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# Dolomite hosted zinc-lead deposits of Zawar, Aravalli Supergroup, Udaipur district, Rajasthan, India

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**Abstract:** India is one of the prominent zinc and lead producers of the world and Rajasthan, the largest state of India, is the main repository of medium to large Zn-Pb ore deposits. The Zawar Zinc-Lead Belt of Rajasthan is the one of oldest carbonate-hosted zinc-lead orefields of the world.

The Zn-Pb deposits of the Zawar Belt are hosted in rocks of the Proterozoic Aravalli Supergroup which comprise volcano-metasediments constituting a multi-cycle megasequence, developed in an ensialic rift setting. Sphalerite and galena are the main ore minerals for zinc and lead respectively and the host rock to the dominantly stratabound mineralization is Palaeoproterozoic poly-deformed dolomite. Isotope studies reveal a marine environment of formation of sediments and involvement of biogenic process in the ore deposition although the model Pb-Pb age of the deposit is 1700Ma, younger than the host dolomite. Three types of mineralization (disseminated stratiform, vein and massive type ores) are recognized. Fluid inclusion studies reveal the involvement of two types of fluids for the vein and massive (galena) type ores. The disseminated stratiform variety of ore is believed to be related to a SedEx type, developed during Palaeoproterozoic rifting, whereas the more significant vein and massive ores are epigenetic formed during folding related to the Aravalli orogeny. Thus, the Zawar deposits are hybrid in nature and may be termed as “Zawar type” for their unique features /characteristics.

There are currently four working mines - Mochia, Baroi, Balaria and Zawarmala in the Zawar Zinc-Lead Belt, with grades ranging from 1.71% to 4.51% Zn and 2.14% to 5.63% Pb along with cadmium and silver as by-products.

**Keywords:** Zinc-Lead deposit, Aravalli Supergroup, Zawar, SedEx, Irish type

## Introduction

The state of Rajasthan, India, is well known for its sediment-hosted zinc-lead sulphide deposits in the Proterozoic Aravalli basin (Fig. 1) (Deb & Sarkar, 1990) with base-metal deposits occurring in all the major Precambrian stratigraphic units. The Zawar Zinc-Lead Belt (“ZZB”) lies within the Aravalli Supergroup, and is located about 35km south of Udaipur city, Rajasthan.

The area around Zawar village was an important site for zinc-lead-silver mining in ancient India and continues to be so even now. The ZZB ores have an ancient history of mining and exploration and represent one of the oldest mining and smelting operations in the world (Gandhi, 2014). Zawar has its name from the Urdu word *jawaharat* or jewelry, as it was a flourishing center for the export of silver in the 13th century CE. Zawar was also an important pilgrimage center in the medieval era, and the Zawar hills are dotted with the ruins of a hundred Jain and Hindu temples. Carbon dating of wooden implements

recovered from old working sites has indicated that mining and smelting operations are nearly 2100 years old (Craddock *et al.* 1989). At present, four working mines *viz.* Mochia, Balaria, Zawarmala and Baroi are being mined in the 20km long ZZB.

For more than seven decades geological studies were carried out to establish the stratigraphy of the sedimentary succession exposed around ZZB (Heron, 1953; Straczek and Srikantan, 1966; Roy, 2000; Roy & Jakhar, 2002), deformational events of the area (Mookherjee, 1965; Roy, 1995), and to characterize the Pb-Zn sulphide mineralization along with tectono-sedimentary evolution of the host basin (Mookherjee, 1964; Poddar, 1965; Chakraborty, 1967; Sarkar, 2000; Talluri *et al.*, 2000; Bhattacharya, 2004, Sarkar & Banerjee, 2004, Bhattacharya & Bull 2010, Bhuyan & Hazarika 2022).

Throughout these years geological, geochemical, and geophysical along with isotope and fluid studies of this Proterozoic deposit were carried out which reveal the nature of mineralization as a variant of SedEx (Sarkar & Banerjee, 2004). The aim of

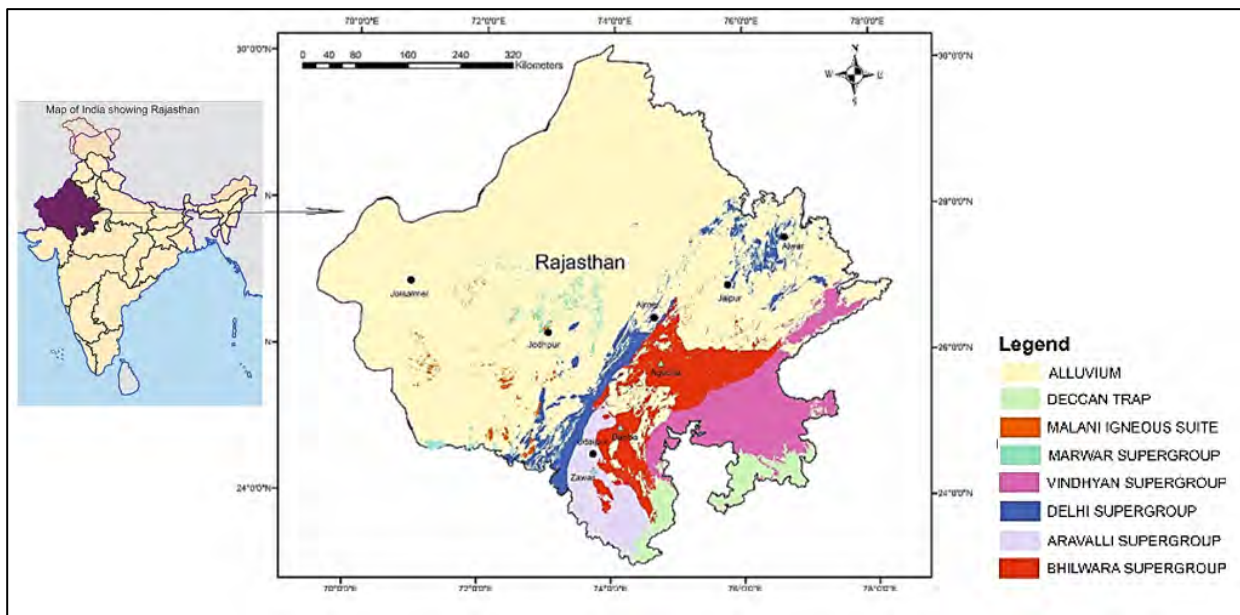


Figure 1: Generalized Geological Map of Rajasthan showing location of Zawar, Dariba and Agucha zinc-lead deposits.

this paper is to present a comprehensive overview of the dolomite-hosted zinc-lead mineralization of the ZZB and make a Geological Nature Analysis (GNA) in relation to Irish type deposits.

**Geological Setting**

The Aravalli Delhi Fold Belt is a major mobile belt in the north-western part of India. It is comprised of a gneissic Archaean basement - the Banded Gneissic Complex (“BGC”) (Gupta, 1934, Heron, 1953), with meta-volcano-sedimentary rocks and intrusive granites of Proterozoic age (Roy & Kröner, 1996, Golani *et al.*, 2002). The Palaeo- to Mesoproterozoic Aravalli Supergroup (“ASG”) metasedimentary rocks unconformably overly the BGC (Heron, 1953; Gupta *et al.*, 1980; Naha & Roy, 1983). This sedimentary sequence is thought to have accumulated in a continental rift basin (Bhattacharya & Bull, 2010). The Aravalli Supergroup is overlain by sedimentary rocks of the Meso to Neoproterozoic Delhi Supergroup (Gupta *et al.*, 1980; Sinha Roy, 1984).

The rock sequence exposed around Zawar belongs to the Middle Aravalli Group and the litho-sequence includes thickly bedded polymictic conglomerate and grit, quartzite, greywacke, phyllite, slate and dolomite. The stratabound Zn-Pb mineralization in the ZZB is confined to the dolomite and its variants. Sphalerite and galena are the main ore minerals for zinc and lead respectively and the sulphide assemblage contains minor recoverable amounts of cadmium and silver.

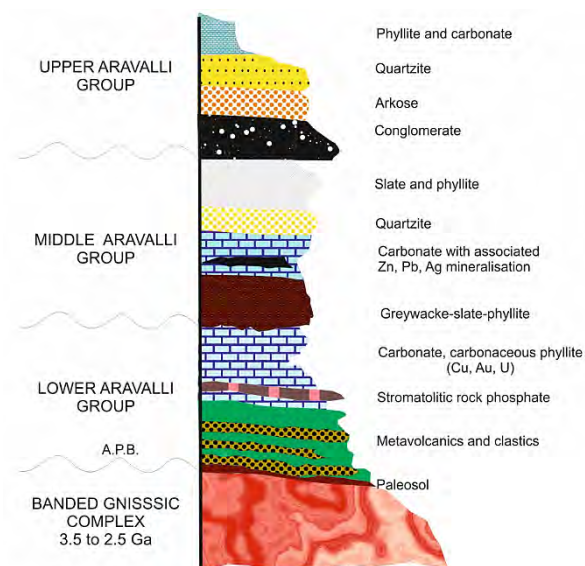
The paucity of geochronological data for the Aravalli Supergroup makes it difficult to precisely define the opening and closure of the Aravalli basin, however the age of the Aravalli Supergroup has been determined from Sm–Nd systematics of the basal volcanic rocks to indicate a maximum age of 2326±321Ma (Ahmad *et al.*, 2008) and a minimum age of 1900±80Ma from Rb–Sr dating of the Darwal Granite that was emplaced synkinematically with the earliest deformation of the Aravalli sedimentary rocks (Choudhary *et al.*, 1984).

A three-fold classification (Lower, Middle and Upper Groups; Fig. 2) has been proposed for the Aravalli Supergroup (Roy, 2000). Meta-sedimentary rocks of the 2.5km thick Middle Aravalli Group host the Zawar Pb–Zn deposits. They comprise phyllite, quartzite, dolomite, conglomerate and greywacke and rest unconformably on a heterogeneous basement represented by granitoids, basic dykes (now amphibolites), quartzite, dolomite, biotite-schist, chlorite quartz schist and magnetite-quartz rock (Roy, 2000). The Precambrian basement rocks are exposed near Sarara, located ~2km of Zawar in a SE direction.

Bhattacharya & Bull (2010) identified four distinct sedimentary facies assemblages in the ZZB and opined frequent changes in depositional environments. Such frequent change can be expected in basins that remain tectonically hyperactive during sedimentation. The sedimentary succession records development of multiple tectonism-induced sedimentary cycles in an intra-continental rift setting. These four facies are as follows:

Aravalli Supergroup	{	Tidi Formation	Phyllite/ quartzite/dolomite
		Bowa Formation	Quartzite
		Mochia Formation	Dolomite/ conglomerate/ arkose
		Mandli Formation	Greywacke
		Kathalia Formation	Phyllite/ dolomite/ carbon phyllite
Bhilwara Supergroup	{	Dantalia Formation	Quartzite and dolomite
		Mangalwar Complex	Granitic gneiss & migmatite

*The generalized stratigraphy of the ZZB area (after Roy, 1995):*



**Figure 2:** Generalized stratigraphy of the Aravalli Supergroup (modified after Roy 2000)

Facies assemblage I - is represented by a siliciclastic-carbonate facies association (Kathalia Fm.)

Facies assemblage II - is a carbonate-free siliciclastic facies, mudstone-greywacke-conglomerate association (Mandli Fm.)

Facies assemblage III - is a siliciclastic-carbonate facies association, host to Zn-Pb ores (Mochia Fm.)

Facies assemblage IV - is a thick siliciclastic, quartz-pebble conglomerate-sandstone association (Bowa Fm.)

Out of these, facies assemblage III (Mochia Fm.) contains sulphide mineralization, where alternating beds of normally graded metamorphosed siltstone, thinly laminated metamorphosed carbonaceous mudstone and layered sulphides of Fe, Zn and Pb, constituting 60cm to 7m thick units. Sulphide interbeds are <1mm to 2cm thick, with thicker pyrite layers and comparatively thinner sphalerite layers with galena at places. This variety of thinly bedded stratified ore, best exposed in the Balaria mine section, resembles SedEx-type. The other types of epigenetic ores are also restricted to this formation.

In general, the rocks of the Aravalli sequence have undergone greenschist facies metamorphism, with the development of a biotite-chlorite-muscovite-quartz assemblage in pelitic rocks and an actinolite-chlorite-epidote-albite-oligoclase-quartz assemblage in metavolcanics (Sharma, 1988, Roy, 1995,) with peak temperature of 400–450°C and the pressure of approximately 3 kbar (Banerjee & Sarkar, 1998).

## Structure

The ZZB is located in the eastern part of the Proterozoic Aravalli basin and the meta-sediments have undergone four phases of deformation. The earliest recognizable phase of deformation led to the formation of tight to isoclinal folds and axial planar schistosity ( $S_1$ ). The second phase of deformation has produced megascopic folds marked by open to tight  $F_2$  folds which control the overall disposition of the rocks. This was followed

by a set of east-west trending ( $F_3$ ) folds (Roy, 1988) of different scale and related  $S_3$  schistosity. The last phase of deformation -  $D_4$  - produced folds with sub-horizontal axial plane foliation and are well preserved in phyllite (Sarkar & Banerjee, 2004). E-W trending faults are prominent in places which are parallel to the axial plane of  $F_3$  folds (Fig. 3).

The superposition of three generations of folds in the Zawarmala mine area results in two types of interference patterns, a hook-shaped pattern due to superposition of coaxial  $F_1$  and  $F_2$  folds, and a dome and basin interference pattern due to superposition of  $F_3$  on  $F_2$  folds. However, the outcrop pattern is dictated by the large  $F_2$  fold. Ductile Shear Zones (“DSZ”) are locally developed in the Aravalli rocks, mostly along the basin marginal faults, during  $D_1$  and  $D_2$  and affected the rocks of the ZZB as well. Movement along these DSZs is more prominent during the second deformation with a strong strike slip component (Roy, 1995).

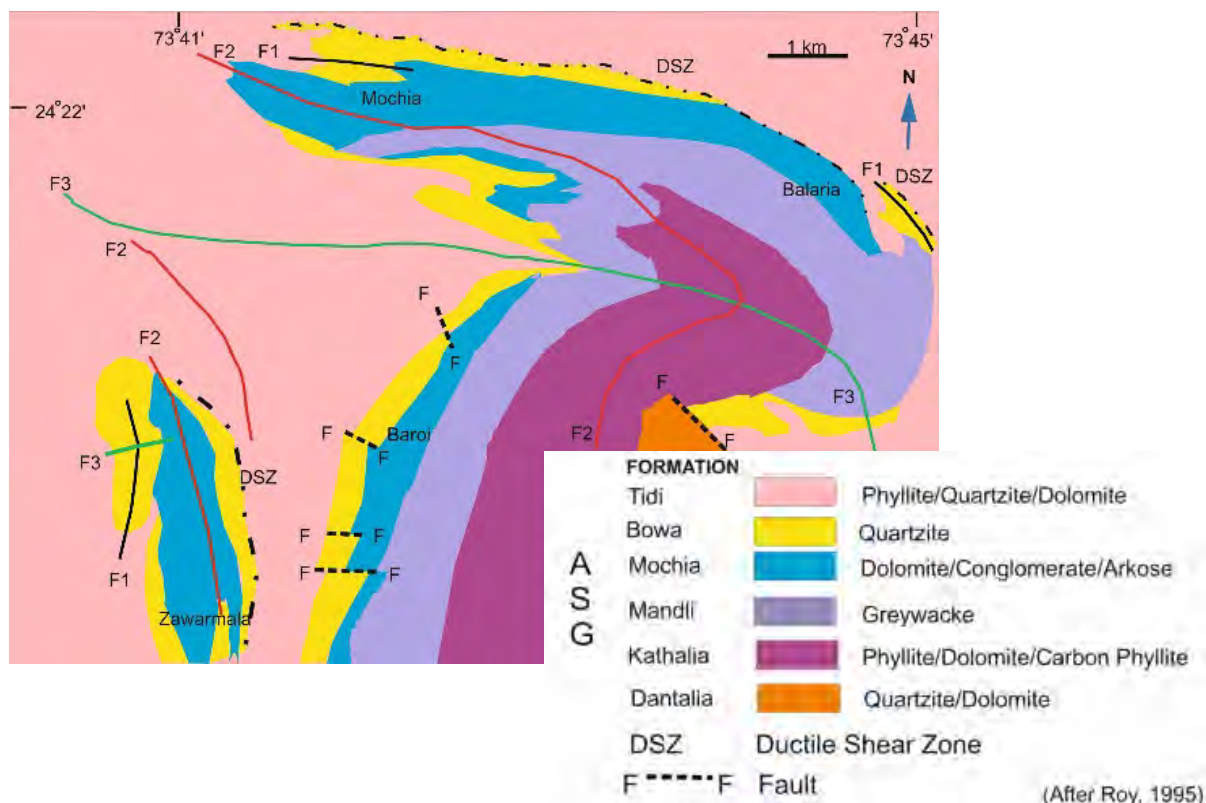
## Mineralization

The host rock to the Zn-Pb mineralization is dolomite and the ore lenses usually terminate at its contact with the underlying phyllite. Brownish white to grey dolomites, medium to coarse grained, massive and at places gritty, often form long strike ridges in the Mochia, Zawarmala and Baroi mine areas. Dolomite often locally grades in to quartzose or feldspathic dolomite, but all not dolomite bands are mineralized (Fig. 3). There are also interbeds of dolomitic phyllite and phyllitic dolomite.

The principal sulphides are sphalerite, galena, pyrrhotite and pyrite (Fig. 7, 8, 9) with minor arsenopyrite, native silver, and chalcopyrite in places. The composition of the sulphide phases from different mines of the ZZB are tabulated in Table 1. Gangue minerals are dolomite, calcite, quartz, K-feldspar, biotite, chlorite, and muscovite. Sphalerite occurs in various shades of grey and honey-brown in places, however gem variety sphalerite with a light green colour and a non-metallic resinous luster (Fig.10) is found to be associated with galena in the Zawarmala underground mine. Petrographic studies show that the gem variety of sphalerite occurs as fine aggregates in association with galena and dyscrasite ( $Ag_3Sb$ ) (Fig.12). The green colour of sphalerite is attributed to the presence of trace amounts of Co and Fe (Mukhopadhyay *et al.* 2019).

In general, three types of sulphide occurrences are observed, a.) stratiform and banded pyrite sphalerite, b.) discordant veins of sphalerite-galena and; c.) massive galena. Salient features of different types of pyrite and sphalerite from Zawarmala are summarised in Table 2.

The first variety comprises laminated fine grained stratiform pyrite-sphalerite  $\pm$  galena ore in bands few millimeters to about 3 cms thick with occasional thicker bands. This bedding-schistosity ( $S_0 // S_1$ ) parallel ore type preserves evidence of deformation in the form of isoclinal to tight folds and brecciation of pyrite at places, (Talluri *et al* 2000), indicating that it was deposited prior to the first major phase of deformation (Fig. 11). This variety of ore (sphalerite and pyrite) is poor in trace elements and considered to be diagenetic and suggests that the initial ore-forming fluid was depleted in several trace elements (Bhuyan & Hazarika 2022). In this variety, diagenetic

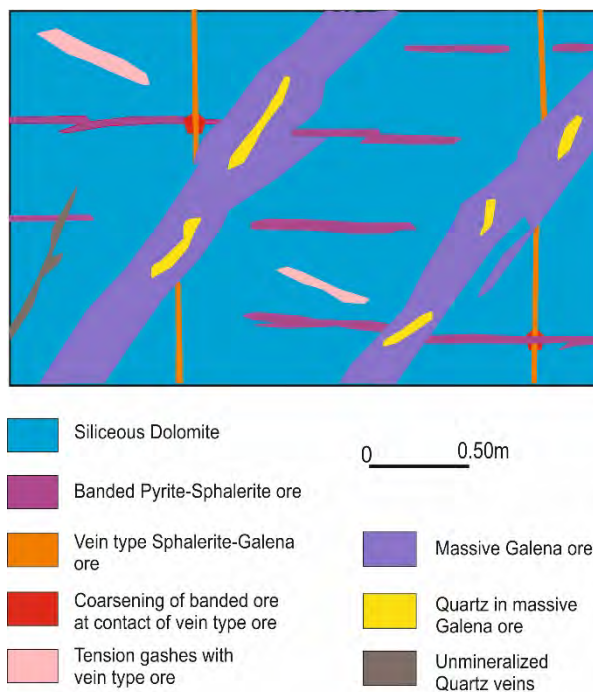


**Figure 3:** Generalized Geological map of ZWB showing the locations of the Zawarmala, Baroi, Balaria and Mochia Mines (after Roy 1995). Fold axes of various generations also shown ( $F_1$ ,  $F_2$  and  $F_3$ )

microstructures preserved in low strain zones, are represented by pyrite frambroids (Fig. 13), zoned pyrite and pyrite-galena intergrowths etc. (Sarkar & Banerjee, 2004).

The second variety, vein-type coarse grained sphalerite-galena-pyrite (Fig. 7) - typically occurs as 2- to 3cm thick fracture-filling veinlets which have sharp contacts with the host dolomite. Other common minor ore mineral phases include arsenopyrite, native silver, chalcopyrite, and pyrrhotite. Sphalerite-pyrite in these veins is characterized by enrichment of trace elements in the pyrite (As, Mn, Tl, Cu) as well as in the sphalerite (Mn, Hg, As, Ga). This variety of sphalerite is interpreted to have formed during metamorphism and is characterized by the highest concentration of Mn, Hg, As and Ga (Bhuyan & Hazarika 2022).

The third type, massive galena ore is the richest ore type and occurs as massive lodes of 0.5 to 3m wide. Galena is the dominant ore mineral (80–90%), followed by sphalerite (10–20%) and pyrite (less than 2%). The high abundance of trace elements in pyrite and sphalerite indicates their precipitation at lower temperatures from a trace element enriched hydrothermal fluid during the massive ore formation. Further, high concentration of Co and Ni in  $Py_{III}$  may indicate that deep circulation of hydrothermal fluids through the underlying mafic volcanics of the Delwara Formation of Lower Aravalli Group was responsible for the massive galena-sphalerite ore generation (Bhuyan & Hazarika, 2022). On the basis of width, braided nature and the embayment into the wall rock of ore



**Figure 4:** Schematic section depicting the disposition of the three main ore types in Zawarmala deposit. (after Talluri et al. 2000).

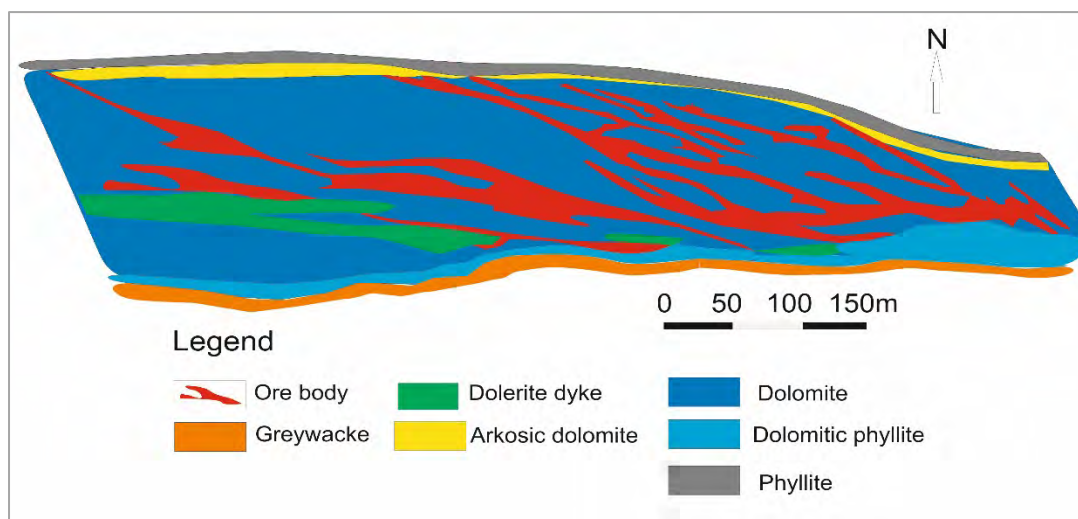


Figure 5: Disposition of ore body within host rock dolomite and other country rocks, Mochia mine 240m Level.

shoots, Talluri *et al.* (2000) opined that dissolution of dolomite took place to make space available for deposition of these ores.

The nature of the three types of ores at the Zawarmala Mine is shown schematically in Fig. 4 (after Talluri *et al.* 2000). The dimensions and disposition of the ore bodies in the different mines. The mineralization is dominantly vein-type, however, laminated ore is present where phyllite occurs as inter-bands within the dolomite. In the Baroi Mine, mineralization occurs as impersistent sub-parallel bands, whereas in the Zawarmala Mine it occurs as thick, folded and broken lenses of varying ore concentration whilst the massive ore is more prominent in the Mochia and Balaria deposits.

There are four working mines - Mochia, Balaria, Baroi and Zawarmala - in the ZZB where resources & reserves of about 141.07 Mt of ore with grades ranging from 1.71% to 4.51% for zinc and 2.14% to 5.63% for lead has been established with cadmium and silver as by-products. There is a variation in grade both along strike and down dip (Fig. 19) and the ore bodies are of variable length, width and disposition (Fig. 5 & Fig. 6) however all the deposits are stratabound and constrained within the dolomite. Salient features of four mines are tabulated in Table 3.

**Geochemical and geobotanical signatures**

The principal host rock to the mineralization is dolomite and places carbonaceous phyllite. Beside these, phyllite and mica schist are also present which are barren of mineralization. Quartz, feldspar and mica in the dolomite show enrichment near the ore zones and patches and stringers of gypsum have been reported from these dolomites (Sarkar & Banerjee, 2004). The chemical composition of phyllite, mica schist and dolomite from mines of the ZZB is tabulated in Table 3 (Chakrabarti, 1966) and trace element and REE analysis (value in ppm) of the ore bearing host rock dolomite are tabulated in Table 5A and 5B (Soni *et al.* 2017).

Chemical analysis of ore (Table 6) from Zaswar run-of-mine ore reveals the presence of significant amounts of silver and

cadmium (Mukherjee & Sen, 1980) which is substantiated by the presence of silver phases associated with sulphides as identified through EPMA.

Mukherjee & Sen (1980) indicated low REE in the carbonate assemblages and concluded that the deposit was formed under

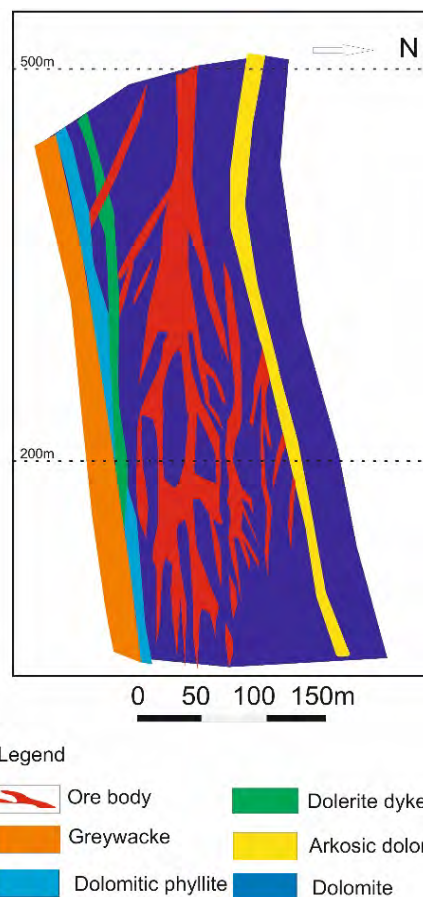


Figure 6: Disposition of ore body in transverse section, Mochia mine.

element %	Sphalerite				Galena				
	1	2	3	4	1	2	3	4	5
S	32.723	31.833	32.374	32.217	13.306	12.059	13.54	13.708	13.484
Zn	57.157	58.625	58.617	60.399	2.434	0	0	0	0
Pb	0.044	0.191	0.092	0.215	84.001	88.642	84.998	86.52	85.889
Fe	7.12	6.866	7.316	5.33	0.18	0	0.329	0.014	0
Cd	0.187	0.16	0.241	0.283	-	-	-	-	-
Ag	-	-	-	-	0.012	0	0	0.055	0
Co	-	-	-	-	0.014	0	0.053	0.022	0.079
	97.231	97.675	98.64	98.444	99.947	100.701	98.92	100.319	99.452

element %	Pyrrhotite				Pyrite		Arsenopyrite			
	1	2	3	4	1	2	1	2	3	4
S	37.906	38.347	38.18	38.459	50.86	50.462	20.577	21.295	20.463	20.476
Fe	57.614	58.068	58.305	58.688	43.994	44.881	34.011	34.165	34.249	33.078
Ni	0.145	0.038	0	0	0	0.009	0.139	0.159	0.128	0.204
Co	0	0.089	0.107	0	-	-	0.057	0.066	0	0.02
Zn	1.207	0	0.015	0.021	0	0.005	0.078	0	0	0
Pb	-	-	-	-	0.319	0.12	-	-	-	-
Ag	-	-	-	-	-	-	0.146	0.054	0.092	0.069
As	0.018	0	0	0.041	0.252	0.117	45.549	45.546	46.184	45.063
	96.89	96.674	96.607	97.209	95.925	95.962	100.557	101.285	101.116	98.91

**Table 1:** Composition of sulphide phases from mines of ZZB (Soni et al. 2017):

Syngenetic to diagenetic	Pyrite -I	Fine grained, subhedral to anhedral, occur within banded layers of sphalerite-I, parallel to S1 schistosity	Mo is high, Zn, Cu, Ga, Ag, Pb, Sb, Tl contents are low	Sphalerite-I	Fine grained, occur as banded layers, parallel to S1 schistosity	Cd, Co high, Zn, Cu, Ga, Ag, Pb, Sb, Tl, Hg, In contents are low	-
Metamorphic recrystallization, syn D2, Temp 395- 290° C, Pressure~ 1,450 bars, pH 5.5	Pyrite -II, occur in vein type	Coarse grained, subhedral to euhedral, occur as polycrystalline aggregates	Cu, Tl, Mn, Ga, As are high	Sphalerite-II	Coarse grained, anhedral to subhedral, occur as polycrystalline aggregates	Mn, Hg, As, Ga contents are high	Low-salinity (4.3–14.7 wt % NaCl equiv) H <sub>2</sub> O-NaCl fluids.
Late stage of D2, Temp 250-150° C, Pressure 2,000 to 750 bars, pH 4.25 to 4.3	Pyrite -III, occur in massive type	Fine to medium grained, anhedral to subhedral	Zn, Pb, Ag, Sb, Co and Ni contents are high	Sphalerite-III	Coarse grained, anhedral to subhedral, occurs in massive galena-sphalerite	Pb, Ag, Sb, In and Ni contents are high	Lower salinity (about 3–4 wt % NaCl equiv). H <sub>2</sub> O-CO <sub>2</sub> -NaCl fluids

**Table 2:** Summarized salient features of different types of pyrite and sphalerite from Zawarmala. Trace element data from Bhuyan & Hazarika (2022), temperature data from Tallari et al., (2000).

	<b>Mochia</b>	<b>Balaria</b>	<b>Baroi</b>	<b>Zawarmala</b>
Rock type	Greywacke, Phyllite, Dolomite, Quartzite, Dolerite Dyke	Greywacke, Phyllite, Dolomite, Quartzite, Dolerite Dyke	Greywacke, Phyllite, Dolomite, Quartzite, Dolerite dyke	Interbedded quartzite, Dolomite, Carbonaceous phyllite
Host rock	Dolomite	Dolomite	Dolomite	Dolomite
Ore minerals	Sphalerite and Galena	Sphalerite and Galena	Sphalerite and Galena	Sphalerite and Galena
Type of ore lenses	Overlapping tabular and sympathetic lenses	Overlapping tabular ore bodies in en-echelon pattern	Overlapping tabular and sympathetic lenses with disseminations	Fracture filling, veins and disseminations, ore at the core of anticline, along axial plane
Strike length of ore lenses and width	60 to 200m, 2 to 45m	60 to 200m, 2 to 40m	60 to 250m, 2 to 20m	60 to 200m, 2 to 40m
Attitude of ore lenses	WNW-ESE, steeply dipping	W10W to N65 W, steeply dipping	N15-50E, moderately dipping	NW-SE to NE-SW, moderately dipping
Total Reserves + Resources	54.46Mt 2.3% Pb, 3.56% Zn, 25 ppm Ag	41.95Mt 5.63% Pb, 1.71 % Zn, 45 ppm Ag	35.70Mt 2.47% Pb, 2.10% Zn, 35 ppm Ag	8.96Mt 2.14% Pb, 4.51% Zn, 24 ppm Ag
Zn/Zn+Pb	0.6	0.23	0.46	0.68

**Table 3:** Salient features of the four mines of the Zawar Zinc-Lead Belt (source HZL).

Rock	Wt %										
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	Na <sub>2</sub> O	K <sub>2</sub> O	MgO	CaO	TiO <sub>2</sub>	H <sub>2</sub> O	CO <sub>2</sub>
<b>Phyllite (n-10)</b>	79.88	11.93	1.68	1.09	-	3.67	trace	trace	0.35	1.43	-
<b>Mica schist (n-10)</b>	61.53	20.70	2.96	2.35	0.26	6.95	1.69	trace	0.75	2.87	-
<b>Dolomite (n-4)</b>	7.12	1.08	1.01	0.82	0.15	0.51	18.12	27.91	-	0.2	41.65

**Table 4:** Chemical composition of phyllite, mica schist and dolomite from mines of the Zawar Zinc-Lead Belt (ZZB), (Chakrabarti, 1966).

**Table 5A:**

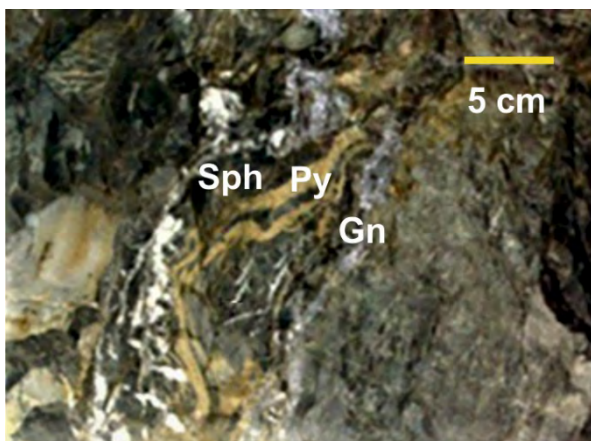
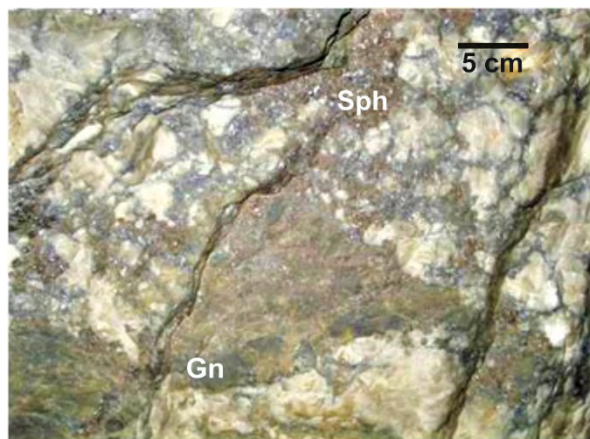
	Sc	V	Th	Ni	Co	Rb	Sr	Zr	Cu	Be	Ge	Y	Ta	W	U
	Values in ppm														
1	23	24	6	41	16	20	12	36	37	0.78	1	20	0.47	0.50	0.58
2	30	19	5	8	5	49	68	119	5	0.54	0.72	7	0.28	0.60	1.40
3	14	18	5	32	8	25	7	60	27	0.47	3	5	0.24	0.75	1.50
4	24	16	7	14	5	28	12	54	18	0.30	1	5	0.55	0.53	0.50
5	23	25	5	26	11	25	11	29	33	1.70	2	9	0.35	0.50	1.53
6	18	115	6	19	5	64	28	40	47	0.82	3	4	0.20	0.70	1.16
7	9	13	25	5	5	40	5	83	23	0.70	2	7	0.20	0.53	1.20

**Table 5B**

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf
	Values in ppm														
1	15.29	30.37	3.67	16.11	3.60	1.58	3.23	0.68	3.84	0.86	2.29	0.35	2.34	0.32	3.08
2	15.29	30.37	3.67	16.11	3.60	1.58	3.23	0.68	1.17	0.26	0.72	0.11	0.71	0.10	3.79
3	8.19	14.95	1.51	5.68	1.04	0.35	0.92	0.16	0.87	0.18	0.56	0.09	0.62	0.10	5.68
4	3.64	5.03	0.44	1.37	0.18	0.07	0.21	0.02	0.09	0.02	0.05	0.01	0.07	0.01	0.50
5	18.20	36.87	3.10	11.61	1.78	1.02	1.67	0.26	1.26	0.28	0.81	0.11	0.78	0.11	2.86
6	8.66	17.06	1.63	5.94	0.96	0.25	0.90	0.13	0.68	0.14	0.42	0.06	0.43	0.06	1.79
7	12.00	20.49	2.03	7.63	1.31	0.41	1.20	0.19	1.08	0.24	0.69	0.12	0.79	0.16	2.32

**Table 5A and 5B:** Trace element and REE analysis (value in ppm) of ore bearing host rock dolomite (Soni et al. 2017)





**Figure 7:** (Top Left) Disseminations of galena (Ga) in dolomite, Baroi Mine

**Figure 8:** (Bottom Left) Pyrite (Py), Sphalerite (Sph) and galena (Gn) with extensive quartz veination, Zawarmala mine,

**Figure 9:** (Top Right) Galena (Gn) and Sphalerite (Sph) with extensive silicification, Zawarmala mine

**Figure 10:** (Bottom Right) Specimen of green sphalerite with galena, Zawarmala mine

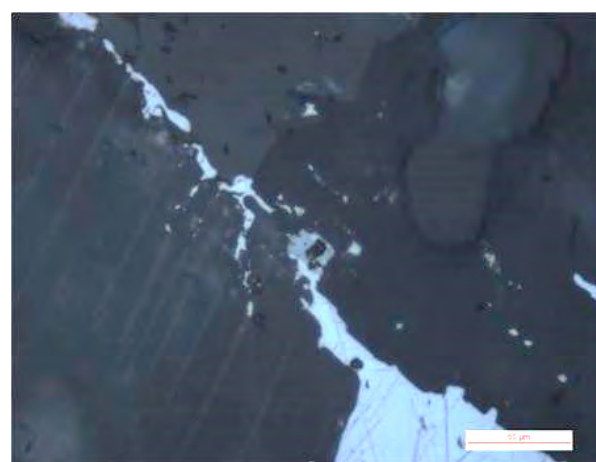
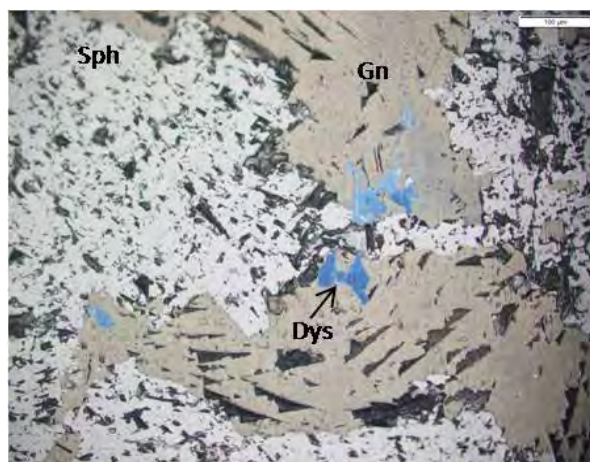
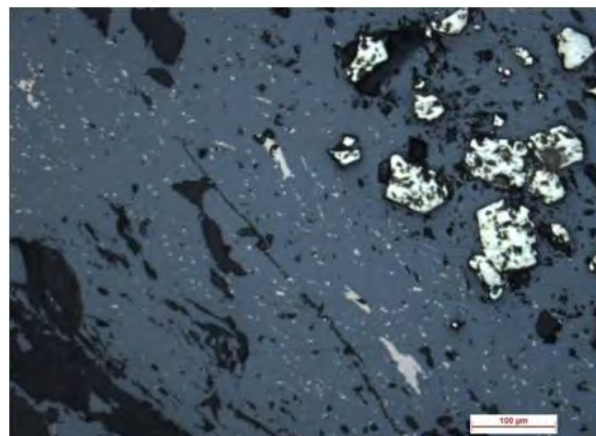
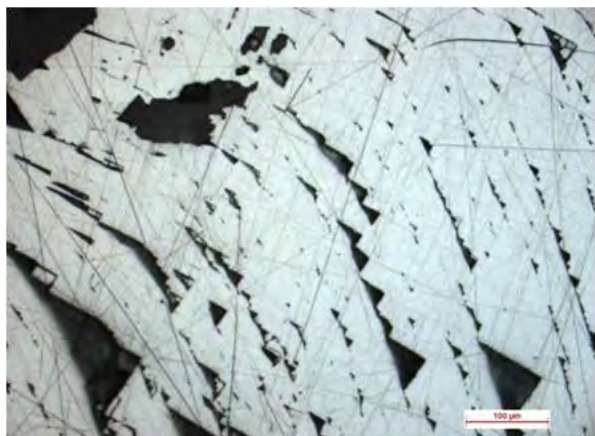
syngenetic and sedimentary marine conditions. They also noted that levels of concentrations of Sc and Th are higher than the general carbonate host rocks. Phyllites in the ZZB are reported to contain radioactive elements and during remobilization Th probably migrated to dolomite. The same observations related to high Th content in rocks of the ZZB have been made in the spectrometric study report of the BRGM (1973). Moreover K/Rb ratio of phyllites varies from 256-261, indicating its similarities with the volcanogenic sediments (Mukherjee & Sen, 1980). It is evident from the Chemical Index of Alteration (Meunier *et al.*, 2013) that the Zawar phyllites are the product of high chemical weathering as suggested by Singh & Khan (2017) in their study of geochemical signatures. The average Th/U ratio in the phyllites and quartzite of the Aravalli

Supergroup ranges from 5.32 to 8.52 and 1.7 to 11.4 respectively of which the ratio in ZZB phyllites is 8.5 and ZZB quartzite is 4.7. The source rocks for the sediments of the Aravalli Supergroup are granitoids, tonalite-trondhjemite-granodiorite gneisses and mafic enclaves of the Banded Gneissic Complex (BGC) with maximum Th/U ratio up to 6.26. Singh & Khan (2017) concluded that elevated Th/U ratio in Aravalli clastics is due to monazite accumulation and the overall synthesis of geochemical data of these clastic rocks suggests low to extreme degrees of chemical weathering in their source area.

In general, the distribution and concentration of different elements in rocks and soil controls the development and growth of different plant species in an area. The same is true in the case

	Zn%	Pb%	Fe%	Cu	Cd	Co	Ni	As	Sb	Mn	Ag	Ce	Ga
Range	2.9-4	0.3-1.2	2.1-3.4	76-168	146-253	0.3-7	0.05-3	0.1-2	0.03-3.6	214-316	526-721	0.1-1.2	0.2-1.5
Average	3.5	1	3	100	200	3	1	1	2	260	600	0.8	1

**Table 6:** Average quantitative analysis of different elements from Zawar Run of Mine ore (n-200) (Mukherjee and Sen, 1980)



**Figure 11:** (Top Left) Photomicrograph showing curved cleavage pits in galena. Baroi mine

**Figure 12:** (Bottom Left) Photomicrograph showing occurrence of sphalerite, galena and dyscrasite (Dys). Zawarmala mine

**Figure 13:** (Top Right) Photomicrograph showing exsolved pyrrhotite and framboidal pyrite (Py) in sphalerite (Sp).

**Figure 14:** (Bottom Right) Photomicrograph showing vein of galena. Baroi mine

of the ZZB, as geobotanical studies reveal a variety of plant - *Impatiens Balsamina* - is the characteristics species which accumulate appreciable amount of zinc as high as 12141 ppm and is considered to be a local indicator of zinc mineralization. Studies have also revealed that twigs concentrate more copper, lead and cadmium whereas leaves contain more zinc.

### Geophysical signatures

Bouguer Gravity and aero-magnetic studies over the ZZB reveal a number of geophysical features. In general, ZZB is located at moderate gravity and medium to moderately high aero-magnetic zone (Fig. 15 and 16). Several NW-SE trending gravity gradient zones in the vicinity of the ZZB mines have been observed and localized high magnetic responses have been noticed over the mines in the ZZB. The Bouguer gravity map has delineated a NW-SE trending sharp gradient over the ZZB district. This gradient is corroborated with the folded structure on the geological map. It appears that the Zawar mines are located at the intersection of a number of geophysical lineaments. A low-pass filtered magnetic map shows that the Zawar Mine is reflected by a high magnetic zone over a very limited strike length (Singh *et al.*, 2017). Gravity surveys

at the Zawarmala Mine point toward several residual gravity highs which might be due to the presence of high-density Pb-Zn ore (Babulal *et al.* 2004).

### Isotope characters and geochronology

Deb (1990), Sarkar & Banerjee (2004) and Fareeduddin *et al.* (2014) presented sulphur and carbon isotopic data for the Zawar deposits. Deb (*op. cit.*) reported  $\delta^{34}\text{S}$  values vary (1) 5.2 to 9.8 ‰ for galena and 2.8 to 9.7 ‰ for sphalerite from Mochia (2) -2.3 to 20.4 ‰ for galena and -2.4 to 20.7 ‰ for sphalerite from Balaria (3) 6.5 to 18.6 ‰ for galena and 5.1 to 18.8 ‰ for sphalerite from Zawarmala and (4) -4.2 to 6 ‰ for galena and 2.0 to 6.2 ‰ for sphalerite from Baroi (Deb, 1990, Sarkar & Banerjee, 2004, Fareeduddin *et al.*, 2014).

The  $\delta^{34}\text{S}$  values range from -2.3 to 20.4‰ for galena and 0.7 to 20.7‰ for sphalerite from ZZB (Sarkar & Banerjee, *op. cit.*) (Fig.17). This large spread of sulphur isotopic values in ZZB may be due to partial biogenic fractionation of the sulphur isotopes. According to Fareeduddin *et al.* (*op. cit.*), the S-isotope distribution appears bimodal with pyrite-pyrrhotite veinlets having a distinctly different or enhanced  $\delta^{34}\text{S}$  values in relation

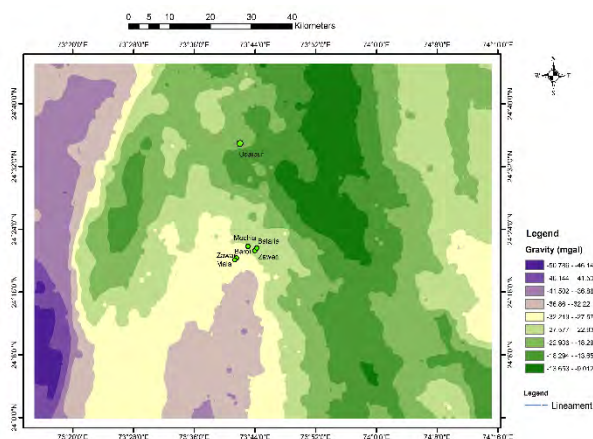


Figure 15: Bouguer gravity map of Zawar and adjacent area.

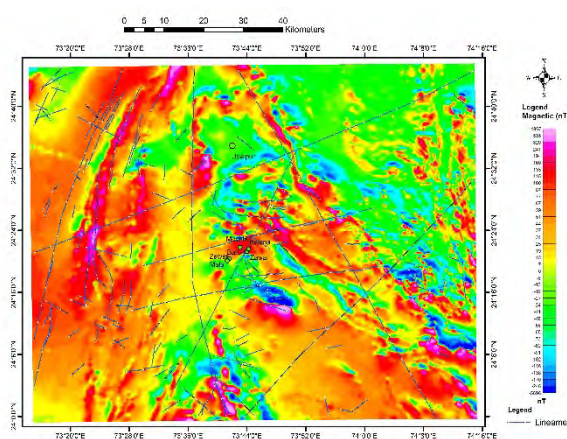


Figure 16: Aeromagnetic and lineament map of Zawar and adjacent area.

to the galena-sphalerite veinlets reflecting different processes of formation and timing of events. The remobilization activity appears to have no significant impact on S-isotopic distribution.

The disseminated sulphides at places show marginally depleted isotopic values.

Carbon and oxygen isotope data from ore zone carbonates in the Mochia, Balaria and Zawarmala Mines are shown in Fig. 18. The mean positive  $\delta^{13}C$  values from the Balaria and Mochia Mines vary from +1.4 to 4.32‰ (PDB, “*Pee Dee Belemnite*”) and are consistent with a marine environment. Decarbonation reactions during metamorphism might have taken place in impure carbonates which have shifted the  $\delta^{13}C$  values to negative side *i.e.* up to -2.5‰ (PDB), however, the negative values in the ZZB indicate the effect of biogenic processes which has also been suggested by the S-isotopic study (Sarkar & Banerjee, 2004).

The  $\delta^{18}O$  values also indicate a marine origin (Sarkar & Banerjee, *op. cit.*). Fareeduddin *et al.* (*op. cit.*) made the

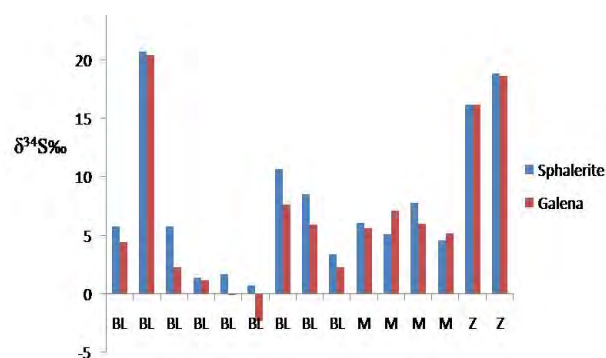


Figure 17:  $\delta^{34}S$  composition of coexisting sphalerite and galena from different mines of Zawar (after Sarkar & Banerjee, 2004).

BL – Balaria; M – Mochia; Z – Zawarmala.

following inferences from their C and O isotopic study from the Zawar Belt: (1) majority of the carbonates exhibit normal marine signatures, (2) carbonates in the vicinity of Pb-Zn mineralization have depleted O-isotopic values (-3 to -9‰) due to the influence of hydrothermal solutions on normal marine carbonates and; (3) depleted the O-isotopic signature is due to post-depositional equilibration with isotopically light meteoric water.

The galena from the belt gives a Pb-Pb model age around 1.7Ga *i.e.*, a Palaeo-Mesoproterozoic age which is broadly contemporaneous with the Pb-Zn mineralization and Aravalli orogeny in Rajasthan. The lead from the ZZB is not only homogenous but bears evidence of having been derived from a source that had a high  $\mu$ -value (calculated  $^{238}U/^{204}U$ ) for a considerable period of geological time (Deb *et al.* 1989; Deb & Thorpe, 2004).

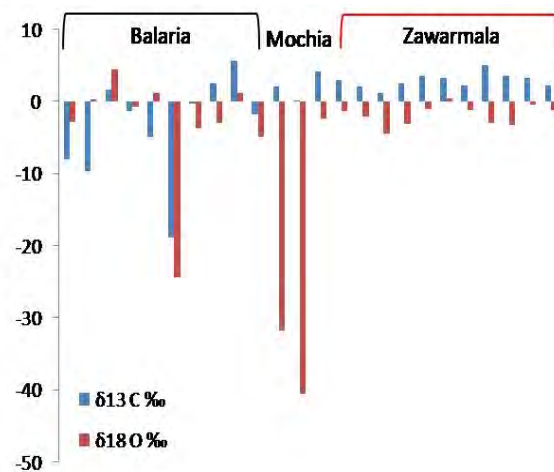


Figure 18: Carbon and Oxygen isotope composition of carbonate rocks associated with ore zones of different mines.(after Sarkar & Banerjee, 2004)

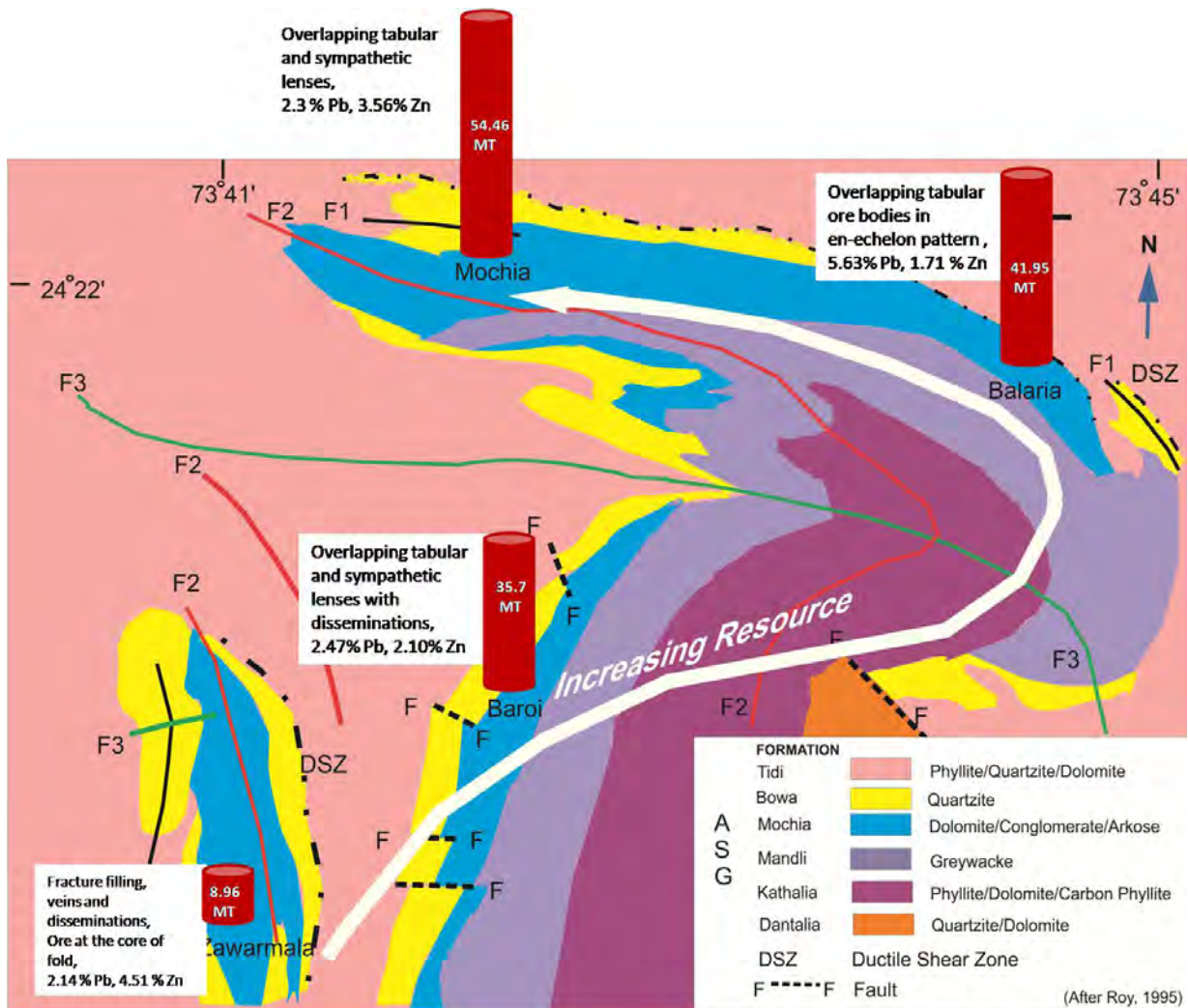


Figure 19: Generalized Geological Map of Zawar showing location of mines and resources.

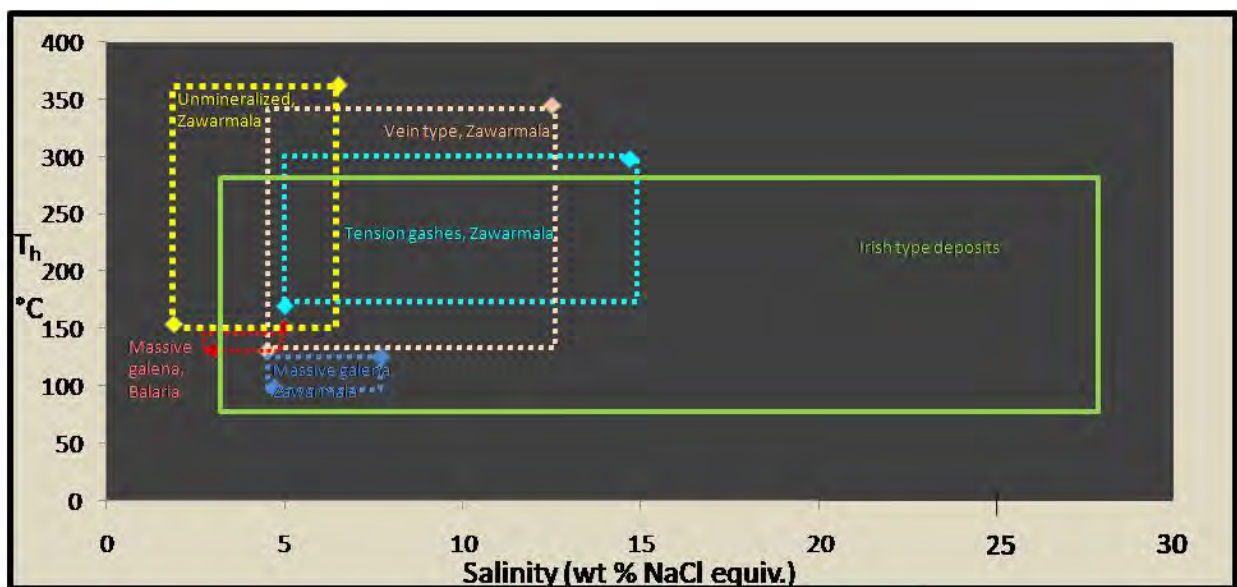


Figure 20: Temperature of homogenization ( $T_h$ ) vs. salinity plot of fluid inclusions in quartz associated with a. vein type ore, b. massive galena ore, c. tension-gash, d. unmineralized quartz vein from Zawarmala, massive galena ore from Balaria. Compared with Irish-type deposits.

Regional setting	<b>Irish type</b> (Wilkinson and Hitzman, 2015)	<b>Zawar Zinc – Lead mineral belt (ZZB)</b>
		Block faulting associated with crustal extension
Host rock	The carbonate-hosted zinc-lead deposits of the Irish Orefield are stratigraphically and structurally controlled. Host rocks are limestones, marls and shales.	The carbonate-hosted zinc-lead deposits of the ZZB are stratigraphically and structurally controlled. Main host rock is dolomite.
Stratigraphy	Ore deposits are restricted to two stratigraphic units of Lower Carboniferous. Waulsortian Limestone Formation and the Navan Group.	Ore deposits are restricted to dolomite of the Mochia Formation of the Middle Aravalli Group of Proterozoic age.
Structure	The Waulsortian-hosted deposits occur largely in the complexly faulted hanging walls of large normal faults formed during transtensional fault movement. Ores at Lisheen and Navan are cut by faults.	Zawar ore bodies are stratabound and occur within a megascopic fold. Disposition of ore bodies are largely controlled by folding and ductile shear zone during D <sub>2</sub> .
Nature of fluid	Two types of fluids: (1) a moderate temperature (mostly 130° to 240°C but locally up to 280°C), low to moderate salinity (8-19 wt% NaCl equiv.), reduced and sulphur-poor, metal-bearing fluid (the “principal ore fluid”); and (2) a relatively low temperature (50-130°C), high salinity (>20 wt% NaCl equiv.), Br-enriched bittern brine.(Fig. 20)	Fluids associated with epigenetic type ores are of two types:  1) Vein-type ore are low-salinity (4.3–14.7 wt % NaCl equiv) H <sub>2</sub> O-NaCl fluids, trapping temperature in the range of 395° to 290°C at a pressure of about 1,450 bars.  2) Fluids associated with massive galena ore are H <sub>2</sub> O-CO <sub>2</sub> -NaCl fluids of lower salinity (about 3–4 wt % NaCl equiv), lower trapping temperature fluid to be between 250° and 150°C at pressures of 2,000 to 750 bars. (Fig. 20)
Isotope nature	Sulphides in the Irish ore deposits exhibit a wide range of δ <sup>34</sup> S values from -45‰ to +15‰.  Sulphur, lead and strontium isotope data and fluid geochemistry indicate that fluid of first type originated as partially evaporated seawater. Second type fluid was reservoirized within the carboniferous sequence and never interacted with siliciclastic rocks and acquired reduced sulphur derived from bacteriogenic reduction of seawater sulphate. (Fig.22).	Sulphides in the ZZB show δ <sup>34</sup> S values range from -2.3 to 20.4‰.  The large spread of sulphur isotopic values in the ZZB may be due to partial biogenic fractionation of the sulphur isotopes. S-isotope distribution appears bimodal reflecting different processes of formation and timing of events. C and O isotope studies of host rock exhibit normal marine signatures. (Fig.22)
Proximity to Igneous activity	The intimate relationship between mineralization and volcanic activity in the Limerick province supports a model involving magmatic heat as a key driver for fluid circulation.	Relation between mineralization and volcanic activity is not well established.
Depth of formation and age of mineralisation	Ore formation occurred episodically over an extended period of time (10-15Ma). Most hydrothermal activity related to mineralisation appears to have occurred around (~359-346Ma). Study suggests that some mineralization could have formed several million years after host rock deposition. (Fig. 22)  The depth of formation and age of mineralization in the Irish ore field as a whole remain contentious but is mostly considered to have been at shallow depths of less than 400-500m.	Three types of ore formation occurred over an extended period. Host rock of mineralisation is of middle Aravalli <i>i.e</i> around 2000Ma, but date of mineralisation is ~ 1700Ma. Epigenetic mineralization could have formed several million years after host rock deposition. (Fig.22)  The depth of formation is equivalent to 2 to 3 kbar pressure and temperature is maximum ~400 to 450°C indicating a depth of formation of about 10 to 12km.
Paleogeography	Position of Ireland was near palaeo-equator at ~ 340Ma.	Position of India was near palaeo-equator at ~1700 Ma.
Grade	Lisheen - 22.4 Mt @ 11.63% zinc, 1.96% lead and 26 ppm silver. Navan - 105 Mt @ 8.1% Zn and 2% Pb	141.07 Mt of ore with grades ranging from 1.71% to 4.51% for zinc and 2.14% to 5.63% for lead, 24 ppm to 45 ppm silver
Zn/(Zn + Pb) Ratio	Varies from 0.8 to 0.85. (Fig. 22)	Varies from 0.23 to 0.68. (Fig. 22)
Ore minerals	Galena, sphalerite, pyrite, chalcocopyrite.	Galena, sphalerite, pyrite, pyrrotite and arsenopyrite, chalcocopyrite at places.

**Table 7:** Comparison of Irish-type and ZZB type deposits

## Fluid Inclusion studies and microthermometry

Petrographic studies of wafers of quartz vein containing specks of sulphides from the Mochia, Balaria and Zawarmala Mines indicate the presence of primary and secondary mono-phase/bi-phase aqueous and carbonic inclusions.

Talluri *et al.* (2000) described the fluid characteristics of massive galena and vein-type ores from the Zawarmala deposit. Fluid inclusions in quartz associated with the ores show that fluids forming vein-type ore are low-salinity (4.3–14.7 wt % NaCl equiv) H<sub>2</sub>O-NaCl fluids. The trapping temperature of vein-type ore fluid was estimated to be in the range of 395° to 290°C at a pressure of about 1,450 bar.

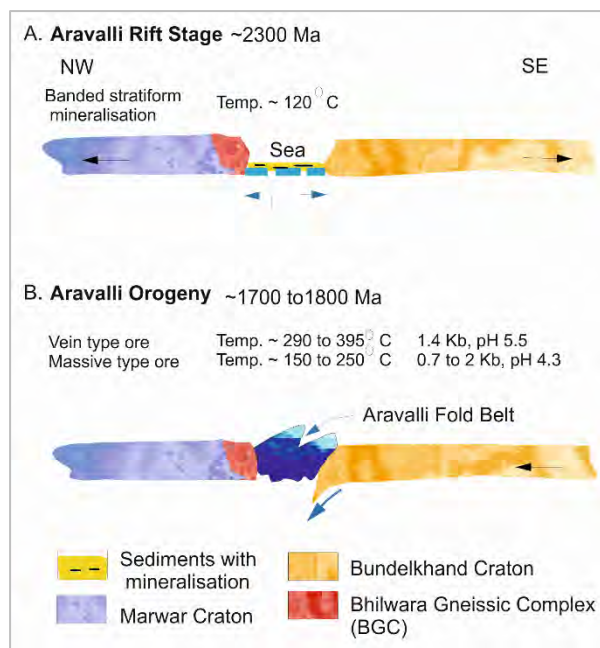
Fluids associated with massive galena ore are H<sub>2</sub>O-CO<sub>2</sub>-NaCl of lower salinity (about 3–4 wt % NaCl equiv). The wide variation in XCO<sub>2</sub> of fluid inclusions that occur near each other within the same sample of massive ore suggests heterogeneous entrapment of the low-salinity H<sub>2</sub>O-CO<sub>2</sub>-NaCl fluids. From the intersection of isochors of local, homogeneously entrapped CO<sub>2</sub> and aqueous biphasic fluids of unmixed CO<sub>2</sub>-H<sub>2</sub>O-NaCl fluid, the trapping temperature of the fluid was estimated to be between 250° and 150°C at pressures of 2,000 to 750 bar. Data from fluid inclusions and solubility calculations reveal that cooling is the important mechanism of vein-type ore deposition. The massive galena ore deposition took place by mixing of a regional, high metal content, low sulphur fluid with a local, high sulphur fluid (Talluri *et al.* 2000).

Ilyas & Pandalai (2016) studied samples from the Balaria deposit and opined that fluids responsible for the massive type ores are made up of variable H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub> contents. This indicates that the fluids may have been derived from basinal sources during burial diagenesis or early metamorphism of sediments containing organic matter. The variation in mol. % of CO<sub>2</sub>, N<sub>2</sub> and CH<sub>4</sub> in the dark bi-phase and dark monophase fluid inclusions spatially located near each other indicates that pulses of fluid had variable composition. They also concluded, as had Talluri *et al.* (2000), that local reaction of fluid with carbonaceous rocks and carbonate rocks took place in close vicinity to the massive ore and that variable mixing of a regional fluid with a local fluid with variable composition.

A temperature of homogenization (T<sub>h</sub>) vs. salinity plot of fluid inclusions data from quartz associated with a.) vein type ore, b.) massive galena ore, c.) tension-gash, d.) unmineralized quartz vein from Zawarmala (Talluri *et al.* 2000) and massive galena ore from Balaria (Ilyas & Pandalai, 2016) show a diverse range with some overlapping domains (Fig. 20). Fluid inclusion salinity ranges from ~ 5 to ~7wt% NaCl equiv. and temperature ranges from ~ 100 to ~ 340°C, in the overlapping domain. Maximum salinity is recorded (14.7wt% NaCl equiv.) in fluid inclusion from tension gashes from the ZZB.

## Genesis

Two theories about the genesis of the deposits in the ZZB came into existence in the 1950s and 1960s initially assuming a hydrothermal origin (Ghosh 1957, Mookherjee 1964) and subsequently a sedimentary origin followed by remobilization of



**Figure 21:** Schematic diagram depicting stages of evolution of Aravalli Fold Belt and formation of types of zinc-lead mineralization of Zawar. (Modified after Rao *et al.* 2000)

sulphides (Smith 1964, Poddar 1965, Chakraborty 1967). Sarkar (2000), Sarkar & Banerjee (2004) and Deb (1989) argued in favour of a SedEx and a SedEx-MVT mixed type of genesis whilst on the basis of element distribution within sphalerite and pyrite at the Zawarmala Mine, Bhuyan & Hazarika (2022), observed an affinity of this deposit was MVT. Large *et al.* (2002) categorized the deposits of Zawar as Irish-type and considered them amongst the 40 top Zn-Pb deposits of the world.

Evidence in favour of a syngenetic origin include the dominantly strata-bound nature of the mineralization over the 20-km-long belt, the presence of sedimentary structures in the bedded ores and the lack of wall rock alteration (Poddar, 1965)

Evidence of remobilization and recrystallization include the coarsening of stratified ore at contacts with vein quartz, the alignment of ore veins with linear and planar features formed during folding and metamorphism, and the abundance of coarsely crystalline galena and sphalerite in the later formed ore-shoots relative to the stratified ore (Talluri *et al.*, 2000).

Observations of the metallogenic features in the Aravalli province indicate that the primary mineralization has invariably been associated with sediment deposition. Ore formation in the ZZB is a combination of several processes which lasted for a prolonged period in association with complex structural history of the area. In this belt, lesser significant carbonaceous phyllite hosted primary stratified ores resemble SEDEX-type (Goodfellow *et al.*, 1993) in macro- and micro-scales, and the textural features (Bhattacharya, 2004) associated with it, indicate synsedimentary/diagenetic origin. The dominant part of the ore *i.e.* vein and massive types are epigenetic and related to secondary planar structures developed during deformation and

metamorphism. During the development of major  $F_3$  fold, different sets of fractures developed due to shear, parallel to  $S_2$  (Banerjee *et al.* 1998). Increased porosity and permeability of the rocks attracted increased hydrothermal activity and caused deposition of veins of ores and massive ore type at different times. Evidence of repeated mineralization is abundant in the textures and structures of the mineralized mass and its wall rocks.

Acid neutralization processes may be the cause of formation of massive ore type where the initial pH of the ore solution is below the pH value at which dolomite dissolution takes place at around 250°C. Contact of such solutions with dolomite leads to an increase in the pH of the ore solution and decrease in solubilities of sulphides, resulting in sulphide precipitation (Talluri *et al.*, 2000). It has been found that an increase in reduced sulphur content of the ore forming fluids causes a precipitation of sulphides (Barton, 1967). Cooling also reduces the solubility of galena and sphalerite and thereby causes deposition as indicated by the solubility calculations (Talluri, 1999).

Basu (1976) reported close association of native sulphur, carbonaceous shale and gypsiferous shale, and opined that the native sulphur was produced by organic reduction in the ZZB. The  $\delta^{13}C$  cluster characterized by negative values suggests involvement of biogenic processes and is substantiated by large spread of sulphur isotopic values in the ZZB. The presence of carbonaceous material within these litho assemblages produced a reduced environment and facilitated precipitation of metal as sulphides (Bhattacharya & Bull 2010).

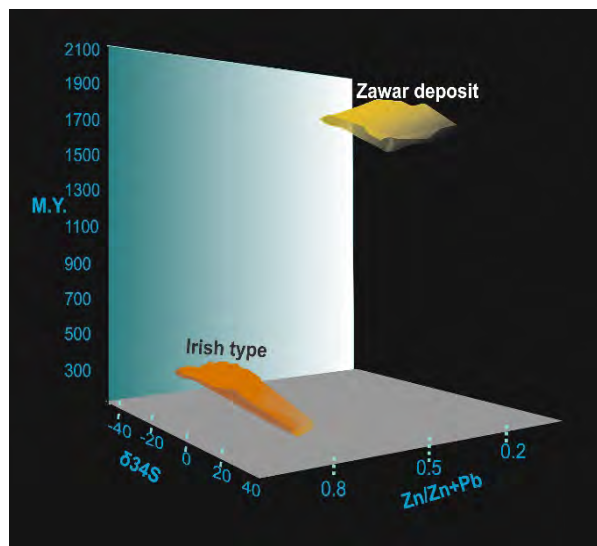
Large *et al.* (2002) observed that carbonaceous material is ubiquitous and abundant in all sediment-hosted Zn-Pb-Ag deposits, and the spread in  $\delta^{34}S$  sulphide values, is strong inferred evidence for biogenic sulphate reduction being an important sulphide generating process, especially for vent distal deposits that form in low temperature brine pools. As biogenic sulphate reduction is not possible at high temperatures (more than about 120°C, Large *et al.* 2002), it may be postulated that the temperature of formation of SedEx-type ore in the ZZB is around 120°C, whereas ore veins formed at a higher temperature 395° to 290°C at a pressure of about 1,450 bar and the massive galena veins formed at 250° and 150°C at pressures of 2,000 to 750 bar and are related to deformation and considered to be structurally controlled (Talluri *et al.*, 2000, Bhuyan & Hazarika, 2022). The early-stage SedEx-type mineralization seems to be the product of rift system developed in an extensional regime related to distal vent whereas the other cross-cutting styles were formed in a compressional regime during the time of folding related to the Aravalli Orogeny (Fig. 21) after a considerable time gap. In the vein-type ores,  $PbCl_3^-$ ,  $ZnCl_4^{2-}$ , and  $FeCl^+$ , are the predominant metal-transporting complexes and in the case of the massive galena ore type  $PbCl_2(aq)$  is the dominant metal complex in the temperature range of 250° to 175°C in the fluid that gave rise to this ore. The  $Pb(HS)_2$  complex becomes the dominant complex in massive galena ore fluid below 175°C. The zinc chloride complex,  $ZnCl_3^-$ , is the dominant zinc complex in the massive galena ore fluid over the entire temperature range (Talluri *et al.*, 2000). Precipitation of metal sulphide took place from metal rich hydrothermal brines that might have emanated from intra-basinal active fault system

(Sawkins, 1984; Large *et al.*, 2004; Lydon, 2004). Overall, the depth of formation is equivalent to 2 to 3 kbar pressure and maximum temperatures are ~400 to 450°C indicating a depth of about 10 to 12km (Jones & Lineweaver, 2010).

As far as source of the metal is concerned, the lead was most probably derived from the feldspar bearing clastic sediments present in litho-package or from the basement granitoids or both, whereas zinc and sulphur were derived from carbonaceous phyllite (Sarkar & Banerjee, 2004). Deb *et al.* (1989) suggested U enriched upper crustal source for the Zawar deposits on the basis of Pb isotope data.

## Discussion

The zinc-lead deposits of ZZB represent a combination of various ore formational phenomenon that have taken place at different times. The Zawar deposits are stratabound, but also structurally controlled and epigenetic with characteristics of different 'type' of deposits (SedEx, MVT and Irish-types). The initial formation of the zinc-lead mineralization commenced with sedimentation in the Aravalli basin, which developed around 2300Ma through rifting of the Kenorland (?) supercontinent (Nance, 2022) (Fig. 21).



**Figure 22:** Schematic diagram showing comparison of Zawar deposits and Irish-type with respect to different parameters.

Palaeogeographic reconstruction reveals that during the period of 1.88 to 1.78Ga, India was near to the palaeo-equator and carbonate-hosted lead-zinc deposits are associated with this orogenic phase (Pehrsson *et al.*, 2016). Proximity to the palaeo-equator indicates a warm and humid climate and facilitated deep weathering and oxidation and leaching of metals from the source rock, deep chemical weathering and proliferation of bacterial activities in the ocean which provided a suitable environment for extraction of metals from source, transportation as chloride complexes and subsequent deposition in a suitable anoxic environment. It is noted that the three major zinc-lead deposits of Rajasthan *i.e.*, Dariba, Agucha and Zawar are aligned along a straight line (N30°E) (Fig. 1), parallel to trend

of D<sub>2</sub> deformation in Rajasthan and probably indicate the strong structural control on the present disposition and genesis of the deposits.

For a better understanding, Geological Nature Analysis (“GNA”) is presented as Table 7 for the ZZB and the Irish-type deposits (Wilkinson & Hitzman, 2015).

This GNA between ZZB and Irish-type reveals similarities with respect to their stratabound nature, host rock, ore minerals and palaeo-geography. Although Zn/Zn+Pb is higher in Irish-type deposits, fluid inclusion and S isotope data overlap but are of a wider range in Irish-type. Deposits of the ZZB are structurally more complex and of older age compared to Irish-type deposits in Ireland. Studies of these parameters reveal the unique character of the ZZB which points towards a hybrid nature and may be termed “Zawar type”.

## Conclusions

The Zawar Zinc Lead Belt is a part of a Proterozoic meta-volcano-sedimentary multi-cycle mega-sequence within the Aravalli Supergroup, which developed in an ensialic rift setting. Three types of mineralization *viz.* disseminated stratiform, vein and massive type ores are the product of a combination of two mineralization periods. The primary less significant ore of the first category is related to rifting, related sedimentation and formation of an ocean basin developed in an extensional regime and may be categorised as SedEx, whereas the more volumetrically significant vein and massive ore types are of an epigenetic nature and formed during tectonism related to the Aravalli orogeny. These features indicate a prolonged history of mineralization which lasted for millions of years in this part of the Precambrian terrain.

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