Scientific Research Publishing

Open Journal of Geology, 2026, 16(10), 722-747
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Geochemical Fluctuations in the South Western Parts of Palaeoproterozoic Bijawar Basin: Field Evidence from the Barwah-Harda Inlier

Rajendra Kumar Sharma[1], Biswajeet Lenka[2], Balasubramaniam Balaji[3]

[1]A-55 Anand Vihar, Jagatpura, Jaipur, India
[2]Geological Survey of India, NER, Shillong, India
[3]Geological Survey of India, State Unit Tamilnadu, Chennai, India
Email: rajsuman87@gmail.com, biswajeetlenka@gmail.com, bbalajis@gmail.com

How to cite this paper: Sharma, R.K., Lenka, B. and Balaji, B. (2026) Geochemical Fluctuations in the South Western Parts of Palaeoproterozoic Bijawar Basin: Field Evidence from the Barwah-Harda Inlier. *Open Journal of Geology*, **16**, 722-747.
https://doi.org/10.4236/ojg.2026.1610035

Received: September 12, 2026
Accepted: October 26, 2026
Published: October 29, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/

Open Access

Abstract

The Palaeoproterozoic basins across the world demonstrate oxygenation of oceans and these have resulted in extensive blanket deposits of Manganese and Phosphorite in various parts of world and also in India. Bijawar basin is one such basin in India which exhibits rich phosphatic deposits of chemogenic origin. The authors have worked in the southwestern part of the Bijawar basinal sediments, in parts of Barwah-Harda Inlier and collected some field evidences suggesting fluctuating geochemical characters of the Proterozoic ocean within the same basin.

Keywords

Palaeoproterozoic, Bijawar, Barwah-Harda Inlier, Geochemical, Phosphorite

1. Introduction

Sedimentary rocks serve as an evidence of the geo-environmental changes and evolution of basin eventually revealing the earth's evolution. The chemogenic sediments act as a direct evidence of the global oceanic conditions while the clastic sediments give insights into the paleogeography and tectonic changes. Paleoproterozoic sedimentary basins record major geochemical shifts driven by progressive, yet fluctuating, oxygenation of Earth's surface and oceans. The sequential deposition of iron (Fe), manganese (Mn) and phosphorous (P), highlights dynamic redox gradients, shifting marine nutrient cycles, and evolving atmospheric O_2 levels between 2.5 and 1.8 billion years ago. Hence, the sedimentary records of iron, manganese, and phosphorus, as well as other trace elements in the Precam-

brian successions provide critical insights into the evolving redox structure and chemical composition of Earth's early oceans [1]-[6]. These elements, though often spatiotemporally co-deposited, respond differently to changes in oxygen and sulfur availability due to their distinct redox couples and mineral affinities [7]-[9]. Iron and manganese exhibit markedly different behaviours under fluctuating redox conditions [7] [10]. Phosphorus behaves differently, still it is not redox-sensitive in itself but is closely coupled to the Fe and Mn cycles through adsorption onto or co-precipitation with metal oxy hydroxides [11] [12].

Sedimentary phosphorite deposits constitute 80% of the world's phosphate resources [13] [14] that are crucial for agriculture and food security, animal nutrition, industrial applications including potential sources of rare earth elements. Deep-ocean upwelling is the key mechanism for the formation of phosphorites. They first appeared ca. 2.0 Gyr ago, suggesting a genetic linkage to the global biogeochemical changes that transpired during the early Paleoproterozoic, such as the Great Oxidation Episode (GOE) [15] [16], carbon isotope excursions, and glaciations. The earlier assumption of progressive oxygenation of the atmosphere through the Proterozoic has also undergone significant revision, with the recognition of the great oxygenation event [17] [18] that occurred during the Archean-Proterozoic transition. The earliest known sedimentary phosphorites date back to the end of the Lomagundi carbon isotope excursion at ca. 2.06 Ga, shortly after the GOE, and ca. 1.88 Ga [19] [20]. The GOE significantly altered the redox state of Earth's surface environments, including the atmosphere and shallow oceans [15] [21]. The increase in atmospheric oxygen following the GOE enhanced oxidative weathering of redox-sensitive elements such as iron (Fe), uranium (U), and manganese (Mn), which were transported and eventually precipitated in marine basins. Oxygenation also stimulated biological activity, increasing organic productivity [22] and facilitating phosphorite formation through microbial and diagenetic processing of organic matter in deep-water settings.

India depends on imports for roughly 90% of its phosphate consumption. Domestic production is restricted to Rajasthan and Madhya Pradesh, meeting only 10% - 15% of the total demand, which necessitates heavy imports of raw rock phosphate, phosphoric acid, and finished fertilizers. India holds limited reserves of phosphorite with total resources of rock phosphate, placed at over 311.25 million tonnes, out of which proved and probable reserves constitute only about 30.87 million tonnes, while the rest fall into the "remaining resources" category requiring extensive processing [23] (IBM Year book 2024). Geographically, the rock phosphate deposits are distributed in Jharkhand (34%) Rajasthan (30%) (Primarily Jhamakotra deposit), Madhya Pradesh (19%) (Hirapur region) and Uttrakhand 8% [23] (IBMY 2024).

Numerous sedimentary basins containing phosphorite deposits have been identified across the country, as evidenced by various studies [24]-[32]. These basins hold major low-to-medium grade phosphorite (rock phosphate) deposits distributed across ancient sedimentary and marine basins, including the Aravalli basin

in Rajasthan, Bijawar Basin in Madhya Pradesh, Sonrai Basin in Uttar Pradesh, Mussoorie Syncline in Uttarakhand, Cuddapah basin in Andhra Pradesh and Cauvery basin in Tamil nadu. Among these basins, Cuddapah basin is a Proterozoic basin, Aravalli and Bijawar basin are Palaeoproterooic basins whereas the Mussoorie syncline is the youngest basin of Tertiary age.

The origin of Paleoproterozoic phosphorite deposits in the Aravalli Basin (Rajasthan/Madhya Pradesh) and the Bijawar Basin (Madhya Pradesh/Uttar Pradesh) represents some of the earliest global phosphogenic events in Earth's history. While both deposits formed around 2.0 to 1.9 Ga, their genetic mechanisms differ significantly: the Aravalli deposits are primarily biogenic (microbial) in origin, whereas the Bijawar deposits are predominantly chemogenic (inorganic) [33]. The Aravalli Supergroup hosts massive rock phosphate deposits, most notably the Jhamarkotra, Matoon, Kanpur, and Sallopat deposits around Udaipur, Rajasthan [27]. Overlying Archaean Bundelkhand Granite Gneiss Complex, the Gwalior and Bijawar Groups of rocks represent two Palaeoproterozoic basin successions which, despite their common sediment provenance and analogous rift-related tectonic setup, record more dissimilarity in their sedimentation pattern than similarity. Whereas early sedimentation in the Gwalior Basin is clastic, the early Bijawar sedimentation is dominantly chemogenic (limestone and chert) except for an early, restricted volcano-clastic record. Although both of the basins record syn-depositional volcanic/volcaniclastic event(s) in the form of occurrence of basaltic and basaltic-andesite sills encased within their respective basin fills, the occurrence of iron formation in the later part of Gwalior sedimentation history and its absence in the Bijawar succession is related to variable oxidation conditions in the water columns of the two basins. Rising sea-level and upwelling on the continental margins of these two rift-related basins possibly generated different water chemistries; these allowed the deposition of iron formation in the Gwalior Basin and phosphorite in the Bijawar Basin. Effects of post-depositional digenetic re-crystallization are noticed within both iron formation and phosphorite deposits present in the basin successions [34]. Therefore, in this study, field evidence, mineralogical, and geochemical data approaches were used to link these elemental cycles to the co-evolution of ocean chemistry, biological productivity, and atmospheric oxygen, highlighting remaining uncertainties and future research directions.

2. Geological Background

The Archaean Bundelkhand Craton is surrounded by a string of Palaeoproterozoic basins, viz. Bijawar, Gwalior and Sonrai basins, that record pre-Vindhyan sedimentation history in north Indian craton. The ENE-WSW-trending Bijawar Basin (c. 1200 sq·km in aerial extent) occurs on the southeastern margin whereas, the east-west-trending Gwalior Basin (c. 2000 km^2 in aerial extent) occurs on the north western margin of the Craton respectively (**Figure 1(a)**). Rocks of both of these basins are overlain unconformably by the late Palaeoproterozoic-Mesoproterozoic Vindhyan Supergroup of sediments [35] [36]. The term "Bijawar" was

coined by Medlicot (1859) [37], is a broad synclinorium, extending ENE-WSW direction for about 80 km length, with its western part representing maximum width that is gradually decreasing towards east [38]-[40]. Based on the Rb-Sr dating of Kurat and Dargawan volcanics (1691 ± 180 and 1789 ± 21 Ma, respectively) of the Bijawar group [41] and the procellanites (1630 Ma) of the overlying Vindhyan Supergroup [42] [43], a Paleoproterozoic age has been assigned to the Bijawar Group. The rock sequence of the Bijawar group is well exposed in the Sagar and Chattarpur district of Madhya Pradesh (M.P.), India (**Figure 1(b)**). They comprise a volcano-sedimentary rock sequence consisting of conglomerate, carbonate rocks, sandstone, shale, and phosphorite rocks with some mafic intrusions [44]. There is an uneven distribution of phosphorite deposition within the Bijawar sediments. Perhaps the best documented part is located at Hirapur in Chhatarpur & Sagar districts of M.P whereas the south western part of the Bijawars, *i.e.*, around Barwah-Harda inlier in Khargone district, documents lithotypes equivalent to Bijawars with minor phosphorite occurrence as evidenced from the present study (**Figure 2**).

The typical lithostratigraphic succession of the Bijawar group of rocks is developed in the vicinity of the Hirapur phosphorite deposit while it extends for 80km in east west direction. The western most part is the thickest while the eastern most part is the thinnest and largely covered by Deccan trap and upper Vindhyan sediments.

3. Methodology

The study involves collecting the field evidence, mineralogical, and geochemical data to record the geological pattern, mineralisation intensity in different parts of the Barwah-Harda inlier. The authors had carried out the study as a field season programme of Geological survey of India, FS 2013-14. The geochemical results of P_2O_5 (n = 39) and MnO (n = 20) in this paper is taken for selective area where certain enrichment pattern was observed, however, the petrochemical data refer in this paper is taken from Jauhari *et al.*, 2021 [45] collected in the area during subsequent years. These data were used to link these elemental cycles to the co-evolution of ocean chemistry, biological productivity, and atmospheric oxygen, highlighting remaining uncertainties and future research directions, through condultation of literatures on Phosphorite mineralisation in Bijawar Basin and its equivalent Barwah-Harda inlier. The samples collected were mostly channel samples (1.0 m sample interval), were collected for P_2O_5 analysis from 1.5 KM south east of Modri village, whereas for MnO, samples were collected from 1.5 km west and 600 m north of Nandiya village. The samples were pulverized up to 120-mesh size and all the adequate precautions were adapted to avoid anthropogenic contamination. These samples were analysed using the M/S Analytical, X-Ray Fluorescence Spectrometer at Chemical Laboratory of GSI. The precision of XRF for major oxide data is ±5%. The standards GSR-1M were used for routine calibration and quantification. The P_2O_5 and MnO content of the samples and petrochemical

analysis have been presented in Tables 1-3 respectively.

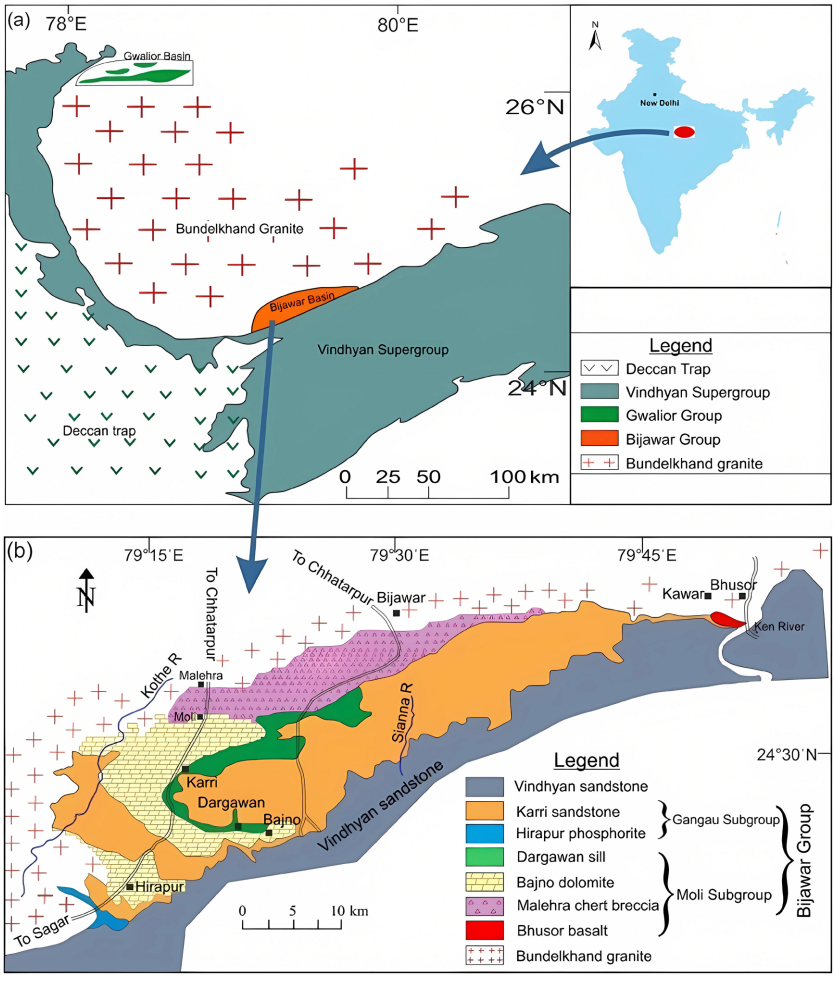


Figure 1. (a) Relative geographical position of the Bijawar basin with respect to Bundelkhand craton in India; (b) Geological map of the Bijawar basin (modified after Kumar *et al.*,1990, Chakraborty *et al.*, 2015).

4. Brief Geological Set up of the Barwa-Harda Inlier

A group of rocks, very similar to the sedimentary rocks of Bijawar type area are exposed and studied in Barwah and Harda and are termed as Harda Inlier, equivalent to that of Bijawars and mainly, consists of chert breccia, quartzite, cherty limestone, dolomitic limestone (stromatolitic) and clay. This Precambrian inlier, located in the Narmada valley of central India contains the southernmost exposures of the Vindhyanchal Basin [46] [47]. The isolated Harda Inlier (also known as the Dhar Forest Inlier) in the central Narmada valley of Madhya Pradesh exposes an isolated window of Precambrian basement rocks and Paleoproterozoic sequences surrounded by younger Vindhyan sediments and Deccan Trap basalts. The inlier is located towards south western part of the Bijawar Group. The Paleoproterozoic sediments of the basin constitute the lithounits of Kishangad Group, having conglomerate/arenitic quartzite of Bhanwartalao Arenite Formation at the

base, followed upward by mafic volcanic flows and argillites of Mangrol Volcanic Formation, chert breccia of Mehdikhera Chert Formation and cherty and stromatolitic dolomite of Lohar Dolomite Formation. The basin has estimated sediment thickness of ~2000 m [48]. The carbonate members of the basin show prolific development of stromatolites of Collenia-Colonnella-Conophyton assemblage [49]-[51]. On the basis of the presence of microbiota of Gunflintia-Huroniospora-Archaerestis assemblage the rocks are correlated with the Gunflint Chert of Ontario, Canada and Franceville Group of Gabon, South Africa of ~2000 Ma [51].

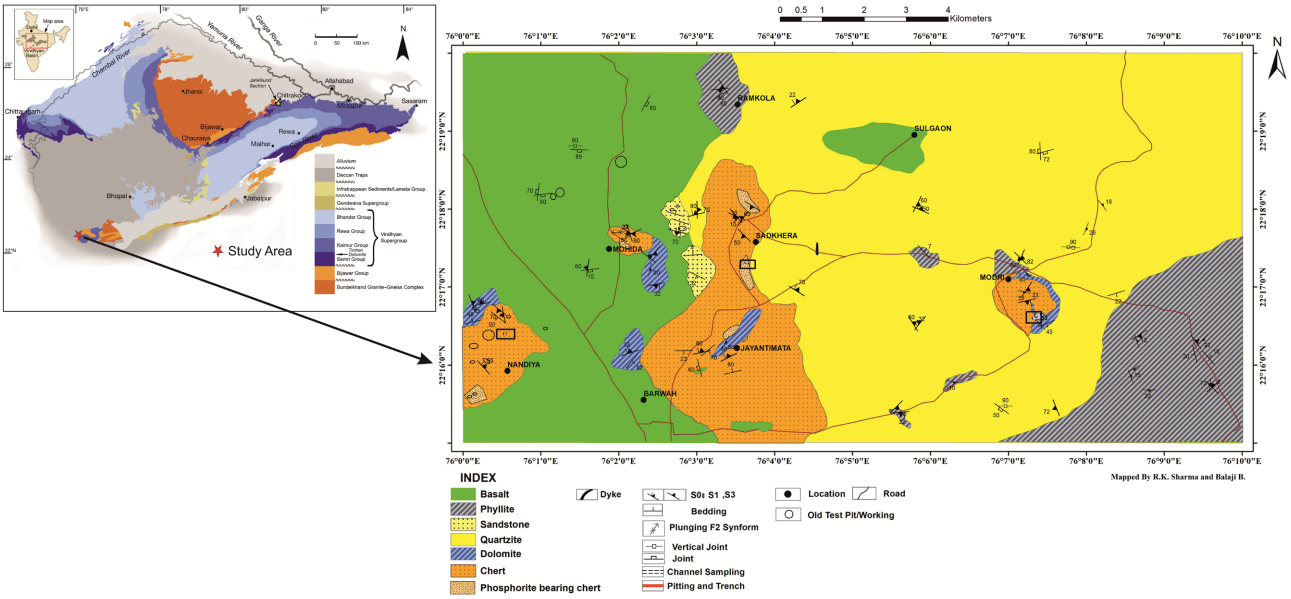


Figure 2. Large scale geological map of parts of Modri, Sadkhera and surrounding area, western part of Harda inlier, Khargone district, Madhya Pradesh [60].

The lithopack similar to that of Bijawar group has been observed north and north-east of Barwah. These rocks are exposed as small inliers amidst Deccan Trap cover. Since the middle of nineteenth century, the area was studied by W.T. Blanford and A.B. Wynne, F.R. Mallet and P.N. Bose [40] [52]. Blanford and Wynne (1869) [53] classified the rocks into metamorphic series and Bijawar series. The metamorphic series comprises granite, gneisses, phyllite, quartzite etc. while the Bijawars include limestone, dolomite, quartzite breecia etc. During the recent past, the area was studied by a number of workers including, M.K. Roy Chowdhury and V.V. Shastri (1954) [54], who worked in the present area, considered the dolomite as a part of the Archaeans and inter bedded with other schistose rocks. According to them the quartzite breccia is intra formational type having uncertain stratigraphic position between Vindhyans and Lametas. S.K. Shrivastava (1959-60) [55] is of the opinion that the phyllite, gneisses and granite belong to the Archaeans while the dolomite, quartzite and breecia constitute the Bijawars. M.M. Munshi and K.K. K. Nair (1974) [56] and K.K.K. Nair (1975) [57] carried

out systematic geological mapping in the area. Munshi and Nair divided the Bijawars into Lohar Dolomite Formation and Medikhera Chert breccia Formation. According to them Lohar-Dolomite is older than the Mehdikhera Chert breecia. S.C. Jain and M.P. Shrivastava (1986) [58] carried out reconnaissance for phosphorite in pars of Barwah-Harda basin. They placed Lohar Formation above the Mehdikhera Formation. Except for few localized phosphatic values, no significant phosphatic horizon is identified by them in this area. Nirmal Dhar (1989) [59] carried out systematic thematic mapping in the area and noticed 0.5 m to 1.5 m thick dolomite and chert bands which contain P_2O_5 in the range of 0.5% to 24% in the Sadkhera area.

The present study area covers the western part of the Barwah-Harda inlier and exposes rock types belonging to the Achaeans, Bijawars, Vindhyans and Lametas as inlier within the Deccan trap (**Figure 2**). Part of the Bijawar and Pre-Bijawar sequence are covered by Vindhyan Supergroup of rocks. The Lithostratigraphic disposition of various lithounits can be summarized as follows: The base for Bijawar here is marked by older metamorphites including Talk tremolite schist, Sericite schist and phyllite followed by Bijawar package resting unconformably over this metamorphites. The Bijawar sequence here is represented by grity quartzite/ quartz areinite, ferruginous quartzite called Medikhera quartzite, and dolomite with thin interlayers of sand stone named as Lohar Dolomite. The general stratigraphic succession of the area after Nirmal Dhar [59] is as follows:

Recent Alluvium Boulder Bed Upper Cretaceous to Eocene Basic dykes Deccan Trap Basalt flows with inter trappean beds
Cretaceous Lameta coarse-grained, Lameta Group Katkut gritty sandstone Sandstone with conglomerate
Precambrian Vindhyan Super group Kanar-sandstone with intercalated silt-stone (Upper Rewa sandstone and silty sandstone) shale
Proterozoic Bijawar Group • Mehdikhera quartzite Quartzite breccia, quartzite chert breccia with minor shale intercalations • Lohar dolomite, Dolomite with minor sandstone and shale intercalations.
Archaean (Quartz sericite/chlorite phyllite, feldspar calc chlorite phyllite meta-conglomerate, porphyry calc-schist, quartzite and meta-basics).

Bijawar sediments as described earlier are exposed in isolated patched due to extensive cover of Deccan trap and Vindhyan rocks. The main localities studied included Modri, North of Barwah town, Mohida, Sadkhera Nandiya etc. The exact nature of contact between Lohar Dolomite and Mehdikhera Quartzite breecia is also much obscured. At places such as North West of Jayantimata temple and east of Mohida, well bedded dolomite is overlain by quartzite breecia. Moreover quartzite breccia generally occupies higher elevation compared to the adjacent dolomite. From these observations, it appears that the Mehdikhera quartzite breccia is probably younger than the Lohar Dolomite. The Lithological assemblage of Bjawar group is restricted to the low lying areas and is only found to expose as detached exposures in isolation restricted to very few localities e.g. Modri, Sadkhera, Jayantimata, Mohida, Nandiya and adjacent areas.

5. Primary and Post-Depositional Sedimentary Structures

Primary and post-depositional sedimentary structures act as physical archives that record ancient hydrodynamic, biogeochemical, and diagenetic conditions. These structures when linked to high-resolution geochemical proxies, can reconstruct ancient ocean chemistry, atmospheric oxygenation, and nutrient cycling in Paleoproterozoic basins. The Bijawar rocks here depict some well-preserved structural feature including non distrophic and distrophic. The bedding and laminations are very well preserved in the quartzite and dolomite and so also in the chert.

Evidences of penecontemporeneous deformation (PCD) (**Figure 3**, **Figure 4**) have also been recorded indicating the occurrences of seismic activity during the depositional period. Non phospatic stromatolites (Oncolites) (**Figure 5**, **Figure 6**) have been recorded from different parts of the area from dolomite, besides crudely developed stromatolites.



Figure 3. PCD in Chert sequence in Bijawar sediments (Sadkhera).



Figure 4. PCD in Dolomite of Bijawar Group (Choral River-Sadkhera).



Figure 5. Oncolite structure in dolomite of Bijawar formation, Modri area.



Figure 6. Oncolite structures in Bijawar dolomite. Jayanti Mata section.



Figure 7. Possible first S fold in Cherty quartzite of Bijawar Gr. (Road section Jaintimata to Badipura).



Figure 8. Doubly plunging Second fold in Quartz vein embedded in dolomite of Bijawar. (Modri area.).

Besides these primary depositional structures, diastrophic structures are also preserved in the different lithologies of the Bijawar group of rocks in the studied area. Possible first fold in Cherty quartzite (**Figure 7**) and folds of the second deformation in the quartz vein (**Figures 8-10**) embedded in the dolomite have been recorded from different parts of the area.



Figure 9. Hematite-quartz veins emplace within the chert are co folded demonstrating Pre F2 emplacement: Modri area.



Figure 10. Post F 2 folding Granulation of quartz vein in yellow chert.

6. Mineralisation in Barwah-Harda Inlier

The co-occurrence of phosphorite, manganese, and iron in Paleoproterozoic sediments (like those in the Aravalli and Bijawar basins of India) is primarily driven by global atmospheric oxygenation, unique basin tectonics, and biogeochemical cycling. These elements, Paleoproterozoic phosphorites and Mn-Fe deposits commonly accumulated along continental margins or in shallow, restricted epicontinental basins. In these semi-isolated settings, upwelling deep-ocean currents brought nutrient-rich (and metal-rich) waters into contact with sunlit, oxygenated coastal zones. This drove rapid algal/cyanobacterial blooms, which in turn caused the decomposition of organic matter. This biological activity created micro-environments that favored both phosphogenesis (the formation of phospho-

rite) and the carbonate or silicate precipitation of Fe and Mn precipitated sequentially as the chemistry of ancient oceans shifted. The origin of Paleoproterozoic phosphorite deposits in the Aravalli Basin (Rajasthan/Madhya Pradesh) and the Bijawar Basin (Madhya Pradesh/Uttar Pradesh) represents some of the earliest global phosphogenic events in Earth's history. While both deposits formed around 2.0 to 1.9 Ga, their genetic mechanisms differ significantly: the Aravalli deposits are primarily biogenic (microbial) in origin, whereas the Bijawar deposits are predominantly chemogenic (inorganic) [33]. The area around Burwah though eventually proved uneconomic due to feeble and sporadic occurrences of Manganese, Iron and phosphate mineralisation what is significant here is its pattern and type of mineralisation. As the three commodities are common in the Proterozoic basins associated mineralisation here also the same characteristics is represented.

(a) Phosphorite Mineralization

The phosphorite mineralisation in the study area is expected to be associated with the dolomite and chert rocks (**Figure 11**, **Figure 12**). However, the phosphate values recorded from the dolomite are generally <1% P_2O_5, which indicates that the rock is weekly to almost non-phosphatic as observed in Sadkhera area. Some mildly phosphatic content (>1% to <5% P_2O_5) are also observed in chert, observed in the same channel at Modri location. The algal matter, stromatolites and oncolites occurring in the area are also found to be non-phosphatic (**Figure 13**). Interestingly host lithology for phosphate mineralization here is ferruginous chert. The samples were collected at 1m interval from brick red coloured chert associated with specularite veins, indicated a very restricted extension of mineralized zone in ferruginised chert. The chemical analytical data (**Table 1**) has given the highest values of P_2O_5 for the chert associated with the specularite, suggesting that the phosphate in the Modri area has precipitation of very fine grained apatite with the specular hematite hence it is associated with the iron fillings (**Figure 14**). It is opined that the phosphate iron veins containing specularite fillings within chert are the source of P_2O_5 here.

Table 1. Chemical analytical results (**P_2O_5**) of Channel samples near Modri and Sadkhera village (after Sharma & Balaji, 2014) [60].

S.No	Name	Lithology	P_2O_5
Location 1.5 km south east of Modri village			
1	MDCH-1/1	Bric red ferruginous Chert	2.44
2	MDCH-1/2	Purple Chert with iron fillings (specularite)	24.52
3	MDCH-1/3	Purple Chert with iron fillings	15.29
4	MDCH-1/4	Bric red ferruginous Chert	16.07
5	MDCH-1/5	Bric red ferruginous Chert	9.92
6	MDCH-1/6	Bric red ferruginous Chert	19.95
7	MDCH-1/7	Regolith-Fragments of chert and quartzite	17.62
8	MDCH-1/8	Regolith-Fragments of chert and quartzite	27.77

Continued

9	MDCH-1/9	Regolith-Fragments of chert and quartzite	0.37
10	MDCH-1/10	Regolith-Fragments of chert and quartzite	0.1
11	MDCH-1/W1	Bric red ferruginous Chert with quartz vein	2.71
12	MDCH-1/W2	Bric red ferruginous Chert with quartz vein	6.32
13	MDCH-1/W3	Bric red ferruginous Chert with quartz vein	7.97
14	MDCH-1/W4	Dolomite with oncholites	0.16
15	MDCH-1/W5	Bric red ferruginous Chert	21.57
16	MDCH-1/W6	Cherty fragments with silica brecciation	0.89
	Location 150 m south east of Sadkhera village		
17	SDCH-5/1	Weathered Dolomite	0.10
18	SDCH-5/2	Dolomite	0.07
19	SDCH-5/3	Dolomite	0.08
20	SDCH-5/4	Dolomite	0.08
21	SDCH-5/5	Dolomite	0.09
22	SDCH-5/6	Dolomite	0.10
23	SDCH-5/7	Ochere yellowChert	0.18
24	SDCH-5/8	Ochere yellowChert	0.19
25	SDCH-5/9	Ochere yellowChert	0.17
26	SDCH-5/10	Phyllite	0.23
27	SDCH-5/11	Ochere yellowChert	0.22
28	SDCH-5/12	Ochere yellowChert	0.11
29	SDCH-5/13	Ochere yellowChert	0.14
30	SDCH-5/14	Ochere yellowChert	0.23
31	SDCH-5/15	Ochere yellowChert	0.24
32	SDCH-5/16	Ochere yellowChert	0.10
33	SDCH-5/17	Ochere yellowChert	0.11
34	SDCH-5/18	Ochere yellowChert	0.20
35	SDCH-5/19	Phyllite	0.25
36	SDCH-5/20	Phyllite	0.17
37	SDCH-5/21	Ochere yellowChert	0.18
38	SDCH-5/22	Ochere yellowChert	0.33
39	SDCH-5/23	Ochere yellowChert	0.22

(b) Manganese Mineralization

Old workings of manganese are noticed in the low lying mounds north of

Nandiya (Figure 15, Figure 16) and east of Mohida (Figure 17) at the right bank of the Odhali nala. In the old workings, the manganese ores occur in calc-ferruginous quartzite breccia of the Bijawar Group in the form of small patchy, discontinuous cavity and fracture fillings. The manganese occurs in botryoidal form is psilomelane and pyrolusite with maximum MnO content of 10.92% (Table 2). It is black to dark grey in colour with dull luster and soils the fingers (Figure 16). From the nature of occurrence, it appears that the manganese was originally precipitated from the oceanic water as syn-depositional layer parallel to quartzite and subsequently has been brecciated together during post depositional deformation. The cavity filled and fracture filled component represents the hydrothermal fluid circulation during the waning stage of F 2 deformation. The incidence of manganese is noticed in 1 sq.km area in the form of sporadic old workings in Nandiya area (Figure 16). Besides Nandiya, the manganese quarries were also been noticed along the left bank of Choral River within the ferruginous sandstone of Vindhyans. Four small quarries are found on the southern slopes of hill 222 located about 1Km SSW of Sadkhera. Sporadic fragments of manganese are also recorded from the brecciated chert 500 m west of Jayantimata temple. The manganese and quartz veins intruding the dolomite-chert-shale sequence are found in the River section north of Sadkhera area represents the auto intrusion of quartz manganese combine from the hydro therms generated during the metamorphism and deformation. A bedded sequence of course grained gritty sandstone, shale, cherty shale with cherty phosphate bands and dark gray dolomite is found to be intruded by irregularly distributed and ramifying manganese veins. A thin Manganese band hosted within this dolomite chert sequence is also located from Mohida area, demonstrates presence of a manganese band 40 m in strike length and 3.5 m to 4 m. in thickness deposited parallel to ferruginous Sand stone further supports its precipitation during the sedimentation process in the basin.

Table 2. Chemical analytical results (MnO) of Channel samples at Nandiya area [60].

S. No.	Name	Lithology	MnO
		Location: 1.5km West of Nandiya village	
1.	NDCH-3/1	Ochere yellow chert with Manganese veins	10.08
2.	NDCH-3/2	Ochere yellow chert with Manganese veins	10.92
3.	NDCH-3/3	Ochere yellow chert with Manganese veins	4.86
4.	NDCH-3/4	Ochere yellow chert with Manganese veins	0.52
5.	NDCH-3/5	Ochere yellow chert with Manganese veins	0.20
6.	NDCH-3/6	Ochere yellow chert with Manganese veins	0.33
7.	NDCH-3/7	Ochere yellow chert with Manganese veins	0.32
8.	NDCH-3/8	Ochere yellow chert with Manganese veins	0.16
9.	NDCH-3/9	Ochere yellow chert with Manganese veins	0.44
10.	NDCH-3/10	Ochere yellow chert with Manganese veins	1.86

Continued

	Location: 600m North of Nandiya village.		
1.	NDCH-1/1	Ferruginous chert with manganese	3.05
2.	NDCH-1/2	Ferruginous chert with manganese	3.55
3.	NDCH-1/3	Ferruginous chert with manganese	0.73
4.	NDCH-1/4	Ferruginous chert with manganese	8.80
5.	NDCH-1/5	Ferruginous chert with manganese	7.06
6.	NDCH-1/6	Ferruginous chert with manganese	9.25
7.	NDCH-1/7	Ferruginous chert with manganese	4.05
8.	NDCH-1/8	Ferruginous chert with manganese	0.32
9.	NDCH-1/9	Ferruginous chert with manganese	1.28
10.	NDCH-1/10	Ferruginous chert with manganese	5.04

Iron Mineralization:

Discontinuous bands and lenses of hematite are observed at places within ferruginous quartzite breccia. Some highly ferruginous quartzite breccia also locally contains iron ore. At places, sporadic flaky hematite (specularite) is found within quartzite breccia as very small cavity and fillings (Figure 14). The iron ore bodies do not appear to be economically significant due to their discontinuous nature and small dimensions. One such band has been located just near the contact of cherty band with quartzite SE of Modri. This band is about 8 m in thickness and extends discontinuously for about 75 m but is sandwiched between chert and quartzite. Enechelon hematite filings (tension gashes), occurring within the quartzite in the area as observed along the Modri-Surtipura road section (Figure 18).



Figure 11. Ochre yellow chert bearing Phosphorite—location near Nandiya.



Figure 12. Mildly phosphatic chert, Sadkhera area.



Figure 13. Non-phosphatic stromatolites in Dolomite-Modri.

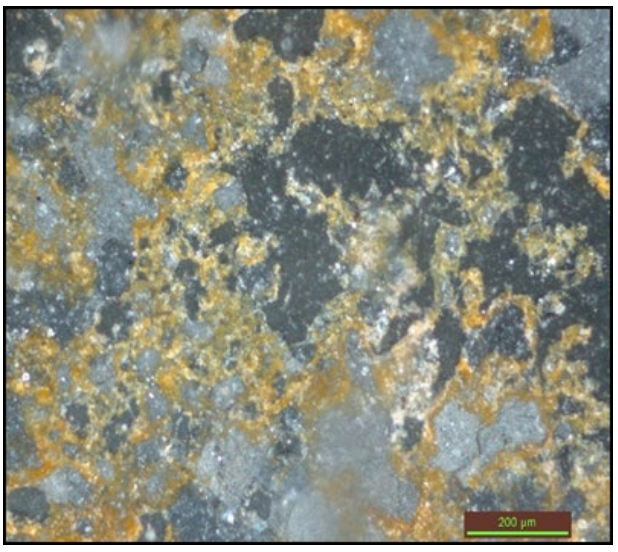


Figure 14. Photomicrograph showing Ferruginous filling in Chert under CPL.



Figure 15. Interlayered Manganese within dolomite, Nandiya.



Figure 16. Massive manganese on the mouth of a rathole quarry in Nandiya.



Figure 17. Chert Manganese band near Mohida.



Figure 18. Tension gash of iron fillings (Hematite) in Quartzite-Modri.

The mineralisation in Bijawar basin main is principally of chemogeneic origin with apatite being the principal mineral and is hosted within the sandstone and cherty rocks besides dolomite. In Hirapura and Sanjoli area the best sections and the richest deposit is found. Here in Barwah-Harda inlier section the depositional enviroment and lithopackage remains the same but only very poor intensity of mineralisation barring few isolated peaks having no continuity or defined zones of Phosphorite calls for a geological reason to explain the absence of mineralisation despite sharing the same spatio-architectural domain. The Harda-Barwah inlier has been designated as time equivalent of Bijawars having the similar lithostratigraphic package.

7. Discussion on Possible Mechanism of Phosphorite Mineralisation of the Study Area

The co-occurrence of phosphorite, manganese, and iron in Paleoproterozoic sediments (like those in the Aravalli and Bijawar basins of India) is primarily driven by global atmospheric oxygenation, unique basin tectonics, and biogeochemical cycling. Proterozoic to early Palaeozoic deposition of iron, manganese and phosphorus in response to the Earth-Life system evolution comprises the geochemistry, and environmental implications of iron (Fe), manganese (Mn), and phosphorus (P) and other trace elemental deposits. These studies require integration of sedimentological, mineralogical, elemental, and isotopic evidence to reconstruct the evolving redox state of ancient oceans and its coupling with global biogeochemical cycles. Contributions reveal that Fe, Mn, and P responded differently to the progressive oxygenation of Earth's surface environments. Iron formation records the onset and intensity of oxidation events in dominantly anoxic oceans. Manganese enrichment marks more strongly oxic conditions in surface waters but also indicates occurrence of local marine anoxia. Phosphorus cycling reflects nutrient feedbacks that regulated primary productivity and dynamic oceanic-atmos-

pheric redox state. The redox sensitivities of Fe, Mn, and P deposits illuminate key transitions in seawater chemistry, climate, and biological evolution through deep time. The importance of integrating field observations, mineralogical analyses, multi-proxy geochemical datasets, and quantitative modelling to better understand the co-evolution of Earth's surface systems during the Precambrian is required.

The phosphorite deposits of the Mardeora area are primarily confined to the Hirapur Formation of the upper Gangau subgroup and occur in the form of brecciated, laminated, and massive phosphorites, which are silica rich. The Hirapur Formation includes ferruginous breccia, shale, and dolomite [38] [61]. On top of that lies the Karri ferruginous Formation, which generally consists of highly ferruginous shale, sandstone, and iron concretionary [38] [62].

Based on the above discussions, it is inferred that the precipitation of phosphorite involves a definite mechanism of upwelling of the nutrients from deep sea by the deep sea currents.

- **Setting**: Formed within a specialized, restricted **epicontinental sea** along the rifted Bundelkhand craton margin.
- **Environment**: Restricted, shallow tidal to intertidal protected waters.
- **Mechanism of Formation (Biogenic/Microbial Origin)**

1) Deep-Ocean Upwelling: Rising oceanic currents brought nutrient- and phosphorus-rich deep waters into the shallow, near-shore environments of the basin.

2) Algal Stromatolite Proliferation: The algal stromatolite proliferation was not present in the Bijawar basin as there are no or rare stromatolites present, indicates deficiency of the development of algal fauna.

3) Chemogenic trapping: The algal matters directly trapped and concentrated the dissolved phosphorus from sea water. This induced the precipitation of microcrystalline carbonate fluorapatite (francolite) within the algal columns. But this is not true for the Bijawar basin here it is chemogenic enrichment through the process of Secondary Enrichment: Post-depositional weathering, diagenesis, and tectonic reworking leached out carbonate minerals, leaving behind highly enriched fragmental and brecciated phosphorite ores.

The absence of algal matter possibly due to shallow nature of the basin in Harda-Burwah inlier had feeble or no upwelling of the nutrients from the deeper parts of the ocean. The isolated basin exposed in terms of inlier south of the main Bijawar basin that is Barwah-Harda inlier demonstrates very shallow thickness of the sediments deposited here being the equivalent of the peripheral Bijawar basin caused restricted deposits of chemogenic sediments and limited post depositional leaching of carbonate leading to non or feeble enrichment in phosphatic component. Further the sediments similar to Bijawar sediments exposed in Harda-Barwah were covered by Deccan trap, there by obstructing these sediments a prolonged leaching responsible for chemogenic and phosphogenic enrichment in oxidants. Both these factors including absence of algal matter supported by occurrence of

Oncolites which are non-algal in nature and presence of no secondary or concretionary deposits of manganese or iron here in the studied area, suggests absence of post depositional leaching of oxidant of the sediments. Hence the field evidences and chemical analysis of Manganese which is rich in silica (Table 3) coupled with absence of algal stromatolites and presence of oncolites, poor phosphatic content and association of phosphatic values with iron, less thickness of the sediments in this part justifiably explain a change in the chemical and biogenic conditions in this part (Barwah Harda inlier) considered equivalent to Bijawar basin responsible for non-accumulation of richer phosphatic deposit, despite sharing the similar geochemical characteristics of the ocean during the Proterozoic eon. This is also supported by phosphate associated restricted iron and manganese precipitation that the global oxygenation process and the fluctuations in the geochemical behaviour of the Proterozoic ocean are faithfully reflected here and are recorded by the present workers in the Burwah-Harda inlier how much ever may the size of the basin.

Key Field Evidences of Ocean Dynamic Shifts

Lithofacies/Feature	Geochemical Sign	Depositional Environment
Phosphorites	High organic matter, suboxic upwelling	Shallow-marine shelf with active photosynthetic microbial mats
Ferruginous Chert Breccia/Jaspers	Influx of dissolved Fe^{2+} oxidized to Fe^{3+}. High SiO_2, volatile hydrothermal additions	Fluctuation from deep stratified basin to oxic shallow interface
Manganese Enriched Beds	Strongly oxidizing seawater	High pH/Eh shallow oxic zone following oxygenation pulses

Table 3. Analysis of Major and Minor Oxides of rock samples of Barwah-Harda Inlier (after Jauhari and Roy, 2021) [45].

Sample No	Name of the rock type	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	LOI
AGR_PCS-01	Chert breccia with calcareous matrix, brown and white quartz, agate	95.19	1.30	0.32	0.46	0.10	0.09	0.13	0.02	0.03	0.03	0.57
AGR_PCS-02	Chert breccia with Mn	11.65	1.44	48.88	7.91	0.38	0.10	0.60	0.08	13.14	0.79	13.59
AGR_PCS-03	Grey basalt with phenocryst of plagioclase feldspar	50.09	15.01	13.11	9.06	4.08	2.72	0.90	2.75	0.32	0.35	1.49
AGR_PCS-04	Fine grained grey coloured compact basalt	48.57	12.81	12.74	9.71	6.08	2.01	0.52	2.48	0.36	0.30	4.33
AGR_PCS-05	Chert breccia with arenaceous and calcareous matrix	87.31	1.14	0.45	5.76	0.13	0.09	0.21	0.05	0.11	0.03	4.48
AGR_PCS-06	Reddish-brown coloured chert breccia	95.25	1.23	0.76	0.28	0.04	0.08	0.15	0.04	0.04	0.06	0.44
AGR_PCS-07	Dolomite with grey bands	6.92	0.34	0.66	30.96	16.69	0.04	0.05	0.04	0.06	0.03	43.04

Continued

AGR_PCS-08	Ferruginised chert breccia with Mn	27.46	3.76	51.85	0.41	0.68	0.09	0.83	0.27	6.94	0.18	6.86
AGR_PCS-09	Mn bearing chert breccia with limonitic capping	38.45	1.55	20.71	12.14	0.29	0.10	0.13	0.11	13.38	0.22	12.57
AGR_PCS-10	Basalt with plagioclase feldspar and clinkery surface	49.63	14.19	14.67	9.25	3.35	2.55	0.74	2.95	0.46	0.31	1.42
AGR_PCS-11	Greyish coloured siliceous dolomite	42.35	0.06	0.42	15.78	13.58	0.01	0.07	0.03	0.02	0.02	27.65
AGR_PCS-12	Ferruginised chert breccia with small clasts of Chert and Mn	87.65	2.77	4.56	0.21	0.31	0.08	0.60	0.08	0.57	0.11	1.30
AGR_PCS-13	Ferruginised chert breccia with Mn mineralisation	74.33	6.12	4.92	0.19	0.47	0.11	1.46	0.17	8.29	0.12	3.67
AGR_PCS-14	Ferruginised chert breccia with Mn mineralisation	45.14	2.74	20.12	13.89	0.20	0.07	0.07	0.16	3.71	0.28	13.03
AGR_PCS-15	Pinkish grey siliceous dolomite	27.68	0.04	0.21	20.68	16.38	0.01	0.03	0.01	0.03	0.01	34.0

8. Conclusion

The Barwah-Harda inlier, though equivalent of Bijawars (but also considered by some workers as south western extension of Bijawar Basin,) demonstrating isolated high phosphatic content lacking continuity, in an otherwise weak to non-mineralised sequence of rocks. This wide variation in phosphatic content in the Bijawar basin and its equivalent sharing same geological and geochemical fluctuations demonstrates that though they are separate basins but the proterozoic epoch had similar oxygenation fluctuations and changing geochemical domains in all equivalent basins also. The supportive field evidences like absence of algal stromatolites, presence of oncolites suggested fluctuating geochemical characters in different basins demonstrates less thickness of sediments as compared to the Bijawar basin around Chhatrapur. This fluctuating geochemical characters being responsible for non-accumulation of significant phosphatic deposit, in the south western possible extension or separate isolated equivalent basin around Barwah-Harda inlier. The sedimentary facies in the Barwah-Harda region capture a crucial transition phase: episodic ocean oxygenation driving chemical precipitation, interrupted by localized upwelling of deeper, reducing, nutrient-loaded waters.

Acknowledgements

The authors wish to thank and acknowledge the authorities of Geological Survey of India and the workers especially, Jauhari, R and Roy, J. who have worked in the Bijawar basin, in particular the Barwah-Harda inlier, thereby identifying the findings and simultaneously giving ample scope for geo-fraternity, researchers in carrying out the research. The authors also acknowledged the contribution made by the concerned officers of different labs, where the requisite lab studies have been carried out.

Author Contributions

Conceptualization, Dr. R.K Sharma and Dr. Biswajeet Lenka; Methodology, Dr.

R.K Sharma; Software, Dr. Biswajeet Lenka; Validation, Dr. R.K Sharma and Balaji.B; Formal analysis, Dr. R.K Sharma and Dr. Biswajeet Lenka; Investigation, Dr. R.K Sharma and Balaji.B; Resources; Data curation, Dr. R.K Sharma; Writing—Dr. R.K Sharma; Writing—review and editing, Dr. Biswajeet Lenka; Visualization, Dr. R.K Sharma, Dr. Biswajeet Lenka and Balaji B; Supervision, Dr. R.K Sharma; Project administration—Dr. R.K Sharma; Funding acquisition, Geological Survey of India. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Bekker, A., Slack, J.F., Planavsky, N., Krapez, B., Hofmann, A., Konhauser, K.O., *et al.* (2010) Iron Formation: The Sedimentary Product of a Complex Interplay among Mantle, Tectonic, Oceanic, and Biospheric Processes. *Economic Geology*, **105**, 467-508. https://doi.org/10.2113/gsecongeo.105.3.467

[2] Jewell, P.W. (2000) Bedded Barite in the Geologic Record. In: *Marine Authigenesis: From Global to Microbial*, SEPM (Society for Sedimentary Geology), 147-161. https://doi.org/10.2110/pec.00.66.0147

[3] Konhauser, K.O., Planavsky, N.J., Hardisty, D.S., Robbins, L.J., Warchola, T.J., Haugaard, R., *et al.* (2017) Iron Formations: A Global Record of Neoarchaean to Palaeoproterozoic Environmental History. *Earth-Science Reviews*, **172**, 140-177. https://doi.org/10.1016/j.earscirev.2017.06.012

[4] Maynard, J.B. (2010) The Chemistry of Manganese Ores through Time: A Signal of Increasing Diversity of Earth-Surface Environments. *Economic Geology*, **105**, 535-552. https://doi.org/10.2113/gsecongeo.105.3.535

[5] Papineau, D. (2010) Global Biogeochemical Changes at Both Ends of the Proterozoic: Insights from Phosphorites. *Astrobiology*, **10**, 165-181. https://doi.org/10.1089/ast.2009.0360

[6] Robbins, L.J., Fakhraee, M., Smith, A.J.B., Bishop, B.A., Swanner, E.D., Peacock, C.L., *et al.* (2023) Manganese Oxides, Earth Surface Oxygenation, and the Rise of Oxygenic Photosynthesis. *Earth-Science Reviews*, **239**, Article 104368. https://doi.org/10.1016/j.earscirev.2023.104368

[7] Algeo, T.J. and Li, C. (2020) Redox Classification and Calibration of Redox Thresholds in Sedimentary Systems. *Geochimica et Cosmochimica Acta*, **287**, 8-26. https://doi.org/10.1016/j.gca.2020.01.055

[8] Bennett, W.W. and Canfield, D.E. (2020) Redox-Sensitive Trace Metals as Paleoredox Proxies: A Review and Analysis of Data from Modern Sediments. *Earth-Science Reviews*, **204**, Article 103175. https://doi.org/10.1016/j.earscirev.2020.103175

[9] Moore, E.K., Jelen, B.I., Giovannelli, D., Raanan, H. and Falkowski, P.G. (2017) Metal Availability and the Expanding Network of Microbial Metabolisms in the Archaean Eon. *Nature Geoscience*, **10**, 629-636. https://doi.org/10.1038/ngeo3006

[10] Canfield, D.E. and Thamdrup, B. (2009) Towards a Consistent Classification Scheme for Geochemical Environments, or, Why We Wish the Term 'Suboxic' Would Go Away. *Geobiology*, **7**, 385-392. https://doi.org/10.1111/j.1472-4669.2009.00214.x

[11] Compton, J., Mallinson, D., Glenn, C.R., Filippelli, G., Föllmi, K., Shields, G., *et al.*

(2000) Variations in the Global Phosphorus Cycle. In: *Marine Authigenesis*: *From Global to Microbial*, SEPM (Society for Sedimentary Geology), 21-33. https://doi.org/10.2110/pec.00.66.0021

[12] Zhao, M.Y., Mills, B.J.W., Poulton, S.W., Wan, B., Xiao, K.Q., Guo, L.C. and Guo, Z.T. (2024) Drivers of the Global Phosphorus Cycle over Geological Time. *Nature Reviews Earth & Environment*, **5**, 873-889. https://doi.org/10.1038/s43017-024-00603-4

[13] Pufahl, P.K. and Groat, L.A. (2017) Sedimentary and Igneous Phosphate Deposits: Formation and Exploration: An Invited Paper. *Economic Geology*, **112**, 483-516. https://doi.org/10.2113/econgeo.112.3.483

[14] Broom-Fendley, S., Siegfried, P.R., Wall, F., O'Neill, M., Brooker, R.A., Fallon, E.K., *et al.* (2021) The Origin and Composition of Carbonatite-Derived Carbonate-Bearing Fluorapatite Deposits. *Mineralium Deposita*, **56**, 863-884. https://doi.org/10.1007/s00126-020-01010-7

[15] Bekker, A., Holland, H.D., Wang, P.L., Rumble, D., Stein, H.J., Hannah, J.L., *et al.* (2004) Dating the Rise of Atmospheric Oxygen. *Nature*, **427**, 117-120. https://doi.org/10.1038/nature02260

[16] Bekker, A., Krapež, B. and Karhu, J.A. (2020) Correlation of the Stratigraphic Cover of the Pilbara and Kaapvaal Cratons Recording the Lead up to Paleoproterozoic Icehouse and the Goe. *Earth-Science Reviews*, **211**, Article 103389. https://doi.org/10.1016/j.earscirev.2020.103389

[17] Och, L.M. and Shields-Zhou, G.A. (2012) The Neoproterozoic Oxygenation Event: Environmental Perturbations and Biogeochemical Cycling. *Earth-Science Reviews*, **110**, 26-57. https://doi.org/10.1016/j.earscirev.2011.09.004

[18] Lyons, T.W., Reinhard, C.T. and Planavsky, N.J. (2014) The Rise of Oxygen in Earth's Early Ocean and Atmosphere. *Nature*, **506**, 307-315. https://doi.org/10.1038/nature13068

[19] Bekker, A., Karhu, J.A., Eriksson, K.A. and Kaufman, A.J. (2003) Chemostratigraphy of Paleoproterozoic Carbonate Successions of the Wyoming Craton: Tectonic Forcing of Biogeochemical Change? *Precambrian Research*, **120**, 279-325. https://doi.org/10.1016/s0301-9268(02)00164-x

[20] Woolley, A.R. and Kjarsgaard, B.A. (2008) Paragenetic Types of Carbonatite as Indicated by the Diversity and Relative Abundances of Associated Silicate Rocks: Evidence from a Global Database. *The Canadian Mineralogist*, **46**, 741-752. https://doi.org/10.3749/canmin.46.4.741

[21] Holland, H.D. (2006) The Oxygenation of the Atmosphere and Oceans. *Philosophical Transactions of the Royal Society B*: *Biological Sciences*, **361**, 903-915. https://doi.org/10.1098/rstb.2006.1838

[22] Bekker, A. and Holland, H.D. (2012) Oxygen Overshoot and Recovery during the Early Paleoproterozoic. *Earth and Planetary Science Letters*, **317**, 295-304. https://doi.org/10.1016/j.epsl.2011.12.012

[23] Indian Bureau of Mines (2024) Apatite and Rock Phosphate. In: *Indian Minerals Yearbook* 2024: *Vol. III. Mineral Reviews* (63rd ed.), Indian Bureau of Mines, 417-426. https://ibm.gov.in/writereaddata/files/177426215469c1178a48453IMYB_2024_EBookFinal.pdf

[24] Choudhuri, R. (1990) Two Decades of Phosphorite Investigations in India. *Geological Society*, *London*, *Special Publications*, **52**, 305-311. https://doi.org/10.1144/gsl.sp.1990.052.01.22

[25] Banerjee, D.M. (1971) Precambrian Stromatolitic Phosphorites of Udaipur, Rajasthan, India. *Geological Society of America Bulletin*, **82**, 2319-2330. https://doi.org/10.1130/0016-7606(1971)82[2319:pspour]2.0.co;2

[26] Banerjee, D.M., Schidlowski, M. and Arneth, J.D. (1986) Genesis of Upper Proterozoic-Cambrian Phosphorite Deposits of India: Isotopic Inferences from Carbonate Fluorapatite, Carbonate and Organic Carbon. *Precambrian Research*, **33**, 239-253. https://doi.org/10.1016/0301-9268(86)90024-0

[27] Banerjee, D.M., Basu, P.C. and Srivastava, N. (1980) Petrology, Mineralogy, Geochemistry, and Origin of the Precambrian Aravallian Phosphorite Deposits of Udaipur and Jhabua, India. *Economic Geology*, **75**, 1181-1199. https://doi.org/10.2113/gsecongeo.75.8.1181

[28] Khan, H.H., Ghosh, D.B., Soni, M.K., Sonakia, A. and Zafar, M. (1989) Phosphorite Deposits of the Jhabua District, Madhya Pradesh, India. Geological Survey of India.

[29] Pant, A. (1980) Resource Status of Rock Phosphate Deposits in India and Areas of Future Potential. Geological Survey of India.

[30] Choudhuri, R., Roy, A.B., Cook, P.J. and Shergold, J.H. (1986) Proterozoic and Cambrian Phosphorites Deposits: Jhamarkotra, Rajasthan, India. In: *Proterozoic and Cambrian Phosphorite*, Cambridge University Press, 209-210.

[31] Sant, V.N. (1980) Geology of the Indian Platform and Its Phosphate Occurrences. Geological Survey of India.

[32] Chauhan, D.S. and Sisodia, M.S. (1989) Phosphorites of Rajasthan. *Memoirs of the Geological Survey of India*, **13**, 9-23.

[33] Dar, S.A., Khan, K.F., Mir, A.R., Komiya, T., Absar, N., Shuaib, M., *et al.* (2025) Geochemical and C-O Isotopic Study of ~2-1.9 Ga Phosphate-Bearing Marine Sedimentary Rocks of the Sonrai Formation, Bijawar Group, Lalitpur District, up, India: Implications for Paleoredox, Paleoclimate, and Paleosalinity. *Geosystems and Geoenvironment*, **4**, Article 100324. https://doi.org/10.1016/j.geogeo.2024.100324

[34] Mazumder, R. and Eriksson, P.G. (2015) Precambrian Basins of India: Stratigraphic and Tectonic Context, Chapter 5. Geological Society.

[35] Chakraborty, P.P., Dey, S. and Mohanty, S.P. (2010) Proterozoic Platform Sequences of Peninsular India: Implications towards Basin Evolution and Supercontinent Assembly. *Journal of Asian Earth Sciences*, **39**, 589-607. https://doi.org/10.1016/j.jseaes.2010.04.030

[36] Meert, J.G., Pandit, M.K., Pradhan, V.R., Banks, J., Sirianni, R., Stroud, M., *et al.* (2010) Precambrian Crustal Evolution of Peninsular India: A 3.0 Billion Year Odyssey. *Journal of Asian Earth Sciences*, **39**, 483-515. https://doi.org/10.1016/j.jseaes.2010.04.026

[37] Medlicott, H.B. (1859) On the Vindhyan Rocks, and Their Associates in Bundelkhand. *Memoirs of the Geological Survey of India*, **2**, 1-95.

[38] Kumar, B., Srivastava, R.K., Jha, D.K., Pant, N.C. and Bhandaru, B.K. (1990) A Revised Stratigraphy of the Rocks of Type Area of the Bijawar Group in Central India. *Indian Minerals*, **44**, 303-314.

[39] Roy, M., Rawat, T.P.S., Bhairam, C.L. and Parihar, P.S. (2014) Diverse Mode of Phosphatic Rocks in the Environs of Proterozoic Bijawar and Sonrai Basins and Its Relevance to Uranium Mineralisation—A Case Study from Central India. *Journal of the Geological Society of India*, **83**, 259-272. https://doi.org/10.1007/s12594-014-0038-x

[40] Bose, P.N. (1884) Geology of Lower Narbada Valley between Nimawar and Kawant. *Memoirs of the Geological Survey of India*, **21**, 1-72.

[41] Haldar, D. and Ghosh, R.N. (2000) Eruption of Bijawar Lava: An Example of Precambrian Volcanicity under Stable Cratonic Conditions. In: *Precambrian Crust in Eastern and Central India*, Geological Survey of India, Hyderabad, Special Publications, 151-170.

[42] Rasmussen, B., Bose, P.K., Sarkar, S., Banerjee, S., Fletcher, I.R. and McNaughton, N.J. (2002) 1.6 Ga U-Pb Zircon Age for the Chorhat Sandstone, Lower Vindhyan, India: Possible Implications for Early Evolution of Animals. *Geology*, **30**, 103-106. https://doi.org/10.1130/0091-7613(2002)030<0103:gupzaf>2.0.co;2

[43] Sarangi, S., Gopalan, K. and Kumar, S. (2004) Pb-Pb Age of Earliest Megascopic, Eukaryotic Alga Bearing Rohtas Formation, Vindhyan Supergroup, India: Implications for Precambrian Atmospheric Oxygen Evolution. *Precambrian Research*, **132**, 107-121. https://doi.org/10.1016/j.precamres.2004.02.006

[44] Khalkho, R. and Trivedi, R.K. (2022) Paleoenvironmental Studies of Bijawar Group of Rocks around Hirapur, Sagar Distirct, Madhya Pradesh. *International Journal of Science and Research*, **11**, 743-750. https://doi.org/10.21275/sr22810213009

[45] Jauhari, R and Roy, J. (2021) Report on Reconnaissance Survey for Manganese Mineralisation in Nandiya-Agarwara-Narsingpur-Jethwai Area, Khargone District, Madhya Pradesh (Stage-G4).

[46] Pascoe, E.H. (1959) A Manual of the Geology of India and Burma. 3rd Edition, Geological Survey of India.

[47] Krishnan, M.S. (1982) Geology of India and Burma. CBS Publishers & Distributors Pvt Ltd.

[48] Kale, V.S. (1989) Stratigraphic and Environmental Significance of Riphean (Bijawar) Stromatolites from Central Narmada Valley. In: Valdiya, K.S. and Tewari, V.C., *Stromatolites and Stromatolitic Deposits*, 63-74.

[49] Dutta, N.P., Mohan Rao, T., De, S. and Singh. R.B. (1981) Geophysical Investigation for Basemetal in Joga, Hoshangabad District, M.P. G.S.I. Sp. Publication No. 3, pp. 269/271.

[50] Verma, K.K., Udhoji, S.C. and Gupta, S. (1990) Stromatolite Based Biostratigraphy, Sedimentary History, Palaeo-Environment, Correlation and Age of Bijawar Group (up. Proterozoic) of Joga Area, Hoshangabad (M.P.) with Special Reference to Basemetal Mineralisation—Pre-Cambrian of Central India. Geological Survey of India Special Publication No. 28.

[51] Pal, A.K., Mishra, M.N. and Chhatri, K.K. (2004) First Report of Early Proterozoic Microfossils from the Bijawar Group of Rocks in Harda District, Madhya Pradesh. *Journal of the Geological Society of India*, **63**, 540-544. https://doi.org/10.17491/jgsi/2004/630509

[52] Blanford, W.T. (1869) On the Geology of the Taptee and Lower Nerbudda Valley and Some Adjoining Districts. *Memoirs of the Geological Survey of India*, **6**, 163-207.

[53] Blanford, W.T. and Wynne, A.B. (1869) On the Geology of the Tapti Narmada Valleys and Some Adjoining Districts. In: *Memoirs of the Geological Survey of India*, *Vol VI*, *Part* 3, Geological Survey of India.

[54] Roy Chowdhury, M.K. and Sastri, V.V. (1954) Of the Geology of the Barwah-Katkut Area of Narmada Valley, Nimar District, Madhya Bharat. *Records of the Geological Survey of India*, **85**, 523-556.

[55] Shrivastava, S.K. (1959-60) Systematic Mapping in Parts of Dewar and Khargone District.

[56] Munshi M.M. and Nair, K.K.K. (1975) Geology of the Katkut Kanargarh Area, Khar-

gone and Dewar Districts.

[57] Nair, K.K.K. (1975) Geology of Punasa-Kotwa Area, Khandwa District.

[58] Jain, S.C. and Shrivastava M.P. (1986) Reconnaissance for Phosphorite in Parts of Barwah-Harda Basin.

[59] Dhar, N. (1989) Report on Large Scale Systematic Geological Mapping and Assessment of Mineral Potentiality in the Western Part of Barwah-Harda Inlier, Khargone and Khandwa District.

[60] Sharma, R.K. and Balaji, B. (2014) Report on Prospecting for Phosphorite Mineralization in Western Part of Harda Inlier by Delineation of Phosphatic Bands in Parts of Modri, Sadkhera and Surrounding Area, Khargone District, Madhya Pradesh. (G4 Stage).

[61] Banerjee, D.M., Khan, M.W.Y., Srivastava, N. and Saigal, G.C. (1982) Precambrian Phosphorites in the Bijawar Rocks of Hirapur-Bassia Areas, Sagar District, Madhya Pradesh, India. *Mineralium Deposita*, **17**, 349-362. https://doi.org/10.1007/bf00204465

[62] Javed, M., Dar, S.A. and Balaram, V. (2026) Tracing Rare Earth Elements Distribution and Enrichment Mechanism in Phosphorites of the Paleoproterozoic Bijawar Group in Mardeora Mine, Chattarpur District, Madhya Pradesh (M.P.), India. *Journal of Asian Earth Sciences*: *X*, **15**, Article 100214. https://doi.org/10.1016/j.jaesx.2026.100214