iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** IX **Month of publication:** September 2025

DOI: https://doi.org/10.22214/ijraset.2025.74349

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IX Sep 2025- Available at www.ijraset.com

The Effects of Metamorphism on the Lead-Zinc Deposits of Rajasthan

Rachit Parihar[1], Vijay Pal Meena[2]
Department of Geology, University of Rajasthan, Jaipur

Abstract: Metamorphism of any mineral deposit easily changes the grades of the ores at that deposit. Metamorphism of an ore deposit can even produce a newer deposit of a proportional grade. Here we try to use the examples of the lead and zinc deposits of Rajasthan, to explain enrichment of elements other than lead and zinc, caused because of metamorphism. Most of the major mineral deposits in the Earth's crust have undergone some degree for metamorphism. It is essential that we study the effect of that metamorphism on the given orebody so that it may be mined sustainably. This understanding of zones in an orebody of distinct grades can lead to their easier extraction and will lead to sustainable mining practices which are safer as well as economic.
Keywords: Metamorphism, Critical Minerals, Sulphide partial melting, lead zinc deposits, Rajasthan

I. INTRODUCTION

Rajasthan is a powerhouse when it comes to its mineral wealth. Just considering the metallic ores, it hosts more than 50% of India's resources of copper, tungsten, lead, zinc, and, silver [1]. Its regular referral as the "Museum of Minerals" is not an overstatement. Rajasthan comprises of all igneous, sedimentary and metamorphic terrains with a slight geographic dominance of sedimentary and metamorphic terrain areas over igneous terrains.

Rajasthan also shows a near perfect succession of rocks ranging from Archean to Recent. Metamorphism in Rajasthan, on an intermediate P-T ratio, ranges from lower greenschist facies to even granulite facies. Although lead and zinc (Pb-Zn) resources are spread throughout India, Rajasthan is also the leading producer of Pb-Zn, with 89% of the country's reserves. Rajasthan has numerous occurrences of Pb-Zn with five mines at Kayad (Ajmer), Rampura-Agucha (Bhilwara), Sindesar-Khurd and Rajpura-Dariba (Rajsamand), and Zawar (Udaipur) [2].

The Kayad mine has a total metal grade (TMC) of 6.95%, Rampura-Agucha 13.1%, Sindesar-Khurd 4.73%, Rajpura-Dariba 5.17% and the Zawar group of mines has 4.86% TMC [3]. In total these mines provide raw materials for smelters at Debari (Udaipur), Chanderiya (Chittorgarh), and Dariba (Rajsamand).

The Kayad deposit lies in the Delhi Supergroup of rocks, Zawar in the Aravalli Supergroup and the Sindesar-Khurd, Rajpura-Dariba and Rampura-Agucha deposits lie within the Bhilwara Supergroup [4]. The Kayad, Rampura-Agucha, Rajpura-Dariba and Sindesar-Khurd deposits are considered to be SEDEX in origin, the Zawar deposit is believed to be a Mississippi-Valley type deposit. The stratigraphy of these supergroups given by workers [4,5,6] are in a graphically compared in Fig.1.

II. ORE MINERALOGY AND METAMORPHISM.

The main ores for these deposits are sphalerite (ZnS), Galena (PbS), although multitudes of minerals belonging to the sulphide and sulfosalt groups viz. pyrite (FeS_2), pyrrhotite ($Fe_{(1-x)}S$, chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS), tetrahedrite-tennantite ($CuSb_4S_{13}$-$CuAs_4S_{13}$) are observed. The orebodies, grades, host and country rocks vary, there are also differences in the grades of metamorphism that these deposits have undergone.

The Zawar deposit being in the Aravalli Supergroup has been metamorphosed to greenschist facies, whereas, Kayad, Rampura-Agucha, Rajpura-Dariba and Sindesar-Khurd deposits have been metamorphosed up to amphibolite facies [7,8]. The Rampura-Agucha deposit is theorized to have even undergone granulite facies metamorphism.

III. PARTIAL MELTING, SULPHIDE PARTIAL MELTING AND ITS EFFECTS

As a limit to metamorphism, partial melting processes are diverse in relation to the rock bulk chemistry and fluid conditions. When a certain rock crosses its partial melting curve (which is controlled by its bulk chemistry and fluids) it starts it melt. They will melt incongruently which is the most dominant case, but can also melt incongruently if the rock is entirely monomineralic, although this is an extreme rarity.

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Partial melting of rocks which are granitic in composition, if wet (consists water) would start at ~600-650°C and if dry (no Water) at ~700-800°C at 1 atm. Rocks of Basaltic compositions melt at ~900-1000°C at ~1 kbar of pressure that is deeper in the crust in presence of fluids. In dry conditions basalts melt at ~1000-1200 C at ~1 kbar of pressure. Sulphides, depending on their composition and under lithostatic pressure or even at 1 atm, could start partially melting at temperatures as low as 300°C, which can be correlated to greenschist facies or even lower metamorphic conditions.

Heron (1953)	Gupta *et. al.* (1997)	Roy and Jakhar (2002)
Delhi System (2000-700m.y.)	Delhi Supergroup	Delhi Supergroup
"Raialo series" Aravalli System (Archaean)	ARAVALLI SUPERGROUP → Jharol Group, Dovda Group, Nathdwara Group → Barilake Group, Kankroli Group → Udaipur Group → Debari Group (Babarmal Formation) (Proterozoic)	ARAVALLI SUPERGROUP → Upper: → Lakhwali Formation, Jhorol Formation; → Kabita Dolomite; → Debari Formation → Middle: → Tidi Formation; → Bowa Formation = Machla Mangra Formation; → Mochia Formation = Zawar Formation; → Udaipur Formation → Lower: → Jhamarkotra Formation (Babarmal); → Delwara Formation (Proterozoic)
	Unconformity	Unconformity
Banded Gneiss Complex (>2500 m. y.)	Bhilwara Supergroup (Archaean)	Mewar Gneiss Complex (Archaean)

Fig. 1. Comparative stratigraphic succession by previous workers

When sulphide minerals undergo patrial melting, they can form melts with viscosity similar to water, they can flow out of the system, concentrate in other weak zones or even be untraceable or lost. Finding evidences of sulphide partial meting is difficult as sulphide melts don’t quench to form a glass as silicate melts do. They also tend to re-equilibrate easily.

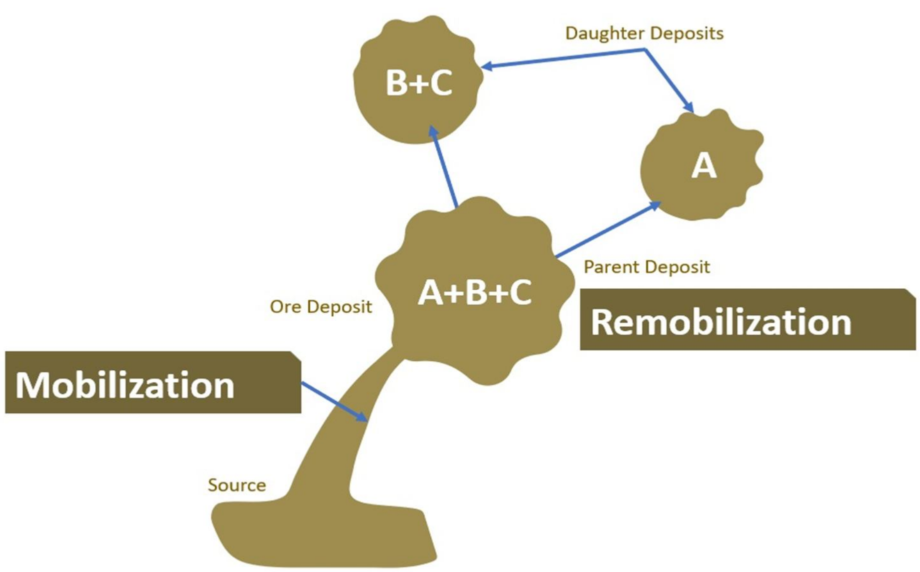

Fig. 2. Graphic showing the processes of mobilization and remobilization along with formation of daughter deposits. Modified after [9].

The process of partial melting of ore deposits can alter, enhance and /or reduce the grade of an ore deposit. The Broken-Hill deposit, western New South Wales, Australia is an excellent example of an ore deposit where the process has created metal enriched zones and the ore can be processed in a better way for metal extraction. Sulphide partial meting leads to the process of remobilization as explained by [9]. A schematic explaining the formation of daughter deposits or orebodies can be seen in Fig.2.

[10] extensively analysed the effect of partial melting on sulphide ore deposits which have undergone metamorphism and listed some ore deposits that could have undergone sulphide partial melting. The Rajpura-Dariba deposit is one on them because it known to have underdone ~580-600°C and 6.1 kbar metamorphism, that is it being metamorphosed up to mid-amphibolite facies [7].

The effect of partial melting is observed on many scales viz. on a polished-section, hand-specimen or even at the ore body level. At the ore body level there can be segregation of a portion of higher grade in any particular element. The average metamorphic grades of the Pb-Zn deposits of Rajasthan is plotted with the diagram of [10] to understand effect of partial melting curves of various sulphide and silicate mineral assemblages (Fig. 3).

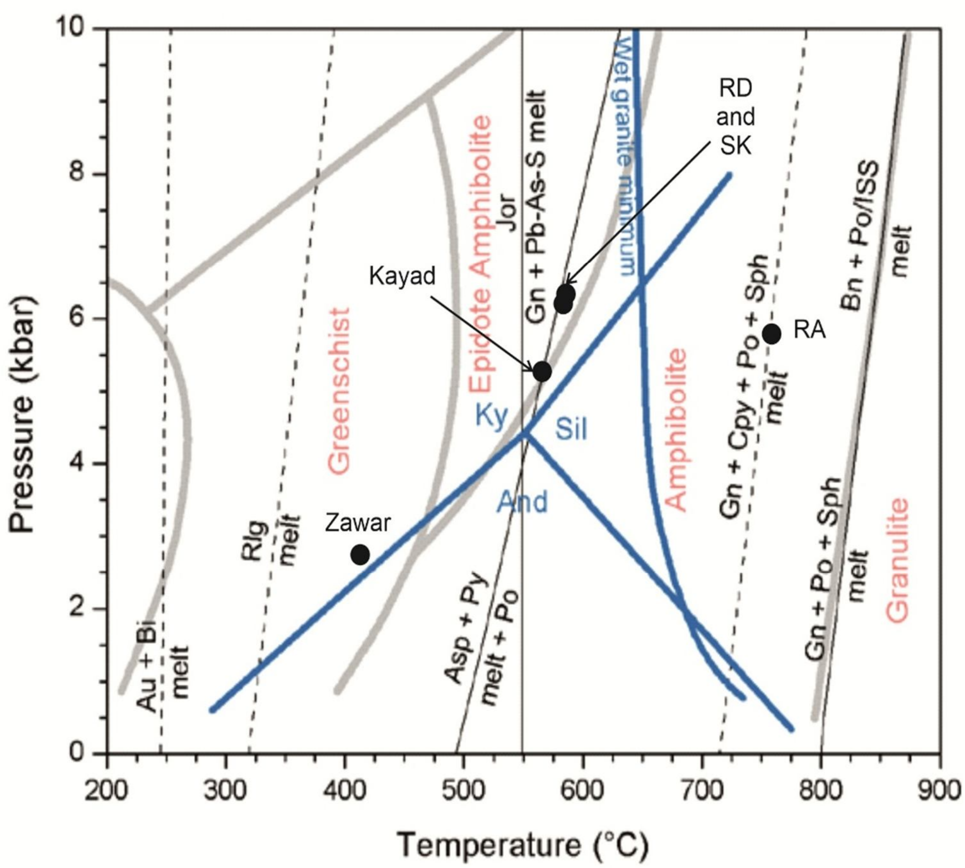

Fig. 3. Average metamorphic grades of Pb-Zn deposits of Rajasthan with sulphide and granite melting curves and metamorphic grades. RD- Rajpura-Dariba, RA-Rampura-Agucha, SK Sindesar-Khurd. Modified after, [10].

IV. ORE GRADES AT RAJASTHAN'S ORE DEPOSITS

Fig. 4. compares the lead and the zinc grades of the five deposits, but when the lead grades of respective deposits are compared with the silver grades (Fig.5) of these deposits [12], it is observed that deposits that have undergone sulphide partial melting tend to have a higher silver content and is similar to lead. This is because of silver substituting lead at its site. This silver is extracted as a by-product of the processes of extraction of lead and zinc. Cadmium is another by-product obtained from the smelting of Zinc ores. Implying substitution of zinc with cadmium.

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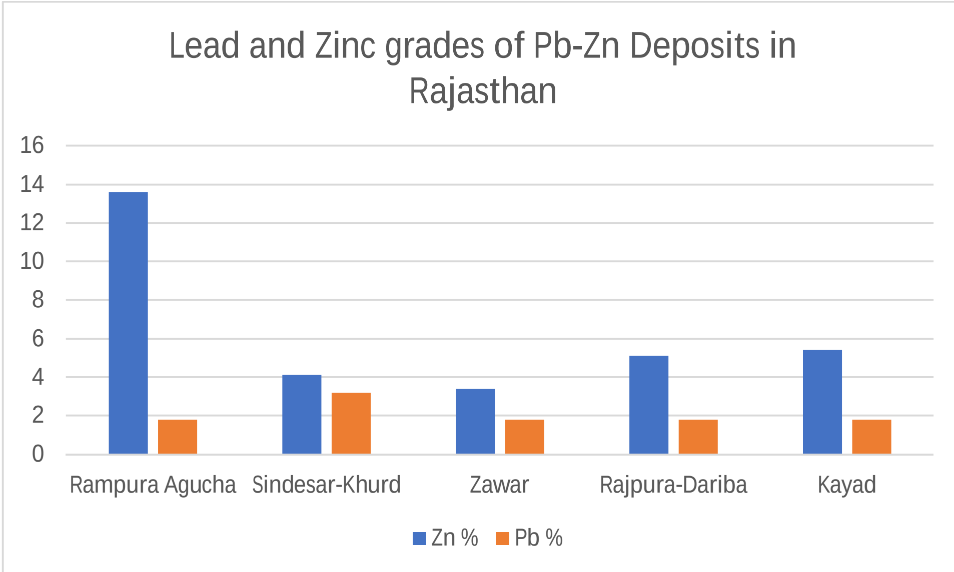

Fig. 4. Ore grades at deposits, modified after [11].

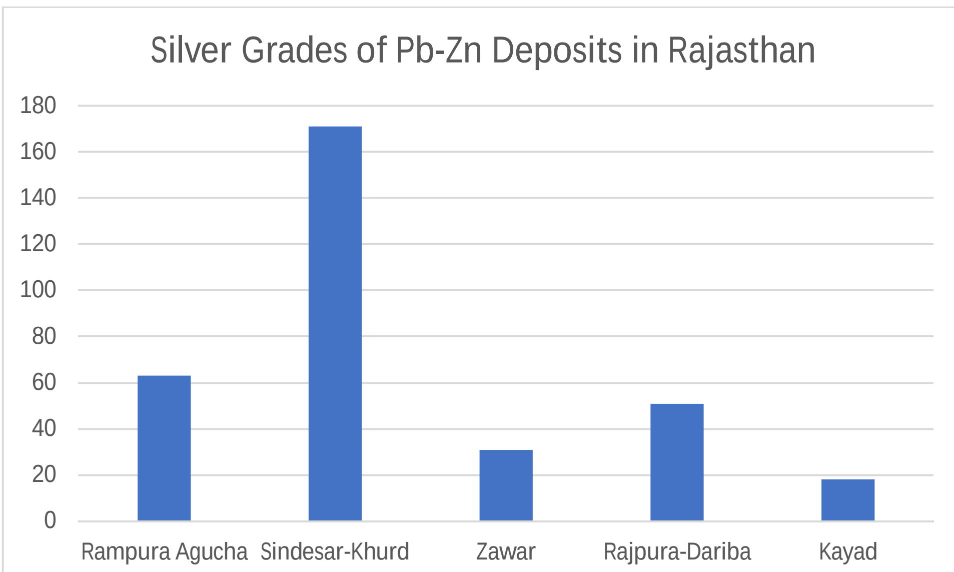

Fig. 5. Silver grades (ppm) at deposits, modified after [11].

V. CONCLUSIONS

India stands sixth in the world reserves of zinc and seventh in lead. These are base metals which are of essential mineral importance. The process of partial melting of ore deposits can alter, enhance and /or reduce the grade of an ore deposit. Considering all other lead-zinc deposits of Rajasthan, apart from the Zawar Deposit, all have undergone metamorphism above or till the mid-amphibolite facies there for should have undergone sulphide partial melting.

The enrichment of silver at Sindesar-Khurd is a testament to ore enrichment during sulphide partial melting. Sulphide partial melting is also characterized by the presence of low melting-point chalcophile elements. These elements consist of silver, arsenic, bismuth, mercury, selenium, antimony, tin, thallium and tellurium. Of these elements, bismuth, selenium, antimony, tin, and tellurium are listed as minerals of critical importance for India. Cadmium a by-product of smelting is also a critical mineral. [12]. It is important the sulphide partial melting is studied for an ore deposit for if it is enriched in any critical mineral a strategic way for further extraction and mining of the deposit can be carried out sustainably.

VI. ACKNOWLEDGEMENT

The authors would like to thank their colleagues for the encouragement received, the Head, Department of Geology for their guidance, and, the students of the Department of Geology , University of Rajasthan, Jaipur, whose curiosities kept them motivated.

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