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ORIGINAL ARTICLE

Late Cretaceous–Early Paleocene Geodiversity of Fatehgarh Formation of Petroliferous Barmer Basin, Western Rajasthan, India: A Potential Geopark Site

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Abstract
The Late Cretaceous–Early Paleocene sediments of Fatehgarh Formation (FGF) of petroliferous Barmer Basin in northwestern India are known for several geological revelations including significant global events of the earth's history. The FGF encompasses textbook examples of numerous outcrops of fluvio-deltaic to marine processes at the Sandhuwa-Bariyada-Borasar Ridge (SBBR). Preservation of a diverse assemblage of fossils with rare magnetic spherules related to the K/T boundary (KTB) event accompanied by sedimentary processes makes SBBR a significant geo-education site in India and a potential global geo-top. The SBBR accredits full potential for declaring the Geoheritage Park with its three geosites viz. Sandhuwa, Bariyada and Borasar. The geologically important sites of SBBR have been subjected to degradation and damage mainly due to natural and anthropogenic activities. The self- sustainable economic development through awareness and geotourism are the best tools for their promotion and conservation. It is proposed here to conserve the internationally significant geoheritage sites of SBBR and to recognize it as the first Geopark of the Barmer Basin in western Rajasthan, India.

Keywords Fatehgarh Formation · Barmer Basin · Global events · Geosites · Geoheritage · Geopark · Geotourism

Introduction

India is endowed with significant geological records, scenic landforms, and wide spectrum of mineral deposits, unique structural features, and archaeological monuments in seven physiographic divisions (Kale 2014). In absence of proper legislation to protect them, several important geological sites in India having global significance are being degraded and destroyed due to unplanned urbanization and mining activities (Mathur et al. 2020a, b). Hence, proper guidelines and legislation are required for the protection and conservation of geologically important sites. The Geopark concept proved successful to conserve the prime geoheritage sites in many countries (Stoffelen 2020). It is also a recognized tool for the sustainable socioeconomic development of the region through geotourism along with awareness and education to the public about the Earth Sciences (Kelley et al. 2019). Additionally, many international agencies are also working on a global platform with common goals of sustainability, conservation, and protection of geoheritage with values related to science, natural heritage, recreation, ecology, history, and culture (Page 2018).

Despite geological sites with global significance, the concepts of geoheritage, geoconservation, geopark, and geotourism in India have not been adequately explored and, hence, are still in a nascent state (UNESCO 2016; Mathur et al. 2021). However, earlier efforts have been initiated in this regard to discuss and address the concept of Geopark and geotourism potentials of India in form of several research papers, book chapters, and reports (Ahluwalia 2006; Anantharamu et al. 2001; Mathur and Singh 2014; Swarna et al. 2013; Kale 2014; Sheth et al. 2017; INTACH 2016, 2021; Mathur 2020a 2020b; Shekhar et al. 2019; Chauhan et al. 2020; Mathur et al. 2020a, b, 2021; Bhosale et al. 2021; Biswas and Chauhan 2021; Chavan et al. 2022; Nayak and Karuppannan 2022; Thakkar et al. 2022; Prizomwala et al. 2022; Kaur et al. 2020; Verma

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et al. 2022; Dhirendra et al. 2022; Joshi and Gorania 2022). Further, 32 national geological monuments declared by the Geological Survey of India (GSI) with legislation (Declaration, Conservation, Protection, and Maintenance Act 2014) on Geological Heritage Sites may help in developing Geoparks in India. Four noteworthy landscapes identified by the GSI have also been declared as UNESCO World Heritage sites (Kale 2014). With rich geological, historical, and cultural diversity of global significance, Barmer Basin has all credits to be included among the national geological monuments. It is the showcase of the sedimentary and igneous geological features and structures that preserved significant geological processes and landscape evolution.

The Barmer Basin of western Rajasthan is a narrow NNW-SSE trending graben comprising of middle Jurassic to lower Eocene sedimentary rocks. It was formed during the Gondwana break-up and post-Cretaceous northward movement of the Indian plate when several other Basins like Cambay graben along with Barmer Basin were formed (Mathur et al. 2006; 2019a, b; Compton 2009). Fatehgarh Formation (FGF) of the Late Cretaceous–Early Paleocene age marks the northern limit of the Barmer Basin represented by Sandhuwa-Bariyada-Borasar Ridge (SBBR). It is a 15.8-km-long discontinuous ridge located 6 km SE of Fatehgarh town on National Highway 68, exhibiting numerous sedimentary features and structures pertaining to the marine and continental processes in the sediments of FGF (Dasgupta and Chandra 1978; Alam 2002). Various strata of FGF of SBBR preserve features and structures that represent global phosphogenic, transgression, volcanism, possibly impact, and mass extinction events related to K/T boundary (KTB) (Mathur et al. 2005a, 2005b, 2006, 2018, 2019a, 2019b and Compton 2009). In the present study, we selected three geosites at Sandhuwa, Bariyada, and Borasar villages to establish the geodiversity and geoheritage values of sediments of FGF. Unplanned infrastructural and industrial development with illegal mining has resulted in the degradation and destruction of many potential geological sites of SBBR of global significance in the Barmer Basin (Mathur et al. 2020a, b). The proposed three geosites of SBBR have geoheritage potential to be recognized as a geopark in the Barmer Basin. In this paper, we have discussed an overview of the geology of the FGF, its global events in time and space, and the significance of fossils with the identification of major threats to the geosites and initiate the idea for proposing the first Geopark in the Barmer Basin, western Rajasthan, India.

Methodology

In the present evaluation of the scientific investigation, the initially published literature of the study area is reviewed thoroughly with the fieldwork to identify significant outcrops of FGF at SBBR in the petroliferous Barmer Basin. Based on remote sensing and GIS techniques by utilizing satellite data from Google earth images, location and geological maps of the study area were prepared. Lithostratigraphy, facies characterization, fossil burial, and preservation environment are analyzed mainly through field surveys, measured lithologs, petrography, and taphonomic techniques at three geological sections of SBBR. Total three geosites are selected based on the abovementioned methodology and their scientific values. Based on the present evaluation and combining previous research outcomes of FGF at three geosites, the geoheritage values of SBBR for sedimentology, stratigraphy, and paleontology are established for the scientific, geotourism, and socio-economic significance.

Geological History of the Barmer Basin

The Barmer Basin principally evolved as an isolated depocentre in the Early Cretaceous in response to down buckling and failed continental rift of the Indian plate (Dutta 1983; Biswas 1987; Roy and Jakhar 2002; Mathur and Kumar 2003; Sharma 2005). The petroliferous Barmer Basin is considered a northern extension of the Cambay Basin that lies transversely to the south of Devikot high and Jaisalmer Basin (Mathur and Kumar 2003). In view of tectono-sedimentary, fossil occurrences, hydrocarbon, and significant global events make this Basin a promising geological entity of India. It is 200 km long, 36 km wide, and < 6 km deep, roughly NNE–SSW trending basin endowed with economically workable sequences that contain the bulk of the 7.3 billion barrels of stock tank oil in place, making it an important petroliferous graben of India (Mathur et al. 2005a, b, 2006; Compton 2009; Bladon et al. 2014; Dolson et al. 2015).

Earlier, Dasgupta (1974) classified the sediments of the Barmer Basin into pre-rift, syn-rift, and post-rift sediments bounded by various faults. The pre-rift sediments of Barmer Basin are represented by Ediacaran to Early Cambrian Randha and Birmania formations which are exposed on the western margin of the Barmer Basin (Fig. 1a; Pareek 1984; Mathur and Chauhan 1994).

The Jurassic Lathi Formation is exposed at the western periphery of the Barmer Basin which is considered as a basement for the Barmer Basin (Dasgupta 1974; Pareek 1981, 1984; Mathur and Kumar 2003). The Late Cretaceous to Eocene sequences represents infilling of the accommodation space created during active rifting deposited the syn-rift sediments of the Barmer Basin. These sediments

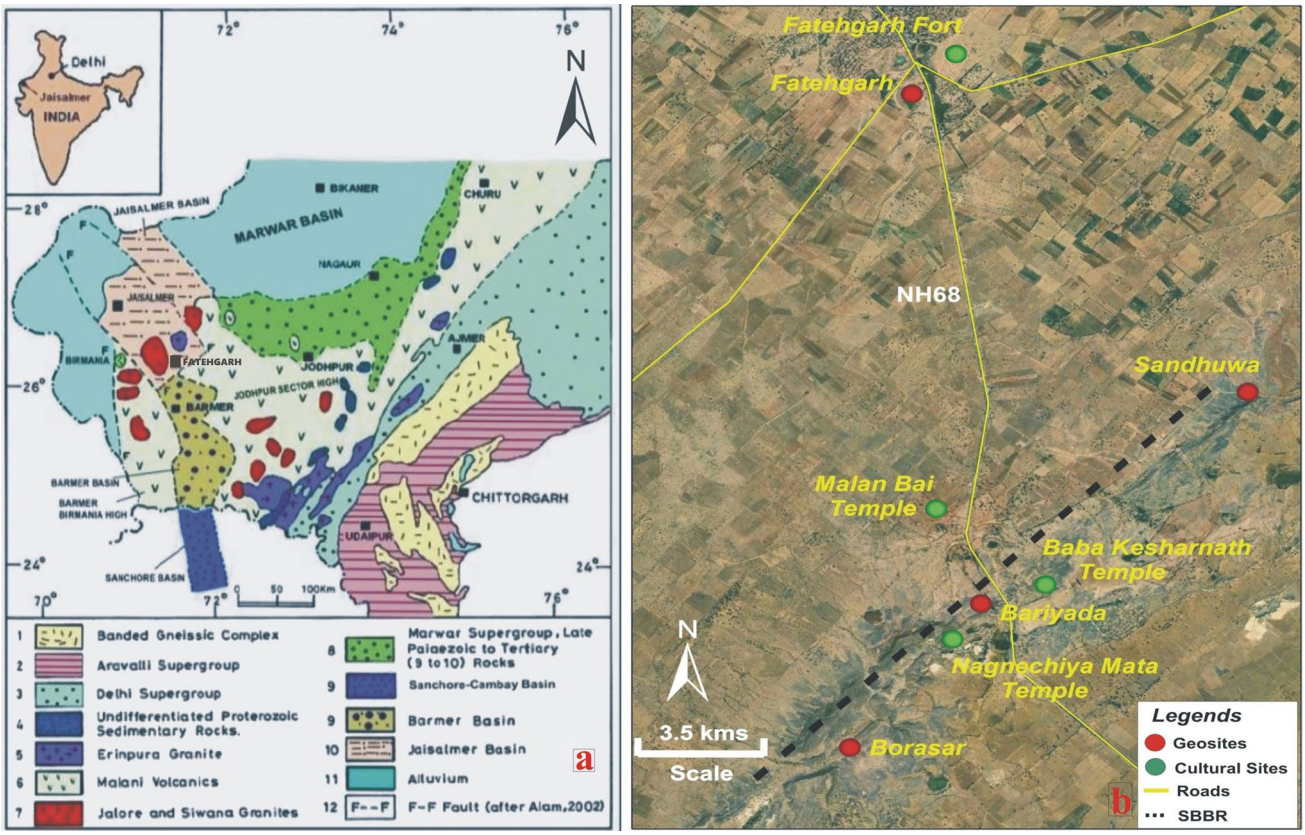

Fig. 1 Geological map showing Western Rajasthan Sedimentary Basins and Malani basement high (After Dasgupta and Chandra 1978; Alam 2002). **b** Google image showing the location of geosites at and near Sandhuwa, Bariyada, and Borasar villages on SBBR situated near Fatehgarh town, Jaisalmer district, western Rajasthan, India

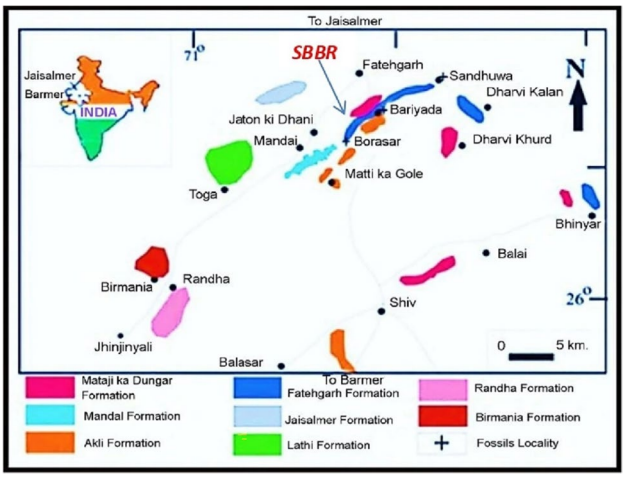

Fig. 2 Geological map showing outcrops of Fatehgarh Formation at SBBR in the northern part of the Barmer Basin (Modified from Mathur et al. 2006)

are represented by Sarnu Formation, Fatehgarh Formation, Mandai Formation, Barmer Hill Formation, and Akli Formation in the Barmer Basin (Fig. 2; Mathur et al. 2006, 2012, 2018, 2020a, b; Compton 2009; Dolson et al. 2015). The syn-rift sediments of Fatehgarh Formations form the northern periphery of the Barmer Basin and are best exposed at the Sandhuwa-Bariyada-Borasar ridge (SBBR; Fig. 2). The SBBR is represented by Cretaceous to Early Paleocene sediments representing fluvio-deltaic to shallow-near coastal marine-influenced depositional environmental range (Mathur and Kumar 2003; Mathur et al. 2005a, b, 2006; Nagori and Khosla 2019; Mathur et al. 2021). Most of the Barmer Basin has been filled up with post-rift sediments, constituting the Akli Formation, Mataji ka Dungar Formation, and Kapurdi Formation of the Late Paleocene to Early Eocene age. These formations are exposed in the northern, north-eastern, north-western, and in the entire central and southern central parts of the Basin. The post-rift subsurface Late Miocene and Plio-Pleistocene continental sedimentation complete the Basin fill (Dolson et al. 2015).

Fatehgarh Formation

SBBR forms the northern fringes of the Barmer Basin (Figs. 1b and 2) and are dominantly represented by the Fatehgarh Formation (FGF) of the Late Cretaceous to

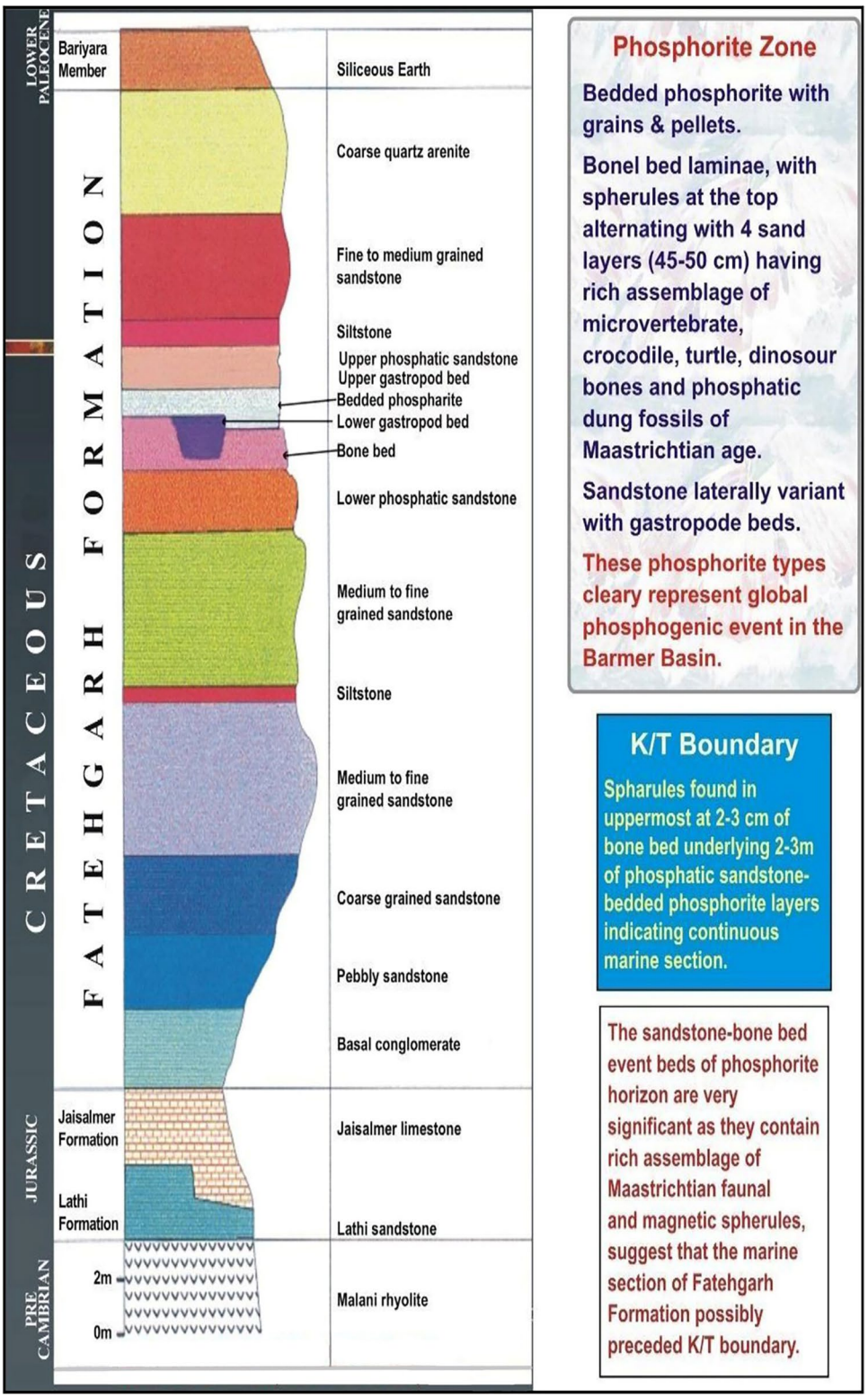

Fig. 3 Lithostratigraphy of the Fatehgarh Formation of SBBR showing details of siliciclastic sequences and phosphorite zone along with fossiliferous and magnetic spherules bearing horizons straddling KTB (Modified from Mathur et al. 2005a and 2006)

Early Paleocene age (Mathur et al. 2006; Compton 2009). FGF is deposited on the Lathi Formation of Jurassic age and overlain by siliceous earth of Bariyada Member of the Akli Formation of Early Paleocene age straddling KTB in it (Fig. 3; Table 1). FGF at SBBR is divided into three zones viz: basal fluvial-deltaic fining upward siliciclastic

Table 1 Various facies, fossils, and depositional environment of the FGF at the SBBR in time and space (Mathur and Kumar 2003; Gour 2005; Compton 2009; Akash 2010; Mathur et al. 2005a; 2006 and 2019)

Formations	Lithology	Inferred depositional environment	Age
Upper Akli Formation	Sandstone, lignite, and bentonite	Continental and chemical weathering products	Early Eocene
Lower Akli Formation (Bariyada Member)	Siliceous earth and sandstone	Volcanic siliceous ejecta	Early Paleocene
Upper FGF	Coarse quartz arenite	Fluvial, braided river channel deposits	Early Paleocene
Coarsening upward siliciclastic sequence	Fine- to medium-grained sandstone, siltstone	Reworking of older beds and influx of volcanoclastic sediments under high energy environment	66 Ma
	Pebbly sandstone, fine to coarse sandstones, and siltstone	K/T boundary	
Middle FGF	Thin ferruginous spherule layer bone bed-bedded phosphorite with microvertebrate and reworked fossils and gastropod bed	Shallow subtidal, high energy reworking events near-shore marine with intertidal pools-storms and tsunamis effects	Late Maastrichtian
Phosphorite zone of Mathur et al., (2005a; 2019a and b)	Lower fine- to medium-grained phosphatic sandstones	Near coastal to shallow subtidal upwelling of phosphate	Early Maastrichtian
Basal-middle siliciclastic sequence (Gour 2005)	Fine- to medium-grained sandstone with fossils of crocodile, dinosaur, *Teredolites*, and turtle	Tide influence near coastal to beach deposits. Reworking of bones and sediments	Early Maastrichtian to Late Campanian
		Transgression of sea	
Lower FGF	Siltstone interbedded with silty shale and fine-grained sandstone, coarse sandstone to pebbly sandstone	Destruction of delta front deposits: auto-cyclic delta front deposits	Early Campanian
Fining upward Siliciclastic sequence (Mathur and Kumar, 2003)	Boulder–cobble conglomerate	Auto-cyclic delta plain deposits: fan apron and channel lag deposits	
Hiatus	Devikot High Upliftment	Passive margin rift	Late Albian
Lathi Formation	Sandstone, petrified wood, and trace fossils	Fluvial	Late Jurassic
Malani Igneous suite	Granite–rhyolite	Continental	Precambrian

sequence, middle marine phosphorite zone, and the upper fluvial volcanogenic siliciclastic sequence (Mathur and Kumar 2003; Mathur et al. 2006). The siliciclastic and phosphorite sequences dominantly represent Cretaceous-Early Paleocene geological processes of earth history in eastern Gondwana land.

Geoheritage of the SBBR of the Barmer Basin

The northern part of the Barmer Basin has excellent outcrops of Sedimentary Type Georesources (STG) that exhibit two different sedimentary siliciclastic sequences and a phosphorite zone in the SBBR region (Figs. 2 and 3). The SBBR is 15.8 km in length and covers about 12.67 km^2 of area located in the Barmer and Jaisalmer districts (Fig. 1b). Elevations of SBBR are ranging from 212 to 363 m from MSL showing highly rugged topography. The outcrops of SBBR are endowed with textbook features for geo-education related to sedimentology, sequence stratigraphy, paleontology, tectonics, geomorphology, etc., with associated cultural and historical heritage of the region. The sediments and associated life are represented by features and structures with unique fossils and rare magnetic spherule deposits in the rock assemblages of continental to the marine environment (Mathur and Kumar, 2003; Mathur et al. 2006). SBBR in Jaisalmer and Barmer districts is represented by the spectacular inselberg-type landscapes in the Thar Desert of India. Three sections at Borasar, Bariyada, and Sandhuwa geosites selected are represented by basal fluvial-deltaic fining upward siliciclastic sequence, marine phosphorite zone, and fluvial volcanogenic siliciclastic sequences respectively of the FGF (Table 1; Fig. 3). These sediments characterize the past record of tectonics, climates, and land-sea environments with their paleogeographic distribution in Eastern Gondwana land. The surrounding areas of selected geosites of the SBBR occur adjoining the territory of the famous National Desert Park (NDP) of India thus imparting additional values to these geosites.

NDP covers an area of 3162 km^2 of the Jaisalmer and Barmer districts of western Rajasthan and is a unique habitat of its type in the Indian subcontinent. It is a showcase of magnificent sand dunes, spectacular oasis, desert flora, animals, and typical traditions in the form of colorful festivals, folk music, dances of local communities, and typical desert huts. It is also endowed with several heritage places like old buildings, forts, and ancient temples (Fig. 4a–d). NDP is additionally endowed with Palaearctic, oriental, and Saharan elements representing extreme arid zone on the Earth.

NDP became the most important site in India as it is also known for the conservation and long-term survival of the globally threatened Great Indian Bustard and other endemic fauna and flora (Fig. 5a). Significantly, NDP territory has also preserved fossilized petrified wood and many trace fossils remain at and around Akal fossil Park (Fig. 5b). It is a famous tourist place of India popularly known as Jurassic Park of Jaisalmer (Mathur et al. 2020a, b; Dhirendra et al. 2022). Akal fossil Park provides unusual evidences of the presence of 180 million-year-old luxuriant forests in the Thar Desert. Because of all these historical, cultural, biological, and geological elements, NDP in the Thar Desert was recently nominated in the list of UNESCO world heritage centers (Mathur et al. 2020a, b). The geodiversity and

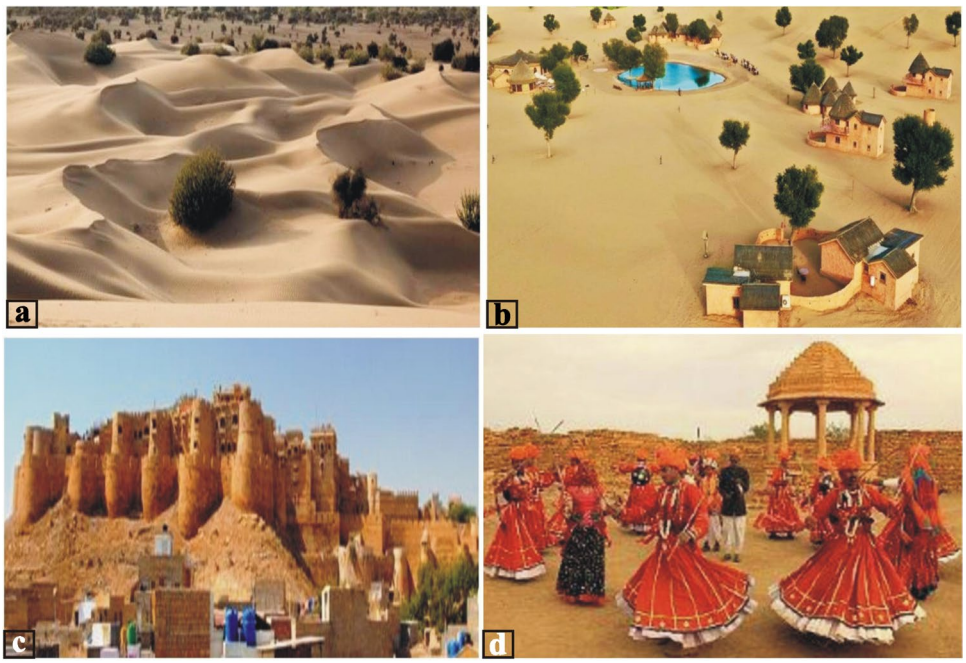

Fig. 4 Photographs showing geoheritage and historical and cultural heritage components in National Desert Park: **a** unique sand dunes and typical plants of the Thar Desert, **b** spectacular oasis and typical huts on desert sand, **c** Sonar Fort of Jaisalmer, and **d** Folk dance, and cultural activities

Fig. 5 **a** Globally threatened Great Indian Bustard in the proposed Geopark area and **b** fossilized petrified wood remains near Akal fossil Park of NDP in the great Thar Desert of India

geoheritage details observed in the outcrops of proposed three geosites of the SBBR (Fig. 6a) with their unique features and possible global events are discussed below (Table 2).

Geosite 1: Borasar Section

The Borasar geosite is located about 5.5 km from *Bariyada* village situated on Jaisalmer Barmer road (NH 68; Fig. 1b) representing the southernmost part of the SBBR. It extends from Borasar village to north of Mandai village covering about 4.5-km^2 area. It is represented by ridges and bold hillocks made of the rocks of the FGF. It is a type section (Borasar ridge) of excellently preserved fluvio-deltaic fining upward siliciclastic sequences of FGF. The basal conglomerate of FGF deposited on the Lathi Sandstone marks the unconformity at the base (Fig. 6b, c; Mathur and Kumar 2003; Mathur et al. 2005a and b; 2006).

Fining Upward Lower Siliciclastic Sequences The 6–12 m-thick multilateral and multi-storied sedimentary sequence extends for about 500 to 2000 m laterally commencing with basal-conglomerate of FGF. The basal conglomerate of FGF unconformably rests over the sandstone and petrified wood beds of the Lathi Formation (Fig. 6b) of the Late Jurassic age. The basal conglomerate followed by pebbly sandstone, coarse-grained sandstone, medium- to fine-grained sandstone, and siltstone at the top constitutes a typical fining upward siliciclastic sequence of FGF at Borasar ridge (Fig. 6c).

The basal conglomerate comprises of sub-rounded to well-rounded pebbles of rhyolite, granite, jasper, quartz, quartz arenite, calcareous sandstone, and petrified wood (Mathur and Kumar 2003). These clasts are set in the medium to coarse-grained matrix consisting dominantly of quartz, feldspar, biotite, heavy minerals, and iron oxide minerals. The majority of clasts are roughly aligned parallel to their longer axis showing imbrication. At this geosite, the basal conglomerate grades upward into pebbly sandstone at the base followed by coarse-grained sandstone, medium- to fine-grained sandstone, and siltstone-clay stone at the top typically forming an upward fining sequence. This sequence is endowed with characteristics features like fining upward sedimentation, the dominance of non-cohesive sediments, the presence of unidirectional trough cross-bedding of the limited thickness (Fig. 7a), and lack of significant crevasse splay deposit; progressive sorting of sediments and syn-deformational features. All these features of fining upward sequence of the FGF suggest a fluvially dominated prograded auto-cyclic delta complex, delta-front, and delta plain deposits having braided channel system as an agency of dispersal and deposition of the sediments (Table 2; Miall 1984; Vos 1977; Akash 2010). The near shore auto-cyclic delta interpreted for fining upward sequence of Borasar ridge appears to match with the typical auto-cyclic fan delta reported by Michalzic and Schumann (1994) from Late Jurassic to Early Cretaceous siliciclastic sequences of Cotton valley Groups in Texas, USA. Significantly, it has also preserved phosphatic dung and coprolites of dinosaurs, crocodiles, and turtles in coarse facies (Gour 2005 Fig. 7b) along with teeth, cranium fragments, dental plate, and vertebrae of the crocodile in its lower beds (Fig. 8a–d). This horizon has also preserved reworked fragmentary femur possibly of dinosaur (Fig. 9) indicating that the basin was dominated by large reptiles during the Early Cretaceous period (Gour 2005 and Akash, 2010) at Borasar geosite.

Medium- to Fine-Grained Beach Sandstone The middle siliciclastic sequence at top of the Borasar ridge is represented by a 4 to 6 m thick horizon of medium to fine-grained sandstone deposited above the lower siliciclastic sequence of the FGF (Fig. 6c). These facies preserve small-scale hummocky cross-bedding, load cast, flame structures, and convolute bedding showing some overturned fore sets and score fill structures. It consists of moderately to well-sorted fine- to medium-grained clean washed sand size mono-crystalline quartz grains dominantly cemented by iron

Fig. 6 **a** Outcrops of the SBBR mark the northern periphery of the Barmer basin situated near NH 68. **b** Outcrops of a conglomerate bed of FGF unconformably rest over the sandstone of Jurassic Lathi formation. **c** Outcrops of Borasar ridge showing well-preserved fining upward lower siliciclastic sequences of FGF

oxide and carbonate minerals. Significantly, it also preserved a few reworked phosphatic dung, coprolites, and teeth of crocodiles (Gour 2005 and Akash, 2010). These fragmentary bones along with *Ophiomorpha*, *Margaritichnus*, and *Teredolites* trace fossils indicate high energy conditions in the near coastal environment in the Barmer Basin (Gour 2005 and Parihar et al. 2016). These features along with similar trends of granulometric variations of these lithofacies match with modern near-shore beaches of a tidally influenced environment. Further, the vertical and lateral relationship of these facies envisaged that clasts have been dominantly derived from the reworking of the delta front and delta margin facies which represents the destructive phase of the deltaic system in the Barmer Basin. All the above sedimentary structures, framework elements, and features with a rich assemblage of the biota of fluvio-deltaic to beach environment make Borasar a significant geosite of India.

Geosite 2: Bariyada Section

The proposed Bariyada geosite is located about 7 km south of Fatehgarh just near Bariyada village situated on Jaisalmer-Barmer Road (NH- 68). It is known for the type section of an excellently preserved wide variety of the phosphorite beds of FGF, named here as the phosphorite zone. It extends from west of Bariyada to south of Kodiasar-Sandha village covering about 3.9-km^2 area and marked the northern periphery of the Barmer basin (Figs. 1b, 2, 6a, and 10; Table 1).

Phosphorite Zone The phosphorite zone of FGF is significantly endowed with a wide variety of phosphorite types represented by phosphatic sandstone at the base followed by the bone bed, bedded phosphorite, gastropod beds, and upper phosphatic sandstone (Figs. 3, 10, and 11a, b). Various lithofacies of this zone encompass many reworked biotas from lower beds, a rich assemblage of microvertebrate biota, unique magnetic spherules, and the signature of five global events that make this geosite an "Outstanding Universal Value" landscape of India (Fig. 10; Table 1; Gour 2005; Mathur et al. 2005a, 2005b, 2006, 2019a, 2019b; Compton 2009).

Lower Phosphatic Sandstone The upper part of fine- to medium-grained beach sandstone grades upward into phosphatic sandstone of the basal phosphorite zone of FGF. It is composed of moderate to well-sorted clean washed sand of quartz and a variety of bioclasts, dominantly cemented by phosphate and a small amount of carbonate minerals. The lower part of this sandstone preserves reworked bioclasts of large bones and phosphatic dung as discussed above. The taphonomy of this bed suggests the stray accumulation of

Table 2 Geosites of the SBBR showing geodiversity with global events of geoheritage significance of national and international values

Geosites of the SBBR	Geodiversity Elements	Geoheritage Elements	Significance
Borasar	Display features and gradational lithofacies from conglomerate to siltstone that built fining upward sequence of the FGF (Fig. 6c). Imbrication structures in conglomerate and its contact with sandstone of the Lathi Formation (Unconformity). Preservation of trough cross-bedding (Fig. 7a), phosphatic dung (Fig. 7b), teeth and bones of crocodile (Fig. 8a–d), and possibly bone of dinosaur (Fig. 9) in lower siliciclastic sequence showing great geodiversity in sediments of lower FGF	Showcase of sedimentary and paleontological type geoheritage. Displaying fluvial-deltaic sedimentary features and processes in fining upward siliciclastic sequences. Preservation of variety of fossils. Signature of abrasion, tossing, and lifting with to and fro movement of bioclasts denoting reworking processes under high energy milieu. Section preserved signatures of destruction of delta margin and delta front deposit	National significance with geotourism and educational values
Bariyada	Phosphorite zone of the FGF preserved various lithofacies at Lordi Nala ridge section (Fig. 10) significantly showcases: Four layers of bone bed-bedded phosphorite preserved wavy laminations of microsphorite, granular, pelletal, phosphate, and reworked bioclasts (Fig. 11a and b) with rich assemblage of microvertebrate vertebra (Fig. 11c) and teeth (Fig. 11d) and foraminifera fossils denoting subtidal marine environment. Gastropod fossils as phosphatic mold and casts in gastropod beds of Maastrichtian age (Fig. 11e and f) showing intertidal pool deposits. Thin ferruginous layer at top contains magnetic spherules, dust, and ejecta material (Fig. 12a–h)	Showcasing beach to near coastal marine sedimentary structures, features and processes. Significantly display five global events: (1) Late Cretaceous Transgression event, (2) Late Cretaceous phosphogenic event, (3) mass extinction event, (4) volcanic orimpact events, and (5) KTB event of the Earth Displaying significant tectonics, sedimentological, paleontological, and volcanic and paleogeographic type geoheritage	International significance with educational and geotourism values
Sandhuwa	Preservation of bone bed-bedded phosphorite (Fig. 11a and b) with overlying various facies and features of upper coarsening upward volcanoclastic sequence of FGF. This geosite also preserved contact (unconformity) between FGF and Mata Ji Ka Dungar Formation	The marine processes similar to Bariyada geosite (bone bed-bedded phosphorite) culminated to deposition of the upper volcanogenic siliciclastic sequence of FGF under fluvial regime	National significance with scientific values

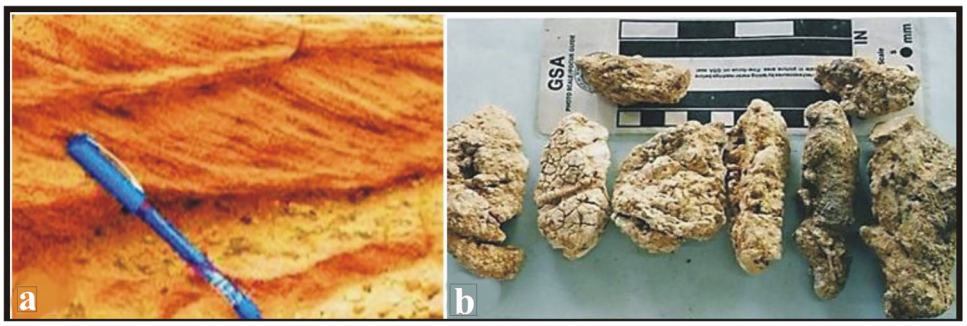

Fig. 7 **a** Co-set of trough cross-bedded sandstone conformably overlays the dung-bearing pebbly sandstone. **b** Phosphatic dung of dinosaurs, crocodiles, and turtles recovered from Bariyada ridge (Gour 2005 and Akash 2010)

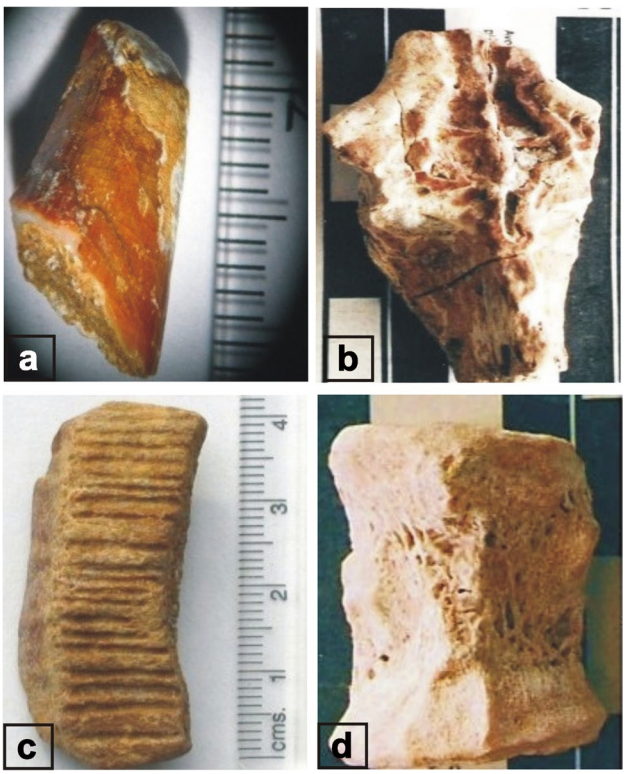

Fig. 8 **a** Crocodile fossils recovered from the high ridge of Bariyada geosite: **a** teeth, **b** cranium fragment, **c** dental plate, and **d** vertebrae (Gour 2005; Akash 2010)

Fig. 9 Fragmentary Femur from the lower siliciclastic sequence of FGF from Bariyada geosite (Gour 2005; Akash 2010)

Fig. 10 Outcrops showing various facies of FGF and underlying Lathi Formation (right bottom) with overlying siliceous earth of the Akli Formation (left bottom) at Bariyada Geosite

these bones and dungs by ancient river jamming processes. The upper part of this horizon displays wavy to lenticular bedding with ripple drift laminations. These features along with the similar trend of granulometric variations match with the modern near-shore environment. Disarticulate and rounded nature of reworked bones reflect abrasion to tossing and lifting to and fro movement of bioclasts indicating the tidal influence on the ancient beaches of the Barmer Basin. Many bones are fragmentary, compressed, and twisted indicating high energy stormy environment in which bones were quickly dumped on proximal ends of the beaches of the ancient Barmer Sea. Various characters with phosphatic and carbonate cement of these facies clearly mark the commencement of fully marine conditions in the Barmer Basin in which a significant bone bed was deposited (Table 1; Mathur et al. 2005a; 2006 and Compton 2009).

Bone Bed The phosphatic sandstone grades upward into a 1.8- to 2-m-thick bone bed composed of four distinct sand layers. Each layer of bone bed significantly preserves signatures of global events (See Table 3). Hence, it is named here as an event bed (Fig. 11a, b) that displays various geological processes of great scientific value of global importance. Accordingly, the first lower sand layer is composed of quartz grains, intraclasts of biota dominantly cemented by carbonate and phosphate minerals. The presence of wavy and ripple

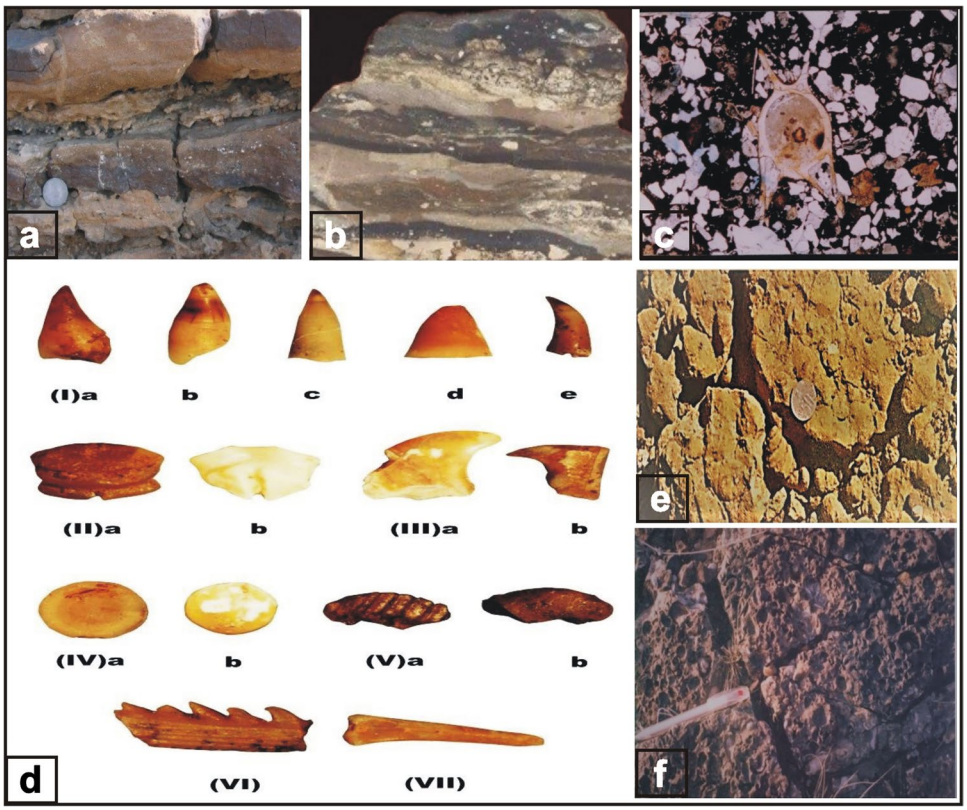

Fig. 11 **a** Outcrop of bone bed showing its various layers, **b** bedded phosphorite, **c** fish vertebrae, **d** microvertebrates fossils preserved in bone bed, **e** non-phosphatic gastropod bed, and **f** phosphatic mold and cast in gastropod bed of phosphorite zone of the FGF at Bariyada geosite (Mathur et al. 2006)

drift laminations with other characters mark the transgression event which destructs and erodes the fossil-bearing fine to medium-grained sandstone (delta front and beach deposits), hence preserving many reworked fragmentary biogenic materials in it. The second sand layer marks the deposition of primary phosphate (microsphorite laminations) purely composed of calcium phosphate representing the commencement of Late Cretaceous phosphatization (global phosphogenic event and the appearance of full marine condition in Barmer Basin (Akash, 2010). The third sand layer of the bone bed is characterized by creamy white granular objects on outcrops of the bone bed which are actually the remains of fish, i.e., rich assemblage of micro-vertebrate (Mathur et al. 2006). It includes many species of fish skeletal debris, fecal pellets, vertebrae (Fig. 11c), scales and fins, and a wide variety of dental plates and teeth of (i) Enchodus ferox, (ii) Lapisostius indicus, (iii) Dasyatis decanansis, (iv) Stephanodus Ibycus, (v) Egertonia, (iv) Igdabatis, and (vi) Siluroid spines (Fig. 11d). This rich assemblage of micro-vertebrate suggests a subtidal environment. The non-phosphatic-phosphatic mold and cast of gastropod (Fig. 11e, f) showcase unique intertidal pool deposits in the Barmer Basin. Besides gastropod fossils, the rich micro-vertebrate, foraminifers, ostracodes, *Teredolites*, and other marine biotas of bone bed represent the typical Maastrichtian global extinction event in the Barmer Basin (Mathur et al. 2006; Compton 2009 and Akash 2010). The similar event and close faunistic affinities with those from infra-trappean and inter-trappean sequences of Lameta, coeval Pab Formation of Pakistan, and Mediterranean sequences of North Africa with Middle East belt suggest its connection with the western Tethyan shorelines (Gour 2005; Mathur et al. 2006; Compton 2009). These features and events significantly showcase the global paleogeographical importance of the scientific values of the bone bed of the FGF.

The fourth and topmost 3–7-cm discontinuous thin ferruginous layer significantly contains high-temperature–pressure ejecta material (Fig. 12a, b), teeth in ejecta (Fig. 12c), highly magnetic dust and rounded magnetic spherules (Fig. 12d, e), dumble shaped spherules (Fig. 12f), microbrecciated matrix and spherules of different composition (Fig. 12g, h) (Mathur et al. 2005a, 2005b, 2012; 2019a, 2019b). The magnetic spherules of this layer are of two types. The first one is dominantly Ti–rich and the second is composed mainly of Fe. The Ti–rich spherules were derived from the intense volcanic event of Late Cretaceous Rageshwari activity in the Barmer Basin (Compton 2009) related to the Deccan Trap (Mathur et al. 2019a, b). The Fe-rich spherules possibly originated from an impact event (?) that occurred at the Siwana Ring Complex (SRC) of western Rajasthan, India (Akash, 2010 and Mathur et al. 2012). Additionally, this magnetite, goethite, and titano-magnetite-rich layer possibly represent global K/T Boundary events in

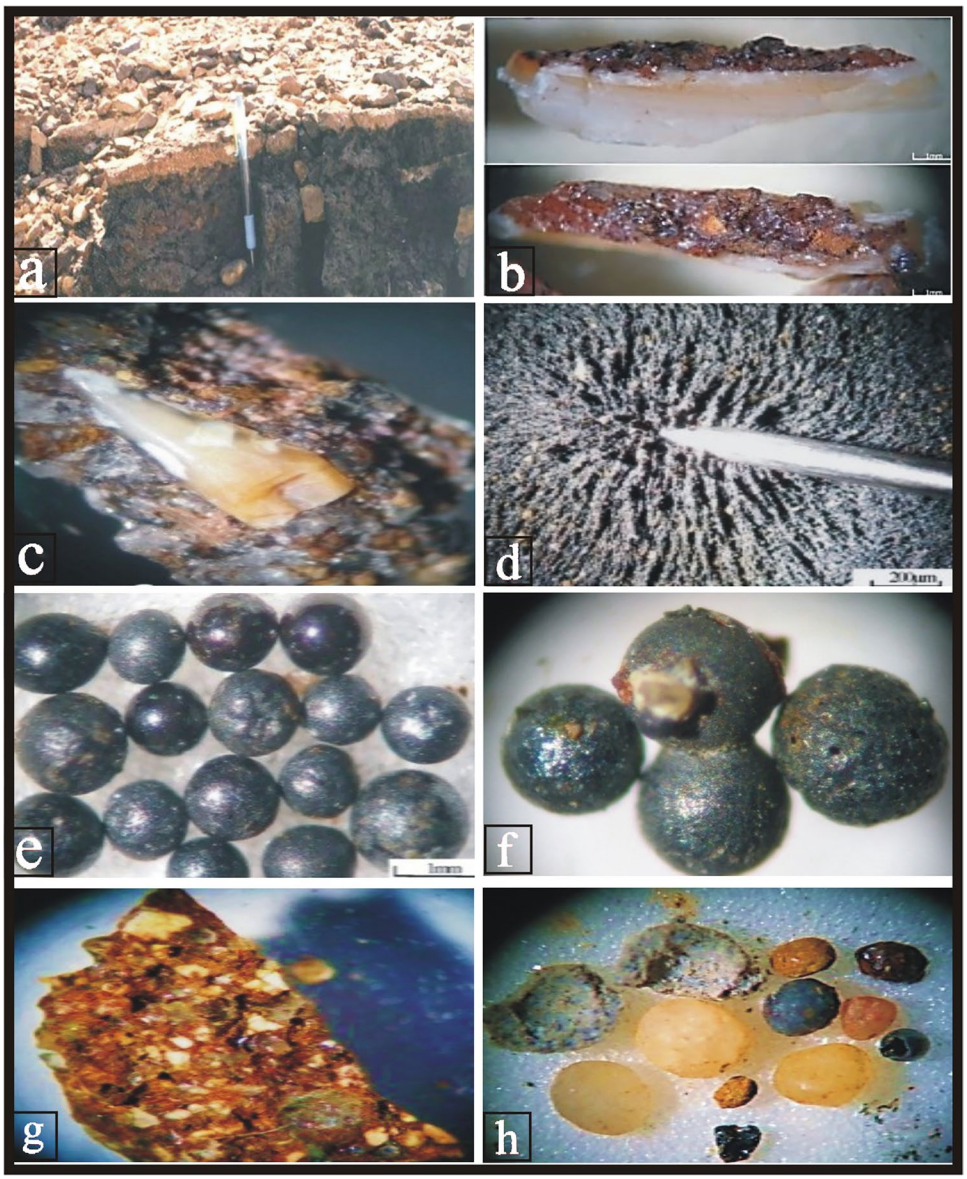

Fig. 12 a Thin ferruginous layer at top of the bone bed significantly contains **b** high-temperature–pressure ejecta material, **c** fish teeth in ejecta material, **d** highly magnetic dust, **e** rounded magnetic spherules, **f** dumble-shaped spherules, **g** microbrecciated matrix, and **h** spherules of different compositions which are preserved in bone bed at the Bariyada geosite (Mathur et al. 2005a and b)

the stratigraphic record of the Barmer Basin (Mathur et al. 2019a; 2019b). As such, the various layers of bone bed preserved signatures of five global events in a thin bone bed horizon indicating a record of sudden catastrophic events which were responsible for the mass destruction of fauna in the Barmer Basin (Tables 1, 2, and 3).

Gastropod Bed Significantly, as lateral deposits of bone beds in the depressions (intertidal pools), a huge amount of gastropod shells preserved are termed as gastropod beds. It is divided into two horizons, the lower non-phosphatic and upper phosphatic in nature. The non-phosphatic gastropod beds are dominantly composed of gastropod remains, detrital quartz, and some micro-vertebrate skeletal material set in a sandy carbonate matrix. The upper beds excellently preserved molds and casts of phosphatic gastropod shells (Fig. 11e, f; Akash, 2010). Such preservation of phosphatic molds and casts of gastropod shells are unique and rare in the world imparting additional scientific values to this geosite. Similar types of phosphate molds and casts of gastropods have only been reported from Negev phosphorite of the Middle East of great scientific values (Abed 1988).

The interbedded layers of bone bed excellently preserve fossils of *Teredolites* indicating full subtidal conditions in the Barmer Basin. All these characteristics, unique types of phosphate deposits, and global events envisaged that this geosite is endowed with many features of great geoheritage values of international significance. Geographically, this geosite is well connected to Akal Fossil Park (petrified wood and trace fossils) and Barmer Fossil Park containing a rare and rich assemblage of wood boring trace fossils situated on the same road (NH-68) can be the excellent

Table 3 Various layers of bone bed of the SBBR showing global events of international significance

SN	Bone Bed	Features and Fauna	Event	Environment
1	Layer-I	Wavy and ripple drift laminations, preservation of reworked bioclasts of phosphatic dung and bones of crocodile, turtle, and dinosaur	Late Cretaceous Global Transgression Event. Destructive phase of Delta	Delta front to near coastal beach environment
2	Layer-II	Thin phosphatic primary microsphorite with pelletal and granular secondary phosphate laminations in bone bedded phosphorite	Display features and signatures of mechanism of Phosphate upwelling in the Barmer Basin with reworking and winnowing processes indicate Global Late Cretaceous Phosphogenic event	Subtidal marine environment
3	Layer-III	Pelletal, granular, and biogenic intraclasts of phosphate with rich assemblage of fossils of microvertebrates. Carbonate and phosphatic Gastropods beds with shells, molds, and cast	Maastrichtian Global Extinction event caused by global KT bolide impact (?) followed by Ragheshwari volcanic activity	Near coastal shallow to subtidal with storm and tsunami features of high energy conditions and intertidal pool deposits
4	Layer-IV	Thin ferruginous layer containing Ti- and Fe-rich ejecta material with magnetic spherules, magnetic dust, and other features	K/T boundary	Shallow marine, near coastal environment

geo-trails in the Barmer Basin (Mathur et al. 2018, 2020a, b). These three fossil sites of significant geoheritage would be helpful in promoting tourism through "geotourism" for the socioeconomic development in western Rajasthan, India. The evidence discussed above clearly manifests that this geosite is represented by the significant landscape of an Outstanding Universal Value that represents the global geodiversity of geoheritage values and provides a narrative for geo-education and geotourism (Table 3). Significantly, these geosites are few among the world's KTB sites that showcase the cause and effect relationship manifested in how life was destructed suddenly by catastrophic events in the Barmer Basin (Mathur et al. 2019a, and 2019b).

Geosite 3: Sandhuwa Section

The Sandhuwa geosite is located about 7 km SE from Fatehgarh town situated on Jaisalmer-Barmer Road (Fig. 1b, 2). This geosite covering about 4.2-km^2 area in the NE part of the Barmer Basin represents the northeastern part of the SBBR. It is known for the type section of excellently preserved coarsening upward volcanoclastic sequences of the FGF and overlying siliceous earth of Bariyada Member of Akli Formation (Fig. 3; Mathur and Kumar 2003; Compton 2009). The upper volcanoclastic sequence consists of siltstone interbedded with clay-stone at the base followed by fine-, medium-, and coarse-grained sandstone and quartz arenite at the top (Mathur et al. 2006). The individual facies of this sequence show a gradational relationship among them and preserve small-scale trough cross beddings, numerous sand ball structures, and a palaeosol marked by a laterite horizon. The sandstones of the FGF form the high-quality reservoirs for petroleum deposits of the Barmer Basin (Compton 2009). The various sedimentological characters show that the upper siliciclastic sequence is represented by braided and meandering sheet-like channels which are well preserved at the Sandhuwa geosite.

The quartz arenite inter-fingers with the siliceous earth deposits of Bariyada Member of Akli Formation of Early Paleocene age represent patchy deposits of the volcanic sand (Fig. 10; Gour 2005; Sisodia et al. 2005; Dolson et al. 2015). The siliceous earth occurs as soft, porous, and homogeneous light-weight opaline silica deposits that form a unique and separate sedimentary unit in the Barmer Basin. It mainly consists of silica (75 to 91%), alumina (3 to 11%) with minor quantities of iron (0.6 to 2.1%), and magnesium (~ 0.4 to 1.4%). The presence of volcanic debris such as glass shards, agglutinates, hollow spheroids, kinked biotite, feldspars showing oscillatory zoning, ilmenite, and native iron clearly reveal that it is a volcanic ash deposit probably derived from Ragheshwari volcanism of the Barmer Basin (Nahar et al. 1997; Sisodia et al. 2005; Compton 2009).

Because of its good quality, siliceous earth is extensively mined in the northern part of the Barmer Basin. The unique characters discussed above clearly manifested that the proposed three geosites (Sandhuwa, Bariyada, and Borasar) of SBBR are showcasing significant geological features of universally outstanding geodiversity of great geoheritage values. Accordingly, the unified geographic area of the three geosites of SBBR can be the first potential Geopark site in the Barmer basin in India.

Geo-conservation of Geosites of the SBBR

The field survey of the proposed three geosites clearly manifested that those geological key sections at various sites of the SBBR are damaging as the siliciclastic material is illegally being used as building and road construction material. Similarly, the carbonate dominant huge gastropod beds are rigorously utilized in lime industries locally along with vandalism of fossils. These activities are going on for a long time and are a great concern to the geoscientific community. The georesource and fossil-bearing sections which are having significant geoheritage elements should be conserved, as the formation of such strato-type sections required millions of years to form. Thus, based on the Nature Conservancy Council (NCC) 1990 (Page 2018), the significant georesources and fossil localities of the SBBR can be categorized into two classes for preparing future protection and conservation plans. Accordingly, the Sandhuwa and Borasar geosites of the SBBR come in the category of exposure sites as both display features, structures, and geological processes of channel lag, delta margin and delta front processes and deposits of Late Cretaceous–Danian geological earth history. Similarly, the Bariyada geosite comes in the category of integrity site of great importance for research and academic values as it showcases five global events, terrestrial to marine geological processes, and significant Late Cretaceous earth history along with rich assemblages of fossils and framework elements in a single section (Tables 2 and 3). This site is under active erosion, local illegal quarrying, and vandalism of fossils resulting in the loss of observational opportunities and important data of international significance. The strata, well-preserved fossils, and geological features are damaged and are also challenging to transport from the in situ to ex situ position resulting in permanent loss of geological material of international importance. This situation relates to movable heritage; the best way to preserve them can be possible through collaboration with the local or nearest geological institute to preserve the exposed or transported specimens to the institutional/local museum as a repository. However, the integrity site protection/conservation needs planning to protect them as in situ preservation. Hence, the proposed Geopark concept under the present study can be the best tool to conserve significant geoheritage sites of the SBBR. It will educate the public and generate awareness about the importance of the Earth Sciences and will contribute to the sustainable economic development of rural regions through geotourism (Kelley et al. 2019).

Discussions

Many landforms in India encompass unique geodiversity elements that are not utilized so far to establish their geoheritage significance for sustainable economic development. Further, due to a lack of public awareness and protection policies, several famous geological sections are degrading and damaged in India. Under such situations, the importance and appreciation for the concepts of geodiversity and geoheritage have grown steadily over the years in India (Ahluwalia 2006; Mazumdar 2010; Biswas and Harinarayana 2013; Swarna et al. 2013; Singh 2013; Singh and Mathur 2014; Phani 2016; Mathur et al. 2019b; Shekhar et al. 2019; Mathur et al. 2020a, 2021; Chauhan et al. 2022). However, the task is still in the preliminary stage in comparison to its developments at the international level (Brilha 2005, 2009, 2016; White and Mitchell 2006; Pereira and Pereira 2010; Wimbledon 2011; Antić and Tomić 2017; Reynard and Brilha 2018). As a result, the concepts of Geopark and geotourism are not explored for sustainable socio-economic development in India. It is oblivion that a developing nation like India has a higher dependency on primary resources and faces tough challenges and hindrances against such developments due to a lack of awareness, devoid of any geoheritage protection policies and guidelines. Among the recognized 32 national geological monuments of India, even a single site is not included from the Barmer Basin despite its rich geological, geographical, geomorphological, historical, and cultural diversity.

The methodology of Mathur et al. (2021) proposed for the selection and assessment of geosites for geoheritage, education, and geotourism values in the Indian context is very helpful for the promotion of these aspects in India. Accordingly, with this assessment, three geosites are selected on the SBBR landscape. These are significantly endowed with varied geological records, geomorphological varieties, rich assemblage of fossils, mineral deposits, numerous structural features, and signatures of global events with scenic landforms. All these geoheritage elements make the SBBR a significant geological entity and a potential site of Geopark in India to be utilized for geo-education and geotourism for the socioeconomic development of the regions in the Thar Desert of western Rajasthan.

Essentially, after getting the protected status, geosite 1 (Borasar) showcases wide geodiversity in its 2.27-km^2

area that includes contact of Lathi sandstone and petrified wood beds (Jurassic) with unique features of fining upward sequence of the FGF showcasing channel lag, delta margin and delta front processes and deposits. The classical preservation of these elements has provided an abundance of sedimentary and ecological models for use in Earth science history analogs for the Jurassic-Cretaceous stratigraphic record. The excellent preservation of the features of tide-dominated delta of the FGF at this geosite is among a few such deltas globally which have an extreme macro-tidal environment set in a tropical warm and humid climate biogeographic zone. The Borasar geosite also significantly preserves fossils of phosphatic dung and coprolites of fishes, turtles, and crocodiles along with teeth, cranium fragments, vertebrae, and a dental plate of the crocodile. Significantly, this geosite also preserved fragmentary femur bone possibly of dinosaurs along with trace fossils like *Ophiomorpha* and *Margaritichnus* and *Teredolites* of the Late Cretaceous age making it a very important Sedimentological and Paleontological geoheritage of India. The conservation of the Borasar geosite must be of primary concern to the government as it holds rich and highly diverse biodiversity granting insights into the Cretaceous biosphere of the earth in this part of eastern Gondwana land.

Similarly, the phosphorite zone of FGF at Bariyada geosite preserves a rich assemblage of fishes (microvertebrates) including vertebrae, teeth, fins, spines, and scales with bone fragments in the bone bed of the FGF with a diverse assemblage of marine benthic gastropods, foraminifers, and dynocysts suggesting Late Maastrichtian to Danian age to FGF straddling KTB (Mathur 2019a and 2019b). These evidences with previous and present work indicate that the Bariyada geosite can be a significant paleontological geoheritage site like many nationally and internationally famous sites (https://www.gsi.gov.in; Gehling et al. 2019; Lewis 2020). Additionally, the Bariyada geosite preserves signatures of global events (phosphogenic, mass extinction, volcanic, and/or impact with KTB) making it an important geoheritage site of the global scientific value. Additionally, this geosite showcases the ecosystem of animals lived in the marine environment highlighting the Cretaceous–Early Paleocene geological history of the Earth and also the paleogeographic connection of the Cretaceous Barmer Sea with Middle East countries. Significantly, it is the only site that displays the cause (sudden catastrophic events) and effect (mass-mortality of animals) relationship related to KTB and the Late Maastrichtian–Denian history of the Barmer Basin.

It is well known that dinosaur fossils attract and fascinate tourists and visitors; hence, availability to observe these fossils with fishes, crocodile, turtle, gastropods, *Teredolites*, and trace fossils makes it an excellent Paleontological site for geo-education and geotourism in India. Additionally, large piles of non-phosphatic gastropods with molds and casts of phosphatic gastropods (rare type) are another attraction imparting great geotourism values to this site. Thus, all these geological features of Bariyada geosite make it a universally outstanding geodiversity site in the first proposed Geopark of the Barmer Basin (Tables 1, 2, and 3; Mathur et al. 2005a,2005b,2006, 2018,2019a, b). Intrinsically, the paleontologically significant geosite has excellent scientific and socioeconomic value, which not only improves our understanding of the earth's evolutionary history but also brings economic effects to the local rural areas by promoting geological tourism and at the same time enhancing regional's visibility.

The Sandhuwa geosite remarkably displays features of post K/T boundary processes and features of regression events in the Barmer Sea with the resulting landscape of vast fluvial plains deposited in the form of coarsening upward volcanoclastic sequences. The unconformably overlying siliceous earth of Bariyada Member of the Akli Formation displays the vast deposits of volcanic ash derived from volcanism in the Barmer Basin. These features with palaeosol of laterite horizon separating the Akli Formation and the Dharvi Dungar Formation in the Barmer Basin make this geosite an attractive site for education.

Essentially, the conversion of unique three geosites into a Geopark is not solely for scientific purposes but it will contribute to the education, tourism, and preservation of natural geoheritage, which will help to develop the local and rural economy. It will also provide basic awareness to the local and international visitors and also gives opportunity to the guides, village leaders, and school teachers for professional training from the local geologists. This will ultimately help in protecting the invaluable geoheritage of the Barmer Basin. Since, all three geosites of the SBBR are located in open areas and hence are subjected to weathering, erosion, illegal mining, and human interaction need protection. The geoheritage significance of the proposed Geopark is immensely increasing as it is endowed with geoheritage of international significance and is closely associated with NDP having archaeological heritage which provides additional value to it. Thus, the Geological Survey of India and the Archaeological Survey of India (principal government authorities) should ally for the protection and conservation of geodiversity and cultural heritage of the proposed Geopark at SBBR.

Conclusion

The SBBR is situated between Jaisalmer and Barmer cities which are well known nationally and internationally through its exceptional geological, historical, and cultural geo-monumental heritage for tourism since the medieval period. The SBBR is a place of the spectacular landscape of two critical periods of the Earth's history with one significant national geological monument that has undeniable potential for being developed as a National Geopark and/or UNESCO Global Geopark. Additionally, the landscape of the SBBR has a strato-type section of land and Sea, providing an understanding of significant processes of Earth's history related to the global transgression and phosphogenic events and their relation to biogenic activities. It also remarkably preserves the signatures of impact and or volcanic events related to mass mortality of fauna at KTB providing great scientific value to SBBR. Thus, three selected outstanding geosites would be helpful in promoting geotourism through the proposed Geopark in India. The knowledge that corresponds to the geoheritage types of SBBR is of educational and geotourism values with the potential to become a unique natural laboratory for all sorts of visitors. Additionally, the civilization and cultural history of this part of India will be presented and interpreted for the visitors in an exciting and engaging way. Further, the historical-cultural tourism combined with the geo-trail of fossil occurrences in Jaisalmer and Barmer would definitely add geotourism elements in western Rajasthan ultimately helping in promoting tourism and allowing research for the advancement of sciences. Hence, geoheritage with existing tourism facilities at Jaisalmer and Barmer puts the proposed area of the SBBR in a strong position to develop the first Geopark in western Rajasthan, India. Further, it will create a multifaceted site of geoheritage conservation imparting public education and tourism with the socio-economic development of the region. On the other hand, this would have a direct impact on the areas by improving human living conditions along with rural developments in India.

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Author Contribution All authors have made equal contributions.

Declarations

Competing Interests The authors declare no competing interests.

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