Prospect of studying Bijaigarh Black Shale, Vindhyan Supergroup, and its implication for Mesoproterozoic oxygenation

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Abstract

This paper reviews the studies of Bijaigarh Shale in the wake of improved trace element and sulphur isotope tools as a potential avenue for the hitherto unknown oxygen fluctuations during Mesoproterozoic Era. Black shale is traditionally known as an indicator for the anaerobic environment. However, the source for high organic remains in the black shales suggests a high primary production pathway which is most likely oxygen-producing photosynthesis. That means atmospheric carbon would have been sequestered in aerobic condition. Mesoproterozoic Era (1600-1000Ma) also has many black shale strata, and it is traditionally accepted that the Mesoproterozoic ocean was sulphidic and anaerobic in nature which retarded the biological evolution for a long time and delayed augmentation of metazoa. However, with improved understanding of trace elements and sulphur isotope analysis very recently Mukherjee and Large (2016) demonstrated a fluctuation in oxygen condition during Mesoproterozoic Era.

Keywords: Black Shale; Palaeoredox; Photosynthesis; Mesoproterozoic Era.

1 Introduction

According to most evidence, Earth's oceans oxygenation started before Greater Oxidation Event (GOE) during early Palaeoproterozoic (∼2.4 Ga) (Holland, 2002) and achieved oxidised deep-ocean after Snowball / Slushball event during the Ediacaran Period (∼635 to ∼541 Ma) (Lenton et al., 2014). This evolution of the ocean-atmosphere system was accompanied by the most enigmatic changes in the development of Earth's biosphere. Sulphur isotopes and iron speciation data of Palaeoproterozoic to Early Neoproterozoic suggest a highly heterogeneous redox structure of the marine environment (Canfield et al., 2008; Johnston et al., 2010; Poulton and Canfield, 2011; Reinhard et al., 2013; Sperling et al., 2014). Mesoproterozoic marine environment persistently had anoxic-ferruginous water restricted between shallow and deep marine environment that would have resulted in a seriously confined zone of liveability for early eukaryotes (Gilleaudeau and Kah, 2015). Abundant, diverse fossils with complex morphological features have been reported from restricted nearshore Mesoproterozoic successions and suggested as eukaryotes (Buick and Knoll, 1999; Javaux et al., 2001; Sharma, 2006; Singh and Sharma, 2014). But, this theory is not supported by molecular studies (Blumenberg et al., 2012; Brocks et al., 2005; Planavsky et al., 2014). Hence, patchy and spatially limited fossil records from Mesoproterozoic successions were apparently driven by onshore-offshore redox variations. Recently, two contradictory models of Mesoproterozoic Earth's climate have been proposed: 1. The Mesoproterozoic climate had low oxygen concentration that caused a morphological stasis (Planavsky et al., 2014); 2. a significant rise in oxygen concentration during Late Mesoproterozoic (Mukherjee and Large, 2016). It points an emerging need for more comprehensive detailed studies on the redox structure reconstruction of Mesoproterozoic Era and has a significant implication for biological evolution that occurred during this and in the later period of the Earth's history. While past studies have concentrated on the Proterozoic time of massive iron-rich sediment deposition, the Cr isotope data from the Proterozoic sedimentary rocks of China, Australia, and North America have proposed a severe oxygen depletion (0.1% of present atmospheric level) condition for Mesoproterozoic Era (Planavsky et al., 2014). According to Cole et al. (2016), Cr isotope data support the perseverance of an Earth framework in which climatic oxygen concentration would have been sufficiently low to hinder the diversification of animals until 0.8 Ga. Furthermore, a high-resolution U study also indicated a less oxic Mesoproterozoic Earth (Partin et al., 2013). However, contrary to previous evidence they demonstrated major fluctuation in surface oxygen level between GOE (∼2.4 Ga) and Neoproterozoic (∼0.8 Ga) oxidation. The Cr isotope study has also been conducted on Mesoproterozoic carbonate successions of El Mreiti Group of Mauritania, West Africa and Vazante Group of Brazil that shows oxygen concentration jumped back above threshold value around 1.1 Ga. That was sufficient to induce biochemical changes in animal evolution much before Neoproterozoic augments (Gilleaudeau et al., 2016). It is contrary to the other Cr isotope study from Mesoproterozoic (Cole et al., 2016). Sulphur isotope study supports the rise in oxygen concentrations, as an exhaustive database demonstrates a substantial extreme change in the fractionation of bacterial sulphate reduction i.e. sulphate to the sulphide of S = 25% before 1 Ga to ≥ 50% after 0.64 Ga. This large fractionation is interpreted as the multistep process in which reduction is also accompanied by oxidation of intermediate sulphur product. In the sulphur cycle, this process is known as disproportionation. Parnell et al.
(2010) recorded $\Delta^{34}S \approx 50\%$ from terrestrial Middle Mesoproterozoic outcrop that supports the presence of oxygen utilising bacteria. Sedimentary black shale is often considered as a suitable site to study prehistoric organic preservation and associated oxygen minimum events. A recent advance in methodology for the separation and analyses of sulphides and sulphates has greatly improved the reconstruction of the secular trend in trace elements (micronutrient) and changing oxygen condition of Precambrian ocean and atmosphere. Therefore, bulk rock chemistry coupled with pyrite in the carbonaceous mudstone provides a novel approach to deciphering basin water conditions of that time (Mukherjee and Large, 2016). Using this approach, they demonstrated that the black shales of a Mesoproterozoic age were deposited in varying geochemical settings. The supply of trace metals (R Cd, Mo, Se, Ni, U, and V) and nutrients in a marine basin are controlled by oxygen availability for terrestrial weathering reactions (Large et al., 2015). That increases the productivity hence more TOC (total organic carbon) in the depositional matter. High TOC is thought to favour the bacterial sulphide production during organic matter degradation (Berner, 1970; Raiswell and Berner, 1985). Furthermore, depositing organic matter traps / adsorbs the trace metal P, Cd, Mo, Se, Ni, U and V therefore, their occurrence in organic-rich shale and associated pyrite is common (Mukherjee and Large, 2016). This study offers an evaluation of 1210 Ma old Bijaigarh Shale (Tripathy and Singh, 2015) of Vindhyan Basin respectively that will impart to understanding the Mesoproterozoic fluctuation of atmospheric oxygen. Thereupon biotic evolution influenced by changes in oxygen level and other biogeochemical parameters in the Mesoproterozoic Vindhyan Basin. Bijaigarh Shale was deposited during global sea level rise (Singh, 1980). Detailed study of sedimentary structures and lithology reveals that the successions are divisible into three major units, the oldest unit is composed of shale with sandstone layers of lagoonal edge environment. Middle unit is mostly composed of black shale locally rich with pyrite of lagoonal pond environment, and the youngest unit is similar to the oldest one. Very little attention has been paid on Mesoproterozoic successions of India. Due to this reason, there is a huge scope on producing redox and other related data from Indian counterparts and compare them with the available global dataset to reconstruct the history of redox changes and biological evolution in this part of the world. The sedimentary environment of Mesoproterozoic Vindhyan basin (Singh, 1980), Chattisgarh basin (Patranabis-Deb et al., 2016), Lesser Himalaya (Ghosh et al., 2016), Kaladgi Bhima Basin (Dey, 2015), Pranhita Godavari Basin (Amarasinghe et al., 2015) has been adequately described. However, their geochemical characterisation is rather poor (low resolution). Most of these studies were focussed on weathering-derived sedimentation or in other words source of sediments during Mesoproterozoic deposition e.g. (Mishra and Sen, 2010, 2011; Rashid, 2002). In a remarkable advance, more recently Tripathy and Singh (2015) used Re-Os dating to date Bijaigarh shale and (Saha et al., 2016) used U-Pb SHRIMP dating to date Ampani basin in Eastern India. In India, redox study of Mesoproterozoic sedimentary rocks is still in early stage. Therefore such study must be undertaken to contribute to ongoing debate upon Mesoproterozoic atmospheric oxygen composition.

2 Sedimentology and Palaeoenvironment of Bijaigarh Shale

Stromatolites and many algal forms have been reported from Bijaigarh Shale as in another part of Vindhyian Basin. These biological forms are used for correlating the sequences from different regions. Bijaigarh Shale is the only formation in the Kaimur Group (Figure 1) that has been reported for the occurrence of stromatolites (Mathur, 1981). However, no description of these stromatolites has been provided by the Schnitzer (1971). The palaeontological and sedimentological studies of Kaimur Group have indicated palaeoenvironmental changes limited to shallow to the moderately deep continental shelf, and tidal mudflats to the sulphidic depositional environment (Gupta et al., 2003). These studies also suggest that sea level during depositional period kept fluctuating probably due to the tectonic activities uplifting southern marginal part of Vindhyan Basin. The association of sedimentary history and tectonism can be demonstrated by cyclic sedimentation of Kaimur and Semri groups in Chopan region in Sonbhadra district, UP. Arangi Formation of Semri Group composed of clasts, greenish grey siltstones and fine sandstone with profused ripple marks and Flaser bedding indicates the typical tidal depositional environment (Singh, 1973). Whereas, thin paper like black carbonaceous with porcellanite and pyritic black shales indicates a back shore tidal flat to the lagoonal environment. Orange Shales are overlain by 600-800 m thick sequence of chemogenic sediments belonging to Kajrahat Limestone which is composed of a thick bed of dolomiticrete, argillaceous limestone with interbedded lenticle of shales and siltstones that represent the first cycle of sedimentation (Gupta et al., 2003). Stromatolites were developed during the terminal phase of carbonate deposition with shallowing upward cycle of sedimentation. In this unit Colonella columnaris, Omechetonia sp, Conophyton gargarusic, and ripple like forms Platella sp, etc. have been recorded (Gupta et al., 2003). Khenjua Shales are finely laminated which are greenish grey, olive grey, and dark in colour. The presence of glauconite and fine varve-like laminated structure of shale indicates warm and moderately deep to calm offshore deposition environment. Although Paleoproterozoic to Mesoproterozoic sediments bed is considered very less deformed, therefore is suitable for microbial mat studies in shales (Banerjee and Schieber, 2003; Banerjee and Jeekankumar, 2005; Sarkar et al., 2005; Sur et al., 2006). The Rampur and Bijaigarh Shales are a part of Kaimur and Semri groups respectively. Rewa and Bhandar groups compose the upper part of Vindhyan Basin. Sur et al. (2006) exclusively study lower Rampur and Bijaigarh Shales of lower Vindhyan. The deposition
of these two Shale Formations was possibly taken place below fair weather wave base (Bose et al., 2001). Rampur Shale overlying the Khenjua Formation is around 70 m thick and contains 80% black shale layers interlaminated with carbonates beds (Singh, 1980). The proportion of black shale decreases upwards as it grades into Rohtas Limestone. Bijaigarh Shale is 60-70 m thick and has been divided into lower micaceous and fissile bed containing a smaller amount of pyrite about upper shale (Singh, 1980). The frequency of sandstone bed decreases towards the top. The upper and lower Bijaigarh Shale is divided by a bed of pyrite that ranges in thickness from 5 cm to 1.1 m (Nair and Ray, 1977). Thin section studies have shown that unlike Phanerozoic Shales, that is typical quite and parallel, Rampur, and Bijaigarh Shale have wavy, crinkly lamination of clayey carbonaceous facies (Sur et al., 2006). This suggests an active mode of sedimentation for Rampur and Bijaigarh Shales (Schieber, 1986). Wavy and crinkly deposition are often found associated with microbial mats both in ancient and modern deposits (Gerdes and Krumbein, 1997; Horodyski et al., 1977; Krumbein and Cohen, 1977; Schieber, 1986) Bijaigarh Shale demonstrates an anoxic depositional environment with abundant biological productivity evidenced by an abundance of carbonaceous pyrite (Guha 1971). Also 0.78 m, thick pyrite rich ore body horizontally spread over an area of about 2.1 km². This ore body can be divided into two types the primary type is cryptocrystalline comprised of spheres and idiomorphic crystals and the minor disseminated type comprised of the dense agglomeration of framboidal and distributed euhedral grain of pyrites with the diameter ranging 100 to 600 (Pandalai et al., 1991; Pandalai et al., 1983). The layer above the ore body encompasses minute pyrite rich laminae whereas the layer below ore body contains some disseminated pyrite. Galena has also been recovered from upper contact of the Bijaigarh Shale (Deb and Pal, 2015). This occurs above 6-10 m above the pyrite horizon, in a transitional zone of siltstone and argillaceous sandstone. Kaimur Group has mainly composed of siliciclastic deposits, and their geochemical evidence suggests their strong weathering, tectonic and depositional environment of Mesoproterozoic Era (Mishra and Sen, 2012). The Kaimur Group is deposited unconformably over slightly eroded and tilted Rohtas Limestone of Semri Group and has a thickness up to 400 m. The outcrop of Semri and Kaimur groups is exposed in the Son Valley region surrounded by Bundelkhand Granitic Complex (BGC) in the North, and by Chotanagpur Gneissic Complex and Mahakashal Group in the south.

### 3 Sediment Origin and Palaeoredox condition

Relatively high concentration in scarp Fe₂O₃ (0.8 to 5% weight) in Bijaigarh Shale suggest the presence of Ferruginous cement (Mishra and Sen, 2011, 2012). Their study demonstrated excess concentration of REE 3.2 fold of Zr, 4.2 fold Y, 3 fold HF and 8.3 fold Nb and 7.4 fold Ti concentration in comparison to Dhandraul Sandstone of Kaimur Group. There is a positive correlation between Zr and HF (r = 0.7). However, the Zr/HF ratio value ≈ 40.7 is found similar to Dhandraul Sandstone (Zr/HF ratio = 39.2). Overall the behaviours of the trace elements are similar to that of major elements because of quartz dilution from Dhandraul Sandstone to Bijaigarh Shale. As Zr/HF ratio for PAAS (Post Archean Average Australian Shale) and average Granite is 42 and 34 respectively, the shale could have been derived from weathering of these individuals or mixture (Mishra and Sen, 2012). A gradual decrease in ΣREE has been recorded from Bijaigarh Shale and Scarp Sandstone to Dhandraul Sandstone though the pattern is identical. The ΣREE abundance of Bijaigarh Shale is equivalent to PAAS. The Bijaigarh Shale shows REE fractionation with [La/Yb]=7.4 and [Gd/Yb]=1.27. Eu/Eu* (0.64) is like PAAS(0.66). The Chemical Alteration Index (CIA) of Bijaigarh Shale, Scarp Sandstone, Dhandraul Sandstone ranges from 72 to 88. This is an indication of moderate to high level of chemical weathering for an extended period in hot and humid climate for the shorter period. The close CIA value of the three depositional type indicates a recycling process among sandstone and shale (Mishra and Sen, 2012). The ferruginous nature of this shale implies that the Fe on terrestrial flowpath was in the mobile stage that is Fe₂⁺. After Fe₂⁺ disposal the ocean through aquatic inflow the local or global environment must have experienced an oxygenation of environments that led to the oxidation of Fe₂⁺ to Fe₃⁺ which is insoluble in the marine system and would have been precipitated to the ocean bottom (Figure 2). Among the three black shales containing units are Kajrahat Shale, Rampur Shale, and Bijaigarh Shale. In which Kajrahat Shale has strong evidence of microbial mats presence that includes features like folded, twisted, rolled up carbonaceous remains and the presence cohesive carbonaceous films (Schieber et al., 2007). They suggested that this consist nature is not likely an attribute of deposited mixture of clays and small organic particles but, is a result of microbial surface binding. The laminae of these Shales also contain strong similarities with the wavy crinkly laminae observed in other places of Proterozoic carbonaceous shale that have been studied in some depth for microbial mat feature (Schieber, 1986). In Rampur Shale, a thin layer (10 mm) of grey coloured with irregular shaped carbonaceous matter are found (Schieber et al., 2007). In these organic remains, cohesiveness plays a key feature to differentiate from abiotic materials. According to Dayal et al. (2014), the organic remains of the Bijaigarh Shale varies from 0.04% to 1.43% which considerably high and must have been derived from a photosynthetic autotrophic activity. Blumberg et al. (2012) identified oxidising condition with the occurrence of gypsum deposits associated coeval to the Mesoproterozoic black shale. This also suggests a regression in oceanic water and dry condition during the anaerobic phase that would have increased the nutrient concentration resulting into higher primary productivity (Figure 2). In this way, ocean transgression and regression cycle might have a close association with the Mesopro-
terozoic oxygen fluctuations. However, according to basic understanding, the black shale may infer an anoxic depositional environment but, the source environment of high organic content in such shale must rely upon the more efficient pathway of organic production which is photosynthesis. In other words, black shale would have been related better oxygen condition. Therefore during the deposition of black shale ocean surface environment must have been aerobic that supplied high organic content to the below photic zone which would have been anaerobic (Figure 2).

4 Conclusion

Palaeoredox studies of such Mesoproterozoic Black Shale thus provide a promising avenue to study anomalous enrichment of organic content and associated environment and its association with the variation in oxygen condition. Therefore Palaeoredox reconstruction of would reveal hitherto unknown oxygen fluctuations yet to know and their probable role in the evolution of dur-

gen condition. Therefore Palaeoredox reconstruction of such Mesoproterozoic Era. Such studies black shale is much needed to reconsider the traditional belief that the Mesoproterozoic Era had persistently low oxygen environment with little biological oxidation.

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References


Banerjee, S., Jeevankumar, S., 2005. Microbially orig-


Deb, M., Pal, T., 2015. Mineral potential of Protero-


Horodyski, R.J., Bloezer, B., Haar, S.V., 1977. Lami-
nated algal mats from a coastal lagoon, Laguna Mormona, Baja California, Mexico. Journal of Sedimentary Research 47.


Schieber, J., 1986. The possible role of benthic microbial mats during the formation of carbonaceous shales in shallow Mid-Proterozoic basins. Sedimentology 33, 521-536.


Sharma, M., 2006. Late Palaeoproterozoic (Statherian) carbonaceous films from the Olive Shale (Koldaha Shale), Semri Group, Vindhyan Supergroup, India. J. Palaeontol. Soc. India 51, 27-35.


a lagoonal deposit. Sedimentary Geology 25, 83-103.
Singh, V.K., Sharma, M., 2014. morphologically com-
plexed organic-walled microfossils(owm) from
the late palaeoproterozoic-early mesoproterozoic
chitrakut formation, vindhyan supergroup, cen-
tral india and their implications on the antiquity
of eukaryotes. Journal of the palaeontological
society of India 59, 89-102.
Sperling, E.A., Rooney, A.D., Hays, L., Sergeev, V.N.,
Vorob’eva, N.G., Sergeeva, N.D., Selby, D., John-
ston, D.T., Knoll, A.H., 2014. Redox heterogeneity
of subsurface waters in the Mesoproterozoic
ocean. Geobiology 12, 373-386.
observations suggestive of microbial mats from
Rampur Shale and Bijaigarh Shale, Vindhyan
basin, India. Journal of earth system science 115, 61.
age for black shales from the Kaimur Group,
Upper Vindhyan, India. Chemical Geology 413, 63-72.