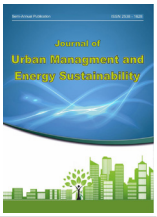
International Journal of Urban Management and Energy Sustainability (IJUMES)

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CASE STUDY RESEARCH PAPER

Mineralization and Geochemical Study of Manganese Deposits Associated with Ophiolites in Northwest Lorestan Province (Noorabad-Delfan)

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ARTICLE INFO

Article History:
Received 2026-06-01
Revised 2026-07-10
Accepted 2026-09-25

Keywords:
Hydrothermal manganese; Neotethys; Ophiolite; pyrolusite; radiolarian chert

ABSTRACT

Manganese deposits hosted by radiolarian cherts in the uppermost parts of Neotethyan ophiolites are common in Iran, yet the geochemical signatures and origin of the occurrences in the Kermanshah–Borujerd ophiolite zone remain poorly documented. This study aims to provide mineralogical and geochemical evidence for the mineralization processes of the manganese deposit in the Noorabad-Delfan area, northwest Lorestan Province, and to support manganese exploration in the region. Forty samples were collected from the ophiolitic sequence for petrographic and mineragraphic study, and ten ore samples were analyzed by X-ray fluorescence spectrometry. The ore forms small, irregular lenses interbedded with radiolarian cherts and mudstones. Mineralization developed in a syngenetic stage, with jasperoid and silicified veins, and a later epigenetic stage of stockworks, veins and veinlets cutting the carbonate units and the syngenetic ore. The paragenesis is simple and dominated by pyrolusite and braunite. The absence of iron-bearing phases and the massive, poorly crystalline pyrolusite indicate rapid primary precipitation from hydrothermal fluids with strong Fe–Mn fractionation. Mn/Fe ratios of 4.32–4.73, low Al and Ti contents, high SiO_2, low Co, Ni and Cu, and Co/Zn ratios of 0.15–2.07 point to a submarine hydrothermal origin. Primary manganese was deposited with biogenic silica near a mid-ocean ridge in the Neotethys and was later remobilized along major faults. The Noorabad-Delfan deposit is therefore of submarine hydrothermal origin, and the combined mineralogical and geochemical criteria can guide focused exploration for radiolarite-hosted manganese in the Zagros ophiolites.

DOI: 10.22034/ijumes.2026.743757

Running Title: Geochemical Study of Manganese Deposits Associated with Ophiolites

NUMBER OF REFERENCES 77

NUMBER OF FIGURES 05

NUMBER OF TABLES 00

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INTRODUCTION

Manganese oxide deposits can be formed in marine and terrestrial environments and under the influence of various processes (Maynard, 2010). The formation and origin of manganese mineralization are very diverse and can be formed by various sedimentary, hydrothermal, hydrogenetic and supergene processes. Hydrothermal manganese deposits are deposited from low-temperature hydrothermal solutions in the form of strata, regular veins and occur in various tectonic environments, including lacustrine environments, inland seas, volcanic arcs of subduction environments (Ghasemi & Talbot, 2006; Ghazi & Hassanipak, 1999; Kuleshov, 2011; Nicholson, 1992; Paravarzar et al., 2023; Pourgholam et al., 2024; Roy, 1997). Manganese mineralization of marine origin also includes hydrogenetic mineralization processes (manganese nodule mineralization process), hydrothermal, diagenetic and biogenic deposits (Afzal et al., 2023; Barak et al., 2024; Bolton et al., 1988; Ghasemi et al., 2024; Hein et al., 1997; Moghaddasi et al., 2019; Öksüz, 2011; Polgári et al., 2012; Rahmatian et al., 2019; Zhang et al., 2013). Known manganese deposits in Iran occur in various geological units and are limited to the Late Precambrian-Early Cambrian to Miocene-Pliocene periods (Heidari et al., 2024; Maanijou et al., 2015; Maghfouri et al., 2017). Generally, the Iranian manganese deposits are divided into four main groups based on the age of formation and genetic characteristics, structural features of the deposit, and the environment of occurrence (Haghighi et al., 2024; Maghfouri et al., 2017). According to the classifications, a group of manganese deposits is associated with Cretaceous ophiolites. Manganese mineralization occurs in the uppermost ophiolite rock sequences in most ophiolite complexes in Iran, including deposits found in ophiolites of Khoy, Kermanshah (Sorkhvand), Neyriz (Nasirabad deposit), Naiin (Benvid deposit), Sistan (Kamartalar deposit) and Sabzevar (Talar deposit) (Emamalipour, 2009; Maghfouri et al., 2017; Rajabzadeh & Zaman-Sani, 2013; Sepahvand, 2014; Zarasvandi et al., 2013a, 2013b, 2014; Zarrinkoob et al., 2009). Manganese mineralization in these areas has occurred along with radiolarian cherts, shale and pelagic limestones. The Noorabad-Delfan area is part of the Kermanshah Borujerd ophiolite zone. However, specific geochemical signatures of the manganese deposits associated with the Neotethys ophiolite unit in the region of the Zagros orogeny have not been considered. Consequently, this study marks the first effort to precisely describe these deposits, conduct comprehensive geochemical investigations, and explore the geological settings of manganese occurrences in this region. Furthermore, utilizing available geochemical datasets of manganese deposits across the region, we propose a geodynamic model that may elucidate the origin of Neotethys manganese and ferromanganese in radiolarite chert. In this study, an attempt is made to study the Noorabad ophiolite complex as the southern part of the Kermanshah ophiolite to determine the mode of manganese mineralization in the region.

Methodology

After collecting basic information during a field visit to the study area, 40 samples were taken from the ophiolitic sequence rocks under study, and thin sections and thin-polished sections were prepared for microscopic petrological and mineralogy studies of the mineral. Considering the importance of geochemistry in determining the type of mineralization, 10 samples were selected for chemical analysis to study the geochemistry of the ore and analyzed using an XRF X-ray fluorescence spectrometer (Latif et al., 2022). (Fig. 1)

The Borujerd Kermanshah ophiolites are part of the ophiolite complex belonging to the Zagros orogenic cycle in the west of the country, which itself has been formed as part of the Alpine-Himalayan belt due to the closure of the Neotethys (Alavi, 1994; Nazari et al., 2023; Nutman et al., 2022; Ousta et al., 2024). The studied ophiolite complex is located in the northern part of the high Zagros zone (thrust Zagros) with a northwest-southeast trend. The high Zagros

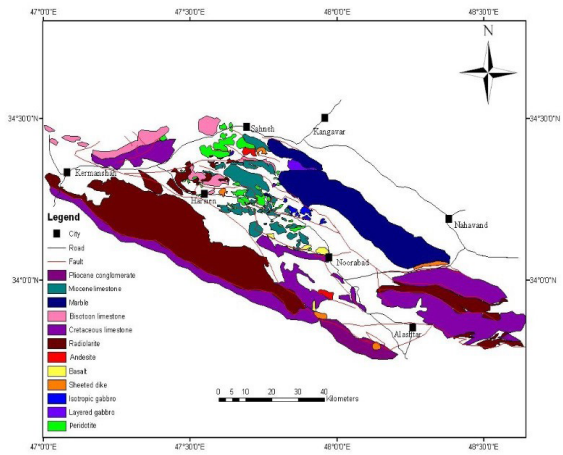


Figure 1: Geological map of the study area

zone is located between the folded Zagros and Sanandaj-Sirjan zones. (Allahyari et al., 2010; Yazdi et al., 2022). The ophiolite complex in the region includes serpentinized peridotites, layered meta-gabbros, isotropic gabbros, sheet dike complexes, basaltic lavas, and sedimentary rocks (including radiolarite and pelagic limestones), in the uppermost part of which radiolarite chert, jasperoid, and pelagic limestone layers are also seen (Frings et al., 2024; Latif et al., 2025; Mohajjel et al., 2003; Saccani et al., 2013). Peridotite rocks account for the largest volume and most altered part of the igneous rocks of the ophiolitic complex of the study area and include harzburgite, dunite and lherzolite. Harzburgite rocks constitute the largest volume of the peridotite section. Other units observed in the area include Upper Miocene shales, sandstone and limestone, Bakhtiari conglomerates, Upper Cretaceous cherts and shallow marine limestones of Upper Jurassic-Lower Cretaceous age (Ahmed et al., 2024; Allahyari et al., 2010; Farfan et al.,; Khodami et al., 20242023). The Sanandaj-Sirjan zone is located in the north and northeast of the study area, and its rocks include Jurassic-Cretaceous limestones that have been transformed into marble due to metamorphism. Also, in the south and southwest of the study area, there is the folded Zagros zone, which includes Upper Cretaceous limestones and Bakhtiari conglomerates that are highly folded. The ophiolites of this region are highly tectonized and are of the coloured mélange type. In structural and geometric studies, the Noorabad melange ophiolite has a folded structure that was created under the influence of two factors: changes in thickness and hardness of the layers (Fotoohi-Rad et al., 2023; Kiani, 2011).

Mineragraphy and Mineralogy

The Kermanshah ophiolite complex lithologically consists of ultrabasic, basic, and acidic intrusive rocks and pillow basaltic lavas overlain by tuffs and pyroclastic rocks and younger calcareous and radiolarite sediments. Most ophiolitic manganese deposits are associated with radiolarites. Radiolarite cherts are observed as hosts for manganese mineralization in the region. Petrographic study of ore-bearing samples shows that manganese oxide mineral, pyrolusite (MnO2) and manganese silicate mineral, braunite ($Mn^{2+}Mn^{3+}{}_6SiO_{12}$) are the most abundant manganese-bearing minerals in the study area. In addition to them, nsutite and rhodochrosite are also identifiable in the studies. Also, the siliceous phase has formed the largest volume of the bedrock. In general, petrographic studies indicate two simultaneous features, syngenetic and late epigenetic. The most prominent mineral of the simultaneous occurrence is the mineral pyrolusite. This mineral was observed in the hand and microscopic sample scale mainly as an amorphous mass without clear crystal surfaces. This can be attributed to the rapid deposition of manganese from hydrothermal mineral fluids (Barak et al., 2023; Gursky, 2023; Mohammad et al., 2021; Rezaei, 2012). In addition, in some cases, this mineral exists as microcrystals of simultaneous occurrence with quartz. Other syngenetic features include the relatively abundant presence of radiolarite microfossil shells in the pyrolusite background, where no mineral replacement has occurred in these shells. On the sedimentary units of the area, the alternation of manganese-bearing layers and the carbonate unit of pelagic limestones is seen, which is an indication of the simultaneous deposition of

ore with the host rock in the first stage of mineralization. Syngenetic mineralization is often formed as layers with radiolarite chert. Manganese nodules and manganese diffuse textures are other features of mineralization of the syngenetic phase. Late-generation epigenetic features are mainly visible in the samples collected from the deposit, which indicates the role of supergene processes. This feature is mainly in the form of pyrolusite crystals filling the open spaces in the host rock and also filling the veins and fractures. Vein mineralization is the most important form of mineralization in the epigenetic phase that in some cases epigenetic veins can be seen in syngenetic ore. The manganese grade in epigenetic ore is higher than in syngenetic, and the diversity of minerals in the epigenetic phase is also greater. (Fig. 2)



Figure 2: View of mineral veins

FINDINGS AND DISCUSSION

Today, geochemical criteria are widely used to determine the origin of manganese ores and deposits, for example: the ratio of major elements, the concentration of trace elements and the enrichment of some elements have been used by various researchers to evaluate the origin of manganese deposits (Nakagawa et al., 2009-2011; Polgári et al., 2012; Sanchez Siachoque, 2023; Sasmaz et al., 2014; Shah & Khan, 1999; Yousefi et al., 2023). Among the main oxides, the content of manganese, iron, silicon, titanium and aluminum oxides is very useful for identifying the origin of manganese ore (Karakus et al., 2010; Safarov et al., 2025; Sasmaz et al., 2014). Geochemical criteria and the use of oxides of major elements and the amounts of some elements such as Al, Ti, Fe, Mn have been very useful and have been proven in differentiating ferromanganese deposits (Karakus et al., 2010; Park et al., 2023; Polgári et al., 2012). Separation and isolation of hydrothermal, diagenetic, hydrogenetic and biogenic-microbial manganese is possible using the ratios of major elements and trace element content (Li et al., 2024; Zarasvandi et al., 2013a). The Fe-Mn-(Co+Ni+Zn) diagram (Berdnikov et al., 2023; Hein et al., 1997) can be used to separate types of manganese deposits. According to this diagram, it can be said that the samples of the studied area have high levels of Mn and Fe and low levels of Co, Ni, Cu and are classified as hydrothermal manganese. Many geologists have used the Mn/Fe ratio to identify the genetic factor between manganese deposits. This ratio can be used to distinguish hydrothermal manganese deposits from hydrogenetic ones. This ratio in the Noorabad manganese deposit is in the range of 4.32 to 4.73, which indicates a hydrothermal or combined hydrothermal–hydrogenetic origin (Liu et al., 2023; Mahmoudi et al., 2017) and confirms deposition in a sedimentary environment. Manganese ores contain low amounts of TiO_2 and Al_2O_3 and high ratios of Si/Al. In the studied samples, the highest aluminum content is 4.1% and the highest TiO2 content is 0.21%, which indicates the hydrothermal origin of manganese. In manganese deposits with hydrothermal origin, the Si content is high. The silicon oxide content of manganese ore samples in the studied area ranges from 18.04 to 76.42%, and the aluminum oxide content in these samples varies from 0.01 to 5.5%. (Fig. 4c). It should be noted that the high silica content in manganese deposits in the study area can indicate the origin of hydrothermal fluid far from its vent site (Jach & Dudek, 2005). The high silica content in the deposits in this area can be explained by the high presence of biogenic silica in the form of radiolarite (Guo et al., 2024; Polgári et al., 2012; Stamm et al., 2025; Toth, 1980; Zarasvandi et al., 2013a). Also, the low content of minor elements Ni (86–193 ppm), Co (31–131 ppm) and Cu (49–277 ppm) along with the small total of REE and the enrichment of LREE compared to HREE indicate the formation of pri-

mary manganese compounds with host cherts in environments adjacent to mid-ocean ridges and along the bronzyme conduits of the seafloor hydrothermal fluid. The origin of effective hydrothermal solutions can be considered to be due to the presence of alkaline basalts in the oceanic intraplate environment.

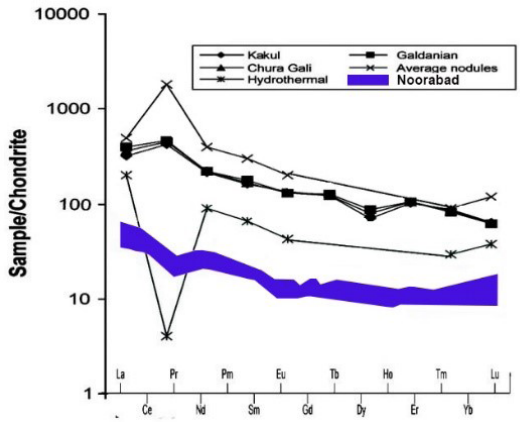


Figure 3: Graph of trace element data normalized to chondrite and its comparison with the average of manganese nodules (Haskin et al., 1966; Ren et al., 2022) and the average of hydrothermal manganese deposits (Hashempour et al., 2023; Ruhlin & Owen, 1986).

In the chemical data obtained from manganese ore, there is a negative correlation between the elements Mn-Al, Mn-Ti, Ba-Co, and a positive correlation between the elements Ba-Cu, Mn-Ba, Al-Ti. The existence of a negative correlation between aluminum-manganese and aluminum-titanium oxides reflects the difference in the origin and geochemical behavior of titanium and aluminum with manganese. The negative correlation coefficient between cobalt and barium also reflects the origin and geochemical behavior of these two elements in hydrothermal manganese deposits. The positive correlation between barium and manganese and copper and barium is similar in origin and geochemical behavior of these elements. In general, the levels of trace elements arsenic, barium, copper, lithium, molybdenum, lead, antimony, strontium, vanadium, and zinc are high in hydrothermal manganese deposits (Nicholson, 1992; Zolotova et al., 2023).

The levels of arsenic, barium, copper, strontium, and zinc in the studied manganese ores are high, which is comparable to hydrothermal deposits (Adachi et al., 1986; Bonatti et al., 1972; Brusnitsyn & Zhukov, 2012; Choi & Hariya, 1992; Crerar et al., 1982; Nicholson, 1992; Peters, 1988; Sasmaz et al., 2014; Shah & Moon, 2007; Toth, 1980). Manganese ores in hydrogenetic and hydrothermal manganese deposits have different Co/Ni and Co/Zn ratios (Sasmaz et al., 2014; Toth, 1980; Zaki-Khedr et al., 2024). The average values of Co/Zn ratio in the study area are 0.15 to 2.07, which is comparable to hydrothermal manganese deposits (Fig. 4a). According to the Zn-Co-Ni diagrams (Azami et al., 2024; Choi & Hariya, 1992; Wang et al., 2024), it can be said that the samples tend to the Ni-Zn line, which indicates submarine hydrothermal manganese deposits. Hydrothermal deposits show relatively high values of Co and tend to the Ni-Co line (Nicholson, 1992) (Fig. 4b).

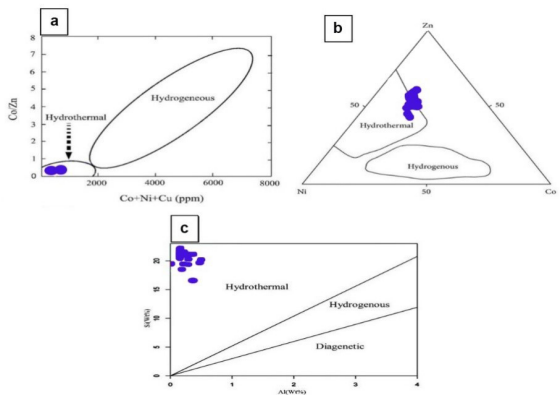


Figure 4: Geochemical diagrams of the manganese deposit in the Noorabad Delfan region, (a) binary diagram Co/Zn –Co+Ni+Cu (Khodami et al., 2024; Toth, 1980), (b) ternary diagram Ni-Co-Zn (Choi & Hariya, 1992), (c) binary diagram Al-Si (Erlandsson et al., 2025; Toth, 1980)

The cyclic nature of hydrothermal vents along the mid ocean ridge (MOR) results in a continuous variation of Eh-pH conditions in the depositional environment. This dynamic environment may contribute to the formation of successive layers containing pyrolusite-rich and pyrolusite-free

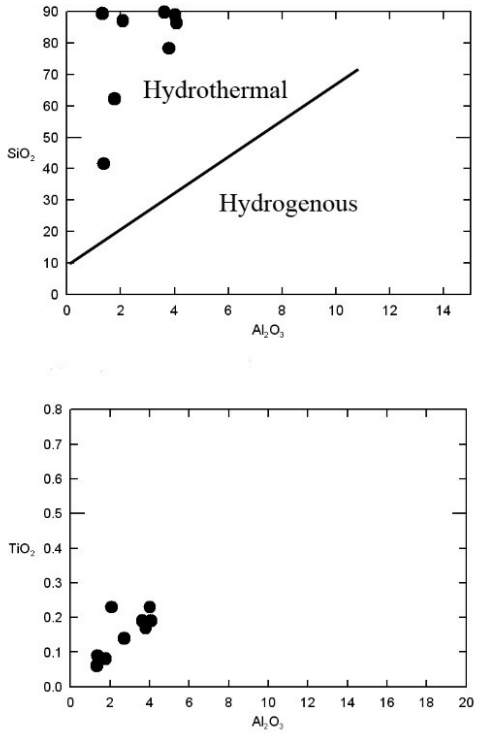


Figure 5: Al-Si and Ti-Al diagrams (Choi & Hariya, 1992; Zhang et al., 2023), indicating the hydrothermal nature and low aluminum and titanium contents in the samples from the study area.

sections. Such cyclic patterns in the form of layered (laminae) type manganese deposit have been observed not only in the study area but also in other parts of the manganese deposit within the Neotethys oceanic basin. As hydrothermal fluids are periodically released from the vents, they interact with the surrounding oceanic water, leading to fluctuations in the redox potential (Eh) and pH levels. These changes influence the mineral formation processes, including the precipitation and deposition of manganese minerals like pyrolusite. Consequently, the manganese-rich layers are formed during periods of favorable conditions for pyrolusite nucleation and growth, while pyrolusite-free layers may occur when the conditions are not suitable for its formation. Moreover, these cyclic nature hydrothermal vents highlight the significance of the hydrothermal vent activity in shaping the manganese deposition and mineralogical characteristics in the area.

RESULTS AND CONCLUSION

Manganese deposits have various origins. Hydrothermal manganese deposits are one of the most common types of manganese deposits, which are closely associated with iron-bearing silica gels. These deposits are associated with submarine volcanic and hydrothermal eruptions and are rich in metal elements and form interlayers with marine sediments (Gómez-Gajardo et al., 2024; Roy, 1992). Manganese mineralization has occurred in the northwestern region of Lorestan (Noorabad County) with Upper Jurassic-Lower Cretaceous radiolarian cherts in the northwest of Noorabad. Based on mineralogical field studies and geochemistry of major and trace elements, these deposits have been classified as having a hydrothermal origin. Petrographic studies in the study area indicate simple mineral paragenesis, with the main minerals consisting of pyrolusite and braunite. This has also been reported in other manganese deposits originating from hydrothermal fluids associated with the Zagros ophiolites. Mineralization in Noorabad-Delfan occurred in two main syngenetic stages, simultaneously with hydrothermal exhalative fluids with colloform layered mass textures and pyrolusite nodules, and an epigenetic stage in the form of veinlets and stockwork in the previous part and surrounding rocks. Pyrolusite, braunite, and manganite are the most important manganese-bearing minerals of the syngenetic phase, and nsutite, braunite, and pyrolusite are the most important minerals of the epigenetic phase. In order to investigate the origin and formation of manganese deposits in the study area, geochemical studies of major and trace elements were carried out, which indicate the effect of hydrothermal activity on the manganese mineralization of the Noorabad, which itself is a result of submarine volcanic processes. The absence of iron-bearing mineral phases in the samples of the coeval phase indicates a strong separation of iron from manganese, which is one of the main characteristics of manganese

deposits originating from hydrothermal fluids and indicates that the mineralization was formed at a distance from the hydrothermal vent. The obtained data indicate the role of hydrothermal fluids in a shallow marine to freshwater-related lake environment. Low levels of Co, Cu, Ni, and Zn elements confirm the hydrothermal origin of the manganese deposits. These minerals show low aluminum and high silica contents, indicating their formation in a high-silica environment. The mineralized layers are highly fractured and folded, and on a hand scale, they are black in color and present as veins and veinlets of varying thickness and as a dispersed phase in joints and fractures. They are sometimes seen as replacements in the radiolarite shell. The host rock of this complex includes carbonate units, pelagic limestones and radiolarites. The association of radiolarite cherts in this complex indicates the conditions of mineralization in the ocean floor environment. The abundant presence of radiolarite shell in co-occurring pyrolusites also reflects an environment with high biological potential along with abundance of essential bioelements. The deposition of primary manganese compounds in radiolarite cherts near the mid-ocean ridge was formed by the activity of silica-rich hydrothermal vents within the Neotethys Ocean. Hydrothermal fluid systems resulting from submarine volcanic activity carry metal-rich phases due to circulation and heating, and during cooling, changes in Eh–pH and reduction in fluid pressure cause phase separation of metals in pure and oxidized forms. (Latif et al., 2025; Zhang et al., 2013). The deposits were eventually emplaced in the high Zagros zone during the Kermanshah ophiolite emplacement and underwent tectonic and supergene processes. The presence of various modes of occurrence and the syn-genetic and diagenetic origins suggest a complex geological history and a combination of processes contributing to the formation of manganese deposits in the Lorestan Province. The multi-trace and REE discriminations signature, coupled with a REE chondrite normalized pattern observed in the majority of samples, indicates that submarine hydrothermal processes have likely played a significant role in the deposition of the Fe-Mn belt in the study area. These conditions play a significant role in influencing the precipitation and accumulation of these elements. The cyclic activity of hydrothermal vents along the mid-oceanic ridges further contributes to the continuous variation in Eh-pH conditions in the depositional environment. The close association of serpentinite and radiolarite bearing manganese deposits may verify a temporal and spatial relationship between these two types of rocks. The serpentinization of ultramafic units and subsequent hydrothermal alteration played a crucial role in providing a significant source of manganese and silica, contributing to the formation of manganese deposits in the studied area and the entire radiolarite facies within the Neotethys realm.

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HOW TO CITE THIS ARTICLE

Safizadeh, M. (2026). Mineralization and Geochemical Study of Manganese Deposits Associated with Ophiolites in Northwest Lorestan Province (Noorabad-Delfan). (e743757). International Journal of Urban Management and Energy Sustainability, 7(3), e743757

DOI:10.22034/ijumes.2026.743757