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Mineral Exploration Using a Ground Magnetic Survey: A Case Study from Western Missi Koh, Chagai District, Baluchistan, Pakistan

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ABSTRACT

Magnetic anomalies can be used to produce lithological maps, alteration zonation maps, and maps of structures that may have controlled fluid and/or magma movement. Precise geological interpretation of a mineralized system therefore requires an understanding of the magmatic and hydrothermal processes responsible for the formation, alteration, or destruction of magnetic minerals in rocks. This study aimed to acquire ground magnetic data to evaluate the subsurface structure, hydrothermal alteration zones, and prospective mineralization zones of the study area. To improve anomaly interpretation and reduce the geometric complexity of causative bodies, the total magnetic intensity (TMI) data were corrected for diurnal variation and processed using reduction to the pole (RTP), analytical signal (AS), and Euler deconvolution depth estimation. The diurnally corrected magnetic field ranges from approximately −399 nT to +251 nT, reflecting variations in lithology, structural framework, and alteration. High magnetic anomalies occur mainly in the eastern and northeastern parts of the area and are interpreted as magnetite-rich intrusive bodies or relatively unaltered host rocks, possibly associated with mafic to intermediate intrusions typical of porphyry systems. Conversely, low magnetic anomalies, concentrated in the central part of the area, are interpreted as hydrothermal alteration zones characterized by magnetite destruction, silicification, and sulfide mineralization. The RTP map improves anomaly positioning, revealing a shallow magnetic source in the eastern part and a demagnetized zone in the central part. The AS map delineates the edges of the magnetic sources and shows semi-elliptical to elongated anomalies trending NE–SW, indicating strong structural control on fluid flow and alteration. Euler deconvolution indicates magnetic sources at depths of approximately 4–95 m, with shallow sources concentrated in the central and northeastern parts, consistent with near-surface alteration zones.

Keywords: *magnetic anomaly; diurnal variation; derivatives; analytical signal; Euler deconvolution*

1. Introduction

The approximately 300-km-long, east–west-trending Chagai belt comprises several superimposed magmatic arcs and associated porphyry copper (± gold, molybdenum) mineralization formed during successive events at 43–37 Ma (middle–late Eocene), 24–22 Ma (early Miocene), 18–16 Ma (early Miocene), 13–10 Ma (middle Miocene), and 6–4 Ma (late Miocene–early Pliocene) [1] (Figure 1). The belt hosts 48 deposits and prospects, predominantly of the porphyry copper and copper–gold types [2, 3]. To the south, the east–west-trending Chagai Hills are bordered by the desert plains of the Dalbandin and Hamun-i-Mashkel depressions and by the Ras Koh and Mirjawa ranges (Figure 1), whereas to the north, the large Helmand depression occupies much of southwestern Afghanistan [4].

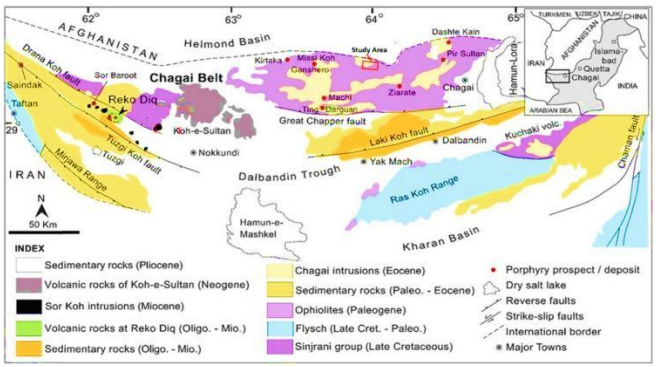


Fig. 1: Geological map of Baluchistan; the red rectangle marks the study area.

Covered porphyry deposits commonly lack visible surface expression because the mineralized system is buried beneath alluvial or sedimentary cover, and conventional geological mapping alone is often insufficient to identify such blind targets. In these settings, indirect exploration techniques, such as integrated geophysical surveys followed by exploratory drilling, are pivotal for discovering and evaluating subsurface resources [5]. Identifying potential targets and selecting optimal drilling sites require detailed interpretation of geophysical anomalies and hydrothermal alteration patterns. Although geophysical methods can reveal evidence of mineralization, only drilling can confirm its presence, geometry, and economic value. Seismic and electromagnetic (EM) methods are quantitative tools for imaging the subsurface beneath sedimentary cover and are rapidly developing into cost-effective means of imaging subsurface geology [6, 7]. The methods most commonly used in porphyry copper exploration are induced polarization (IP), magnetic, and gravity surveys. These methods are very effective at detecting sulfide-rich zones, alteration halos, intrusive bodies, and associated structural controls, enabling the three-dimensional characterization of blind mineral systems [8, 9].

In particular, the magnetic method is one of the most widely used geophysical technique in hard-rock mineral exploration, from prospect to regional scale. Magnetic anomaly patterns can be used to map lithology, metamorphic zonation, and hydrothermal alteration assemblages, and to identify structures that may have controlled the movement of magmas or hydrothermal fluids associated with mineralization [10]. Magnetic anomalies can also provide a

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direct indication of certain types of ore deposits or mineralized systems. However, the magnetic signatures of mineralization are not always associated with strongly magnetic sources; they may instead be expressed as zones of anomalously weak magnetization [10]. For example, epithermal precious-metal deposits hosted by mafic or intermediate volcanic rocks are often associated with smooth magnetic lows produced by magnetite-destructive alteration, surrounded by the short-wavelength, high-amplitude anomaly patterns characteristic of heterogeneously magnetized, unaltered volcanic rocks [11, 13]. Because hydrothermal alteration exerts a major influence on the magnetic properties of rocks and on the associated anomaly patterns, magnetic surveys can be very useful for mapping mineralized systems and, in some cases, for defining ore deposits within them [13].

The Missi Koh study area lies within an east–west-trending metallogenic belt that hosts porphyry copper mineralization. The area remains poorly explored, particularly with respect to its subsurface structural architecture, the distribution of magnetic sources, and its mineralization potential; consequently, its geology, structural framework, and mineral prospectivity are poorly understood. High-resolution ground magnetic data, combined with a comprehensive geophysical interpretation, can define subsurface lithological variations, structural controls, and mineralization-related magnetic anomalies. The present study aims to fill this gap by acquiring high-resolution ground magnetic data in the Missi Koh area. The data were interpreted to define the subsurface distribution of magnetic sources, to outline structures that may control mineralization, and to identify areas for further mineral exploration. The resulting magnetic model provides a useful interpretation of the subsurface geology and a geophysical framework for ranking drilling targets and guiding future exploration.

2. Study Area

The study area is located east of Missi Koh, between longitudes 64°05′00″ E and 64°05′30″ E and latitudes 29°21′55″ N and 29°22′10″ N, in Chagai District, Baluchistan, Pakistan. It forms part of the Chagai magmatic arc, a subduction-related calc-alkaline volcanic arc developed along the Tethyan metallogenic belt (Figure 1) [14]. The study area covers 0.378 km² at an average elevation of 1700 m above mean sea level (amsl). The region is geologically significant because of its association with arc magmatism and porphyry systems, which make it highly prospective for copper and gold [15]. The study area lies within the western segment of the Tethyan metallogenic belt, which is related to the subduction of the Neo-Tethys Ocean beneath the Eurasian Plate during the Mesozoic–Cenozoic [16]. Although the area is less explored than the major deposits, its geological setting, alteration signatures, and proximity to world-class base-metal deposits indicate high mineral potential, particularly for porphyry and epithermal Cu–Au systems.

3. Regional Geological Setting

The Chagai belt is dominated by the Cretaceous Sinjrani Volcano-Sedimentary Group, which constitutes its principal lithological unit (Figure 2) [17, 18]. These volcanic and sedimentary rocks are unconformably overlain by the clastic and carbonate-rich deposits of the Late Cretaceous Humai Formation [19], which is in turn overlain by the Paleocene to Oligocene Juzzak, Saindak, and Amalaf formations. These formations consist of marine clastic sediments and fluvial deposits interbedded with volcanic units, including andesitic lava flows, volcanic breccias, tuffs, and volcaniclastic debris [17, 19]. The Paleogene volcano-sedimentary succession is overlain by the Late Oligocene Dalbandin Formation, which consists mainly of subaerial red-bed sequences of cross-bedded sandstones, conglomerates, mudstones, and gypsiferous evaporites [20]. In the Reko Diq area, the Dalbandin Formation is conformably overlain by the Miocene Reko Diq Formation, which comprises more than 350 m of andesitic volcanic rocks, pyroclastic breccias, tuffs, and volcaniclastic deposits [21]. The volcano-sedimentary succession of the Chagai belt has been extensively intruded by multiple generations of igneous bodies emplaced from the Late Cretaceous to the Quaternary. These intrusions occur as batholiths, stocks, domes, lopoliths, dykes, and sills, with compositions ranging from granitic and dioritic to dacitic and gabbroic [15]. Large batholithic complexes are particularly common in eastern Chagai, whereas smaller intrusive bodies are widespread in the western part of the belt.

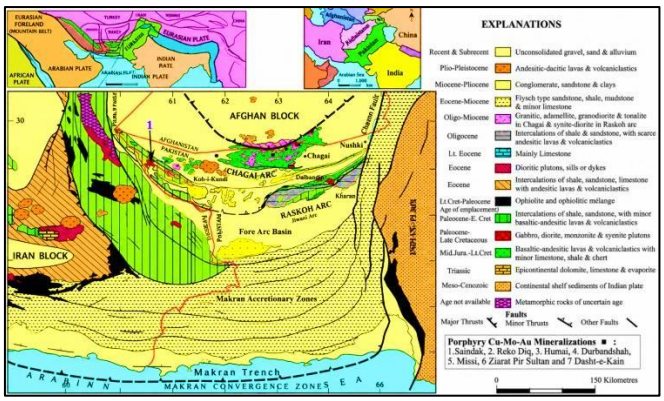


Fig. 2: Regional geological and structural map of Baluchistan showing the major lithological units and tectonic structures.

The youngest magmatic products of the region are the Plio-Pleistocene volcanic centers of Koh-e-Sultan, Dam Koh, Alam Reg, and several smaller volcanic complexes, which collectively form the Neogene Baluchistan volcanic arc. This arc extends westward into the Bazman–Taftan volcanic fields of southeastern Iran and was formed by the ongoing subduction of the Arabian Plate beneath the Afghan block of the Eurasian Plate along the Makran subduction zone [22]. Volcanism in this tectonic setting generated mainly calc-alkaline magmas [23]. The Siah Diq porphyry copper prospect is considered a product of this younger episode of arc magmatism and related hydrothermal activity [24]. Tectonically, the Chagai belt is an important segment of the Tethyan metallogenic belt, one of the world's most important porphyry copper, gold, and molybdenum provinces. The metallogenic evolution of this belt is related to long-lived subduction, which produced large Andean-type magmatic

arcs and associated mineralization [16]. The Chagai segment contains more than 48 known porphyry copper and gold prospects and deposits, including the world-class Reko Diq deposit with approximately 5.56 Mt of contained copper. Other major deposits include Saindak (>1 Mt Cu), Dasht-e-Kain, and Koh-e-Sultan, along with a number of underexplored but highly prospective mineral occurrences across eastern Chagai [25].

4. Materials and Methods

The study area was covered by a systematic ground magnetic survey on a 30 m × 30 m grid (30 m station interval and 30 m line spacing), with survey lines-oriented N–S and a constant line spacing throughout (Figure 3). Total magnetic intensity (TMI) was measured with a GPM proton precession magnetometer, which offers high sensitivity and reliability. A base station was established 80 m north of the survey area, and readings were repeated there at regular intervals throughout the survey to monitor temporal variations of the geomagnetic field caused by ionospheric currents (Figure 4). These variations were removed by applying a diurnal correction in MAGMAP software.

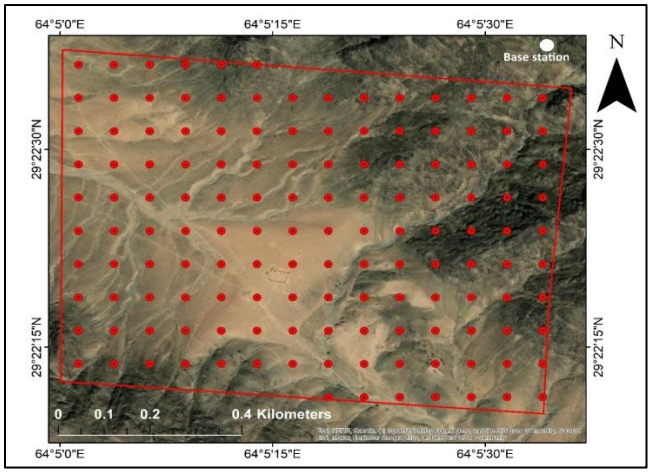


Fig. 3: Layout of the ground magnetic survey showing the data acquisition grid, station and line spacing, base station, and extent of the study area.

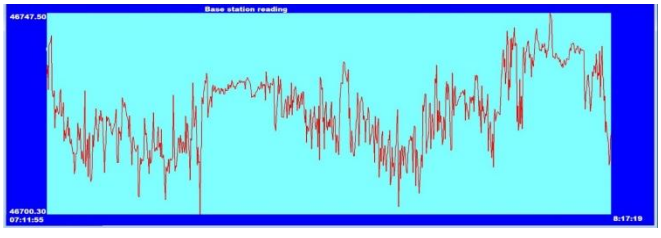


Fig. 4: Base station magnetic readings used to monitor diurnal variations during the survey.

The corrected data were then processed as follows: removal of the International Geomagnetic Reference Field (IGRF, 2015 model; regional field of 46,700 nT); reduction to the pole (RTP) using an inclination of 46.7° and a declination of 2.4°; application of vertical- and horizontal-derivative filters; and computation of the analytical signal to enhance the boundaries of shallow sources. Source depths were estimated by 3D Euler deconvolution (structural index 1, window size 150, and depth tolerance 15%), and a three-dimensional voxel model of the magnetic anomalies was generated by 3D gridding to show their spatial distribution and subsurface extent. Processing was performed in MAGMAP 2000 and Oasis montaj. The processed data were used to delineate variations in magnetic susceptibility in order to identify lithological boundaries, structural features (including faults and fractures), and potential zones of hydrothermal alteration. Such anomalies are particularly relevant to mineral exploration because they can reveal concealed mineralization and the destruction or enrichment of magnetite, as is typical of porphyry Cu–Au systems.

5. Results

A high-resolution ground magnetic survey was conducted to assess the base-metal prospectivity of the area and to identify the most anomalous zones for exploratory drilling. The processed total magnetic intensity (TMI) map (Figure 5) shows zones of high (pink) and low (blue) magnetic intensity, revealing clear differences in magnetic response across the study area. These variations reflect changes in subsurface structure, lithology, and alteration [26, 27].

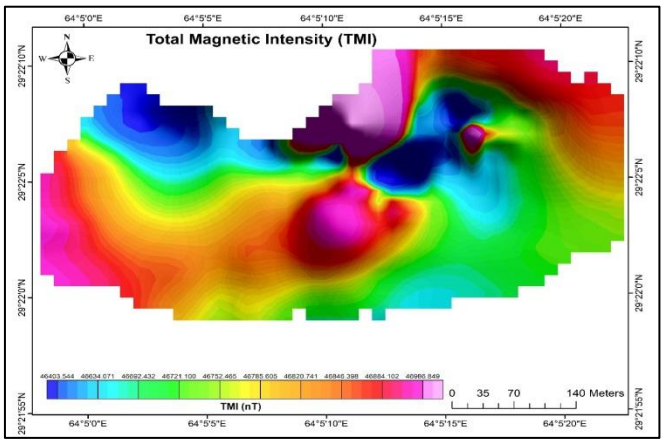


Fig. 5: Total magnetic intensity (TMI) map showing the distribution of magnetic field intensity across the study area.

The diurnally corrected magnetic map (Figure 6) shows spatial variations in the magnetic field that reflect contrasts in subsurface magnetic susceptibility arising from lithology, structural features, and hydrothermal alteration. Values range from approximately −399 nT to +251 nT, indicating high variability. Low magnetic anomalies (blue and dark-blue zones) occur in the central part of the study area, whereas high magnetic anomalies (red and pink zones) are mainly distributed in the eastern and northeastern parts.

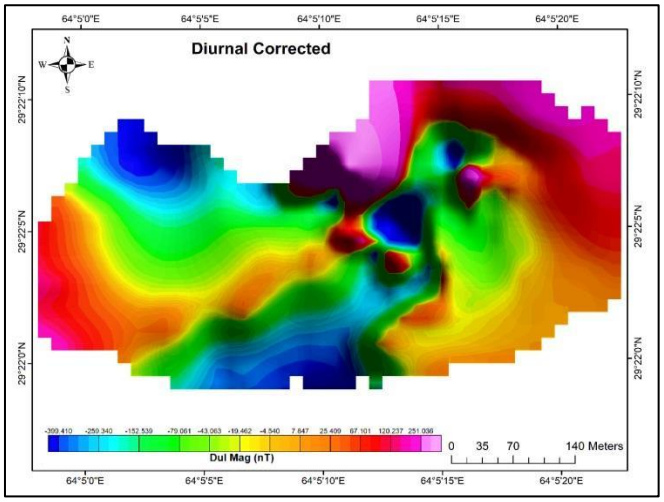


Fig. 6: Diurnally corrected magnetic map of the study area.

Because the reduction-to-the-pole (RTP) transformation places magnetic anomalies directly above their causative sources, the RTP map (Figure 7) allows a more accurate geological interpretation; its values range from approximately −722 nT to +763 nT. A prominent positive anomaly in the eastern part of the RTP map suggests a relatively shallow, highly magnetized source, most likely an intrusive body or a magnetite-rich lithology. In contrast, a distinct negative anomaly in the central zone is surrounded by mixed-polarity gradients; this feature is interpreted as a zone of magnetite destruction and is strongly suggestive of hydrothermal alteration.

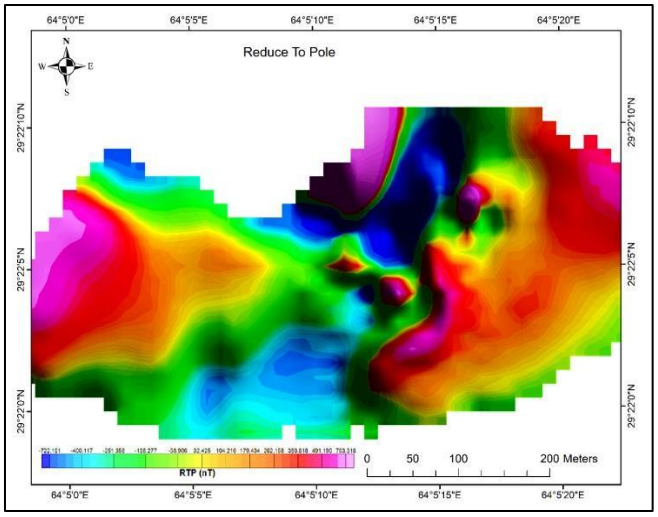


Fig. 7: Reduced-to-the-pole (RTP) magnetic map showing the corrected positions of the magnetic sources.

The analytical signal (AS) map (Figure 8) is particularly useful for delineating subsurface features because it highlights the edges of magnetic sources and is largely independent of the direction of magnetization. Low AS amplitudes (blue–green zones) correspond to areas of reduced magnetic susceptibility, interpreted as zones of magnetite breakdown caused by hydrothermal alteration. The anomalies are semi-elliptical to elongated with a general NE–SW trend, indicating structural control on fluid flow and alteration.

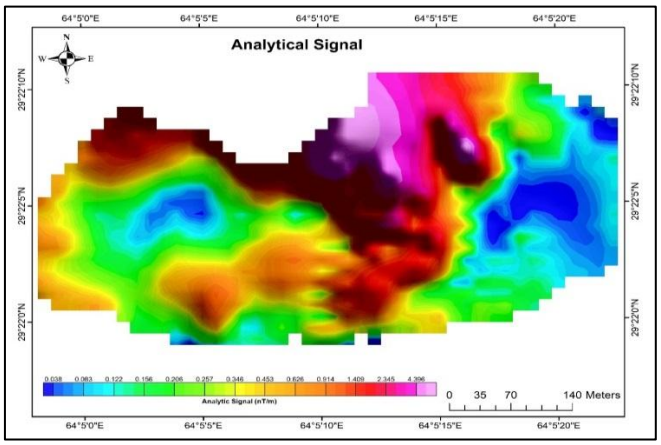


Fig. 8: Analytical signal (AS) map delineating the edges and contacts of magnetic sources independently of the magnetization direction, aiding the interpretation of subsurface geological structures and alteration zones.

Estimating the depth of anomalous zones is an important step in exploration. For this purpose, Euler deconvolution was applied, and the resulting solutions are plotted on the analytical signal map (Figure 9). The magnetic sources occur at depths of approximately 4–95 m; shallow sources are concentrated mainly in the central and northeastern sectors, whereas deeper sources are distributed mainly in the western and southern parts of the study area. These variations reflect differences in source geometry, burial depth, and structural setting. Finally, a 3D voxel model was constructed in Oasis montaj to evaluate the distribution of the anomalies along the X, Y, and Z axes (Figure 10).

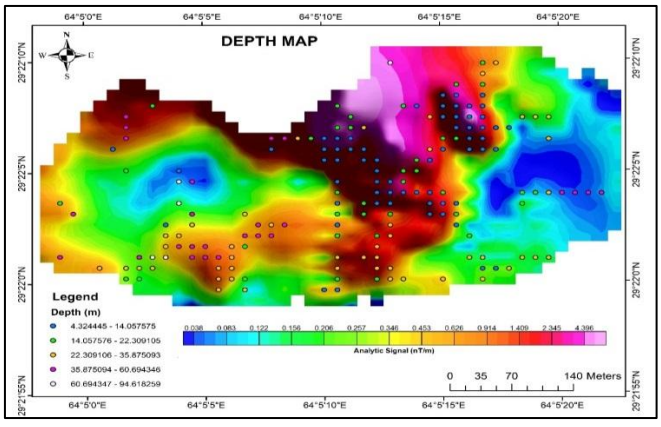


Fig. 9: Euler deconvolution depth estimates plotted on the analytical signal map.

6. Discussion

High magnetic anomalies are thought to occur where mafic to intermediate intrusions are associated with magnetite-rich porphyry systems (intrusive bodies) and largely unaltered host rocks [6, 11]. Low magnetic anomalies, on the other hand, are usually linked to silicification and to phyllic and other hydrothermal alteration zones in which magnetite has been destroyed; they may also coincide with

sulfide minerals such as bornite and chalcopyrite [28]. Magnetic responses are usually moderate to high in the potassic core zone, which is commonly associated with magnetite ± biotite. Magnetite is destroyed in the phyllic and argillic alteration zones, producing magnetic lows, whereas moderate magnetic highs are typically produced in the propylitic zone, which contains chlorite–epidote–magnetite assemblages [29]. A well-developed hydrothermal system is characterized by concentric alteration zoning, in which the intensity of alteration decreases progressively away from the intrusive center, consistent with the porphyry alteration model of Lowell and Guilbert [30]. The magnetic signatures of porphyry systems are therefore influenced by both primary magmatic processes and secondary hydrothermal alteration. Magnetic data, combined with edge-enhancement filters and upward continuation, have been used to delineate the distribution of porphyry copper deposits in the Tertiary magmatic belts of the Lut Block, Iran [31], and high-resolution ground magnetic surveys have been used for Cu exploration at Yueliangshan in the western Liupanshan Basin, China [32]. Porphyry Cu–Au systems are commonly characterized by circular to semi-circular magnetic lows over intensely altered zones in which magnetite has been partially or completely replaced by less magnetic minerals such as sericite, chlorite, epidote, and clay minerals. Magnetite destruction is especially pronounced in the phyllic, argillic, and advanced argillic alteration zones, leading to a significant decrease in the magnetic susceptibility of the stock and its host rocks [33, 34].

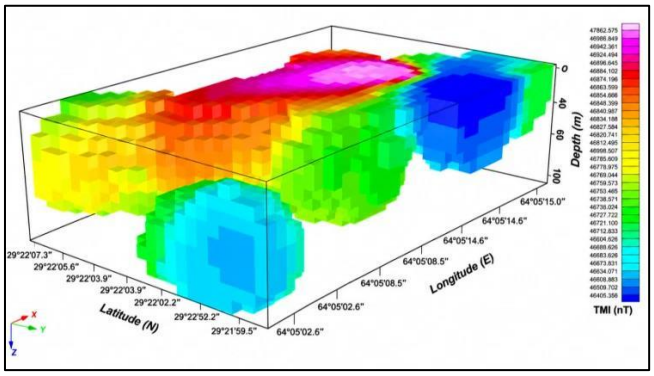


Fig.10: 3D voxel model of the magnetic data showing the variation in magnetic intensity with depth.

The combined interpretation of the diurnally corrected magnetic data, RTP, analytical signal amplitude, and Euler depth estimates (Figures 6–9) identifies a well-developed, structurally controlled hydrothermal system within the study area. The positive magnetic anomalies (Figure 7) are attributed to magnetite-enriched intrusive bodies and comparatively unaltered host lithologies. In contrast, the broad zones of low magnetic response in the eastern and western segments (Figure 8) indicate intense hydrothermal alteration accompanied by sulfidation and magnetite destruction, features characteristic of porphyry-related mineral systems. The analytical signal provides high-resolution delineation of lithological contacts and discontinuities, helping to define magnetic bodies largely independently of the magnetization direction, accounting for the effects of remanent magnetization. Notably, the western and eastern parts of the study area display a coincident pattern of low magnetic intensity, subdued analytical signal amplitudes, and very shallow to moderate source depths (Figure 9). Two prospective areas are therefore identified: a magnetic low in the eastern part and another in the western part. The western area appears more intensely altered and is the preferred location for drilling targets. A magnetic low surrounded by magnetic highs is a key indicator of hydrothermally altered zones that may host mineralization introduced by hot fluids.

According to the 3D magnetic intensity model (Figure 10), the magnetic intensity decreases with depth in the northern part of the study area but remains nearly constant elsewhere. The NE–SW-trending anomalies are thought to primarily reflect a network of deep-seated faults and fractures that served as pathways for hydrothermal fluid migration and metal transport. The spatial correlation among demagnetized zones, structural trends, and shallow source geometry greatly increases exploration confidence. Displaying all the essential geophysical indicators of a concealed, possibly high-grade mineralized system, the western and eastern areas appear highly prospective. These zones warrant follow-up with advanced exploration techniques, such as induced polarization (IP) surveys, to confirm the presence of economically viable porphyry Cu–Au mineralization, and this study provides prospective targets for future drilling.

7. Conclusions

Magnetic data are widely used to investigate subsurface geology, structural architecture, and mineralization potential, because magnetic responses are controlled by lithology, structure, and hydrothermal alteration. The main conclusions of this study are as follows:

(1) High magnetic values are interpreted as magnetite-rich, relatively unaltered host rocks and mafic to intermediate intrusions. Low magnetic anomalies are interpreted to be associated mainly with hydrothermal alteration and occur in the eastern and western parts of the study area.

(2) The analytical signal enhances source boundaries and helps identifying structurally controlled features. The NE–SW trend of the anomalies indicates fracture or fault systems that may have served as conduits for hydrothermal fluids.

(3) Euler depth estimates of 4–95 m indicates the coexistence of shallow and deeper magnetic sources, with shallow sources concentrated in the central and northeastern parts of the study area. The estimates are subject to limitations arising from the structural complexity of the subsurface.

This study integrates high-resolution ground magnetic data with depth-estimation techniques to delineate concealed mineralization associated with hydrothermal alteration. The findings have practical implications for mineral exploration companies, as the identified structural trends and depth estimates provide a preliminary framework for future exploration targeting.

The principal limitation of this study is that the interpretations are based solely from magnetic data, which reflect contrast in magnetic susceptibility and cannot uniquely characterize lithology or hydrothermal alteration. Therefore, the interpreted alteration and mineralization zones require validation through trenching, drilling, geological investigations, and other geophysical methods.

References

[1] J. Perelló, A. Razique, J. Schloderer, and Asad-ur-Rehman, "The Chagai porphyry copper belt, Baluchistan Province, Pakistan," *Econ. Geol.*, vol. 103, no. 8, pp. 1583–1612, 2008.

[2] R. H. Sillitoe and S. N. Khan, "Geology of the Saindak porphyry copper deposit, Pakistan," *Trans. Inst. Min. Metall., Sect. B: Appl. Earth Sci.*, vol. 86, pp. B27–B42, 1977.

[3] R. H. Sillitoe, "Metallogenic evolution of a collisional mountain belt in Pakistan: A preliminary analysis," *J. Geol. Soc. London*, vol. 135, no. 4, pp. 377–387, 1978.

[4] R. H. Siddiqui and W. Khan, "A comparison of hydrothermal alteration in porphyry copper mineralization of the Chagai calc-alkaline magmatic belt, Baluchistan, Pakistan," *Acta Mineral. Pakistanica*, vol. 2, pp. 100–106, 1986.

[5] J. Schloderer and B. I. A. McInnes, "Exploration, discovery and genesis of the Reko Diq copper-gold porphyry district, Pakistan," in *Proc. Australian Earth Sci. Conv.*, Melbourne, VIC, Australia, 2006. [CD-ROM].

[6] M. Dentith and S. T. Mudge, *Geophysics for the Mineral Exploration Geoscientist*. Cambridge, U.K.: Cambridge Univ. Press, 2014.

[7] D. J. Holden, J. Poniewierski, and R. Lane, "Geophysical exploration for porphyry copper deposits," in *Proc. Exploration 11: Fifth Decennial Int. Conf. Mineral Exploration*, 2011, pp. 989–1003.

[8] T. Hoschke, "Geophysical signatures of Australian porphyry copper deposits," in *Proc. Exploration: Fifth Decennial Int. Conf. Mineral Exploration*, 2011.

[9] R. Schodde, "The search for giant hidden porphyry copper deposits: Trends, challenges and opportunities," MinEx Consulting, Industry Rep., 2019.

[10] P. Kearey, M. Brooks, and I. Hill, *An Introduction to Geophysical Exploration*, 3rd ed. Oxford, U.K.: Blackwell Science, 2002.

[11] D. A. Clark, "Magnetic effects of hydrothermal alteration in porphyry copper and iron-oxide copper–gold systems: A review," *Tectonophysics*, vol. 624–625, pp. 46–65, 2014, doi: 10.1016/j.tecto.2013.12.011.

[12] R. E. Criss and D. E. Champion, "Magnetic properties of granitic rocks from the southern half of the Idaho batholith: Influences of hydrothermal alteration and implications for aeromagnetic interpretation," *J. Geophys. Res.: Solid Earth*, vol. 89, no. B8, pp. 7061–7076, 1984, doi: 10.1029/JB089iB08p07061.

[13] P. Lapointe, W. A. Morris, and K. L. Harding, "Interpretation of magnetic susceptibility: A new approach to geophysical evaluation of the degree of rock alteration," *Can. J. Earth Sci.*, vol. 23, no. 3, pp. 393–401, 1986, doi: 10.1139/e86-041.

[14] L. Wang *et al.*, "The subduction-related Saindak porphyry Cu-Au deposit formed by remelting of a thickened juvenile lower crust underneath the Chagai belt, Pakistan," *Ore Geol. Rev.*, vol. 149, Art. no. 105062, 2022.

[15] K. N. Nicholson, M. Khan, and K. Mahmood, "Geochemistry of the Chagai–Raskoh arc, Pakistan: Complex arc dynamics spanning the Cretaceous to the Quaternary," *Lithos*, vol. 118, no. 3–4, pp. 338–348, 2010.

[16] J. P. Richards, "Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: From subduction to collision," *Ore Geol. Rev.*, vol. 70, pp. 323–345, 2015.

[17] Hunting Survey Corporation Ltd., *Reconnaissance Geology of Part of West Pakistan: A Colombo Plan Cooperative Project*. Toronto, ON, Canada: Government of Canada for the Government of Pakistan, 1960.

[18] M. R. H. Siddiqui, "Crustal evolution of Chagai-Raskoh arc terrane, Balochistan, Pakistan," Ph.D. dissertation, Univ. Peshawar, Peshawar, Pakistan, 2014.

[19] R. S. Arthurton, A. Farah, and W. Ahmed, "The Late Cretaceous–Cenozoic history of western Baluchistan Pakistan—The northern margin of the Makran subduction complex," *Geol. Soc. London Spec. Publ.*, vol. 10, pp. 373–385, 1982, doi: 10.1144/GSL.SP.1982.010.01.25.

[20] S. A. Ahmad, I. Ahmad, F. Khan, and M. A. Hafeez, *Geologic Map of Borghar Quadrangle 30G/16 (1:50,000), Chagai District, Balochistan, Pakistan*. Quetta, Pakistan: Geol. Surv. Pakistan, 1983.

[21] F. Khan and W. Ahmed, *Geological Map of the Koh-i-Dalil Quadrangle 30K/4 (1:50,000), Chagai District, Balochistan, Pakistan*. Quetta, Pakistan: Geol. Surv. Pakistan, 1981.

[22] G. Grando and K. McClay, "Morphotectonic domains and structural styles in the Makran accretionary prism, offshore Iran," *Sediment. Geol.*, vol. 196, no. 1–4, pp. 157–179, 2007, doi: 10.1016/j.sedgeo.2006.05.030.

[23] S. Saadat and C. R. Stern, "Petrochemistry and genesis of olivine basalts from small monogenetic parasitic cones of Bazman stratovolcano, Makran arc, southeastern Iran," *Lithos*, vol. 125, no. 1–2, pp. 607–619, 2011, doi: 10.1016/j.lithos.2011.03.014.

[24] Y. S. Khalil and M. N. Siddiq, "Exploration of copper, gold and molybdenum deposits in Durban Chah–Mashki Chah, District Chagai, Balochistan: Report on collaborative project between the Geological Survey of Pakistan and Saindak Metals Limited," Geol. Surv. Pakistan, Quetta, Pakistan, Inf. Release 1027, 2017.

[25] Lake Resources N.L., "Exploration activities in Chagai, Balochistan," Quarterly Rep., Jan.–Mar. 2014, pp. 1–5.

[26] J. M. Reynolds, *An Introduction to Applied and Environmental Geophysics*, 2nd ed. Chichester, U.K.: Wiley, 2011.

[27] M. N. Nabighian *et al.*, "The historical development of the magnetic method in exploration," *Geophysics*, vol. 70, no. 6, pp. 33ND–61ND, 2005.

[28] R. S. Arthurton, G. S. Alam, S. Anisuddin-Ahmad, and S. Iqbal, "Geological history of the Alamreg–Mashki Chah area, Chagai district, Baluchistan," in *Geodynamics of Pakistan*, A. Farah and K. A. DeJong, Eds. Quetta, Pakistan: Geol. Surv. Pakistan, 1979, pp. 325–331.

[29] R. H. Sillitoe, "Porphyry copper systems," *Econ. Geol.*, vol. 105, no. 1, pp. 3–41, 2010.

[30] J. D. Lowell and J. M. Guilbert, "Lateral and vertical alteration–mineralization zoning in porphyry ore deposits," *Econ. Geol.*, vol. 65, no. 4, pp. 373–408, 1970.

[31] S. Hassanpour, M. S. Bayraktutan, and S. Komatina, "Application of the magnetic geophysical method to exploration of the potassic zone in some porphyry copper deposits (Iran)," *First Break*, vol. 40, no. 8, pp. 91–96, 2022.

[32] R. Tao, T. Qiang, and T. Gong, "Integrated magnetic and electrical geophysical methods for detecting concealed porphyry copper deposits in sedimentary basins: A case study from the western Liupanshan Basin, Northwest China," *Geol. J.*, vol. 60, no. 8, pp. 1942–1955, 2025.

[33] J. P. Richards, "Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation," *Econ. Geol.*, vol. 98, no. 8, pp. 1515–1533, 2003.

[34] W. D. Sinclair, "Porphyry deposits," in *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods*, W. D. Goodfellow, Ed. St. John's, NL, Canada: Geol. Assoc. Canada, Mineral Deposits Div., Spec. Publ. 5, 2007, pp. 223–243.