Corey *et al*., 1983). Additionally, the minimum value of the anomaly is considered to align with the central point of the mineralized zone implying a strong connection between the self potential signal and the subsurface mineralization (Kearey and Brooks, 1991). The spatially heterogeneous pattern of SP anomalies across the study area implying the potential existence of sulfide ore-shoots, with areas characterized by pronounced negative SP anomalies being the most prospective targets. As negative SP anomalies are a reliable indicator of mineralization, it is reasonable to infer that these areas may host subsurface sulfide ore deposits (Akpunonu, 2021; Chukwu, 2013). This observation is particularly pertinent when dealing with sulfide ore bodies, especially those comprising chalcopyrite, pyrite, galena and pyrrhotite, as these minerals are known for generating pronounced and distinctive SP anomalies (Okonkwo and Odoh, 2014; Beck, 1981).

The SP anomalies identified in Blocks-1 and Block-2 display a distinct NNE-SSW trend in their contours, which is consistent with the geological strike of the host rock, Gawuch formation in the area. This correlation reveals a significant structural impact on the anomaly distribution, with the anomalies likely being controlled by the underlying geological framework or structural lineaments. A thorough analysis of the anomaly contour maps of Block-1 and 2 suggests that the study area can be broadly characterized as a complex system of numerous faults or fractured zones, trending in a NNE-SSW direction, which may potentially host sulfide mineralization. This interpretation implies a structurally controlled mineralization scenario, where the NNE-SSW trending faults or fractures may have provided conduits for mineral bearing fluids, leading to the formation of sulfide deposits in the survey area. This interpretation is further substantiated by the examination of longitudinal profile plots of self potential values (Figs. 6c, 7c, 8c and 9c), which reveal the presence of steeply dipping veins or fractures that could potentially host subsurface sulfide mineralization. Moreover, the quantitative analysis of the SP anomaly profiles using the half width method indicates that the average depth to the center of the anomalies varies from near surface levels to approximately 22.48 meters, suggesting a relatively shallow depth to the potential mineralization targets in the study area.

In order to verify the aforementioned findings, two shallow exploratory holes were drilled using a Shaw portable drill rig in the study area. The holes were inclined between 55° and 65° and reached average depths of 6 feet each. Visual inspection of the core samples from both holes exhibit fracture filled and disseminated sulfide minerals within the altered/oxidized rocks of Gawuch formation, including pyrite and chalcopyrite, accompanied by magnetite and supergene enrichment of copper bearing sulfides, manifesting as malachite (Fig. 11b). The mineralogical and petrographic analysis carried out by Tahirkheli *et al*. (2012) which offer additional confirmation that the presence of sulfide mineralization in the Gawuch formation, Chitral region was greatly influenced by igneous activity, particularly in the shape of diorite and granodiorite intrusions. The resultant geochemical analysis of core and grab samples from the identified geophysical anomalous sites shows a high degree of correlation with the geophysical findings which revealed a polymetallic mineralization profile, characterized by an average composition of 7.84% copper, 28.34% iron and significant concentration of lead (87.2 ppm), antimony (157 ppm), zinc (446 ppm), silver (75.5 ppm) and gold (0.141 ppm) (Table 3), thus confirming the presence of a polymetallic sulfide ore deposit in the study area. Moreover, XRD analysis confirmed that predominant orebodies within the study area comprises of chalcopyrite, pyrite and magnetite. These results correlate well with the observed geophysical anomalies, as these minerals typically exhibit strong negative SP response. Furthermore, XRD analysis identifies alteration mineral assemblages comprising epidote, albite, chlorite and pyrite (Fig. 12), which are characteristic of porphyry deposits, high and low sulfidation epithermal and geothermal settings (Pirajno, 2009). Moreover, these assemblages are in agreement with the epidote-chlorite-actinolite zone (Susanto and Suparka, 2012), and the inner propylitic alteration type (Corbett and Leach, 1998). The co-occurrence of albite, epidote, chlorite and pyrite within a temperature window of 150-300 °C, which suggests that the rocks in the Gawuch formation of the study area experienced an alteration process, characteristic of porphyry-style alteration (Farhan, 2021). Alteration haloes in porphyry systems, comprising propylitic and phyllic zones which frequently contain sulfide mineralization, exhibit distinct geophysical finger prints, including high chargeability, low resistivity and high conductivity anomalies in IP and SP surveys, which can be leveraged to identify sulfide mineralization, as elucidated by Fatehi and Haroni (2019). Moreover, the presence of magnetite in the study area is particularly noteworthy as studies by Clarke (2014) and Pisiak *et al*. (2017), underscore the significance of magnetite as a pathfinder element in porphyry deposit exploration, given its widespread occurrence within these systems. As a result, magnetite can be a valuable tool in the exploration toolkit, helping to guide efforts and increase the likelihood of discovering concealed porphyry deposits.

The acquired geophysical data in the present study discloses a shallow and sporadic pattern of circular to semicircular, negative or high conductive SP anomalies closures. These anomalies are interpreted to be associated with geologic discontinuities/fracture zones, a characteristic common in porphyry deposits. This interpretation is reinforced by a suite of data including surface geology, drilling results and geochemical analyses which collectively indicate the presence of subsurface stock work of fractures/veins that may serve as potential targets for sulfide mineral exploration in the area. Examining the electrical self potential responses alongside the presence of alteration mineral assemblages (epidote, chlorite, and albite) and sulfide and oxide minerals (pyrite, chalcopyrite, and magnetite), leads to the conclusion that the sulfide mineralization in the study region resembles a porphyry-type deposit. This mineralization is associated with diorite-granodiorite intrusions and is influenced by NNE-SSW structural lineaments.

Conclusion

In the present study integrated geophysical and geochemical exploration techniques were utilized to investigate the characteristics of sulfide mineralization in the Gawuch formation, Chitral, northern Pakistan. The geophysical survey, utilizing the electrical self-potential method, identified and mapped five anomalous regions (A, B, C, D and E) that exhibited negative or minimal potential difference signatures on the self-potential profiles and maps. These anomalies were interpreted as indicative of prospective subsurface sulfide mineralization in the study area. The half-width method reveals that the sources of the anomalies are located from near the surface to approximately 22.48 meters deep, suggesting that the potential mineralization targets are situated at shallow depths.

To confirm the findings exploratory shallow drilling was carried out at locations coinciding with identified geophysical anomalies, accompanied by core and grab samplings for subsequent geochemical analysis which reveals an average composition of 7.84% copper, 28.34% iron, 87.2 ppm lead, 157 ppm antimony, 446 ppm zinc, 75.5 ppm silver and 0.14 ppm gold in the study area. The integrated analysis of geophysical and geochemical data reveals that sulfide mineralization in the study area displays characteristics diagnostic of a porphyry system, with NNE-SSW trending fault/fracture systems and diorite-granodiorite intrusions playing a pivotal role in shaping the mineralization patterns. The present study demonstrates that the use of self potential method, in combination with geochemical data, is an effective and reliable tool for detecting and tracing subsurface sulfide mineralization in areas with similar complex topographic and geological conditions.

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Conflict of Interest. The authors declare that they have no conflict of interest.

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