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Biotite chemistry as petrogenetic discriminator: IOA type magnetite deposits in North Delhi Fold Belt, Western India

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Abstract: In India, most iron ore deposits are related to Precambrian Banded Iron Formations (BIFs), while comparatively limited occurrences of magnetite mineralization are documented from a variety of other geological environments. In western India, economically significant non-BIF iron ore bodies, largely dominated by magnetite, are hosted within rocks belonging to the Delhi Supergroup. Within the Khetri Basin, medium- to high-grade iron ores (44.1–65 wt% Fe) occur as lens-shaped bodies and localized pockets within the Meso- to Neo-Proterozoic albitites and associated meta-sedimentary units of the Ajabgarh Group. Petrographic examination shows that magnetite and hematite represent the principal iron oxide minerals. These ore minerals occur in association with silicate-rich host rocks composed mainly of quartz, actinolite, muscovite, biotite, albite, and K-feldspar, along with accessory phases such as apatite, sphene, ilmenite, monazite, and several rare earth elements (REE)–bearing minerals. Biotite mineral chemistry indicates that most biotite grains are secondary in nature, formed through alteration of primary biotite during widespread metasomatic activity. Integration of field observations, mineral assemblages, and biotite compositional data suggests that the iron mineralization was most likely emplaced during regional-scale metasomatic processes.

Index Terms- Biotite chemistry, magnetite deposits, North Delhi fold belt

I. INTRODUCTION

Iron ore occurrences in Rajasthan and the adjoining Mahendragarh district of Haryana are reported as discontinuous lenticular bodies hosted within biotite schist (Pant et al., 2004). Airborne magnetic surveys conducted by the Geological Survey of India (GSI), followed by detailed ground verification around the Khetri copper deposit and the Neem-Ka-Thana region of Rajasthan, resulted in the identification of pocket-type iron ore mineralization (Rao and Bhamboo, 2008). In northern Rajasthan, particularly around the Khetri copper deposits, iron mineralization occurs as lensoidal to irregularly shaped bodies of varying sizes (Dwivedy and Sahoo, 2021; Dwivedy,2024). On a regional scale, magnetite–hematite–dominated iron ore bodies are distributed along two linear zones: one located south of the Khetri copper deposit (hereafter referred to as the western iron ore band) and the other along its south-eastern margin (hereafter referred to as the eastern iron ore band). These occurrences are situated approximately 15–40 km from the Khetri copper deposit.

Iron ore bodies in the western sector are mainly associated with albitites, reflecting the close spatial relationship with zones of intense albitization along the western flank. In contrast, the eastern occurrences are primarily hosted within meta-sedimentary rocks, especially biotite schist, and only occasionally show association with albitized rocks, unlike the more frequent association observed in the western flank (Dwivedy and Sahoo, 2021). Consequently, biotite chemistry has been utilized to interpret the magmatic conditions responsible for the formation of the host rocks. The chemical composition of biotite serves as an important indicator of temperature, pressure, compositional characteristics, and redox conditions in both magmatic and hydrothermal environments (Munoz, 1984; Speer, 1984). Numerous recent studies have employed biotite geochemistry to understand deposit genesis and to constrain the physicochemical conditions prevailing during hydrothermal evolution (Afshooni et al., 2013; Tang et al., 2019). For classification of biotite compositions, interpretation of fluid characteristics, and reconstruction of hydrothermal alteration history in the study area, major oxides including MgO, MnO, FeO, Al_2O_3, and TiO_2 were analyzed using an electron probe micro-analyzer (Foster, 1960; Abdel Rahman, 1994; Nachit et al., 2005).

II. Geological setting

The Proterozoic fold belts of the Aravalli–Delhi Province are represented by two principal stratigraphic units: the older Aravalli Supergroup and the younger Delhi Supergroup. The Aravalli Supergroup predominantly extends across the southern and south-eastern regions of Rajasthan, whereas the Delhi Supergroup is mainly distributed in the south-western and north-eastern parts of the state. The Aravalli Supergroup comprises an extensive succession of clastic and chemogenic sedimentary rocks interlayered with basic volcanic units, reflecting complex deformation histories and formation under varied depositional settings. In comparison, the Delhi Supergroup is largely composed of pelitic and psammitic rocks associated with carbonate and volcanic units, and records multiple phases of deformation and metamorphism.

The oldest basement in the region is the Archean Banded Gneissic Complex (BGC; ~3.3–2.5 Ga), upon which the Aravalli Supergroup rests unconformably. This basement complex mainly consists of granites, pegmatites, and granitic gneisses, along with subordinate metavolcano-sedimentary rocks (Heron, 1953; Choudhary et al., 1984; Gopalan et al., 1990; Golani et al., 2002). Overlying the BGC are the supracrustal successions of the Palaeoproterozoic Aravalli Fold Belt (2.2–1.85 Ga) and the younger Mesoproterozoic Delhi Fold Belt (1.8–0.85 Ga). Together, these tectonostratigraphic units constitute the Aravalli–Delhi Fold Belt (ADFB) (Fig. 1) (Roy, 1988; Kaur et al., 2007, 2011).

Among the three major basins of the NDFB, the present study area is located within the Khetri Basin and comprises rocks belonging to the oldest Banded Gneissic Complex (BGC), younger metasedimentary units of the Alwar and Ajabgarh Groups, as well as granitic intrusives (Fig. 1). The Alwar Group is dominantly characterized by gritty arenaceous lithologies, whereas the Ajabgarh Group mainly consists of fine-grained, massive argillaceous rocks (Heron, 1953). Within the Khetri Basin, a gradational relationship between the Alwar and Ajabgarh Groups is recognized, as indicated by the occurrence of local pebble beds in the Chapoli area (Dasgupta, 1968). The principal lithologies of the region include metapelites, calc-silicate rocks, quartzites, quartz-mica schists, biotite schists, and phyllites, along with minor meta-carbonate units. These rocks are intruded by both concordant and discordant veins of quartz, calcite, fluorite, pegmatite, and albitite. The belt is well known for copper mineralization dominated by bornite–chalcocite–covellite assemblages, accompanied by iron ore and minor barite occurrences (Sharma et al., 2020). In addition, uranium mineralization associated with albitized zones has been reported by the Atomic Mineral Directorate for Exploration and Research (AMD).

The region has undergone intense Na-metasomatism affecting the BGC, the Meso- to Neo-Proterozoic Delhi metasediments, and associated granitic bodies (Kaur et al., 2019a). Extensive albitization of basement rocks along the western margin is exposed near Rohil, Salwari, and the Tonda-Karath areas, along with metasomatic modification of metasediments marked by the development of scapolite (Baidya et al., 2017; Kaur et al., 2016; Sharma et al., 2020). Metasomatic alteration in the area is interpreted as a post-hydrothermal event related to regional metamorphism, involving processes such as chloritization, biotization, Fe–Mg metasomatism, and silicification (Knight et al., 2002).

III. Analytical methods used

Petrographic investigations play a crucial role in identifying mineral assemblages, understanding textural relationships among minerals, and reconstructing the paragenetic evolution of mineralization. Representative samples were collected from iron ore bodies and their associated host rocks exposed in and around the Neem-Ka-Thana area. Fresh and unaltered samples were selected for the preparation of polished thin sections in order to examine mineralogical characteristics, textural variations, and the extent of hydrothermal alteration within the study area. Approximately 30 polished thin sections were examined using a Leica DM27 microscope for detailed petrographic characterization. The petrographic interpretations were further supported and confirmed through analyses carried out using an Electron Probe Micro Analyzer (EPMA).

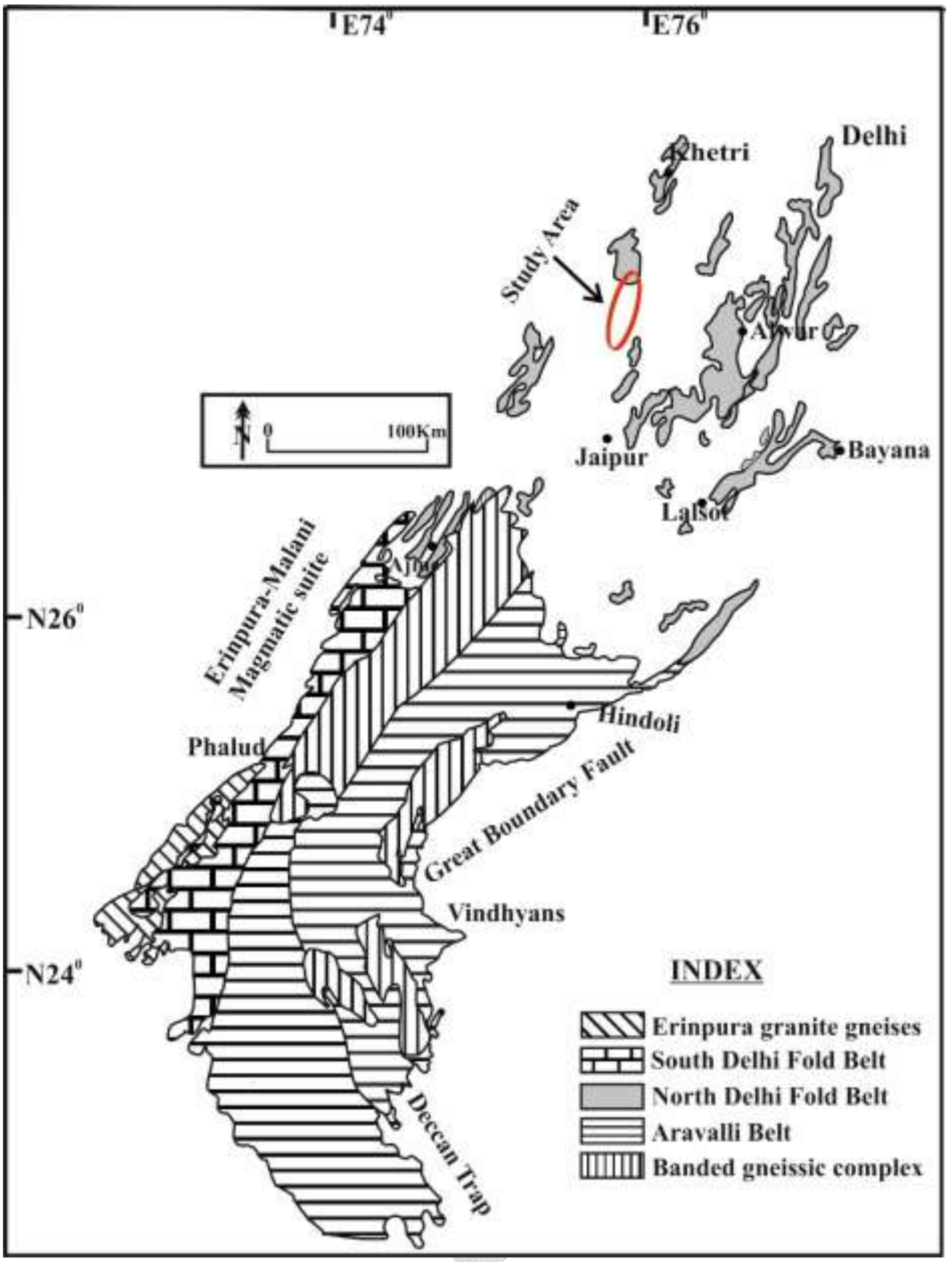

Fig.1 Geological map of the Aravalli–Delhi Fold Belt showing the position of the present study area (modified after Roy, 1988).

IV. PETROGRAPHY AND EPMA STUDIES

Iron ores from the study area are dominantly composed of oxide minerals, including massive magnetite, hematite, and specularite (micaceous hematite), typically occurring as vein-filling bodies and lacking associated sulfide phases (Figs. 2, 3). Petrographic observations indicate magnetite as the primary ore mineral, with hematite forming mainly through partial oxidation along fractures and grain boundaries, reflecting oxidizing conditions during mineralization (Fig. 2A, B). The host rocks primarily belong to the metapelitic sequence of the Ajabgarh Group and include schistose rocks, amphibole-bearing quartzites, phyllites, and locally impure dolomitic marble. Albitite bodies are commonly associated with these regional metasedimentary rocks (Fig. 2C–F). Petrographic studies of eastern flank metapelites reveal mineral assemblages dominated by quartz, biotite, albite, and actinolite (Fig. 2E). EPMA analyses confirm altered magnetite and hematite with minor goethite as the principal iron-bearing minerals (Fig. 3). Associated phases include albite, biotite, and actinolite, along with accessory minerals such as apatite and monazite. Monazite commonly occurs along magnetite grain boundaries, whereas fluorapatite is associated with both albitites and magnetite–hematite assemblages.

V. RESULT AND DISCUSSION

The major elemental concentration of biotite grains found from the study areas are analysed by the help of EPMA studies. The SiO_2, Al_2O_3, MgO, FeO and TiO_2 content varies from 35.56-42.85 wt%,10.95-17.13 wt%,10.58-21.92 wt%,7.59-19.51 wt% and 0.03-2.89 wt% respectively.

Biotite chemistry: Tracking the hydrothermal signature for iron mineralization

Biotite is an important ferromagnesian mineral occurring as a major to accessory phase in felsic, intermediate, and mafic igneous rocks (Abdel-Rahman, 1994). Its chemical composition serves as a reliable indicator for evaluating magma characteristics, including petrogenetic evolution, oxygen fugacity, and crystallization temperature of the parental melt (Wones et al., 1971; Abbot Jr and Clarke, 1979; Abdel-Rahman, 1994; Nachit et al., 2005). The mica classification scheme proposed by Foster (1960), based on the distribution of AlVI, Fe^{3+}, Fe^{2+}, Mn^{2+}, Mg, and Ti within trioctahedral mica structures, categorizes micas into groups such as phlogopite, Mg-biotite, ferro-biotite, siderophyllite, and lepidomelane.

Compositional plots indicate that most biotite samples from the study area fall within the ferro-biotite to Mg-biotite fields (Fig. 4A). Variations in TiO_2, FeO*, and MgO contents further suggest that these biotites are re-equilibrated or neo-formed rather than primary magmatic phases (Fig. 4B) (Nachit et al., 2005; Azadbakht et al., 2018; Dubosq et al., 2019). The relative depletion of Ti in biotite is interpreted as a consequence of hydrothermal alteration during post-magmatic processes. Such hydrothermal modification associated with magmatic activity is consistent with a rift-related tectonic setting characterized by calc-alkaline biotite assemblages (Abdel-Rahman, 1994) (Fig. 4C).

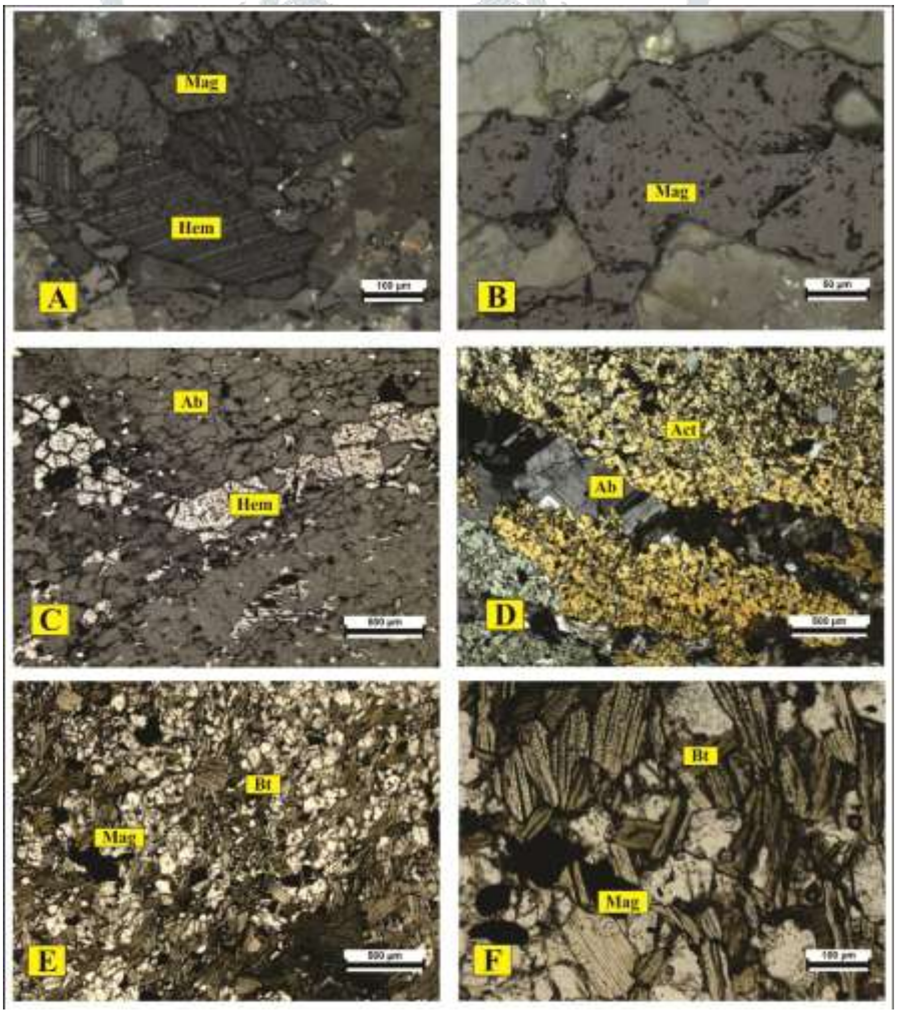

Fig. 2 Photomicrographs showing (A,B) Martitization of the massive and granular magnetite ores (C,D)Magnetite veins intruded into the host rocks (E) Disseminated magnetite found within the micaceous phyllitic rocks.

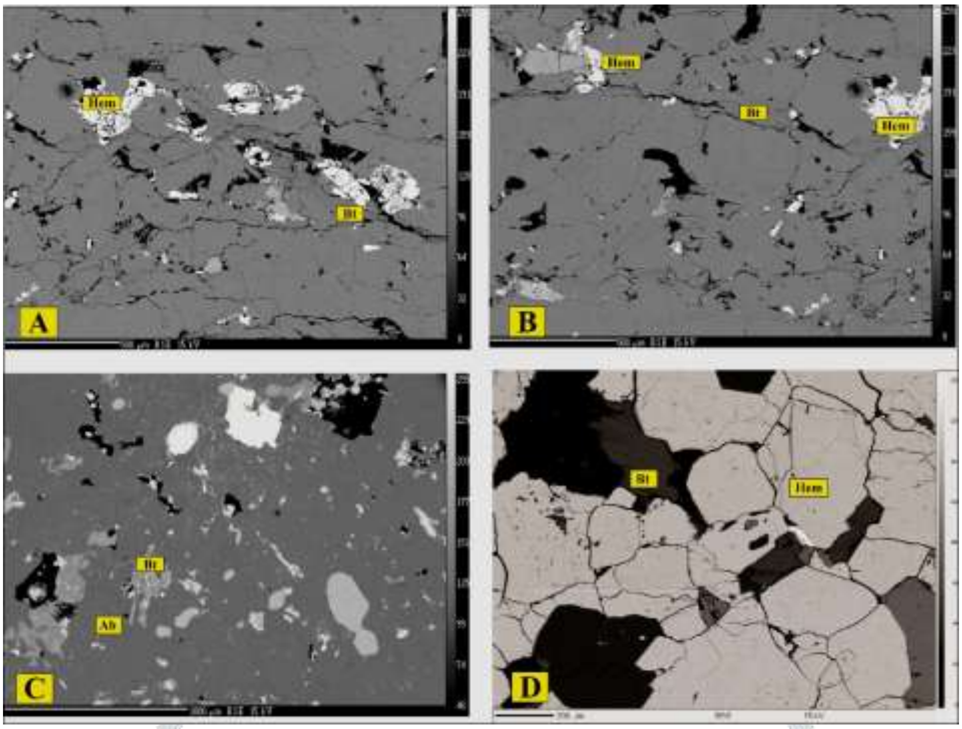

Fig.3 BSE images showing **(A-D)** Disseminated magnetite occurs within micaceous phyllitic rocks.

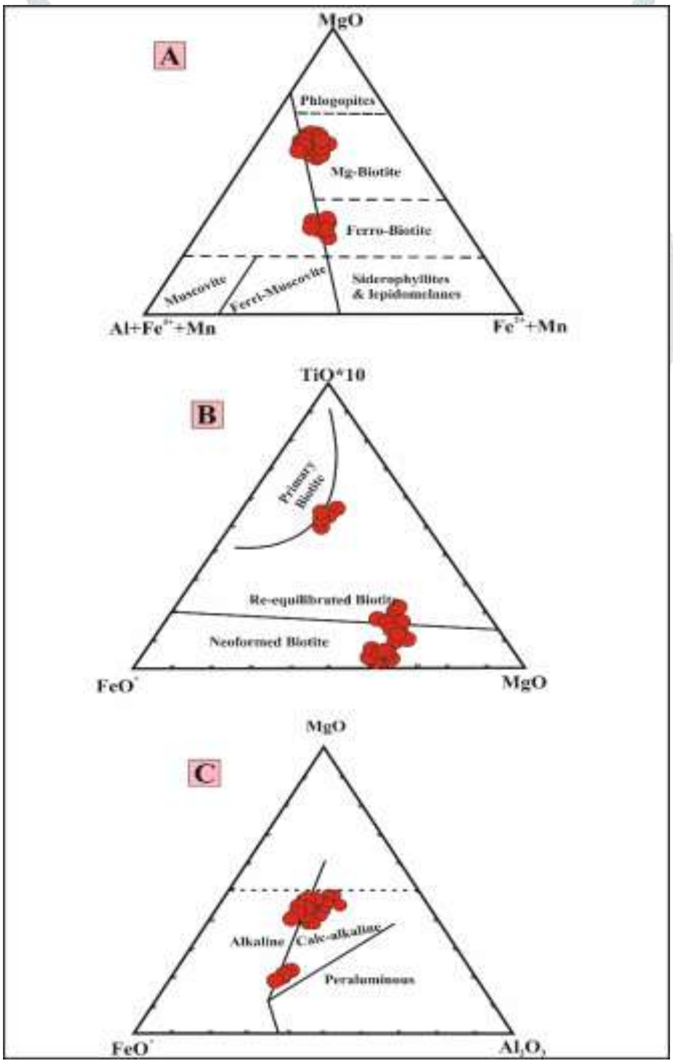

Fig.4 **(A)** Classification diagram of mica after Foster (1960); **(B)** ternary compositional diagram showing TiO_2–(FeO + MnO)–MgO relationships following Nachit et al. (2005); and **(C)** tectonic discrimination diagram based on FeO–MgO–Al_2O_3 contents of biotite after Abdel Rahman (1994).

VI. CONCLUSION

The investigated iron ore prospects and deposits are located within the Jhunjhunu and Sikar districts of Rajasthan in western India. The iron ore bodies display significant variability in size, ranging from meter-scale occurrences to bodies exceeding 10 m in width and extending up to nearly 2 km along strike. These mineralized zones occur mainly as pocket-type and disseminated bodies exposed in outcrops and quarry sections along the southern and south-eastern parts of the Khetri copper deposit. Unlike the magnetite mineralization associated with the Khetri copper belt, where magnetite commonly occurs as thin bands, veins, and disseminations within amphibolites and schists together with sulfide phases, the magnetite mineralization in the present study area forms massive bodies and thick veins that are notably devoid of sulfide minerals. The ores show a strong spatial association with albitites as well as metasedimentary rocks such as quartz–biotite schist and phyllite of the Paleo- to Meso-Proterozoic Ajabgarh Group of the Delhi Supergroup. Chemical variations observed in biotite, particularly the decrease in Mg content coupled with enrichment in Ti, indicate that the biotites have undergone hydrothermal re-equilibration and are largely neo-formed rather than primary magmatic phases. Such compositional modification and neoformation of biotite are widely interpreted as signatures of hydrothermal–metasomatic alteration driven by the circulation of late- to post-magmatic fluids. These processes likely played a significant role in controlling mineralogical transformation and ore formation at a regional scale, suggesting that fluid-mediated metasomatism was an important factor in the evolution of iron mineralization in the study area.

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