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Integrated geophysical exploration on aeromagnetic anomaly-18 for iron and copper exploration in the Chagai volcano magmatic arc, SW Pakistan by using Magnetic and Wenner methods

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Abstract

The Geological Survey of Pakistan conducted an extensive geophysical investigation as part of its research and development program in 2023. The focus was on exploring metallic minerals on Aeromagnetic Anomalies (AMA-18) in the Nokkundi region of Chagai District, Balochistan. The investigation employed Magnetic and IP/Resistivity Wenner methods to uncover valuable insights. The survey area lies in the mineral-rich belt. The rocks in the study area include mafic to felsic volcanic with occasional sediments and ironstone intercalations. Based on the promising results from the magnetic surveys, induced polarization (IP) surveys were completed. Array results show south-east north-west trending zones of high chargeability and low resistivity. A zone towards the southern end of the blocks shows high resistivity and low chargeability. Induced Polarization was done over 52 lines to determine the apparent behavior of the anomalies with depth. The results from this survey showed the nature of the ore body with depth and along strike. Possible drilling targets were delineated along each of these lines. Upon the project's completion, noteworthy discoveries were made particularly in AMA-18. Within this anomaly, two distinct zones were identified and earmarked for potential iron ore drilling. Additionally, a third zone was identified in the northern part of the area, exhibiting low magnetic properties but with a high chargeability.

Further investigation expanded this area towards the north, aiming to encompass the entire anomalous zone. The extension was carried out using the Wenner IP method, a technique used for exploring subsurface properties, to thoroughly cover the identified area of interest. These findings suggest promising prospects for mineral exploration in the region, especially in terms of iron ore deposits within the marked zones. The presence of anomalies with varying magnetic and chargeability characteristics hints at diverse mineral compositions, motivating further exploration and detailed assessments in the northern extension zone. Following the findings from both the magnetic and IP surveys, three exploration wells are suggested to evaluate the potential for ore containing disseminated copper in the area. While this paper primarily discusses the IP survey and its findings, it also connects them to the physical geological mapping of exposed outcrops and magnetic survey data. A comprehensive study of the project area's completeness will be achieved after referencing additional data from assay results obtained during the trial milling of ore extracted from the suggested exploration wells.

Keywords: Aeromagnetic Anomaly-18, Iron, Copper, Chagai, Pakistan

Introduction

Mashkichah has served as a primary hub for field parties operating in the Chagai region for an extensive duration. Historical records have highlighted the existence of iron ore deposits encircling Mashkichah. An aero-magnetic anomaly has unveiled a promising zone for iron ore, along with multiple shallow mines extracting iron and marble. Furthermore, an extensive survey of the region, involving 36 Wenner profiles, has indicated the likelihood of copper mineralization. Notably, the chargeability assessment during this phase has depicted the consistent characteristics of the porphyry system located at the northern extremity of the map. The paper outlines the data interpretations derived from comprehensive ground magnetic and IP/resistivity surveys conducted at the site of Aeromagnetic Anomaly-18. These surveys, comprising ground magnetic and geoelectric data numbered 1 to 52, were carried out in May 2023 as part of ongoing R&D investigations. The primary aim of this endeavor is to examine the expansion of lineaments situated in the northwest region, previously identified during the initial exploration phase. Notably, the analysis of IP/resistivity data within the purview of this study indicates the presence of high-grade copper mineralization. The data were processed and interpreted using standard techniques at that time, and all interpretation products and deliveries were mapped. However, with today's state-of-the-art processing and visualization software, it is now possible to identify more subtle anomaly patterns, and interpretation products are digital and connected to databases. Additionally, it is now convenient to make combined interpretations and simultaneously view details in different datasets. This work present the AMA-18 data and interpretation products in the same format as corresponding data from the site investigations at the Siahdik copper discovery. Individual interpretations of lineaments in the magnetic, geoelectric, and topographic data are presented, primarily identified as topographic lows, magnetic, and resistivity lows, and chargeability highs. The project area displays various magnetic signatures, with high anomalies of 1200 nT and 650 nT at two prominent geophysical features. These areas were further investigated, and depth sections were prepared. The current exploration program aims to map the copper-bearing deposits based on their MAG and IP signatures, while also assuming that the delineated structures may host gold and silver-bearing mineralization. The deposit extends from approximately 100 meters to 600 meters below the surface and has a maximum width of approximately 1200 meters.

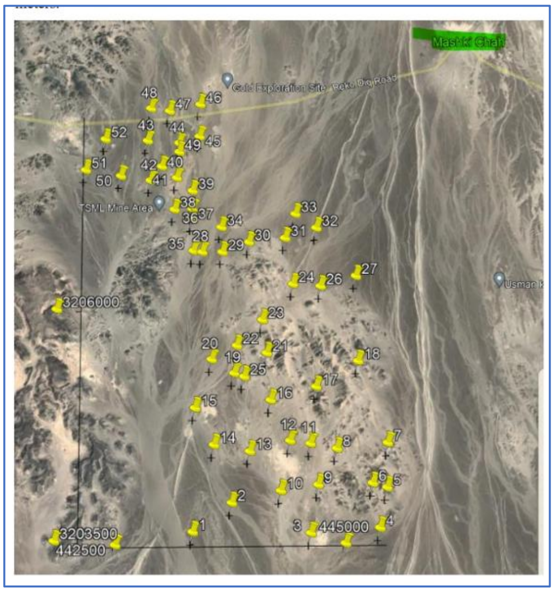

Fig 1. Project area map showing the Wenner profiles (1-52) on the project area.

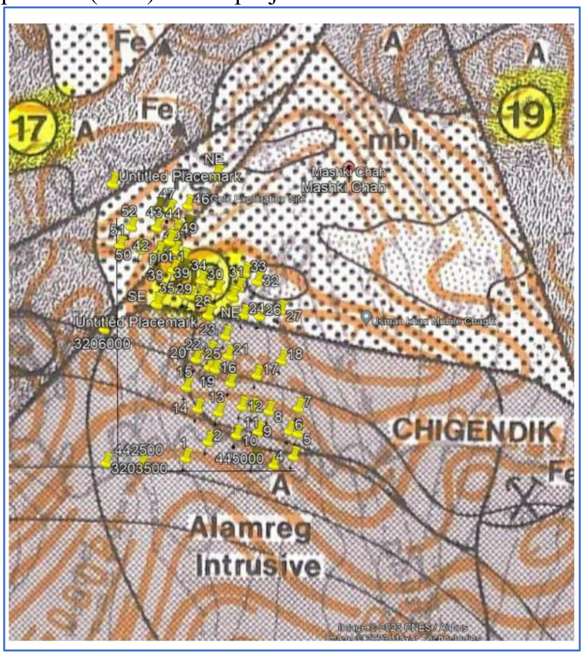

Fig 2. Project area map on Aeromagnetic Map 1:50,000.

Objective And Scope

For 45 years, the Chagai region in southern Pakistan has been recognized for its potential in porphyry copper-gold. The Chagai porphyry copper belt spans approximately 300 km along the Chagai hills and adjacent ranges of the Balochistan plateau in Pakistan. The porphyry centers are identified by stocks and dyke swarms of diorite, quartz diorite, and granodiorite composition. This report presents a summary of the geological setting, alteration, and mineralization features linked to the porphyry centers of the Siahdik cluster, which serve as the foundation for the magmatic-hydrothermal evolution of the district. The Porphyry Copper Deposit (PCD) is a significant source of copper worldwide and can be found using various exploration techniques. These methods include analyzing alteration zones in geology, utilizing high-precision magnetic and electrical techniques in geophysics, conducting stream sediment and soil geochemical surveys in geochemistry, and identifying alteration anomalies through remote sensing (Zheng et al., 2006; Cooke et al., 2014; Sillitoe, 2010; Sun et al., 2017). It's essential to locate the true hydrothermal and/or mineralization center of the porphyry system to identify the PCD accurately (Yang et al., 2012). Research on Porphyry Copper Deposits has shown that the depth of the ore body is over 700 meters, and mineralization gradually becomes more intense with increasing temperature, pressure, and salinity from 100 meters. The studies suggest that the

PCD may belong to the same porphyry system as the Siahdik system. Porphyry Copper Deposits (PCDs) are comprised of disseminated copper minerals and copper minerals in veins and breccia that are relatively distributed in a vast volume of rock-forming high tonnage (greater than 100 million tons) low-moderate grade (0.3%- 1.0% copper) ores. Host rocks are altered and genetically related to granitoid porphyry intrusions and adjacent wall rocks. This report analyzes data from ground magnetic and resistivity surveys conducted on AMA-18, specifically IP data (W-1 to 36) collected in May 2023 as part of pre-investigations. The data was processed and interpreted using standard techniques at the time, and the interpretation products were analog maps. However, with today's advanced processing and visualization software, it is possible to identify more subtle anomaly patterns, and interpretation products are digital and connected to databases. This report presents the data and interpretation products in the same format as the corresponding data from the site investigations at the Siahdik copper discovery. Lineaments on the site are primarily identified as topographic lows, intermediate magnetic, low resistivity, and chargeability highs. The Mashkichah deposit is covered by 80- to 100-meter-thick alluvium and was not explored before May 2023. A detailed IP survey conducted in May 2023 identified a prospective chargeability anomaly located almost 9 kilometers east. Whether the anomaly was a direct result of the Siahdik mineralization or a disseminated sulfide above the ore was uncertain. This report describes the characteristics of Mashkichah mineralization and its host sequence, investigates the source of the "discovery" IP anomaly, and examines the implications of the properties for exploration for Siahdik style deposits. The magnetic susceptibility of rocks is often low in strongly deformed, fractured, altered, or porous bedrock. This is due to the destruction of ferromagnetic minerals, which forms a basis for magnetic lineament interpretation. Linear topographic lows can indicate depressions in the bedrock related to brittle deformation zones along which the bedrock is more easily eroded, due to decreased mechanical strength. The electric resistivity of rocks is affected by their porosity and mineralogy. When rocks have frequent fractures and/or clay alteration, their electric resistivity decreases. This report provides a foundation for interpreting and modeling deformation zones at AMA-18 (Mashkichah).

Project Location and Access

The project site is situated close to Mashkichah, a village situated approximately 40 km north of Nokundi City and roughly 700 km southwest of the capital city of Quetta. To reach this location, one must travel through dirt tracks from Nokundi towards the south. 4.2 Description & Survey Grids The project site near Mashkichah village spans 15 square kilometers. Magnetic mapping led to the implementation of 52 IP profiles. The magnetic map includes grids with N/S lines every 100 meters, surveyed using a GPS receiver. The IP lines were numbered and positioned accordingly.

Fig 2. Project area map on Google Earth showing locations of Mashkichah and Nokundi

Theory

Geo-electric properties are exploited commercially in the search for valuable ore bodies which may be located by their anomalous properties (Lowrie 2011). The IP surveys aim to detect and map possible sulfide mineralization as it is known that gold in this area is associated with pyritization. The IP method is widely used for detecting possible sulfide mineralization (usually an indicator for gold occurrence) that is expected to give a high chargeability response. There are two main mechanisms of rock polarization which are grain polarization and membrane polarization (Milsom, 2003). The overvoltage effect is caused by minerals which are good conductors whose magnitude depends on both the magnitude of impressed voltage and mineral concentration. It is most pronounced when the mineral is disseminated throughout the host rock as the surface area available for ionic–electronic interchange is then at a maximum. The effect decreases with increasing porosity as more alternative paths become available for more efficient ionic conduction (Kearey et al., 2002). In IP methods electrical current is alternately induced into the ground and switched off usually in cycles of 2 seconds. The induced current ionizes the ground temporarily for 2 seconds, thereby creating a temporary cell in the ground that results in an "over voltage" which decays to zero during the off phase of the cycle. The size of the stored charge, and hence the time it takes for the over voltage to decay, depends on the presence of electrically chargeable minerals in the ground such as sulfides. Complex impedance measurements of materials have been made at least since 1941(Cole and Cole 1941, Grant 1958). In the hope that mineralized rocks would have a unique spectral signature (Van Voohris et al, 1973) did not find any significant variation using earlier equipment. Although resistivity can also be obtained, the main parameter measured from the IP survey is chargeability of significant variation than using earlier equipment. Although resistivity can also be obtained, the main parameter measured from the IP survey is the chargeability of minerals and rocks. Chargeability is defined as the ratio of the area under the decay curve to the potential difference measured before switching the current off. True chargeability is the ratio of over-or-secondary voltage, Vs, to the observed voltage, V0 (Seigel, 1959). The chargeability figures of common minerals and rocks range from 0.2 to 30 (Telford et al, 1990).

Magnetic Survey

Magnetic Data Acquisition and Processing

During the survey, magnetic measurements are taken along regularly spaced traverses to identify magnetic materials such as magnetite and/or pyrrhotite that are usually associated with metallic mineralization. These measurements also serve as a mapping tool to differentiate rock types and to pinpoint faults, bedding, structure, and alteration zones. The magnetic data is available in digital format and as stacked profile and color contour displays of the total field data, after being corrected for diurnal and Normal variations. Additionally, the magnetic data has undergone processing through a reduction to the pole filter, which modifies the observed responses to mimic the responses recorded if the survey was conducted at the magnetic north pole, where the earth's magnetic field is vertically inclined.

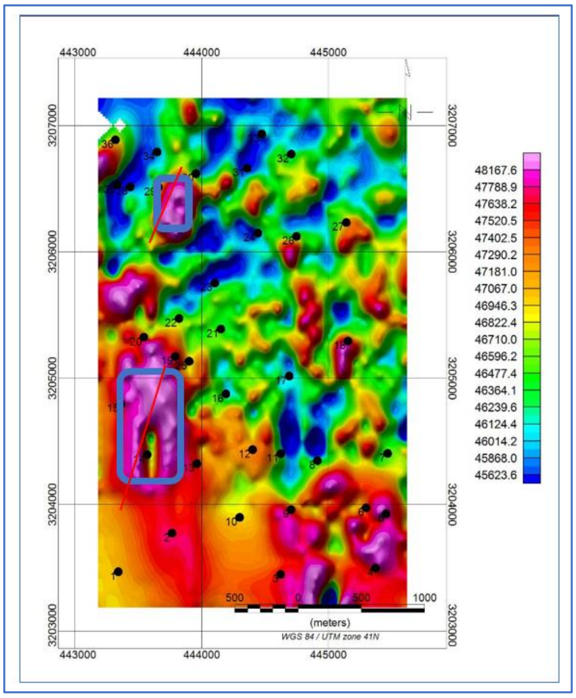

Fig. 4 Total Magnetic Intensity Anomaly map of Aeromagnetic anomaly-18**.**

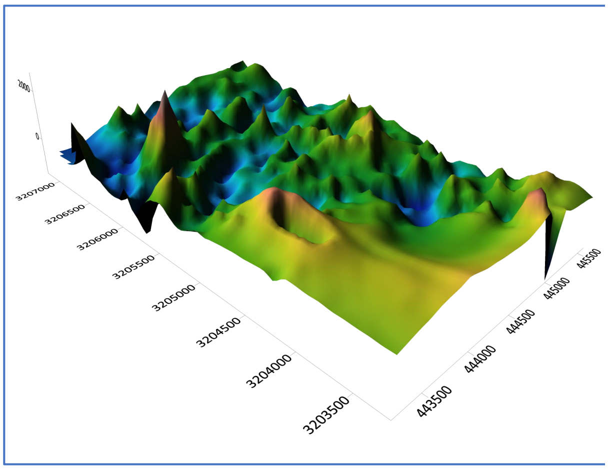

Fig. 5 3D Total Magnetic Intensity Map.

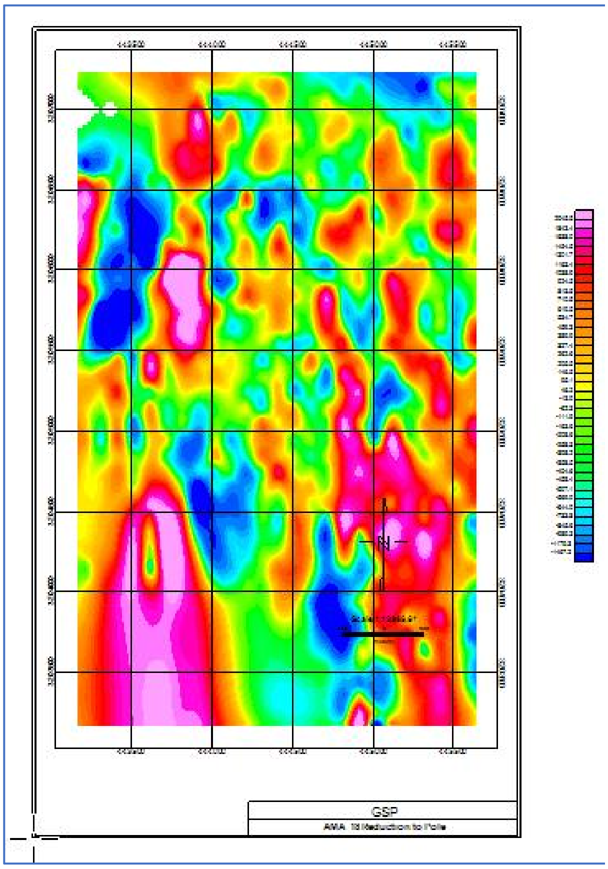

Fig. 6 Reduction to Pole Map of Aeromagnetic Anomaly-18.

Interpretation

The magnetic survey was meticulously conducted, capturing data along continuous N/S lines, and ensuring a comprehensive assessment of the area. This method involved taking total field intensity readings at intervals of 100 meters along the survey lines, resulting in an extensive magnetic database with over 1100 readings. This rich dataset offers a remarkably high information density, enabling the creation of detailed, high-resolution maps. The increased granularity facilitates a superior delineation of subtle and short-wavelength anomalies that might otherwise be overlooked.

A crucial aspect of analyzing magnetic data involves assessing the configuration of the anomalous source within the total field component across the area of interest. The magnetic response exhibited a bipolar (+/-) anomaly pattern, with the central point of interest situated around the inflection or gradient point between these two poles. In the southern section of the grid, the underlying geological formations appear notably distinct. The transition from one lithological domain to another aligns predominantly along ENE to E/W striking contacts. Notably, a significant NE to SW contact is more prominently evident in the IP maps.

The reduced-to-pole total field map reveals a regional gradient that intensifies toward the north. However, this impact is mitigated in the first vertical derivative map, resulting in a clearer delineation of magnetic anomalies. These anomalies generally exhibit elliptical shapes with predominant E/W to ENE strikes, occasionally displaying localized EW orientations. The wavelengths associated with these anomalies suggest the presence of deeper or sub-outcropping targets, indicating prospects for further ground mapping and exploration endeavors in these areas.

Specifically, the most robust anomalies, measuring approximately 1600 nanoteslas (nT), are situated in the northern region of the grid. These anomalies are understood to primarily arise from lithological variations, particularly associated with the contact zone between andesite and Sinjrani volcanic formations.

The regions exhibiting low magnetic signatures at the northwest edge of the magnetic data have piqued further interest. This curiosity has led to an in-depth exploration utilizing detailed IP profiles, a methodology that had been recommended based on preceding surveys completed in May 2023. The aim is to gain a comprehensive understanding of the characteristics and potential mineralization in these areas displaying diminished magnetic signatures.

Induced Polarization Survey (Wenner Profiling)

Daily, we diligently assessed the data quality, meticulously storing pertinent information in distinct databases dedicated to each survey line. These databases were formatted in Excel/Surfer and Geosoft Oasis Montaj, allowing for comprehensive data organization and management. To ensure meticulous quality control and to identify any potential inaccuracies, we conducted multiple readings—often three times—for each data point in the field.

Following data collection, specific details from these databases were later transferred to file formats compatible with Surfer software. The 2D models employed in our analysis comprise multiple blocks, and their distribution and size are automatically determined by the program based on the points' distribution within the sections, a function intricately linked to the electrode array used during the surveys.

The Induced Polarization (IP) technique, a method employed to measure two key physical properties of the ground chargeability and resistivity was instrumental in our investigations. Our primary objective in setting up the IP survey was to locate a concealed porphyry system. Our focus primarily centered on identifying higher chargeabilities associated with metallic mineralization (specifically sulfide) and high resistivities indicative of a silica cap. Additionally, we also considered secondary targets encompassing variations in both parameters, aiming to identify potential geological structures and lithological variations within the surveyed area. These secondary targets served as additional indicators to guide our exploration efforts.

IP Contours Maps

The values of resistivity/IP (Wenner electrode configuration) extracted at 100 to 250 meters of vertical depth were used to create maps.

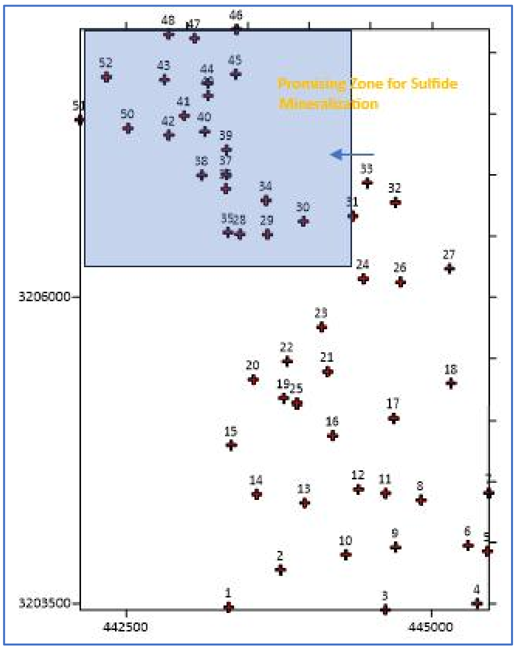

Fig. 7 IP Survey locations on aeromagnetic anomaly-18.

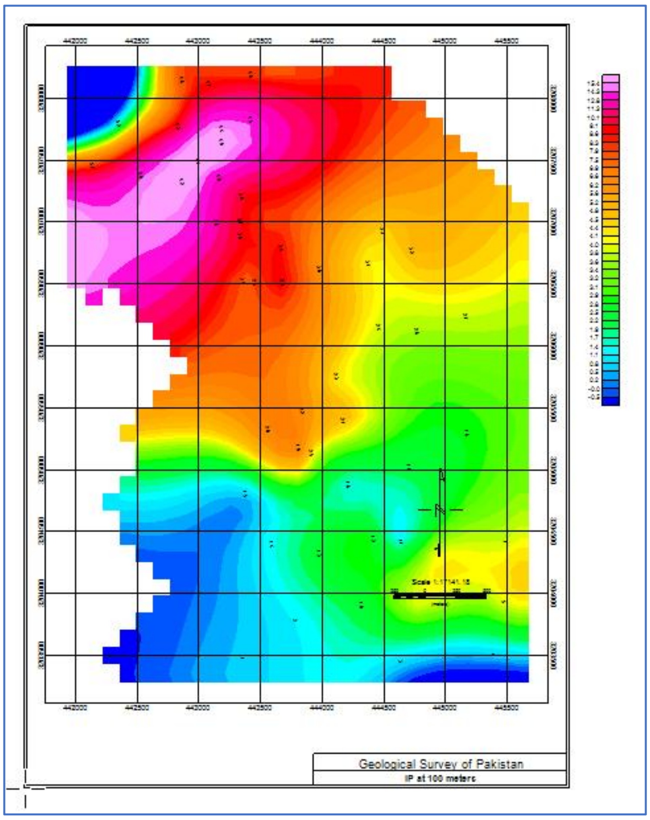

Fig. 8 IP Survey model at 100 m.

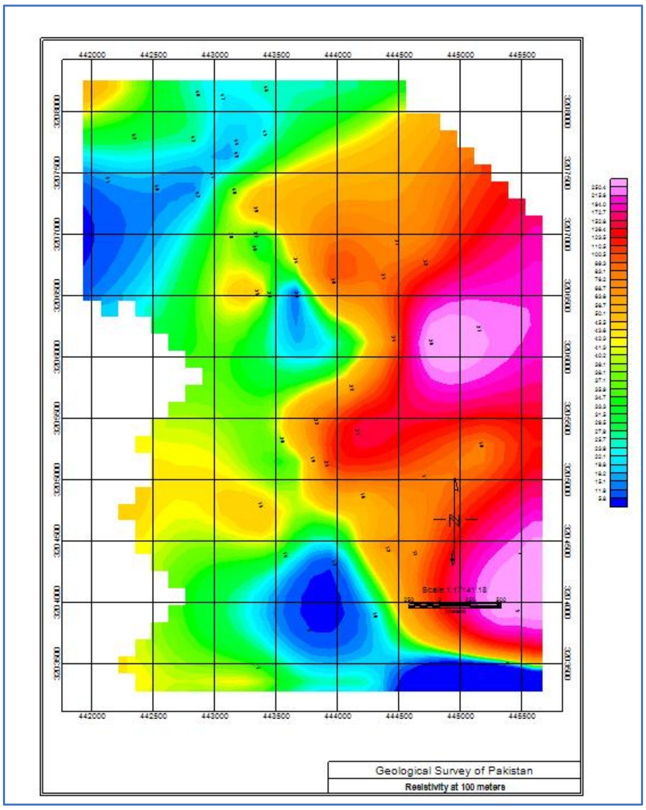

Fig. 9 Resistivity Survey model at 100 m

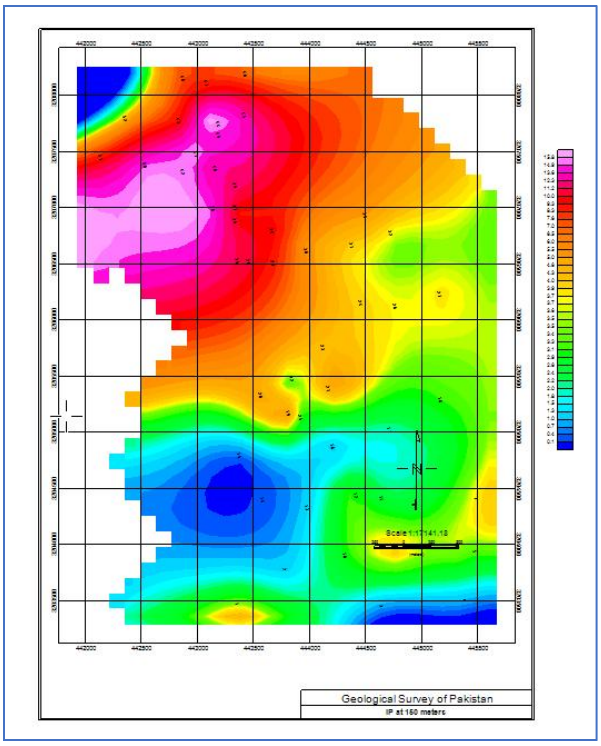

Fig. 10 IP Survey model at 150 m.

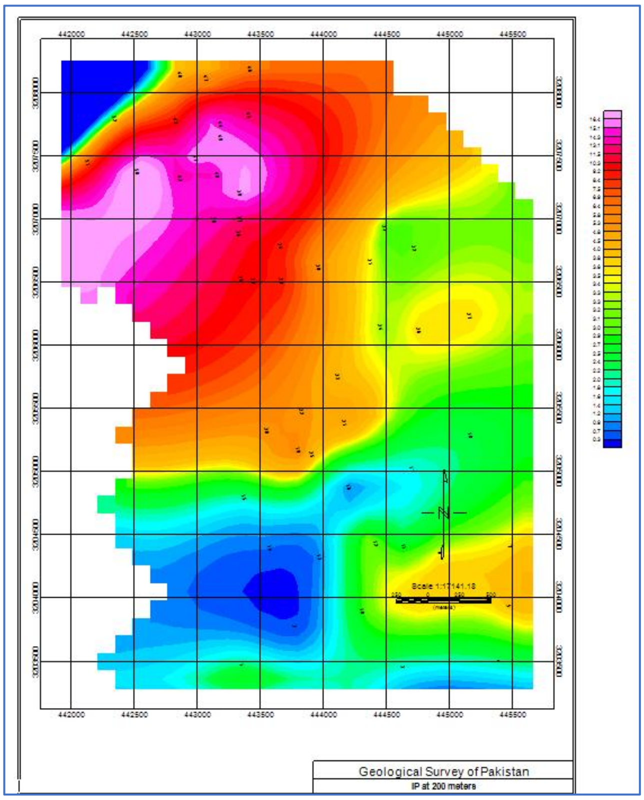

Fig. 12 IP Survey model at 200 m.

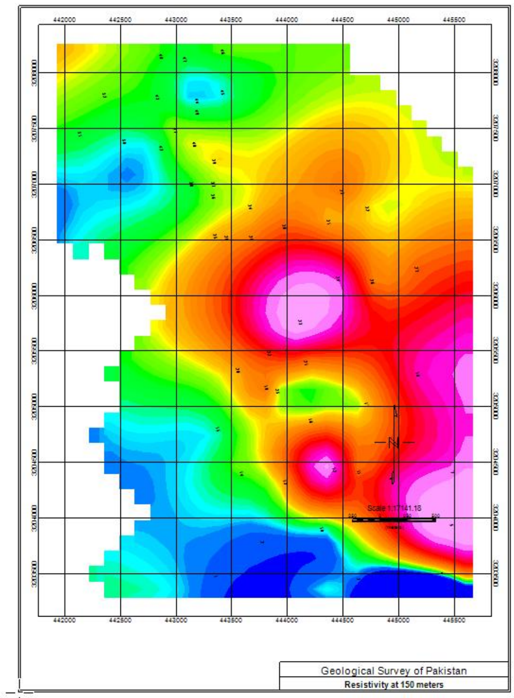

Fig. 11 Resistivity Survey model at 150 m.

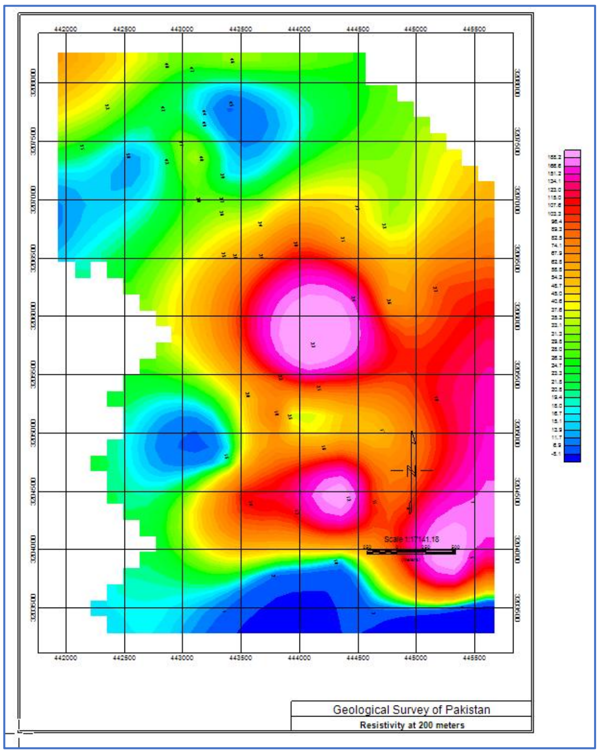

Fig. 13 Resistivity Survey model at 200 m.

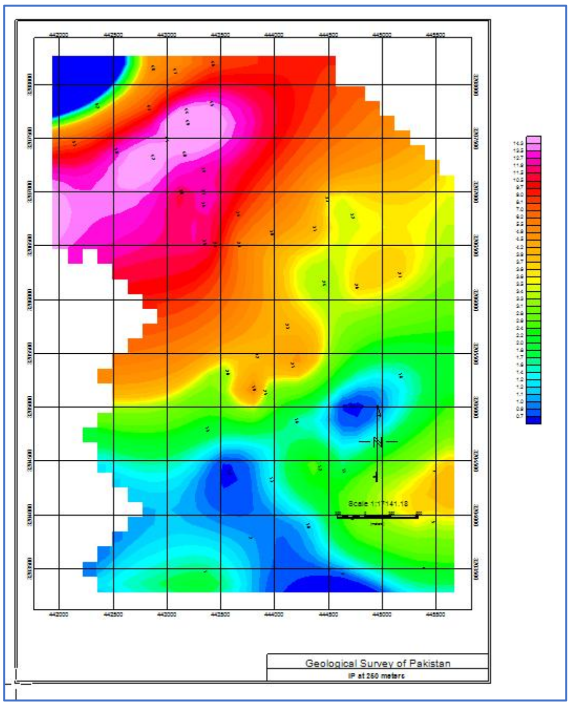

Fig. 14 IP Survey model at 250 m.

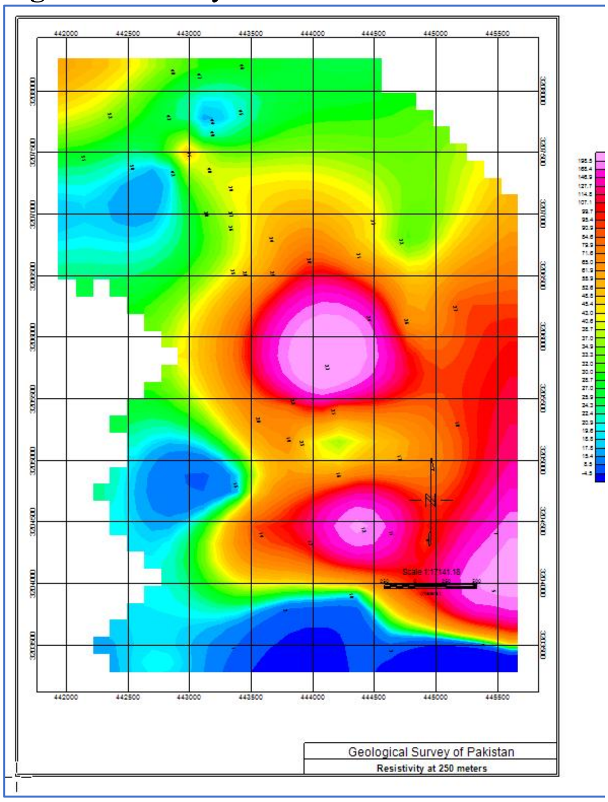

Fig. 15 IP Survey model at 250 m.

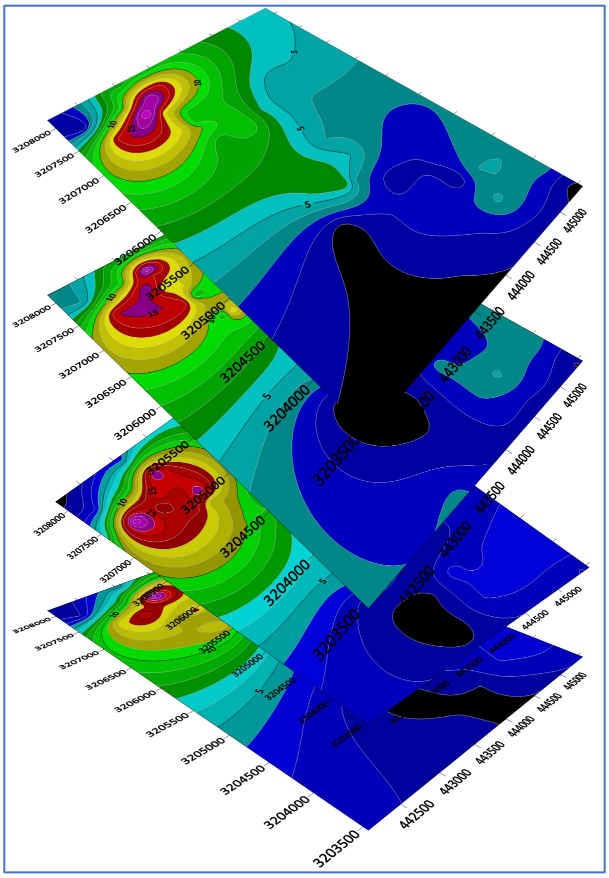

Fig. 16 IP Survey model from 100 to 250 m.

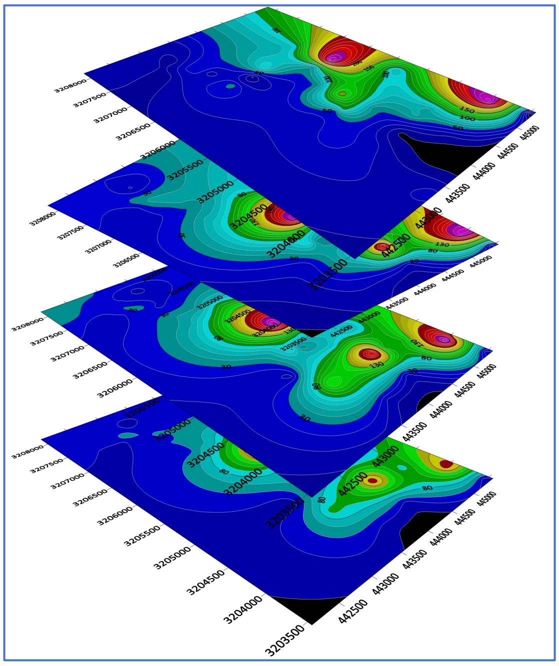

Fig. 17 Resistivity Survey model from 100 to 250 m.

Review of Maps and Models For IP

The signature of copper-bearing structures depends on the percentage of certain accessory minerals such as pyrite or clays. Additionally, the percentage content of other minerals like pyrrhotite, arsenopyrite, or magnetite (if present) will indirectly help to identify mineralized structures, layers, or bodies. The strength of the anomaly is determined by the percentage content of sulfide, thickness, lateral, and depth extent of the mineralized structures. As mineralization is expected to be found in altered areas and along faults, anomalies indicative of this mineralization are associated with resistivity lows and chargeabilities high.

On the IP maps, areas with high chargeability and low resistivity have been identified and categorized based on their relative strength. The northwest corner of the mapped region shows a clear correlation and alignment among the magnetic, resistivity, and IP contours. Notably, this area exhibits significant chargeability anomalies. In addition, there are some weak chargeability responses in the eastern and southern portions of the grid, but they cannot be easily linked to form an axis.

Conclusion & Recommendations

Based on the outlined survey objectives and a comprehensive review of the geophysical findings, several significant conclusions can be drawn:

Enhanced Mineral Potential for Sulfide Deposits: Overlaying previously mapped structures and existing data onto the geophysical maps has significantly enriched comprehension of the sulfide deposit potential in the northern region. The IP anomaly has been detected, exhibiting a correlation with low resistivity and diminished magnetic signatures. Notably, these characteristics are observed to expand further northward, indicating a promising area for potential sulfide deposits.

Identification of Priority Exploration Zones for Iron Deposits: The analysis has identified two primary exploration zones, namely zone-1 and zone-2, which exhibit characteristics conducive to potential iron deposits. These delineations have been primarily based on magnetic data, highlighting areas with substantial potential for iron ore deposits.

Definition of Prospective Iron Zone: A specific area designated as the prospective iron zone has been delineated by geographical coordinates (442060.00 m E 3207311.00 m N, 443518.01 m E 3207583.10 m N, 443058.69 m E 3208460.68 m N, and 442133.94 m E 3208177.86 m N).

Chargeability Insights in Different Zones: The drill hole data from Siahdik indicates varying chargeabilities ranging from 12 to 25 in Zone 3, suggesting potential mineralization prospects within this area. The identified prospective copper zone has been determined to initiate at a depth of approximately 100 meters and shows indications of potential continuation beyond depths exceeding 300 meters. This depth assessment suggests a substantial vertical extent for the copper-bearing zone, implying the likelihood of significant copper mineralization present in this area at considerable depths, offering promising prospects for further exploration and mining activities.

Exploration Findings in the Southern Area: Extensive exploration in the southern region did not yield prominent chargeabilities, with measurements ranging from 5 to 6 mv/v recorded at the central portion of the mapped area. This indicates the potential presence of Bornite or magnetite-type mineralization. Moreover, the higher resistivities observed in this region are likely attributed to the presence of quartzite or mafic rock.

Overall, these conclusions provide valuable insights into the mineral potential and distinctive characteristics observed within the surveyed area, guiding further exploration and investigation efforts in targeted zones for potential mineral deposits.

The total reserve estimation is about 288,000,000 cubic meters.

Based on geophysical surveys and data, the following drill holes are recommended:

- For Copper, drill at 3207613 N, 443167 E down to a depth of 300m. (Priority-I)
- For Iron Ore, drill at 3204645 N, 443666 E down to a depth of 200m (Priority-II)
- For Iron Ore, drill at 3206164 N, 443772 E down to a depth of 200m (Priority-III)

❖ **In 2024, the drill hole at Aeromagnetic anomaly-18 exhibited a response identical to that of the sulfide system documented in the report. The promising results from the drilling to uncover extensive geological data concerning the porphyry system within the region. This exploration marks a significant step towards enhancing our understanding of the geophysical characteristics and potential mineral resources present in the area.**

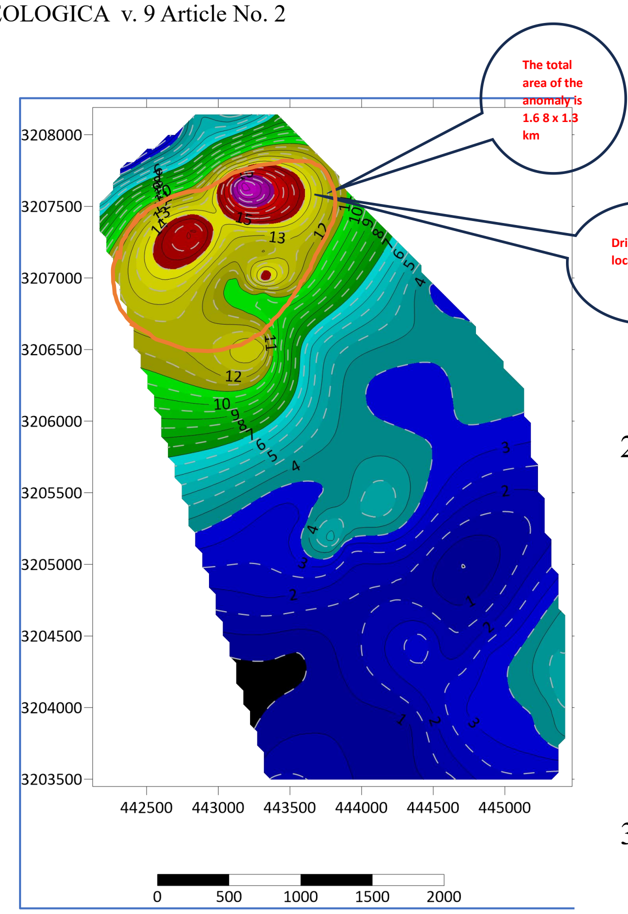

Fig. 18 Map showing the total area of the anomaly zone (IP >12 mVs/V) showing drill hole locations and HM zone

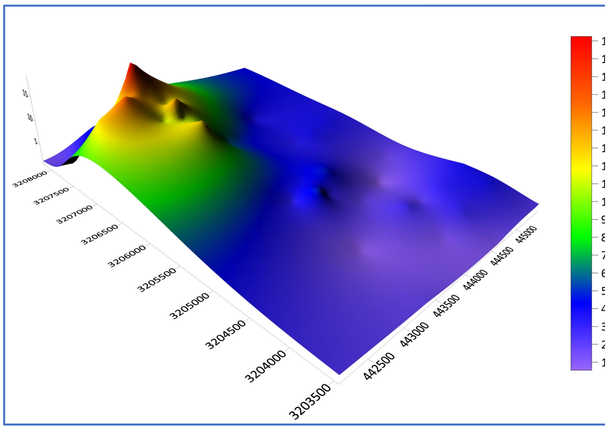

Fig. 19 3D Map showing the IP map at 250 meters depth.

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