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Origin and Evolution of the Vindhyan Basin: A Geochemical Perspective

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The Indian Peninsula hosts several Proterozoic sedimentary basins, popularly known as the Purana basins. The Vindhyan Basin of central India, comprising ~5 km thick sediment pile, is the largest among the Purana basins. The sedimentary units comprise mostly of undeformed and unmetamorphosed siliciclastic and carbonate rocks. With an initiation age of late Paleoproterozoic, the sedimentation in the Vindhyan Basin continued up to late Mesoproterozoic to early Neoproterozoic. The undeformed and unmetamorphosed nature of the sediments with a prolonged extent of sedimentation makes the Vindhyan Basin an excellent archive for geochemical and isotopic studies. The present study provides an overview of the existing geochemical, geochronological and isotopic data for the sedimentary and volcanic rocks exposed in the Vindhyan Basin and their implications in terms of basin evolution as well as global events.

Keywords: Vindhyan Basin; Geochemistry; Provenance and Tectonic Evolution; Chemostratigraphy; Paleoclimate

Introduction

The Archean-Proterozoic transition is marked by globally synchronous changes in tectono-thermal and climatic patterns. The tectono-thermal changes are broadly related to cooling of the mantle and extraction of the continental crust followed by stabilization of major cratons around 2.7-2.5 Ga (Condie and O'Neill, 2010). Cooling of the mantle is reflected by decrease in komatiite abundance and its MgO content, as well as decrease in Ni/Fe ratio (Konhauser *et al.*, 2017) and Eu/Eu* (Viehmann *et al.*, 2015) in Banded Iron Formations. Peak in Re depletion age in mantle xenoliths around 2.7 Ga suggest thickening of the continental lithosphere (Irvine *et al.*, 2001; Carlson, 2005). In addition to this, increase in Nb/Th and $\epsilon_{\text{Nd}(t)}$ in non-arc derived basalts are consistent with extraction of continental crust from the mantle. From a climatic aspect, a major oxygenation event, popularly known as the Great Oxidation Event (GOE) occurred during Paleoproterozoic around ~2.3 Ga (c.f., Holland, 2006) which substantially modified the biogeochemical cycles and is a crucial step towards development of a complex eukaryote dominated biosystem (Lyons *et al.*, 2014). The Archean-Proterozoic transition also recorded development of widespread epicontinental

seas with aerially extensive shelf sedimentation in the stable cratons (Eriksson, 1995). Globally, the Proterozoic sedimentation sites include the Kaapvaal Province, the Superior Province, the Pilbara Craton, the Baltic Shield, and the Indian Shield.

Starting from the Paleoproterozoic, the Indian Shield evidenced development of large-scale sedimentary basins, popularly known as Purana basins. Sedimentation in the Cuddapah Basin, which is the oldest among the Puranas, started around 1.9 Ga ago (Anand, 2003; French and Heaman, 2010; Vadlamani *et al.*, 2014) while the youngest Marwar Basin closed around 0.54 Ga ago, the latter estimate being constrained by U-Pb ages of detrital zircons (McKenzie *et al.*, 2011). The opening and closure of the different Purana basins are considered to be related to the amalgamation and fragmentation of Proterozoic supercontinents Columbia and Rodinia (Basu and Bickford, 2015). The Vindhyan Basin, with an aerial extent of 178,000 Km² (Tandon *et al.*, 1991), is the largest among the Purana basins of India (Chakraborty, 2006; Chakraborty *et al.*, 2012). Globally, the Vindhyan Basin is the second largest Proterozoic sedimentary basin (Chakraborty, 2006; Chakraborty *et al.*, 2012) comprising mostly

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undeformed and unmetamorphosed sequences of siliciclastic and carbonate rocks. Pb-Pb age dating of carbonates from the basal Kajrahat Formation suggests initiation of sedimentation in this basin 1729 ± 110 Ma ago (Sarangi *et al.*, 2004) while Pb-Pb ages of carbonates from Bhander Formation of the Upper Vindhyan suggest closure of the basin around 900 Ma ago (Gopalan *et al.*, 2013). However, presence of Bitter Springs $\delta^{13}\text{C}$ anomaly (George *et al.*, 2018) and the 866 ± 180 Ma Pb-Pb age of the Balwan Limestone in the Rajasthan sector (Gopalan *et al.*, 2013) suggest a younger Tonian closure age which is consistent with trace fossil studies (Chakrabarti, 1990). With an archive of approximately one billion years of sedimentation history starting from ~ 1.8 Ga ago, the Vindhyan Basin has the potential to record tectono-thermal and climatic changes during late Paleoproterozoic to early Neoproterozoic. The Vindhyan Basin has been studied thoroughly in terms of its geophysical, sedimentological, and palaeontological evolution (c.f., Adnan *et al.*, 2015; Banerjee, 2000; Banerjee and Banerjee, 2010; Banerjee and Chopra, 1986; Banerjee and Jeevan Kumar, 2007; Banerjee *et al.*, 2014; Bengtson *et al.*, 2009; Bose *et al.*, 2001, 2015; Chakraborty, 2004, 2011; Kumar, 2016; Mishra, 2011, 2015; Prasad and Asher, 2016; Prasad and Rao, 2006; Sarkar *et al.*, 2004; Samanta *et al.*, 2016; Seilacher, 1998; Sur *et al.*, 2006; Verma and Shukla, 2015) while geochemical and isotopic studies have tried to address sediment provenance, tectonic evolution and sub-basin connectivity (c.f., Kumar *et al.*, 2002; Ray *et al.*, 2003; Chakrabarti *et al.*, 2007; Shukla *et al.*, 2019). This article reviews our current understanding of the origin and evolution of the Vindhyan Basin, primarily from a geochemical perspective, and its relation to Proterozoic events globally.

Geology and Stratigraphy of the Vindhyan Basin

The Vindhyan Basin (Fig. 1) is bound by the Aravalli-Delhi orogenic belt and the Great Boundary Fault to the west and the Central Indian Tectonic Zone to south covering a vast area from Chittorgarh in Rajasthan to Sasaram in Bihar (Verma, 1991; Kumar *et al.*, 2001a). The northern part of the Vindhyan Basin is overlain by the Indo-Gangetic alluvium plain (Sengupta, 1996). The southern part of the Vindhyan Basin is overlain by the Deccan Traps (Krishnan, 1968). The Bundelkhand Granite Massif occurs at the central part

of the basin and divides the basin into the Son Valley sub-basin in the east and the Chambal Valley sub-basin in the Rajasthan sector (west). At the south-eastern edge of the basin occurs a linear belt of metavolcanic and metasedimentary supracrustal sequence known as the Mahakoshal and Bijawar Group (Das *et al.*, 1990). The sediments exposed to east of the Bundelkhand Massif are mostly undeformed and unmetamorphosed (Raza *et al.*, 2002). In the Rajasthan sector, near the Great Boundary Fault, folded strata and vertically dipping beds are observed (Gilleaudeau *et al.*, 2018). A generalised stratigraphy of the Vindhyan Supergroup in the Son, Chitrakut and Rajasthan sectors is shown in Fig. 2. Basement rocks of the Vindhyan Supergroup include the Bundelkhand Granite, the Paleoproterozoic Bijawar Group and Aravalli Supergroup (Kumar *et al.*, 2002). In the western sector, Vindhyan sediments unconformably overly the Banded Gneissic Complex (BGC) (Raza *et al.*, 2002). Sediments in the Vindhyan Basin are mostly dominated by sandstone, shale, limestone with intercalated tuff horizons. The Vindhyan Supergroup is subdivided into four Groups: Semri, Kaimur, Rewa, and Bhander (Krishnan, 1968). Semri Group is referred to as the Lower Vindhyan and Kaimur, Rewa, and Bhander groups as the Upper Vindhyan. The unconformity between the Lower and Upper Vindhyan has been characterized in several studies (e.g., Mandal *et al.*, 2019).

Semri Group consists of repetitive sandstone-shale-carbonate sequences with the presence of volcanoclastic units. The depositional environment of the Semri Group is considered to be shallow water (Banerjee, 1974) to deeper water below storm wave base (Chakraborty *et al.*, 1996b). The oldest carbonate unit in the eastern sector is Kajrahat Limestone which shows development of stromatolites (Kumar *et al.*, 2002). In the upper part, Kajrahat Limestone also shows large fan-fabrics (Sharma and Kumar, 2012). This carbonate unit is considered to be deposited under subtidal to supratidal conditions (Banerjee, 1974). Presence of intraformational conglomerates suggest repetitive transgression and regression (Kumar *et al.*, 2002). Gypsum layers are also reported from this unit which indicates an evaporative condition (Aktar, 1996). The Bhagwanpura Limestone in the Rajasthan sector is considered to be the stratigraphic equivalent of the Kajrahat Limestone of the Son Valley (Prasad, 1984;

Fig. 1: A simplified geological map of the Vindhyan Basin, India (modified after Ray *et al.*, 2003; Gilleadeau *et al.*, 2018)

Banerjee and Chopra, 1986). However, this sequence is extensively dolomitic in nature with local occurrence of microbialites (Ray *et al.*, 2003). The second and final phase of carbonate sedimentation in the Lower Vindhyan are represented by the Rohtas and Nimbahera Limestone horizons from the Son Valley and Rajasthan sector, respectively. In the Son valley, the Rohtas Limestone shows rhythmite-like intercalations between thin bedded limestone and shale. Poorly developed columnar stromatolites are also reported from the Rohtas Limestone (Kumar, 1977). This carbonate unit is deposited under subtidal to intertidal settings (Aktar, 1996). The Nimbahera Limestone from the Rajasthan sector is massive in nature and devoid of stromatolites and is considered to be deposited as a transgressive sequence (Prasad, 1981).

Presence of a thick silicified tuff unit, known as the Porcellanite Formation occurs in the Semri Group of Son Valley sector. Occurrence of this unit suggests active volcanism in the near vicinity of the basin during Lower Vindhyan sedimentation. Raza *et al.* (2002)

reported presence of porcellanite beds with similar features as the Son Valley porcellanites within the Palri Shale of the Chambal Valley sector. Clays associated with the porcellanites (Mageswarii *et al.*, 2019) and glauconites from the Lower Vindhyan (Mishra and Sen, 2017) also provide geochemical evidence of felsic volcanism.

Sedimentation in the Upper Vindhyan started after a prolonged depositional hiatus marked by the Dulchipur Conglomerate at the base of Kaimur Group (Kumar *et al.*, 2002; Tripathi and Singh, 2015). Compared to the Lower Vindhyan, the Upper Vindhyan is mostly dominated by siliciclastic sequences with carbonate units occurring at the top. Presence of pyroclastic units in the Kaimur Group has been reported by Chakraborty *et al.* (1996a) and Sen and Mishra (2019). The clastic units of the Kaimur Group are deposited under fluvial to shallow marine conditions (Bhattacharya and Morad, 1993; Kumar *et al.*, 2002). The next clastic sequence above Kaimur is the Rewa Group which is considered to be deposited under lagoonal conditions (Kumar *et al.*, 2002). In the Upper

Fig. 2: A generalised stratigraphy of the Vindhyan Basin in the Son Valley, Chambal Valley, and Chitrakut sector (after Kumar *et al.*, 2002; Ray *et al.*, 2003; Gilleadeau *et al.*, 2018) along with recent geochronological data. The geochronological data are taken from the following studies: 1. Kumar *et al.* (2001b), 2. Ray *et al.* (2002); 3. Rasmussen *et al.* (2002); 4. Ray *et al.* (2003); 5. Sarangi *et al.* (2004); 6. Gregory *et al.* (2006); 7. Chakrabarti *et al.* (2007); 8. Malone *et al.* (2008); 9. Bengtson *et al.* (2009); 10. Gopalan *et al.* (2013); 11. Tripathi and Singh (2015); 12. George *et al.* (2018)

Vindhyan, the Bhandar Group carbonates overlie the Ganurgarh Shale Formation. The carbonate units are referred as Nagod/Bhandar Limestone in the central and eastern Vindhyan and as Lakheri Limestone in the Rajasthan sector. Presence of oolitic and intraclastic horizons with mega-ripples in the Son Valley sector suggest high energy conditions during deposition of these litho-units (Ray *et al.*, 2003). Sedimentation in the central and eastern sector culminated with deposition of Upper Bhandar Sandstone. Depositional environment for this unit is variably suggested to be near shore littoral (Kumar *et al.*, 2002) to fluvial and deltaic (Soni *et al.*, 1987). In the Rajasthan sector, sedimentation continued with the deposition of stromatolite bearing Balwan Limestone followed by the Dholpura Shale (Prasad *et al.*, 1981; George *et al.*, 2018).

Vindhyan Basin: A Billion-year Geologic Record

A significant shift in knowledge regarding Vindhyan geochronology has been documented in recent years. Earlier studies suggested that sedimentation in the Vindhyan Basin has been confined to Mesoproterozoic-Neoproterozoic (1400-600 Ma). Most of these ages are based on carbonaceous megafossils (Kumar and Srivastava, 1997; Rai *et al.*, 1997, Kumar, 2001a), K-Ar (Vinogradov *et al.*, 1964) and Fission-Track technique (Srivastava *et al.*, 1986). The reliability of these ages has been questioned as they have large errors (Ray *et al.*, 2006). Rb-Sr isochron ages of $1140 \pm 24\text{Ma}$, $1044 \pm 22\text{Ma}$ and $1067 \pm 31\text{Ma}$ of a kimberlite and lamproite pipe intruding the Kaimur Group set the upper limit of Lower Vindhyan sedimentation (Crawford and Compston, 1969; Kumar *et al.*, 1993). With technical advancements, measurements of the absolute

radiometric ages have provided better constraints on the age of the Vindhyan Supergroup. Due to the absence of fossiliferous strata, the absolute age determination for Vindhyan Basin, similar to other Precambrian sedimentary systems, is constrained mostly by radiometric dating of intercalated volcanic tuffs, authigenic glauconites, and carbonate horizons.

A compilation of recent radiometric ages is given in Table 1 and Fig. 2. Rb-Sr age from Semri Group glauconites near Chitrakut area suggests onset of Lower Vindhyan sedimentation around 1600 Ma ago (Kumar *et al.*, 2001b). This age is 200 Ma older than previously determined K-Ar age of glauconites from Semri Group by Vinogradov *et al.* (1964). A late Paleoproterozoic initiation age of the Vindhyan Basin is further supported by U-Pb zircon dating of a rhyolitic tuff horizon from Deonar Formation, between Kajrahat and Rohtas Limestone, which yielded 1631 ± 5 Ma and 1631 ± 1 Ma ages (Ray *et al.*, 2002). Similar ages have been reported by Rasmussen *et al.* (2002) from U-Pb zircon dating of tuff layers from Rampur Shale and Porcellanite Formation (1602 ± 10 , 1593 ± 12 , 1628 ± 8 Ma) and more recently, by Mishra *et al.* (2018), also by U-Pb dating of magmatic zircons from the Porcellanite Formation. In addition to this, Pb-Pb isochron age of Kajrahat Limestone, which is the lowermost carbonate horizon in the Son Valley, is 1729 ± 110 and 1707 ± 190 Ma with a mean age of 1721 ± 90 Ma (Sarangi *et al.*, 2004). Although the Pb-Pb ages are associated with large errors, they suggest that the sedimentation in the Vindhyan Basin had started from the late Paleoproterozoic. A late Paleoproterozoic initiation is also consistent with a 1854 ± 7 U-Pb age of underlying volcanic rocks in the Rajasthan sector (Deb *et al.*, 2002). An unequivocal ~ 1600 Ma age of Rohtas Limestone has been reported by several authors (1601 ± 130 , 1599 ± 48 , 1514 ± 120 Ma) (Ray *et al.*, 2003; Sarangi *et al.*, 2004; Chakrabarti *et al.*, 2007). Pb-Pb age dating of fossiliferous phosphorites near Chitrakut area suggest a similar depositional age for the Tirohann dolostone (Bengtson *et al.*, 2009). These radiometric ages of the different lithologies from the Lower Vindhyan has set reasonable lower- and upper-time limits for the Semri Group sedimentation. However, diverse opinion exists regarding the depositional ages of the Upper Vindhyan sediments. Lower part of the Upper Vindhyan is dominated by clastic sequences and hence, limits the application for popularly used absolute

age determination techniques. In addition to previously reported ages, Gregory *et al.* (2006) reported an Ar-Ar age of 1073.5 ± 13.7 Ma from Majhgawan Kimberlite. This suggest that the Upper Vindhyan Bhandar-Rewa Group is younger than ~ 1075 Ma. A direct age of 1210 ± 52 Ma using Re-Os technique from the Bijaigarh Shale of the Kaimur Group suggests a long depositional hiatus as Kaimur Group is ~ 400 Ma younger than the underlying Semri Group (Tripathy and Singh, 2015). Based on Sr isotope stratigraphy, Kumar *et al.* (2002) and Ray *et al.* (2003) suggested that the Bhandar Formation of the Upper Vindhyan is Neoproterozoic in age. Based on the least radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7065, which is similar to the post-Sturtian (< 750 Ma) sea water composition, Kumar *et al.* (2002) suggested that the Bhandar Group carbonates are Neoproterozoic in age with depositional ages ranging from ~ 700 to > 540 Ma. Ray *et al.* (2003) provided a better constrained depositional age of 750-725 Ma for the Son Valley Bhandar Limestone and a ~ 650 Ma depositional age for the Lakheri Limestone in Rajasthan. However, these ages were indirect estimations, based on Sr isotope evolution curve of marine carbonates (Shields and Veizer, 2002) and contrast with paleomagnetic evidence from Bhandar and Rewa Group. Malone *et al.* (2008) that showed that the Bhandar and Rewa palaeopoles bear resemblance with the 1073 Ma Majhgawan kimberlite palaeopoles suggesting an older, late Mesoproterozoic depositional age for the Upper Vindhyan. Detrital zircon geochronology from Upper Vindhyan sandstones also show absence of younger (< 1000 Ma old) zircons (Malone *et al.*, 2008; Turner *et al.*, 2014), which support the paleomagnetic data of Malone *et al.* (2008). Direct age estimates of Upper Vindhyan sediments come from Pb-Pb isochron ages of carbonates which show a depositional age of 908 ± 72 Ma for Son Valley Bhandar Limestone and 1073 ± 210 Ma and 866 ± 180 Ma ages for Lakheri and Balwan Limestone units, respectively, in Rajasthan (Gopalan *et al.*, 2013). These ages suggest that the Lakheri Limestone is stratigraphically older than Bhandar Limestone while the younger age of the Balwan Limestone had placed its stratigraphic position higher than Bhandar-Lakheri sequence (Gopalan *et al.*, 2013). With younger Pb-Pb isochron age estimates of Balwan Limestone and the presence of an overlying shale horizon (Prasad, 1984), the closure age of Upper Vindhyan sedimentation is expected to

be even younger which contrasts with the paleomagnetic evidence. Additionally, George *et al.* (2018) reported presence of Bitter Springs $\delta^{13}\text{C}$ anomaly from Balwan Limestone suggesting a younger ~770-800 Ma closure age for Vindhyan Basin in the Rajasthan sector.

Provenance and Tectonic Evolution of the Vindhyan Basin

Sediment provenance studies can provide insights into the exhumation history of a terrain, tectonic evolution of a basin and reconstruction of continents (e.g., Millers and O’Nions, 1984; Basu *et al.*, 1990). The techniques related for provenance analysis include sandstone petrography, heavy mineral analysis, major and trace elemental analysis, Nd isotope geochemistry, and U-Pb zircon geochronology. However, geochemistry-based provenance studies of clastic sediments could be affected by post depositional alteration, recycling of sediments, limited information about the potential sources, similar signatures of different sources and variability within a single source (Nie *et al.*, 2012). For the Vindhyan Basin, multiple approaches have been undertaken to understand the sediment provenance (Tandon *et al.*, 1991; Raza *et al.*, 2002; Gregory *et al.*, 2006; Chakrabarti *et al.*, 2007; Malone *et al.*, 2008; Raza *et al.*, 2010, 2012; Turner *et al.*, 2014; Sen *et al.*, 2014). Based on heavy mineral analysis, Tandon *et al.* (1991) suggested that the main source of Lower Vindhyan sediments is the Archean Bundelkhand Granite, which is the basement rock of the Vindhyan Basin. Sandstone petrography and heavy mineral analysis suggests that in addition to the Archean Bundelkhand Granite, the Proterozoic Mahakoshal Group could also act as a dominant sediment source for the Patherwa Formation in the basal part of the Semri Group in the Son Valley (Ahmad *et al.*, 2009). Modal analysis and geochemistry of Upper Vindhyan Bhandar sandstone suggests derivation from a recycled orogen source (Banerjee and Banerjee, 2010). Based on the petrographic characteristics, Sen *et al.* (2014) suggested a shift of provenance from Lower to Upper Kaimur Group of the Upper Vindhyan. It was suggested that the Lower Kaimur Group received sediments from the uplifted Bundelkhand craton while the Upper Kaimur Group received sediments from the Mahakoshal Group and the Chhotanagpur Gneissic Complex (CGC) of the Central Indian Tectonic Zone

(CITZ). This shift in provenance is related with tectonic activity of the CITZ around 1.1 Ga. Chakrabarti *et al.* (2007) provided an integrated approach using elemental and Nd isotope measurements from the Son Valley clastic sediments. Based on the difference in Nd isotopic composition between the basement Bundelkhand Granite and Son-Valley Vindhyan sediments, it was suggested that the Bundelkhand Granite is not the dominant source of sediments for the Vindhyan. In contrast, an extinct Andean-type arc is considered as a major source of sediments which is consistent with paleocurrent measurements (Chakrabarti *et al.*, 2007). In the Rajasthan sector, geochemical evidence suggests that the Lower Vindhyan received sediments from granitoids and mafic enclaves of the Banded Gneissic Complex (BGC), which forms the basement (Raza *et al.*, 2002; 2010). Geochemical evidence suggests that the upper Vindhyan clastic rocks from the Rajasthan sector received sediments mostly from stable cratonic sources with the Kaimur Group of rocks being derived from a TTG-like source. Immobile trace element mixing models suggests components of unidentified gneiss, TTG, mafic enclaves, and Berach Granite of the BGC in Kaimur Group sediments while Rewa and Bhandar group sediments show compositions suggesting variable mixing between sources comprising gneiss, mafic enclaves and the Berach Granite (Raza *et al.*, 2012). Mixing models coupled with paleocurrent measurements suggest that the Bundelkhand Granite Gneiss Complex (BGCC) and the Chotanagpur Granite Gneiss Complex (CGGC) were the dominant sources for Rewa and Bhandar Groups in the Rajasthan sector (Raza *et al.*, 2012). Based on the Nd isotopic composition of Rajasthan Vindhyan sediments, Shukla *et al.* (2019) suggested that in the Rajasthan sector, the lower Vindhyan received sediments from BGC and a younger magmatic arc, while in the Upper Vindhyan the provenance has been shifted to pre-1.7 Ga rocks of the Aravalli and Delhi supergroups.

Malone *et al.* (2008) and Turner *et al.* (2014) provided additional insights on the provenance and closure age of the Vindhyan Basin from U-Pb ages of detrital zircons. Detrital zircon geochronology from the Upper Bhandar Sandstone of Rajasthan shows that the most prominent peak is at 1.6 Ga, which is interpreted as inputs from the Lower Vindhyan Deonar Porcellanite the 1.85 Ga and 1.8 Ga peaks

correlated with the Hindoli Group and Banded Gneissic Complex, respectively, 1.4-1.1 Ga peaks suggesting derivation from the Delhi Fold Belt, and the younger 1.02 Ga peak corresponds to 1.0 Ga old regional volcanism (Malone *et al.*, 2008). As noted in the previous section, composite of detrital zircon U-Pb ages show absence of <1000 Ma old zircons in the sediment population, which is interpreted as closure of the basin around 1.0 Ga (Malone *et al.*, 2008; McKenzie *et al.*, 2011; Turner *et al.*, 2014). This observation is particularly significant as sedimentary basins on the Bastar Craton also show similar closure ages (Basu *et al.*, 2008; Mukherjee *et al.*, 2012). It has been suggested that the collision between the Eastern Ghats Mobile Belt (EGMB) and Antarctica around 1.0 Ga, due to the formation of the Rodinia supercontinent, might have led to the closure of these sedimentary basins (Turner *et al.*, 2014). The above arguments are, however, not consistent with the younger Pb-Pb ages (Goapalan *et al.*, 2013) and presence of Neoproterozoic $\delta^{13}\text{C}$ bitter spring anomaly in the Balwan Limestone as well as presence of a shale horizon above it in the Rajasthan sector, which suggests that sedimentation continued even after 1.0 Ga (George *et al.*, 2018).

Differences in opinion exist regarding the tectonic evolution of the Vindhyan Basin (Raza and Cassyap, 1996; Bose *et al.*, 2001; Chakraborty 2006; Chakrabarti *et al.*, 2007; Raza *et al.*, 2012; Basu and Bickford 2015; Bickford *et al.*, 2017). Traditionally the Vindhyan Basin as well as the other Purana basins are considered as intracratonic sedimentary basins (Holland, 1906) and are broadly considered to have developed in a continental rift setting (Chaudhuri *et al.*, 2002). Based on limited deformation and metamorphism of Vindhyan sediments along with geophysical evidence showing rifting across faults, Bose *et al.* (2001) suggested an intracratonic rift origin for the Vindhyan Basin with tectonism-driven sedimentation cycles. Based on a sequence stratigraphy study, it was suggested that all the major flooding events in this basin correlated with volcanic activity and hence, were related to tectonic subsidence of the basin (Bose *et al.*, 2001). In contrast, it has been suggested that the early Vindhyan sedimentation took place in a foreland basin setting (Acharya *et al.*, 2003; Chakrabarti *et al.*, 2007; Raza *et al.*, 2009). This suggestion is based on the geochemical and Nd isotope signatures of the porcellanites from the Semri

Fig. 3: A literature compilation of the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ composition of carbonates from different stratigraphic units from the Vindhyan basin, India (data compilation from Kumar *et al.* (2002); Ray *et al.* (2003); Gilleadeau *et al.* (2018)). The grey bar is showing 'muted' $\delta^{13}\text{C}$ variation during Paleo-Mesoproterozoic (Kah *et al.*, 1999, 2012; Frank *et al.*, 2003)

Group. Geochemical and Nd isotope signatures of Deonar Porcellanites suggest derivation from an

Andean-type arc located to the south of the basin. This tectonic model suggests that the Vindhyan Basin developed as a foreland basin as a result of collision between Bundelkhand Craton in the North and Bhandara/Bastar Craton in the south (Chakrabarti *et al.*, 2007).

By re-interpreting existing geophysical data along with new geochemical data from basal volcanic units from both the Rajasthan and the Son sector, Raza *et al.* (2009) further supported the foreland model of Chakrabarti *et al.* (2007). The position of Vindhyan Basin between two Proterozoic mobile belts (i.e., the Aravalli Delhi Fold Belt and the Central Indian Tectonic Zone) is suggestive of formation of the basin in relation to an active tectonic setting (Raza and Casshyap, 1996). Geochemical evidence from basal volcanics further suggests that the Khairmalia volcanic unit in the Rajasthan and Jungel volcanics in the Son sector have a continental flood basalt and ocean island basalt origin (Raza *et al.*, 2009). Presence of rift related volcanism suggests an extensional tectonic regime during the initiation of Vindhyan Basin. Following the initiation phase, Vindhyan Basin had evolved to a peripheral foreland basin during its course of evolution (Raza and Casshyap, 1996). Based on several lines of geophysical, structural, sedimentological and geochemical evidences, these authors suggested that the Proterozoic Vindhyan Basin originated as a rift which evolved into a foreland basin having similar geological features of Himalayan Foreland Basin (HFB). Recently, based on the Nd isotopic composition of the Rajasthan Vindhyan sediments, Shukla *et al.* (2019) suggested that Lower Vindhyan received sediments from a younger magmatic arc. Presence of a younger magmatic arc in the near vicinity of Vindhyan Basin at the time of deposition, as well as presence of the Great Boundary Fault at the western margin suggest a foreland depositional setting for the Vindhyan Basin. A foreland basin model for the Rajasthan sector have also been established by seismic reflection images, gravity and magnetotelluric data (Mandal *et al.*, 2018).

Bickford *et al.* (2017) however suggested that occurrence of the felsic volcanic events can also be explained without invoking the foreland basin concept. It was also suggested that flat-lying Vindhyan sedimentary units cannot be explained by foreland model. Based on the Hf isotope composition of zircons

from 1642 ± 7 Ma rhyolitic flow within the Porcellanite Formation in the Lower Vindhyan, Bickford *et al.* (2017) suggested derivation from an old felsic crust due to the far-field effect of 1.65 Ga collisional events due to the amalgamation of the Columbia supercontinent. Based on geochemical characteristics of the ~ 1.6 Ga Deonar Pyroclastics of the Porcellanite Formation, Mishra *et al.* (2017b) further suggested formation due to mixing between mantle-derived rocks and average continental crust possibly under a continental rift environment. A similar conclusion has also been reached from the Chopan unit of the Porcellanite Formation (Mishra *et al.*, 2017a).

Chemostratigraphic Studies of the Vindhyan Basin: Implications for Correlations of The Sub-Basins and Mid-Proterozoic Climate Reconstruction

Correlation Between the Son Valley and Chambal Valley Sub-basins

The Bundelkhand Granite Complex divides the Vindhyan Basin into two sub-basins, the Son Valley sub-basin to the east and the Chambal Valley sub-basin to the west. Correlation of the lithological units in these two sub-basins is often difficult because of the extensive spatial distribution of the basin. Sub-basinal correlation has been attempted based on lithological similarities and the relative stratigraphic position of these sedimentary units (Prasad, 1984; Sastry and Moitra, 1984; Soni *et al.*, 1987). Chemostratigraphic correlation of the limestone units from the two sub-basins, using C and Sr isotope systems, has also been attempted for sub-basinal correlation (Kumar *et al.*, 2002; Gilleaudeau *et al.*, 2018). This approach is based on the assumption that conservative elements like Sr, which have a much longer residence time compared to ocean mixing timescales, show similar isotopic compositions in all parts of the global ocean at any instant of time. Hence, carbonates precipitating from seawater are expected to show comparable isotopic signatures if they are stratigraphically equivalent. Although, this technique has been widely used in Phanerozoic stratigraphy, for ancient carbonates, this approach is particularly challenging as carbonates are prone to diagenetic alterations which affects the chemistry of some of these conservative elements. In general, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values are more susceptible to diagenetic

Chambal Valley

Son valley

Fig. 4: $\delta^{13}\text{C}$ variation between the carbonate units from Son and Chambal sub-basin record a large range (Kumar *et al.*, 2002; Ray *et al.*, 2003; Gilleadeau *et al.*, 2018). Mean and Median values show Lower and Upper Vindhyan carbonates have different $\delta^{13}\text{C}$ composition. This variation can also be explained as intrabasinal heterogeneity

alterations by meteoric water compared to $\delta^{13}\text{C}$. Mn/Sr, Rb/Sr, $\delta^{18}\text{O}$ composition of Vindhyan carbonates were evaluated for possible diagenetic alterations and only samples which have preserved their primary isotopic signatures were considered (Kumar *et al.*, 2002; Ray *et al.*, 2003; Gilleadeau *et al.*, 2018). Ray *et al.* (2003) presented a theoretical approach considering close system water-rock alteration and its effect on C, O, and Sr isotope system.

The $\delta^{13}\text{C}$ composition of Bhagwanpura Limestone from the Chambal Valley sub-basin is different from the so-called stratigraphically equivalent Kajrahat Limestone of the Son Valley sub-basin. Extensive dolomitized nature of Bhagwanpura Formation limits the application of Sr isotope chemostratigraphy. The younger carbonate horizons from the Lower Vindhyan Semri Group are the Rohtas Formation in the Son Valley and Nimbahera Formation in the Rajasthan sector. Both carbonate horizons record different $\delta^{13}\text{C}$ compositions: Rohtas $\delta^{13}\text{C}$ ranging from -1.1 to -1.5 ‰ and Nimbahera from 2.3 – 3.1 ‰. (Kumar *et al.*, 2002; Ray *et al.*, 2003). In

the Upper Vindhyan, carbonates from Bhandar Formation in the Son Valley and Lakheri Formation in the Rajasthan sector show different $^{87}\text{Sr}/^{86}\text{Sr}$ compositions. Based on the Sr isotope compositions, Ray *et al.* (2003) suggested that Lakheri Limestone is relatively younger. Both Ray *et al.* (2003) and Kumar *et al.* (2002) reported variable $\delta^{13}\text{C}$ composition of Upper Vindhyan carbonates. In general, Bhandar Formation carbonates in the Son Valley sub-basin show $\delta^{13}\text{C}$ ranging from 2.7 to 5.1 ‰ (Kumar *et al.*, 2002; Ray *et al.*, 2003; Gilleadeau *et al.*, 2018). Ray *et al.* (2002) reported significantly depleted $\delta^{13}\text{C}$ composition (-3.5 to -4.8 ‰) from Ramnoi section of the Bhandar Group in the Son Valley sub-basin while Lakheri Formation carbonates show $\delta^{13}\text{C}$ of 1.5 ± 1 ‰ (Ray *et al.*, 2003; Gilleadeau *et al.*, 2018). Kumar *et al.* (2002) reported strongly depleted $\delta^{13}\text{C}$ values from the Lakheri Formation ranging from -3.3 to -5.2 ‰. Kumar *et al.* (2002) suggested that these carbonates strongly resemble cap carbonates overlying the Neoproterozoic glacial deposits. Also, presence of a tilloid horizon underlying Lakheri Limestone might strengthen this claim.

Fig. 5: A compilation of $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the Vindhyan carbonates (Kumar *et al.*, 2002; Ray *et al.*, 2003). Seawater Sr isotope evolution line has been reconstructed using the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ composition of marine carbonates at any instant of time (filled square) (Sheilds and Veizer, 2002). $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the Vindhyan carbonates are plotted against their absolute radiometric ages (Ray *et al.*, 2003; Sarangi *et al.*, 2004; Chakrabarti *et al.*, 2007; Gopalan *et al.*, 2013). Chambal Valley carbonates show higher $^{87}\text{Sr}/^{86}\text{Sr}$ composition compared to Son Valley carbonates, possibly due to diagenetic alterations

However, strongly negative $\delta^{13}\text{C}$ from both Ramnoi section of the Son Valley sub-basin and few samples from Rajasthan sector reported by Kumar *et al.* (2002) requires further investigation. Based on C and Sr isotope composition of carbonates from both sub-basins, Kumar *et al.* (2002) and Ray *et al.* (2003) suggested that these supposedly equivalent formations are not exclusively coeval (Figs. 3, 4, 5). However, chemostratigraphic application during the Paleo-Mesoproterozoic is particularly difficult due to the absence of any significant excursion in $\delta^{13}\text{C}$ values (Kah, 1999, 2012; Frank *et al.*, 2003). Additionally, difference in $\delta^{13}\text{C}$ composition does not necessarily

mean that the sub-basins were not coeval as substantial difference in $\delta^{13}\text{C}$ can also be observed because of intrabasinal heterogeneity (Gilleadeau *et al.*, 2018). This has been observed in the case of Phanerozoic as well as Proterozoic sedimentary basins (Holmden *et al.*, 1998; Gilleaudeau and Kah, 2015). In the Mesoproterozoic, $\delta^{13}\text{C}$ gradient can result due to difference in organic carbon mineralization pathways under low oxygen availability (Gilleaudeau and Kah, 2013, 2015). Gilleadeau *et al.* (2018) suggested that progressively lighter values from Rajasthan to Son Valley sub-basin during the Lower Vindhyan can be interpreted as intrabasinal heterogeneity in $\delta^{13}\text{C}$

composition. Depleted $\delta^{13}\text{C}$ in Rohtas Limestone is consistent with restricted environment in the Son sub-basin, compared to Rajasthan sector. Paleocurrent analysis also supports open ocean connection in the west. As a result, the carbonate horizons in Lower Vindhyan, having different $\delta^{13}\text{C}$ compositions could be stratigraphic equivalents. However, in the Upper Vindhyan, $\delta^{13}\text{C}$ composition between two carbonate horizons is up to 5‰, compared to Lower Vindhyan (2 to 4‰). This difference in $\delta^{13}\text{C}$ composition is higher than any Mesoproterozoic sedimentary basin studied. In addition, excluding strongly negative $\delta^{13}\text{C}$ of glacial origin from the dataset of Kumar *et al.* (2002), the compositions of the carbonates from the Upper Vindhyan Rajasthan sector is consistent with late Mesoproterozoic age where as Bhander Group carbonates in the Son sub-basin record strongly positive $\delta^{13}\text{C}$ ranging from +4 to +6‰ which is common in Neoproterozoic rocks (Gilleadeau *et al.*, 2018). Based on this observations Gilleadeau *et al.* (2018) suggested that carbonate horizons in the Upper Vindhyan are not stratigraphic equivalents.

Mid-Proterozoic Climate Reconstruction

Several independent lines of geological and geochemical evidences suggest that the oxygenation of the Earth's atmosphere occurred in two broad steps (Farquhar, 2000; Holland, 2006; Lyons *et al.*, 2014). The first rise of atmospheric oxygen took place around 2.45-2.2 Ga ago, which is known as the Great Oxidation Event (GOE) and the second rise occurred around late Neoproterozoic (800-542Ma) (Farquhar, 2000; Lyons *et al.*, 2014). Compared to the dramatic changes in Paleoproterozoic and Neoproterozoic, the Mesoproterozoic (1.6-1.0 Ga) has long been recognized to be a period of biogeochemical stasis (Kah *et al.*, 2004). The time period extending from 1.8-0.8 Ga is also notable for the environmental, evolutionary and tectonic stability and famously known as the 'Earth's middle age' or 'The boring billion' (Holland, 2006; Lyons *et al.*, 2014). The redox evolution of the ocean-atmosphere system during the boring billion is still not fully understood but is important in order to understand the radiation of complex life on Earth. The Vindhyan Basin with a prolonged sedimentation history is an excellent archive for understanding the ocean-atmosphere evolution during

the mid-Proterozoic. Sarkar *et al.* (2010) reported $\delta^{34}\text{S}$ composition of sedimentary pyrites from the Vindhyan Basin as well as from the other Purana basins (e.g. Cuddapah and Chhattisgarh). These sedimentary pyrites show highly positive $\delta^{34}\text{S}$ composition of >25‰ as compared to extremely negative phanerozoic $\delta^{34}\text{S}$ values (Canfield and Raiswell, 1999; Strauss, 1999) suggesting an euxinic ocean with low concentration of marine sulphates (Sarkar *et al.*, 2004). Based on TOC composition and Mo concentration of Vindhyan shales from different stratigraphic units, Singh *et al.* (2018) suggested that during the initial stage the Vindhyan sedimentation, the water-mass was stratified and euxinic in nature. However, this euxinic condition did not prevail during the entire course of evolution of the basin. During the Upper Vindhyan sedimentation, the Vindhyan water-mass was nearly oxic in nature.

Summary

The Vindhyan Basin is the largest among the Purana basins of India. Extensive sedimentary units comprising mostly undeformed and unmetamorphosed sediments makes the Vindhyan Basin an excellent record of Proterozoic geologic events. Radiometric ages from Vindhyan Basin suggests a late Paleoproterozoic initiation age. In the Son Valley sector, the sedimentation is considered to have ceased around ~1000 Ma ago. However, very recent radiometric and isotopic studies suggest that in the Rajasthan sector sedimentation continued up to early Neoproterozoic. Two contrasting tectonic evolutionary histories have been suggested for the Vindhyan Basin: geochemical and isotopic studies suggest a foreland basin depositional model which contrasts with the traditional intracratonic model. The extent of correlation of the lithounits between the two Vindhyan sub-basins remains an open question. Variation in C isotopic composition of carbonate units have been traditionally interpreted as a lack of correlation between the two sub-basins. However, this variation can also be due to intrabasinal C isotopic heterogeneity. Difference in opinion exists regarding the redox structure of mid-Proterozoic oceans. $\delta^{34}\text{S}$ studies suggest Vindhyan water-mass was mostly euxinic in nature. However, the euxinic condition was not persistent during all stages of basin evolution.

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