The Marwar Supergroup of the western India is one of the largest Proterozoic sedimentary sequences of peninsular India. Due to its terminal Neoproterozoic-early Cambrian antiquity, these deposits are believed to hold potential clues to our understanding of the Proterozoic ocean, atmosphere, and origin of the complex multicellular life. Numerous paleobiological investigations in these largely fluvial and shallow marine deposits have brought out some intriguing results over the last decade. Similarly, chemostratigraphic studies have correlated the Bilara Group carbonates with Hanseran Group evaporites, and placed the middle and upper Marwar Supergroup alongside a host of late Ediacaran trans-Gondwanan basins. In this review, I have compiled the available lithostratigraphic, paleobiological, chemostratigraphic, and geochronological data from the Marwar Supergroup. In the wake of new age constraints for the Jodhpur Group, some of the trace fossil assemblages might require revisiting whereas new geochronologic data from within the supergroup would come in handy as we continue to look for the evidence of various Neoproterozoic global events in India.

Keywords: Neoproterozoic, Western India, Chemostratigraphy, Provenance, Biostratigraphy

Introduction

The Marwar Supergroup, formerly known as the Trans-Aravalli Vindhyans (Heron, 1932), of NW India is one of the largest Proterozoic sedimentary successions of India. Spread across an area of over 100,000 km² (Kumar, 1999), the supergroup consists of largely unmetamorphosed and undeformed fluvial and marginal marine siliciclastics, marine carbonates, and minor volcaniclastics, deposited in an intracratonic sag setting (Fig. 1; Chauhan et al., 2004). Sedimentation in the Marwar Basin initiated over the ~750 Ma Malani Igneous Suite (MIS) subsequent to the break-up of Rodinia (Roy and Jakhar, 2002; George and Ray, 2017), and continued up to the early Cambrian (McKenzie et al., 2011) making the sedimentary succession unique among the traditional Paleo-Neoproterozoic ‘Purana’ basins of India (Fig. 2).

Owing to its continuity well into the Cambrian, the supergroup has been subject to a number of paleobiological investigations. Various evidence of biological activity in the form of microbially induced sedimentary structures (MISS; Sarkar et al., 2008; Kumar and Ahmad, 2014) and trace fossils of suspected Ediacaran fauna (Kumar and Pandey, 2009; Kumar and Ahmad, 2016; Pandey and Sharma, 2016) from the Neoproterozoic lower part of the Marwar Supergroup have reiterated the belief that this sedimentary sequence potentially hold clues to our understanding of the origin and evolution of the complex multicellular life. The paleomagnetic studies from within the Marwar Supergroup suggest an equatorial paleogeographic position for the Indian shield during the development of basin, alongside the Arabian-Nubian shield, Eastern Antarctica, and Australia in the Ediacaran-early Cambrian Period (Davis et al., 2014); whereas data from the basement Malani Igneous Suite (MIS) places it at intermediate northerly latitudes along with Laurentia, Baltica, South China, and Seychelles, that formed the western margin of the Rodinia (Gregory et al., 2009). Due to its temporal occurrence and spatial configuration, the sedimentary succession of the Marwar Basin is likely to encompass the history of evolution of the Indian...
shield during the late Neoproterozoic and early Cambrian; an era which has witnessed dynamic changes in climate, like the snowball Earth glaciations, (Hoffman et al., 1998; Och and Shields-Zhou, 2012), evolution of metazoans (Canfield et al., 2007; McFadden et al., 2008), and tectonics in terms of continental configurations (Meert, 2003; Collins and Pisarevsky, 2005). This review is a brief compilation and synthesis of the available lithostratigraphic, paleobiological, chemostratigraphic, and geochronological data from the Marwar Supergroup.

**Lithostratigraphy of the Marwar Supergroup**

The rocks of the Marwar Supergroup are exposed predominantly in the southern part of the basin (Fig. 1). A large part of the basin, mostly in the north and central regions, is buried under the Quaternary sand deposits of the Thar Desert where the stratigraphy is based on the available borehole data (Roy, 2001). The Marwar Basin, also referred to as the Nagaur-Ganganagar and Nagaur-Bikaner basins, is bounded by the Aravalli Mountain range, the Delhi-Lahore subsurface ridge and the Devikot-Nachna subsurface high in the east, north, and southwest, respectively (Pareek, 1984). The sedimentary succession unconformably overlies the MIS which forms the basement of the basin in the central and western regions (Fig. 3A). The outcrops of the Marwar Supergroup in the east, exposed near the Khatu village, are deposited over a sequence of highly deformed metasedimentary rocks which belong to the ~850 Ma old Sirohi Group (Paliwal, 1998). Erinpura Granite also forms the basement at places in the eastern fringe of the basin (Linnemann and Sharma, 2014).

The Marwar Supergroup has an estimated maximum thickness of 2000 m (Pareek, 1981) and is classified into three groups from bottom to top as: the Jodhpur Group, the Bilara Group, and the Nagaur Group.

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**Fig. 1: Geological map of western India showing Marwar Supergroup with stratigraphic subdivisions and surrounding lithotectonic units (modified after Roy and Jakhar, 2002; Pareek, 1981)**
The unconformity between the MIS and the Marwar Supergroup is represented by the Pokaran Boulder Bed which is exposed on the western margin of the basin (Fig. 3B). The origin and chronology of this boulder bed remains equivocal and are highly debated in the context of Neoproterozoic global glaciations (Paliwal, 2005). While some researchers believe it to be of glacial origin due to the presence of striation marks on the boulders (Chauhan et al., 2001; Bhatt et al., 2005), others suggest such striation marks could be generated by the erosive action of the wind-blown sand (Cozzi et al., 2012). Also, there are suggestions that the boulder bed could be locally derived as a part of the overall transgression during the initiation of deposition of the overlying Sonia sandstone formation (Cozzi et al., 2012). Well-developed imbrication at parts of the boulder bed also supports the fluvial origin argument (Cozzi et al., 2012), whereas it is also quite possible that the boulder bed is reworked. The overlying Sonia Formation consists of red and white sandstones and maroon shales believed to have formed in deltaic and beach environment in a marginal marine setting (Chauhan et al., 2004; Sarkar et al., 2008). A dolostone member of a few metres thickness exists near the top of the Sonia Formation (Fig. 3C). This cherty carbonate unit, overlain by the shaly sandstone of Sonia Formation, is exposed at Artiya Kalan, near Jodhpur. The Girbhakar Formation, which forms the topmost part of the Jodhpur Group, is a coarse-grained pebbly sandstone of braided fluvial origin (Chauhan et al., 2004).

Paliwal (1998) first reported the occurrence of ~4 m thick volcanic-volcaniclastic formation on the...
The metasediments of the Sirohi Group form the basement at Chhoti Khatu. The Sonia Formation unconformably overlies the basement, with the unconformity being represented by a polymictic conglomerate horizon. The calcareous tuff which overlies the Sonia Formation, consists of angular fragments of quartz, K-feldspar, randomly oriented blades of biotite and muscovite, minor chert and glass shards. They are embedded in a siliceous-micritic groundmass suggesting a subaqueous deposition for them (Paliwal, 1998).

The marginal marine and fluvial sandstones of the Jodhpur Group are overlain by the shallow marine carbonate rocks of the Bilara Group which forms the middle part of the Marwar Supergroup (Fig. 2). The Bilara Group is divided, from bottom to top, into three formations based on exposures in the southern part of the basin: 1) the Dhanapa Formation which consists of stromatolitic dolostone (Fig. 5A); 2) the Gotan Formation that contains wavy, laminated limestone; and 3) the Pondlo Formation made entirely up of dolostone. In Phalodi, the Dhanapa dolostone formation overlies the Jodhpur Group (Fig. 5A). However, in other parts of the basin, this boundary is marked by chert breccia made up of chert clasts embedded in a fine grained chert matrix (Fig. 5B) indicating a probable depositional hiatus. In the central and northern parts of the Marwar Basin, evaporites are reported from borehole data above the Jodhpur Group. They are classified as Hanseran Evaporite Group (HEG; Das Gupta, 1996). The group comprises cyclic deposits of halite, which forms the most dominant constituent, with associated potash minerals, alternating with laminated anhydrite, clay, dolomite and magnesite. Each of the seven cycles begins with dolomite, anhydrite, minor magnesite and claystone, and ends with layers of halite containing anhydrite, potash minerals, fragments of dolomite, reddish-brown clays and secondary void-filling gypsum (Das Gupta, 1996). These subsurface evaporites are considered to be a facies variation of the Bilara carbonates and are correlated with the contemporaneous evaporite succession, the Ara Group of Oman (Mazumdar and Bhattacharya, 2004; Mazumdar and Strauss, 2006).

The Nagaur Group, which includes the Nagaur and Tunklian formations, unconformably overlies the Bilara Group and forms the youngest succession of the Marwar Supergroup. The initiation of deposition made up of rhyolite and calcareous tuff, sandwiched between the Sonia and Girbhakar formations (Fig. 4). The presence of Chhoti Khatu felsic tuff above the basal Sonia Formation suggests that the Marwar Basin had remained volcanically active even after significant amount of sedimentation, well beyond the final phase of Malani volcanism. This formation has so far been reported only at the Chhoti Khatu village near Nagaur on the eastern fringe of the Marwar Basin.
of the Nagaur Group is marked by the Khichan Conglomerate, an assemblage of cobbles and pebbles in a sandy to calcareous matrix. The group comprises fine to coarse grained reddish brown sandstones and siltstones of braided fluvial and marginal marine origin (Singh et al., 2014). They are unconformably overlain by the Permo-Carboniferous Bap Boulder Bed (Pandey and Bahadur, 2009).

**Age of Marwar Supergroup**

*Constraints from Biostratigraphy*

Most of our understanding about the age of formation of various units in the Marwar Supergroup is primarily based on biostratigraphy. One of the earliest instances of reported trace fossil discovery was made from the silt layers of the Sonia Formation. Awasthi and Parkash (1981) reported two types of trace fossils: 1) thin, flat, circular objects of 0.5-3 cm diameter and thickness of about 4 mm, with the flatter side parallel to the bedding plane and marked by a slightly raised rim of 1 mm high, which resemble the burrows of *Laevicyclus*; and 2) burrows, that are about 3 mm in diameter cutting through the bedding and joined along the bedding planes by tracks. Based on the occurrence of similar trace fossils in Salt Range they argued an early Cambrian age for the formation.
The sedimentary sequence of the Marwar Supergroup had been subjected to intense paleobiological investigations lately following reports of the discovery of medusoidal Ediacaran fossil *Marsonia artiyansis* from the Sonia Formation (Fig. 6A; Raghav et al., 2005). This was followed by similar reports of Ediacaran fossils *Aspidella*, *Hiemalora*, *Beltanelliformis minuta* (Kumar and Pandey, 2009), exceptionally large-sized Ediacaran discs of a few mm to 75 cm diameter and morphologically comparable to *Aspidella* (Srivastava, 2014), and non-carbonaceous mega plant fossils of Vaucheriacean affinity (Fig. 6B; Kumar et al., 2009) from the middle part of the Jodhpur Group. The latter is, however reinterpreted both as giant benthic seaweeds (Pandey and Sharma, 2016) and as body fossil of algae family *incertiesedis* (Kumar and Ahmad, 2016). Besides, Kumar et al. (2012) have reported a five armed body fossil morphologically similar to the echinoderms and suggested they could represent a pre-biomineralization stage in the evolution of the echinoids. There were also preliminary reports of the discovery of trace fossils *Thalassinoides* from the Sonia Formation near Pokaran (Kumar and Ahmad, 2012) and from the Girbkhar Formation (Parihar et al., 2012).

Microbially induced sedimentary structures (MISS) are ubiquitous in the middle part of the Jodhpur Group. The extracellular polymeric substances of the microbial mats make the sand cohesive; binding the sediment grains and produces a wide variety of rather peculiar morphologies (Samanta et al., 2011). There are a number of reports of preservation of such inorganic sedimentary structures (Sarkar et al., 2008; Samanta et al., 2015). Kumar and Ahmad, (2014) classified MISS into three categories: 1) structures that can be compared with inorganically formed sedimentary structures like flat laminated beds, wrinkle marks, cracks, buns, mounds and discs, 2) structures that could not be produced by inorganic processes alone which included *Aristophycus*, *Arumberia banski*, *Rameshia rampurensis* and *Jodhpuria circularis*, and 3) structures without any specific morphology. These fossil assemblages suggested an Ediacaran age for the Jodhpur Group.

The chert associated with the Gotan limestone formation of the Bilara Group had preserved palynofossil assemblage made up of eight taxa of acritarchs with characteristic features of *Sphaero morphida*, *Sphaerohystrichomorphida* and *Versimorphida* subgroups, four taxa of cyanobacteria which show unbranched trichomes with a coccoidal form, and one bio-mineralized tube comparable to modern families *Croococcaceae*, *Nostocaceae* and *Oscillatoriaceae* (Babu et al., 2009). Another acritarch assemblage of *Asteridium*, *Dictyotidium birvetense*, *Pterospermella solida* and *Annulum*...
squamecnum from the lower part of the Bilara Group suggest a late Ediacaran to early Cambrian age for the middle Marwar Supergroup. Similarly, the Hanseran Evaporite Group is marked by an abundance of acritarchs represented by Retisphaeridium dichamerum, Dichtyotidium birvetense, Cristallinum cambriense, Comasphaeridium and Archaeodiscina umbonulata, suggesting an early to middle Cambrian age for the formation (Prasad et al., 2010).

A number of well-preserved trace fossil assemblages including Rusophycus disymus, Chondrites, Cruziana, Dimorphicnus obliquus, Monomorphichnus monolinearis, Diplichnites (Fig. 6C), Skolithos, Palaeophycus tubalaris, Planolites, Gyrophylmites, Lockeia, Merostomichnites, and Psammichnites (Kumar and Pandey, 2010; Pandey et al., 2014) were reported from the Nagaur Group. Also, there were reports of index fossil Treptichnus pedum (Srivastava, 2012; Pandey et al., 2014; Singh et al., 2014; Sharma et al., 2018) and body fossil of suspected arthropod redlichid trilobite (Singh et al., 2013) supporting Cambrian age for the deposition of the upper Marwars.

**Constraints from Chemostratigraphy**

Most of the chemostratigraphic efforts to constrain the age of the Supergroup were attempted in the Gotan limestone formation of the Bilara Group. Two separate efforts (Mazumdar and Strauss, 2006; George and Ray, 2017) to constrain the age of Bilara Group using Sr isotope stratigraphy have yielded lowest $^{87}$Sr/$^{86}$Sr of 0.7082 and 0.7081, respectively, for the Gotan Formation. These results suggested a late Ediacaran depositional age of ~570 Ma for the Bilara Group corroborating the biostratigraphy.

Carbon isotope stratigraphy had been widely used as a potent tool for making both intra and interbasinal correlations, as well as to better understand the ocean chemistry during the terminal Proterozoic (Halverson and Shields-Zhou, 2011). The period is marked by large scale negative and positive excursions in $^{13}$C of the marine carbonates in association with the global glaciations - 'the Snowball Earth’ events (Hoffman et al., 1998). Similar negative $^{13}$C excursions were also reported during the ~580 Ma Gaskiers glaciation, and the Shuram anomaly, with the $^{13}$C going down to −12‰ during the latter (Le Guerroue, 2006). Due to its terminal Proterozoic depositional age and proximity to the continents from which these events are reported (Davis et al., 2014), the Bilara Group had been subjected to a number of $^{13}$C isotope stratigraphy investigations. Overall, the reported $^{13}$C values range from −10.3 to 2.4‰ for the bottommost Dhanapa dolostone formation and −1.9 to −0.6‰ for the topmost Pondlo Dolostone. The bulk of the Bilara Group is comprised of the middle Gotan limestone formation which has $^{13}$C varying from −10.7 to +4.7‰ (Pandit et al., 2001; Maheshwari et al., 2003; Mazumdar and Bhattacharya, 2004; Ansari et al., 2018). Some of the very low $^{13}$C values reported in both the Dhanapa and Gotan Formations could be potential candidates for the Shuram anomaly (Ansari et al., 2018) in the wake of the ~570 Ma age suggested by Sr isotope stratigraphy; however, further chemostratigraphic and geochronological constraints are required to ascertain the case.

Mazumdar and Bhattacharya (2004) have carried out $^{13}$C measurements in the Bilara Group ($^{13}$C = −8 to +4‰) and found their $^{13}$C pattern comparable with that of the Hanseran Evaporite Group ($^{13}$C = −8 to +2‰; Banerjee et al., 1998). Similarly, both the units have comparable $^{34}$S (average $^{34}$S ~ 33‰) measured in sulphates, and $^{87}$Sr/$^{86}$Sr (lowest $^{87}$Sr/$^{86}$Sr = 0.7081), suggesting that they are coeval and the Hanseran Group is a homotaxial facies variant of the Bilara Group (Mazumdar and Strauss, 2006). These chemostratigraphic constraints correlate the Bilara Group with a host of Ediacaran-early Cambrian carbonate deposits such as the Nafun and Ara Groups of Oman, Salt Range Formation of the Pakistan, Krol Group of the Lesser Himalaya, and Doushantuo Formation of the South China (Fig. 7).

**Constraints from Radioisotope Data**

The lower time bound for the initiation of sedimentation in the Marwar Supergroup is given by the 752±18 Ma (Pb-Pb zircon) age obtained for the terminal dyke phase of Malani magmatism (Fig. 2; Meert et al., 2013). Though, a late Neoproterozoic-early Cambrian deposition period was suggested traditionally for the Marwars (Pandit et al., 2001), there were hardly any radiometric age data available from the Supergroup to corroborate it until recently. It was generally perceived that the sedimentation in the Marwar Basin...
got initiated in the late Ediacaran period, ~115 Ma after the Malani magmatism. The lack of physical evidence for either of the Neoproterozoic ‘snowball Earth’ events in the basin was often cited as the rationale behind this argument (Davis et al., 2014; Turner et al., 2014). However, a felsic tuff located near the Chhoti Khatu village in the eastern flank of the Marwar Basin had been dated to 703±40 Ma using Rb-Sr whole rock isochron method recently (George and Ray, 2017). The new age information from the tuff, which is sandwiched between the Sonia and Girbhakar formations, shows that the sedimentation in the Marwar Supergroup began very much during the Cryogenian period, and that the apparent hiatus between the Malani volcanism and the initiation of deposition of the Marwar Supergroup may not have been protracted as thought before.

There were attempts to constrain the maximum age of deposition of various formations in the Marwar Supergroup using U-Pb dating of detrital zircons. The detrital zircon age data from the Jodhpur Group show major peaks at ~750 Ma, ~850 Ma, and ~1.8 Ga suggesting a maximum depositional age of ~750 Ma.
for the Jodhpur Group. The first two ages are more likely the ages of the basalts, MIS and Erinpura Granites, respectively, while the zircons of ~1.8 Ga age peak could be derived from either BGC-II or the granites located in the northern part of the Delhi Supergroup (Malone et al., 2008; Turner et al., 2014). McKenzie et al. (2011) carried out detrital zircon analyses of the Nagaur Formation and reported youngest zircon ages of ~540 Ma. This can be considered as the maximum depositional age of the Nagaur Formation and is well in agreement with the biostratigraphy.

**Sediment Provenance**

The paleocurrent analyses (Awasthi and Parkash, 1981; Chauhan et al., 2001; Chauhan et al., 2004) in the Sonia and Girbhakar formations suggest paleoflow directions from west-southwest, implying majority of the sediment sources could be located along the eastern fringes of the basin. The U-Pb detrital zircon analyses of the Marwar siliciclastics have shown two major age peaks ~0.7-0.9 Ga and ~1.8 Ga, and a minor peak at ~2.5 Ga, indicating majority of the sediments were sourced from Erinpura Granite and/or MIS, and BGC-2 and/or Delhi Supergroup granites, respectively, with minor input from the basement BGC-1 (Malone et al., 2008; Turner et al., 2014). It was also suggested that the source of ~1.8 Ga zircons, either BGC-2 and/or Delhi Supergroup, acted as a common sediment source/s for both Marwar and the Vindhyan basins during their evolution (Turner et al., 2014). Similarly, George and Ray (2017) carried out quantitative provenance analysis of the Marwar siliciclastics using rare earth elements and neodymium isotopes, and have suggested a combined source of Delhi Supergroup and BGC-2 contributing sediments to the Jodhpur Group. Also, the Delhi Supergroup and/or Erinpura Granites supplied sediments to the subsequently formed Bilara and Nagaur Groups while the sediment supply from the BGC-2 got truncated. They suggested a hiatus of ~100 Ma between the deposition of lower and the middle Marwars based on the available geochronologic and chemostratigraphic constraints as well as the sharp change in provenance, and speculated that this break in deposition could likely be the reason for the absence of any evidence for the ‘snowball Earth’ events in the Marwar Basin.

**Looking to the Future**

Although, a large number of studies have been carried out in the Marwar Basin in the last decade, there are a few areas which might require some rethinking. In light of the new radiometric age data from the Jodhpur Group, the trace fossil discoveries from the Sonia Formation may be viewed in a new perspective. Some of the reported trace fossils which closely resemble the Ediacaran fauna may actually be precursors to them. Multiple chemostratigraphic studies in the Bilara carbonates have reported δ13C negative excursions of varying magnitude. Although they provided valuable data for inter and intra-basinal correlations, none of these excursions could be correlated to any of the Neoproterozoic global events (Fig. 7), apart from the suspected Shuram anomaly reported by Ansari et al. (2018). The position of the Pe-C boundary remains ambiguous in the Marwar Supergroup. The rich fossil assemblage and the reported presence of index fossil *Treptichnus pedum* suggest early Cambrian antiquity for the Nagaur Group; however, there is no evidence yet to suggest that the boundary lies in the underlying Pondlo or Gotan formations. Constraining ages of the sedimentary sequences in Precambrian terrain are often hard for want of biostratigraphic records. Lack of volcanics or volcaniclastics in the sequences make the task harder, which is the case with Marwar-Supergroup. It is high time for more focussed geochronologic efforts within the supergroup to better constrain its time frames of deposition.

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