Geoheritage (2023) 15:127
https://doi.org/10.1007/s12371-023-00896-9

ORIGINAL ARTICLE

Assessment and Threat to Significant Geoheritage of Soorsagar Formation of Jodhpur Group of Marwar Supergroup, Western Rajasthan, India: A Geological and Remote Sensing Approach

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Received: 25 April 2023 / Accepted: 17 October 2023

Abstract
The landscape of the northern part of Jodhpur located in western Rajasthan, India is endowed with a wide variety of volcanic and sedimentary type geoheritage of global significance. These are represented by rocks of Malani Igneous Suite (MIS) of Cryogenian age forming basement for overlying Ediacaran Jodhpur Group (JG) of Marwar Supergroup (MSG). Unique and rare volcanic features of MIS and its interface with the sandstone of JG have been declared as the National Geological Monuments of India. The site-specific landscape of the Soorsagar Formation (SSF) of JG covering about 54 sq. km area in the northern rural part of Jodhpur provides an outstanding record of seven types of geoheritage. Among these, the most significant sedimentary and paleontological geoheritage is represented by a treasure of sedimentary structures and a rich assemblage of Ediacaran fossils of marine paleo-ecosystem. Such records of past tectonics, climate, paleogeography, paleoecology, and environments showcasing 200 million years of Earth's history characterize the land-sea interaction and distribution in this part of Eastern Gondwana land. Thus, it displays global geodiversity of both intrinsic and extrinsic geoheritage values that provide eminent narratives for geo-education and geotourism. However, the unique geoheritage of the SSF landscape is under great threat to degradation and damage dominantly due to anthropological activities. To study such threats and damage, a study is conducted using various geological and remote sensing techniques. Interpretation of satellite images of about fifty years reveals that dominantly sandstone mining along with urbanization activities is responsible for damaging the significant geoheritage of SSF. The present paper embodies geoheritage characterization and assessment of the landscape of SSF with its progressive damage to understand the necessity for its conservation through protected status by Geopark creation in the northern rural part of Jodhpur.

Keywords *Mehrangarh—Soorsagar* ridge · Jodhpur · Ediacaran landscape · Geoheritage · Geotourism · Threat · Remote sensing techniques · Geopark and promotion of tourism

Introduction

Culturally vibrant Jodhpur City also referred to as "Blue City" and "Sun City" is a gateway to the Great Thar Desert situated in the Marwar region of northwestern India. The study area is situated about 13 km in the northwest rural part of Jodhpur city and is represented by a landscape of igneous and dominantly sedimentary terrain (Fig. 1). Geomorphologically, it represents the northern part of Kayalana-Soorsagar Ridge (KSR) which is highest (260–404 m) and largest among the four ridges of Jodhpur (Mathur et al. 2021). The northern part of KSR, covering about 54 Sq. km of the study area is represented by low-lying ridges and bold hillocks, forming a spectacular inselberg-type landscape in

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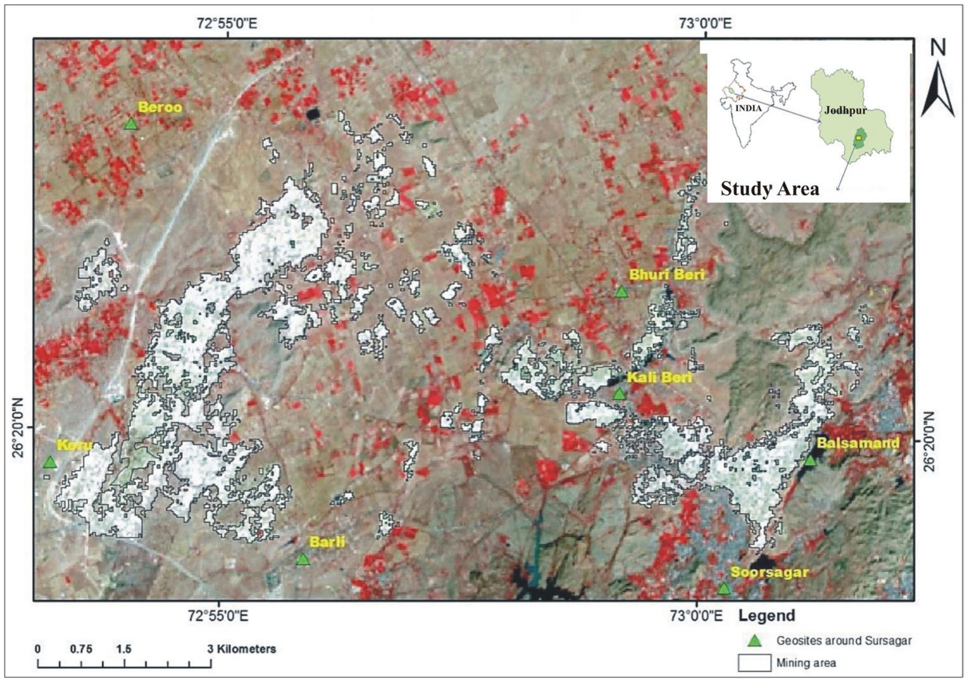

Fig. 1 Landsat image of the northern part of Mehrangarh-Soorsagar Ridge in Jodhpur showing mining areas (white), settlements, vegetation and water bodies

Jodhpur, western Rajasthan, India. Geologically, the study area is dominantly represented by rocks of SSF of JG of MSG and underlying basement of rhyolite of MIS. Significantly, these rocks are endowed with a remarkable geodiversity of seven magnificent types of geoheritage showing international and national significance. However, this area is also known for rigorous mining activities (Fig. 2; Mathur 2021) and significant geoheritage sites are under great threat of damage thus, require their characterization and geoconservation. Geoconservation concept at the international level is strictly the protection of geoheritage and geodiversity sites that initially need assessment of threat (Brilha 2016). However, several geoheritage sites having global significance are being degraded and destroyed due to unplanned urbanization and mining activities. Therefore, the authors identify, characterize and critically analyse the geoheritage elements in the rocks of the landscape of the study area. Further, to assess the threat to significant geoheritage of SSF we utilized various geological, remote sensing and GIS techniques. In this paper, we have discussed an overview of the geology of the Jodhpur Group and seven types of geoheritage of global and national significance. The combination of all geoheritage types in one complex type geosite with existing tourism facilities puts the proposed area in a favourable position to develop a dynamic Geopark in Jodhpur.

Fig. 2 Spectacular landscape of basement rocks of MIS (in back background) and outcrops of rocks of SSF of JG (foreground) in mining areas of KSR

Geological Setting

Geologically, the landscape of the study area is represented by volcanic rocks of Malani Igneous Suite (MIS) of Cryogenian age forming basement and overlying sediments of Jodhpur Group (JG) of Ediacaran age of Marwar Supergroup (MSG). MIS in the study area has evolved through two stages which are represented by I. Acid lava flows, and II. Acidic inter pyroclastic flows. MIS is considered the third largest, terrestrial, anorogenic, and felsic, volcanic province of the world that witnessed Pan-African orogeny related to the splitting of the Rodinia Supercontinent (Bhushan 2000; Pradhan et al. 2010; Mathur et al. 2021). Unique and rare volcanic features of MIS have been declared as the National Geological Monuments of India. Recently, nine magnificent geosites have been established in the southern part of the Mehrangarh-Soorsagar ridge of Jodhpur endowed with several geoheritage elements of global values (Mathur et al. 2021). The northern part of the ridge is dominantly comprised of thick multilateral and multi-storeyed siliciclastic sequences of JG of MSG. Chronostratigraphically; JG is divided into *Umed Bhawan* Formation (UBF), *Soorsagar* Formation (SSF), and *Motisar* Hill Formation (MHF; Fig. 3) representing different lithofacies associations and sedimentary environments (Fig. 4; Pareek 1984; Chauhan 1999; Mathur et al. 2019a, b). The UBF of JG has unconformably overlain the uneven basement of rocks of MIS. UBF forms coarsening upward sequences comprising shale at the base followed by sandy shale, shaley sandstone, fine to medium-grained sandstone and coarse-grained to pebbly sandstone at the top. The abundant presence of textbook style trough and festoon cross beddings with other characters indicate a typical Deltaic environment for UBF (Chauhan et al. 2004; Pandey and Bahadur 2009; Mathur et al. 2022).

The study area is mainly represented by siliciclastic rocks of SSF comprised of minor siltstone, and fine, medium and coarse-grained sandstones with the occurrence of treasure of sedimentary structures and Ediacaran fossils. The typical section of the landscape of SSF can be observed in Mandore-Balsamand, Chopar-Soorsagar, Bhuri Beri, Kali Beri, Keru, Beroo and Barli areas. These areas are known for extensive mining of Jodhpur sandstone (Fig. 1 and 2). Sedimentological and paleontological evidences reveal beach to near coastal shallow marine setting for the sediments of SSF (Fig. 4). Under this environment due to repeated reworking and winnowing processes, well-sorted and mineralogically well-mature fine to medium-grained sandstones formed under moderate to high energy regime.

Petrographically, it is classified as 'quartz arenite' comprising sub-rounded to rounded monocrystalline quartz grains with cementation by silica and iron oxide minerals. It is a pink to creamish pink colored, hard and compact rock with high endurance and resistance to weathering. These

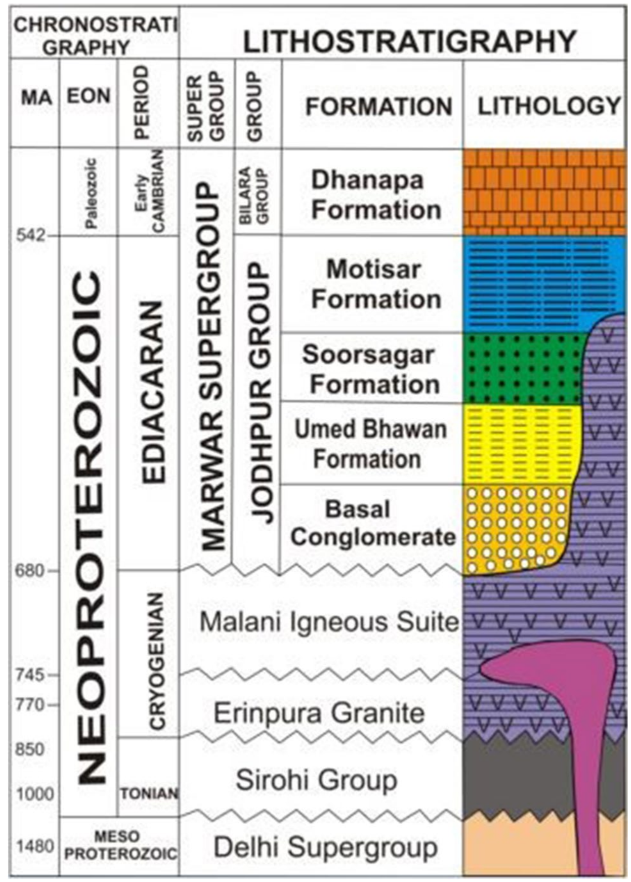

Fig. 3 Lithostratigraphy of rocks of the JG of MSG (Mathur et al. 2019a and b)

characters render it suitable for intricate carving and provide aesthetic value hence, also utilized in a range of artefacts and handicrafts within India and abroad. Popularly, medium-grained sandstone of the study area is known as Jodhpur sandstone (*Chittar ka Pathar*). It is a good quality building and dimensional stone used in the construction of several regional heritage buildings in north-western India hence, considered as a heritage stone resource (HSR) of India (Singh and Mathur 2014; Kaur et al. 2020; Mathur 2021). Jodhpur Sandstone is the most preferred building and dimension stone variety, excavated from several open quarries in the study area (Fig. 1).

Besides HSR, the quality of the Jodhpur sandstone of SSF significantly preserves a treasure of textbook-style sedimentary structures and diverse species of complex Ediacaran fossils. Among sedimentary structures, most profuse preservation of parallel laminations, beddings, tabular-planar cross-bedding, wave and current ripples; interference, adhesion wart ripples, graded bedding, scour-channel structures, and sand ball structures suggest a beach to shallow marine environment (Chauhan et al. 2004; Kumar and Ahmad 2014; Mathur et al. 2019a,

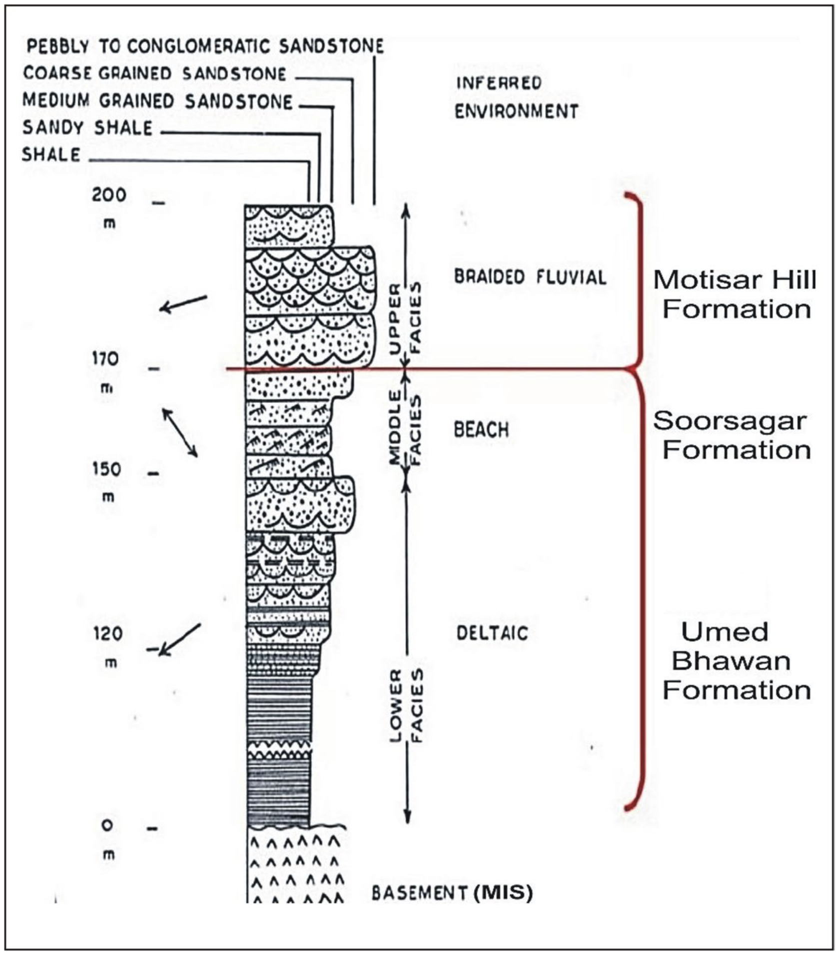

Fig. 4 Lithofacies, paleo-current directions and inferred sedimentary environments of three Formations of the Jodhpur Group (Modified after Chauhan et al. 2004)

b, 2021). The microbial mat bearing Jodhpur sandstone (HSR) also excellently preserved many Ediacaran fossils including medusoid body fossil Marsonia artiyansis, Ediacaran body fossils Aspidella, Hiemalora, Beltanelliformis minuta, Arumberia banksi, Rameshia rampurensis, five armed body fossil, Ediacaran discs with microbially induced sedimentary structures (Raghav et al. 2005; Kumar and Ahmad 2012; Sarkar et al. 2008, 2014; Kumar and Pandey 2009; Samanta et al. 2011; Kumar and Ahmad 2014; Srivastava 2012, 2014; Mathur et al. 2019a, 2021). The preservation of a wide variety of textbook-style sedimentary structures, a rich assemblage of Ediacaran fossils provides great geoheritage values to Jodhpur sandstone. All these characters of the landscape of study area of MIS and JG constitute the strato-type sections and outdoor geological museums in India that display geological processes of about 200 million years of Earth's history. Such records of past tectonics, climates, and environments characterize the land-sea interaction and distribution in this part of Eastern Gondwana land. Thus, the landscape of the study area represents global geodiversity and provides eminent geoheritage narratives for geo-education and geotourism.

Assessment of Geoheritage

Based on the criteria of Brilha (2015) and Mikhailenko et al. (2019), the geoheritage of the study area can be categorized into seven types viz: 1. sedimentary, 2. paleontological, 3. stratigraphic, 4. geomorphological, 5. paleogeographical, 6. ecological and 7. Archaeological. Based on the above-discussed geological attributes, seven types of significant geoheritage are characterized and discussed below:

1. **Sedimentary Type**

   SSF in the northern part of the Jodhpur is represented by 20 to 28-m thick interbedded sequences of siltstone, fine-grained sandstone, medium-grained sandstone and coarse-grained sandstone (Fig. 2). Fine to coarse-grained sandstones are endorsed with the treasure of sedimentary structures viz: a. Ripple marks, b. Cross beddings, c. Graded bedding and d. Other types are laminations, beds, chromatographic, syn-sedimentary, raindrop imprints, rill marks and scour marks structures. All these structures can be observed which profusely occur at quarry sections of Soorsagar Keroo, Beroo, Keru, Bhuri Beri, Balsamand and Mandore mining areas of Jodhpur (Fig. 1 and 2).

a) **Ripple Marks**

Based on published literature and present work, three types of ripple marks observed in the study area are wavy, current and mega ripples (Chauhan et al. 2004; Kumar and Ahmad 2014; Mathur et al. 2019a, b, 2021). Wavy ripples are dominantly represented by straight crest ripples and rounded crest ripples indicating wave erosion and lowering of water level. Sometimes, the ripples crest line appears divided into two or more smaller crests called as branched ripples. The undulatory ripples grade upward into linguoid, adhesion wart and interference ripples which dominantly occur in medium-grained sandstone of the study area. Sometimes the crests become discontinuous and appear as nobs and saddles forming interference ripples. Rarely, ladder-back ripples are also found in which ripple troughs are occupied by mini ripples and give a ladder shape to interference ripples. (Fig. 5a-f). The current ripples occur in the upper part of shallowing upward cycles, represented by irregular and discontinuous crest lines with flat troughs called adhesion ripples. Usually, they have irregularly developed crest lines and are highly asymmetrical in profile. The topmost horizon of the sandstone of SSF is represented by mega ripples.

Significantly, it is noted that various types of ripples developed in sandstones of SSF occur in hierarchical order denoting 3-4 m thick six shallowing upward cycles in the Soorsagar mines (Chauhan et al. 2004; Mathur et al. 2019a, b). Wavy ripples occur in different types like straight and crest ripples that have formed under relatively deep-water conditions and undulatory ripples, sinuous ripples and interference ripples developed under gradually shallowing water conditions. Finally, the hierarchy of ripples culminates into adhesion wart ripples denoting sub-aerial conditions (Fig. 5a-f). Such a hierarchy of ripples exposed at one outcrop at the Soorsagar mine section is a magnificent outdoor lab to understand hydrodynamics and environmental variation of shallowing upward sedimentation. The variety of textbook style preservation and hierarchical order of ripple marks of Jodhpur sandstone in a typical beach environment is a rare type of occurrence in the sedimentary history of the Ediacaran period of India denoting unique geoheritage of great educational values.

b) **Cross Beddings**

The medium to coarse sandstone of SSF displays profuse and excellent preservation of cross-bed-

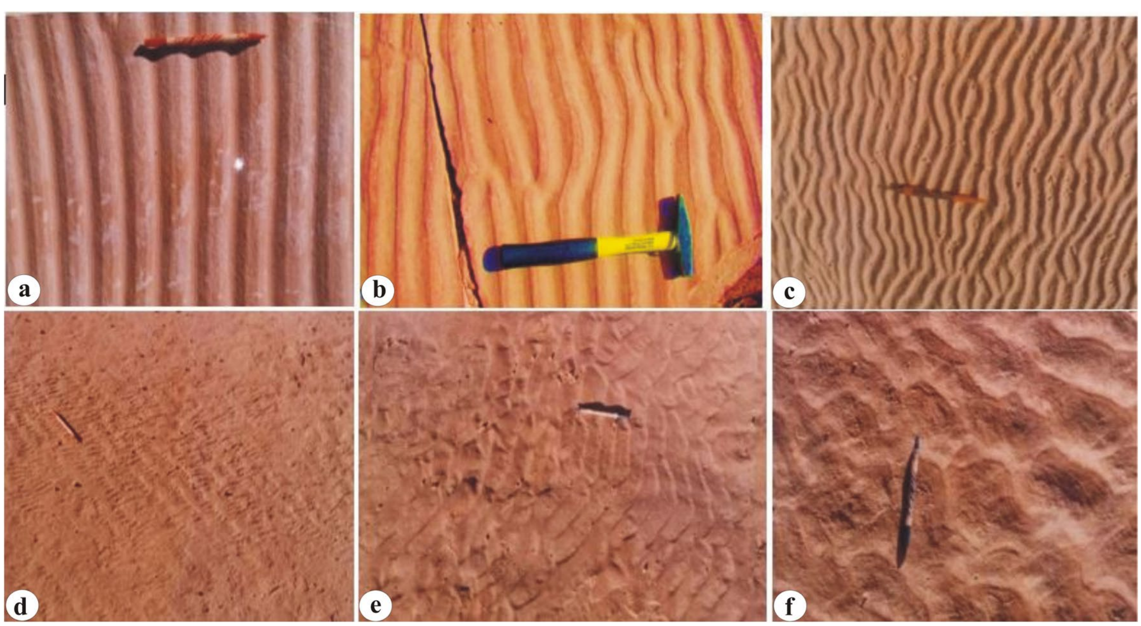

Fig. 5 Ripple marks showing preservation hierarchy i.e. from (**a**) straight crested ripples at the base followed by (**b**) branched, **c** undulatory (**d**) linguoid, **e** adhesion wart and **f** interference ripples at the top representing shallowing upward sedimentation in the beach environment in Soorsagar mine

dings that range from planar, tabular and herringbone cross-beddings of small-scale to large-scale on the outcrops. Mostly the planar and tabular types of cross beds are of maximum 25 cm thickness in which co-sets are clearly visible. The foreset lamiae are 2-6 mm thick showing a 9^0 to 18^0 dip indicating a bi-directional flow trend, current reversal, and migrating bed forms in foreset (Fig. 6a). These characters clearly manifested shallow water depositional environment for medium to coarse sandstone of SSF (Chauhan et al. 2004 and Pandey 2009).

c) **Graded Beddings**

Graded beddings are common in medium to coarse-grained sandstone of the study area of siliciclastic landscape showing change in grain size within a single sedimentary bed (Fig. 6b). At the bottom, coarse particles deposited which get progressively smaller vertically up in the bed. The presence of graded beds in the study area represents depositional environment in which transport energy decreased progressively over time and rapid depositional events, possibly from turbidity currents.

d) **Other Sedimentary Structures**

Excellent and textbook style occurrence of laminations, beds, chromatographic, syn-sedimentary features (Fig. 7a, b and c) with raindrop imprints, rill marks and scour marks are very common structures found in fine to medium-grained sandstone of SSF. Beds and laminations display beautiful and different colour sheds of brown, pinkish white, greyish brown, pinkish yellow, and pinkish colour due to the cementation of iron oxide minerals. These characteristics of chromatography also impart an excellent appearance that makes it a popular and magnificent decorative stone of great aesthetic value. Raindrop imprints occur as circular craters of 2-6 mm diameter with 1-2 mm depth on rippled surfaces as well as on plain bedding surfaces giving a beautiful appearance to sandstones. The other structures, rill marks and scour marks are erosional channels found only on the lower foreshore areas giving a beautiful appearance to sandstone on outcrop. Excellent, occurrence of a variety of textbook-style preservation of sedimentary structures in sandstone horizons of the SSF makes the study area a magnificent

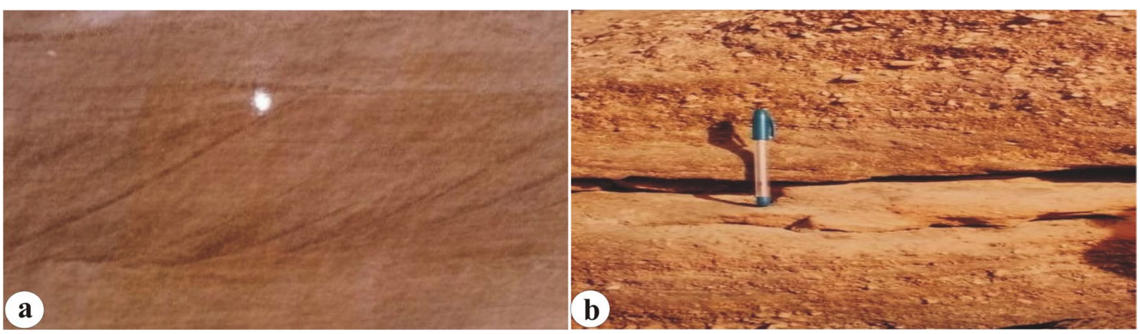

Fig. 6 **a** Cross bedding in medium-grained sandstone of SSF and **b** Graded bedding in medium to coarse sandstone of SSF at Soorsagar mine

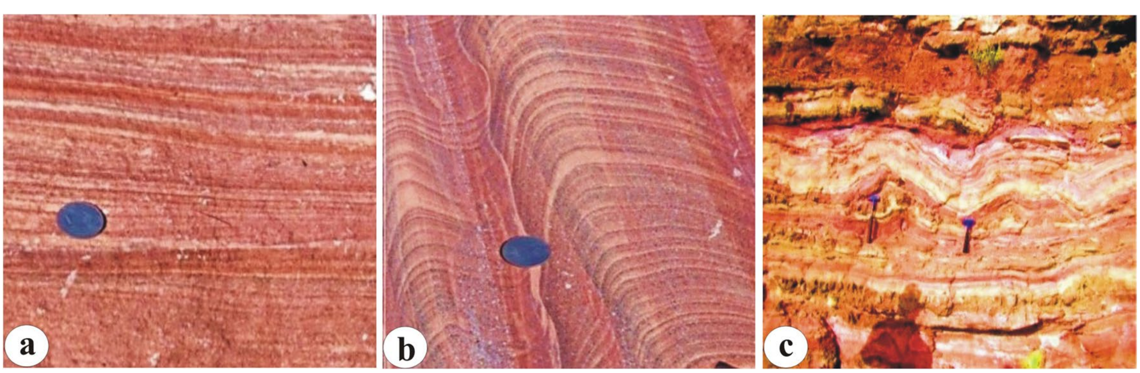

Fig. 7 **a** Laminations and beds, **b** chromatographic structures and **c** syn-sedimentary features excellently preserved in medium-grained sandstone of SSF

outdoor museum of significant geoheritage of great educational values.

2. **Paleontological Type**
Fine to medium-grained sandstone of SSF has emerged as one of the best repositories and occurrences of diversified Ediacaran fossil assemblage (Fig. 8a-h) in India. These fossils are represented by mega algal fossils, plant fossils and microbial mats as well as microbial mat-mediated structures (Raghav et al. 2005; Kumar and Pandey 2009; Srivastava 2012, 2014; Parihar et al. 2015). History of Ediacaran fossils from rocks of JG commences with the first reporting of distinct body fossil *medusoid Marsonia* by Raghav et al., (2005). Subsequently, Kumar et al. (2009) have reported typical Ediacaran forms like *Aspidella* sp. *Beltanelliformis minuta*, cf. *Hiemalora* sp. and giant plant fossils with Vaucherian affinity (Hofmann et al. 2008). Other important reports of Ediacaran fauna from SSF are microbial mats (Sarkar et al. 2008, Kumar and Ahmad 2014), five-armed Echinoderms (Kumar et al. 2012), *Arumberia banksi,* (Sharma and Mathur 2014), Priapulid worm-like fossils (Srivastava 2012), *Thalassinoides,* and other trace fossils (Xiao and Sharma 2014; Kumar and Ahmad

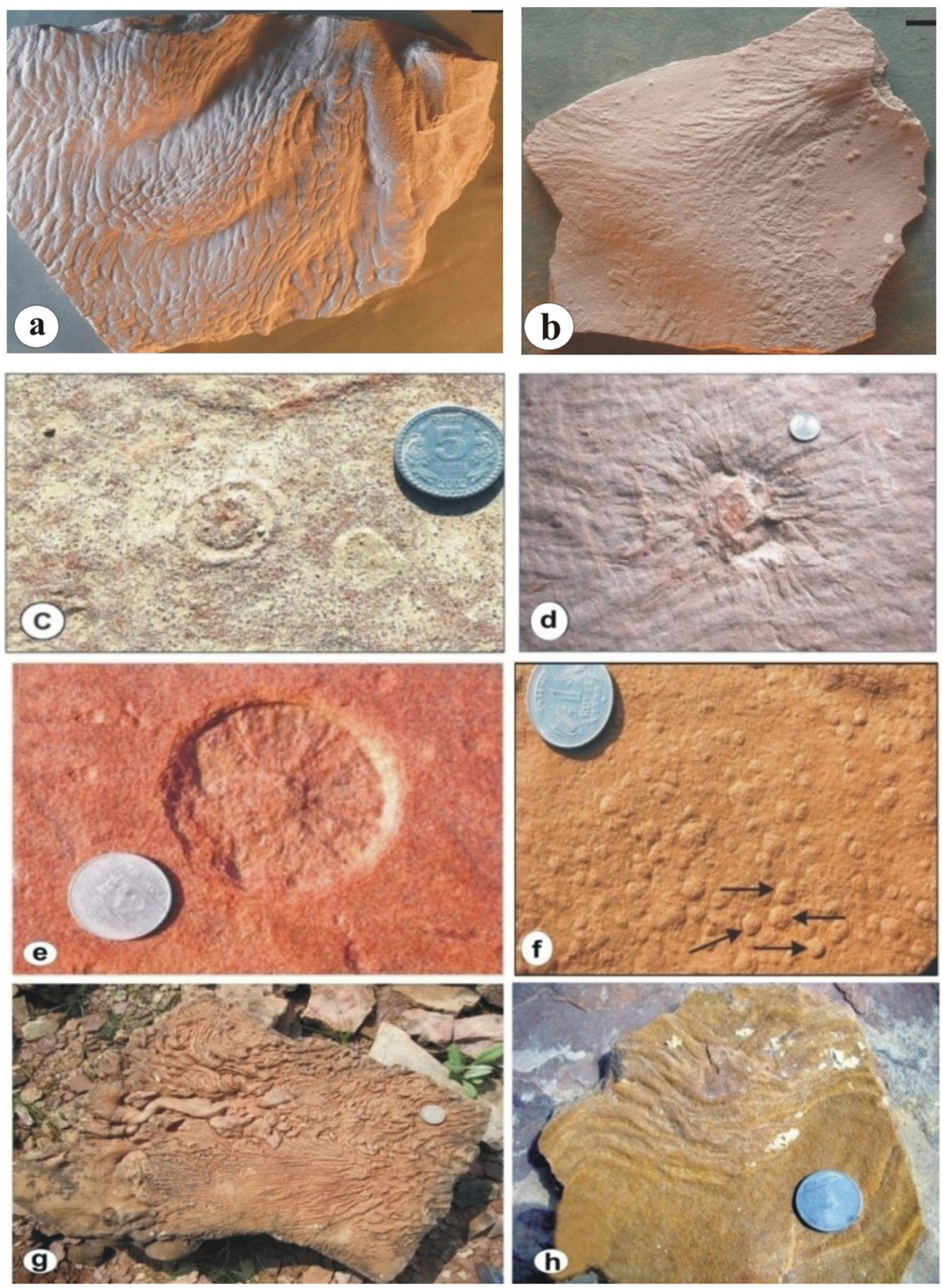

Fig. 8 **a** and **b** Arumberia banksi, **c** Aspidella, **d** Heimalora, **e**, Cyclomedusa, **f** Beltanelliformis, **g** Arumberia banksi, **h** macroalgal Ediacaran fossils from Sandstone of SSF (Kumar and Pandey 2009; Srivastava 2012; Sharma and Mathur 2014 and references therein)

2012; Parihar et al. 2015; 2019). These fossils along with mega-algal fossils (Kumar et al. 2009; Srivastava 2013), Ediacaran discs (Srivastava 2013) and *Thalassinoides,* and other trace fossils (Xiao and Sharma 2014) have confirmed Ediacaran age to SSF. Giant size preservation of plant fossils of SSF opened a new window for understanding the evolution of life during the Ediacaran period, mainly in gigantisms in plant life. Additionally, the occurrence of these faunas in SSF represents the Ediacaran period of non-skeletal extinct organisms before the radiation event of the Earth's history (Maheshwari et al. 2003) of great educational values (Mathur et al. 2021).

3. **Stratigraphic Type**

   MIS forming basement for rocks of SSF is considered the third largest, felsic, anorogenic, and terrestrial volcanic province of the world that witnessed Pan-African orogeny related to the splitting of the Rodinia Supercontinent (Mathur et al. 2021). Rocks of MIS and JG displayed a major discontinuity of stratigraphic significance that represents an interface between two major periods of Cryogenian and Ediacaran of remarkable serenity in the geological history of the Earth. A rare unconformity between both has been declared as a national geological monument of India. The contact between the two also provides an insight into the changes from volcanic to marine environments that indicate the transition from non-life to the first appearance of life in the vast Marwar Sea in the eastern Gondwana land. Most of our understanding of various sedimentary structures and the Ediacaran fossils from various units of SSF primarily suggest bio-stratigraphic and sequence stratigraphic significance. Thus, the Cryogenian-Ediacaran volcano-siliciclastic thick sequence of about 100 m constitutes the strato-type sections and outdoor geological museums in India that display geological processes of about 200 million years of stratigraphic record in the Earth's history.

4. **Geomorphological Type**

   Geomorphologically, the study area exhibits gentle undulating topography represented by NNE—SSW trending KSR in which rocks of MIS and sediments of JG form a spectacular inselberg-like landscape. Some of the flat top sandstone landscape formed Butt and Mesa structures displaying rigorous fluvial processes. Besides these several sandstone plateaus, alluvial plains, calcrete plains, piedmonts plains, sand dunes and interdunal plains form a beautiful topographic landscape in the study area additionally of geotourism values.

5. **Paleogeographic Type** Besides SSF, Ediacaran fossil occurrences in India have been reported only from the Lesser Himalayan region, Maihar Sandstone, Bhima Group, and Bundi Hill Sandstone of the Vindhyan Supergroup (Mathur and Shanker 1990; De 2006; Srivastava 2006, 2012). This correlation of the Ediacaran period clearly conceptualizes an important paleogeographic implication in India and suggests that the Marwar Basin and the Vindhyan Basin existed during the Ediacaran period and must have been linked with each other through a corridor up to the Lesser Himalaya indicating their paleogeographic geoheritage significance. Globally, this Ediacaran assemblage is comparable with the Fengyang Mountain, China, Long Mynd Group, Shropshire, UK, Fermuse Formation, Mistaken Point, Newfoundland, South Australia, White Sea, Russia and Norway indicating a significant period in the history of life on Earth, "when life got big" after almost 3 billion years of microbe-dominated the evolution.

6. **Ecological Type** Ediacaran Fossil assemblages of SSF are the earliest records of ecosystems dominated by macroscopic, multicellular, complex organisms thus; providing a critical window into the radiation of complex life. The majority of Ediacaran fossil assemblages of SSF are preserved in the distinctive "Ediacaran style" as sandstone casts and moulds (c.f. Tarhan et al. 2017 and references therein). Medium-grained sandstone of SSF showcases the treasure of ripple marks with rich assemblage of Ediacaran communities thus preserving rare insights into the ecology of these ancestral animals and the early colonization of shallow sea floor.

7. **Archaeological Type (Cultural and Monumental Heritage)**

   Fine to medium-grained sandstone (locally known as *Chittar ka patthar*) and ferruginous sandstone (locally known as *Ghatu ka patthar*) are the best quality building and decorative stones, extensively quarried in the study area. Jodhpur sandstone of SSF has an old mining history that dates back to its use in the fourth century fort and cenotaphs at Mandore, several historic and cultural geo-monuments are constructed by using these stones. Important heritage geo-monuments include Mehrangarh Fort, Clock Tower, Umed Palace, ship house and more than a hundred Jhalra and Baories (Fig. 9). Several present-day buildings in Jodhpur city including the magnificent Rajasthan High Court, Jodhpur Indian Institute of Technology, All India Institute of Medical Sciences of national eminence exemplify the continued use of Jodhpur sandstone in contemporary times. Heritage geo-monuments, traditional water bodies and buildings with magnificent architectural and civil engineering work constructed from medieval to modern times utilizing Jodhpur sandstones (HSR) provide additional archaeological values (Brilha 2016) to the landscape of SSF.

Fig. 9 **a**. Panoramic view of geo-monuments including *Mehrangarh* Fort and Jaswant palace, **b** *Umed* Palace**, c** Clock Tower**, d** traditional water bodies (*Toor ji ka Jhalara*), **e** and **f** *Mandore* Palace- Cenotaphs and status in the temple at Jodhpur were constructed in 1459 by HSR

Assessment of Threat to Geoheritage

Based on the present study, it is found that significant geoheritage elements of the study area are subjected to degradation and damage mainly due to anthropogenic activities such as resource extraction, land and infrastructure development, unsustainable land management, and inadequate management and protections. To assess the threat to significant geoheritage of the study area authors utilize various geological and remote sensing techniques.

Anthropological Threats

People are strong human agents who always influence and try to destroy abiotic natural landscapes. These human acts not only transform and damage but also create false landforms which are the major anthropogenic threat to the study area. Anthropogenic threats to the geoheritage are also related to visitors coming for scientific purposes (educational tours or visits for research) and the public coming for recreational uses that may damage the originality of landscape features. Equally, the infrastructure developmental activities and human interventions for development activities are other major threats to geoheritage along with anthropogenic vulnerability i.e. practices for collecting samples of minerals, and rocks illegally and vandalism of fossils. In reference to the above threats to geoheritage of the study area, authors identified anthropogenic threats to the geoheritage of the study area which are mainly arising from two factors: a. Urbanization and b. Mining Activities.

a **Threat Due to Urbanization**

Jodhpur city is endowed with a wide variety of landforms represented by hilly terrain of MIS and JG, pediment–alluvium, Aeolian areas-sand dunes, and linear valley with settlements and built areas, the landscape of vegetation and mining terrain (Fig. 1). It is clear from figure that rocky terrain has been encroached and occupied by the built-up area marking the human intervention with abiotic landforms. In the process of urbanization, hilly terrain was mainly damaged along with pediment–alluvium and Aeolian areas which were either destroyed or completely vanished under developmental activities. Hence, anthropogenic activities changed the landform with the reduction in hilly terrain, vegetation and agricultural area. Additionally, this activity has also developed heterogeneity in the landform. Huge dumping and produced overburden from sandstone quarries created pockets of false topography (Fig. 2). In the catchment areas, many artificially created small water bodies developed due to digging and excavation of sandstone for infrastructural development works which ultimately increased surface heterogeneity and water pollution.

b **Threat Due to Mining Activities**

Ancient beaches to the near coastal environment with exposures of the basement-cover relationship in the form of unconformities, the treasure of sedimentary structures and the preservation of the oldest and most complex Ediacaran fossils in rocks make the SSF landscape a significant geological entity of India. This landscape is famous for extensive mining activities damaging significant geoheritage elements that have created a serious geological problem (Fig. 1). To address this problem, authors critically analyse and assess the threat and damage to geoheritage due to mining activities from 1963 to 2021 by utilizing various geological, remote sensing and GIS techniques.

Although, sandstone mining in Jodhpur has been witnessed since the thirteenth century at Mandore, the capital of the princely state of Marwar when the large fort was built during the *Pratiharas* dynasty along with other palaces, monuments, cenotaphs and temples that are attractive archaeological geoheritage sites. Later on, mining activities were evident from the Balsamand-Soorsagar area from where sandstones were excavated to build Mehrangarh Fort in 1459 AD by the Rajput King Rao Jodha who founded the Jodhpur city as the new capital of Marwar state. Such small quarrying activity was not noticed on the map scale till the year 1973 except for the very small area that was shown in the toposheet of 1963. In the SSF landscape, large-scale mining activities have been a regular feature since 1973 and can be clearly observed in Landsat data. In the past, the majority of sandstone quarries were unorganized and were part of a small-scale sector. More than 20,000 quarries (30 × 60-m leases) have been operating since the decade of seventies (DMG website). These units catered to the growing demands of the infrastructure sector and provided employment to a large number of people contributing to the economic development of the region. However, sandstone mining damaged significant geoheritage is a great concern to geoscientists. Hence, the authors have assessed the loss to the geoheritage due to mining operations for about the last sixty years. The present estimations are based on satellite data interpretation considering mining as the main negative factor to damage geoheritage. After impact assessment, to protect the remaining geoheritage, a conservation and future management plan is urgently required without stopping mining activities.

Methodological Procedure

Remote sensing and GIS techniques are well-known internationally for successful methodological solutions to various problems of geosciences including the assessment of threat to georesources (Prost 2014; Jain and Verma 2006; Kubalíkova et al. 2017; Mathur 2021). Significantly, remote sensing techniques provide up-to-date information and knowledge on the development activities through GIS for an effective analysis. The produced data can be utilized for identifying, and characterizing the geoheritage of small, large and difficult-to-access areas by assessing the natural and anthropological threats to them. These techniques also allowed for establishing past to present changes in territory/landforms due to any geological activity, disaster (natural), mining and urbanization (anthropological). Thus, these techniques are applied to assess the threat to geoheritage (c. f, Kubalíkova et al. 2017). The growth of mining areas within the SSF landscape appears to be the main trigger to damage rich geoheritage. This growth along with a little bit of urbanization increases the anthropogenic pressure on the territory due to the construction of buildings, roads, other infrastructures and waste storage etc. All these activities directly lead to an impact on the land as physical influences on geoheritage and its destruction. To address the noted problem in the study area, the spatial growth of the mining area was detected and recorded based on analysis of satellite data. To estimate the spatial growth of the mining area, firstly, authors procured satellite data from an authentic USGS website.

Various layers in images were stacked Using ERDAS IMAGINE 2014 software, subsequently, false colour composites of all the stacked layers were generated using Arc Map 10.6. Further, the area with mining activities was delineated using the "Create polygon" tool and various polygons were obtained. After, applying the "Calculate Geometry" tool, the total mining area was calculated periodically. The same methodology was applied to all the used datasets shown in Table 1. Secondly, GPS coordinate data were also added in Arc Map 10.6 to obtain the point data in the study area**.** Finally, both the end products were merged to obtain the historical mining maps by utilising the methodology given in Fig. 10. The interpreted data and information were presented utilizing a toposheet of the year 1963 (Fig. 11) and spatial maps of 1973 to 2023 (Figs. 12, 13, 14, 15, 16, 17

Table 1 Various datasets of Landsat images utilized for the present study

Sensor	Date of Acquisition	Path	Row	Resolution (m)
Landsat MSS	10 Jan 1973	160	42	79
Landsat TM	24 Jan 1989	149	42	30
Landsat TM	25 March 1999	149	42	30
Landsat TM	31 Jan 2009	149	42	30
Landsat 8 OLI	27 Jan 2019	149	42	30
Landsat 8 OLI	16 Jan 2021	149	42	30
Landsat 8 OLI	18 Jan 2023	149	42	30

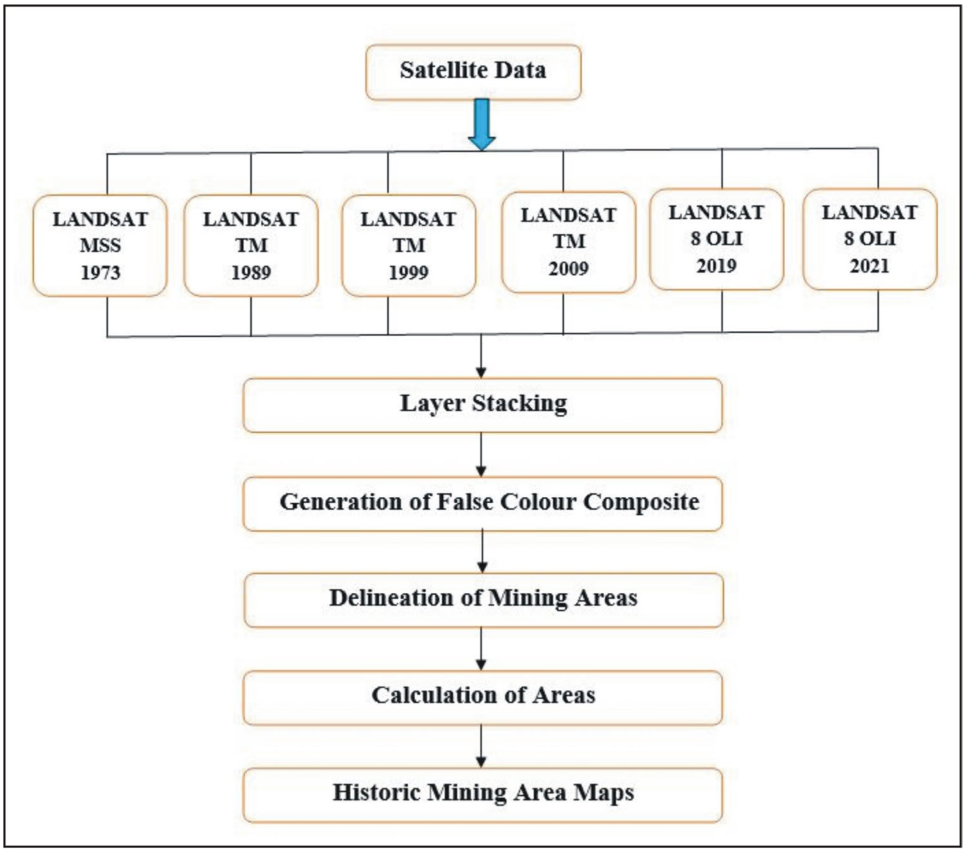

Fig. 10 Flow chart of methodology applied to assess the mining area

Fig.11 Toposheet of the year 1963 of Jodhpur showing negligible mining activities (Dark Yellow) around Balsamand-Mandore areas

and 18) along with the rate of progressive growth (Fig. 19) of the impact of mining in the period of about sixty years. Two different approaches are utilised, first, the geological assessment of geoheritage and second one is the impact of mining on geoheritage utilizing remote sensing and GIS techniques.

To quantify and evaluate the impact of mining on geoheritage, three types of images are utilized viz: Landsat MSS (1973 and 1989) Landsat TM (1999 and 2009) and Landsat 8 OLI (2019, 2021, 2022 and 2023) as per available data of respective years from USGS Earth explorer website. The interpretation of these images clearly manifested that mining activity is the major threat to creating geomorphological heterogeneity and permanent loss of geoheritage in the sandstones of SSF (Mathur 2021). The Landsat images were not available before 1973 hence; the author utilized the available toposheet of the year 1963 (Fig. 11) in which negligible mining area is noticed. Hence, systematic quantification of the impact of mining activity and its adverse effects on geoheritage is assessed by utilizing toposheet and various Landsat images of the past about sixty years. The interpretation of images clearly reveal that initially, 3.19 sq. km area was covered under mining activities in the year 1973 (Fig. 12) indicating a small increase in mining area since 1963. During this period, the mining was distributed only around Mandore and Balsamand areas. However, till 1989 drastic changes in mining activities took place covering about 9.52 sq. km area (Fig. 13) showing a fast and increasing trend of mining. During this period mining activities spread in the additional new areas of Keroo, Soorsagar and Bhuri Beri with Balsamand and Mandore.

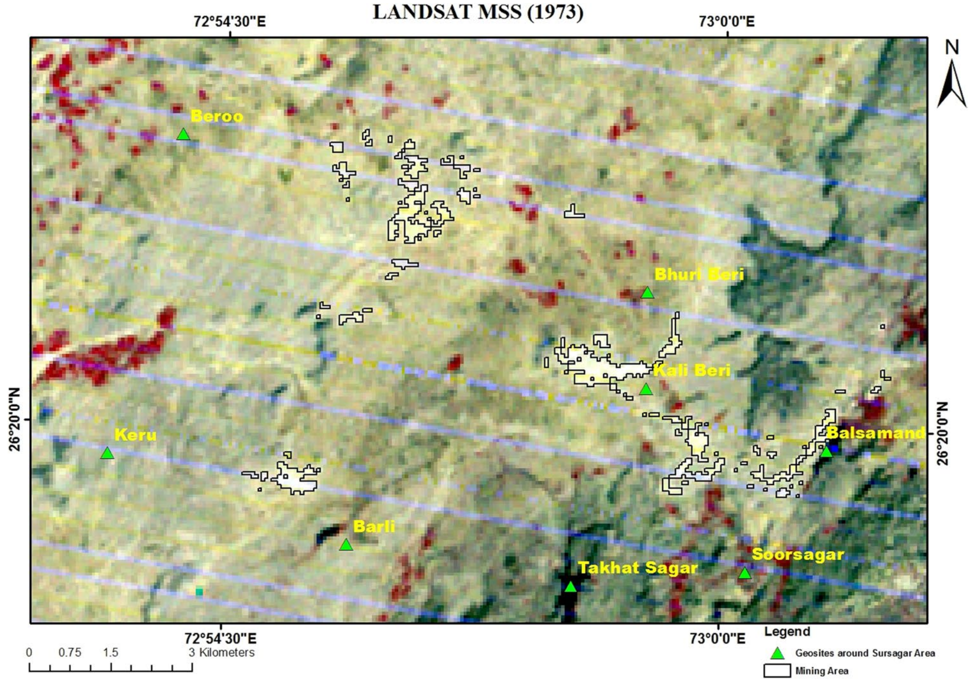

Fig. 12 Landsat MSS Image showing 3.19 sq. km area of mining in the year 1973 around Balsamand Kali Beri and Barli areas in the SSF landscape of Jodhpur

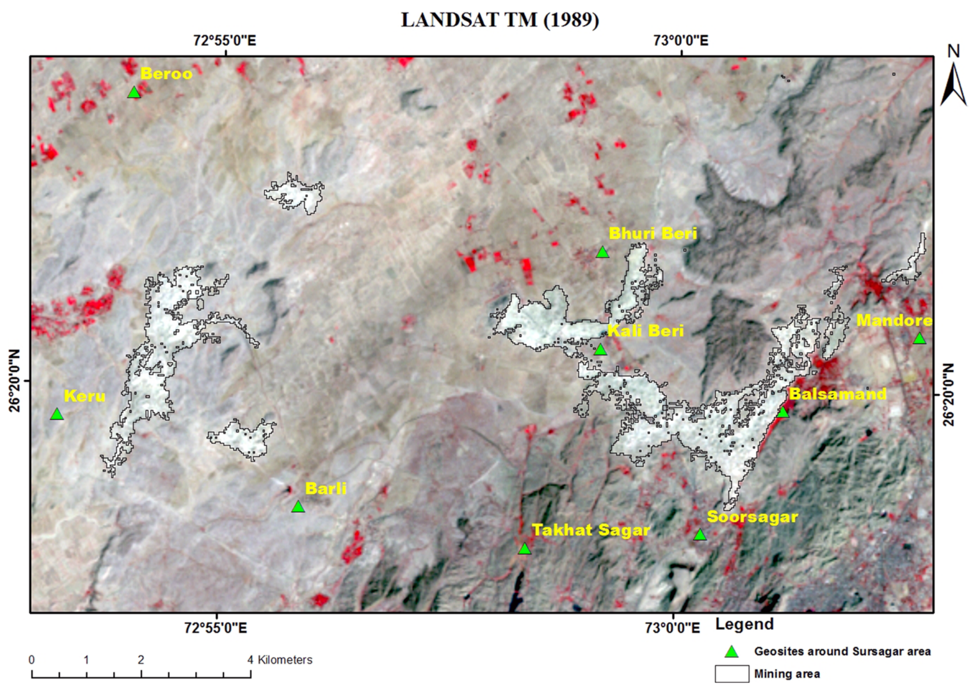

Fig. 13 Landsat MSS image showing mining areas increased to 9.52 sq. km area in the year 1989 as noticed in new areas of Soorsagar, Bhuri Beri and Keroo in the SSF landscape

The interpretation of the satellite image of 1999 shows a rapid growth of 14.13 sq. km area in the period of ten years. However, mining was additionally shown in new areas of Barli (Fig. 14). During the period of next ten years, mining areas marked a steady growth and are estimated to be 14.49 sq. km in 2009 (Fig. 15). Upto this period, no new area came under mining operations but the previous areas were expanded. Similarly, in the year 2019 (Fig. 16) mining activities expanded rapidly to 16.79 sq. km, and 16.92 sq. km in 2021 and 22.12 sq. km in the year 2023 (Figs. 17 and 18) in all aforesaid areas. Results of the rate of progressive mining activities (Fig. 19) if clubbed with geological data, the study show that most of the adverse effects of mining are concentrated in areas with high indices of geoheritage at the landscape of SSF in the study area. These interpretations reveal an alarming situation for the world-class geoheritage that has vanished completely with time. If mining is going on at the present

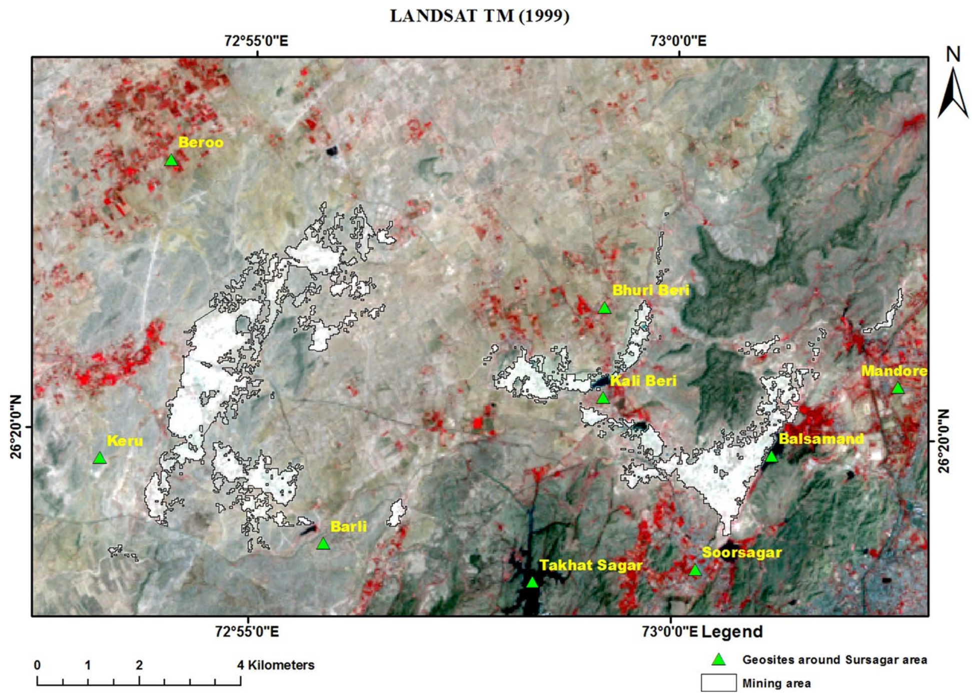

Fig. 14 Landsat MSS image showing mining area increased to 14.13 sq. km area in the year 1999 as noticed in new areas around Keroo, Barli and Soorsagar in the SSF landscape

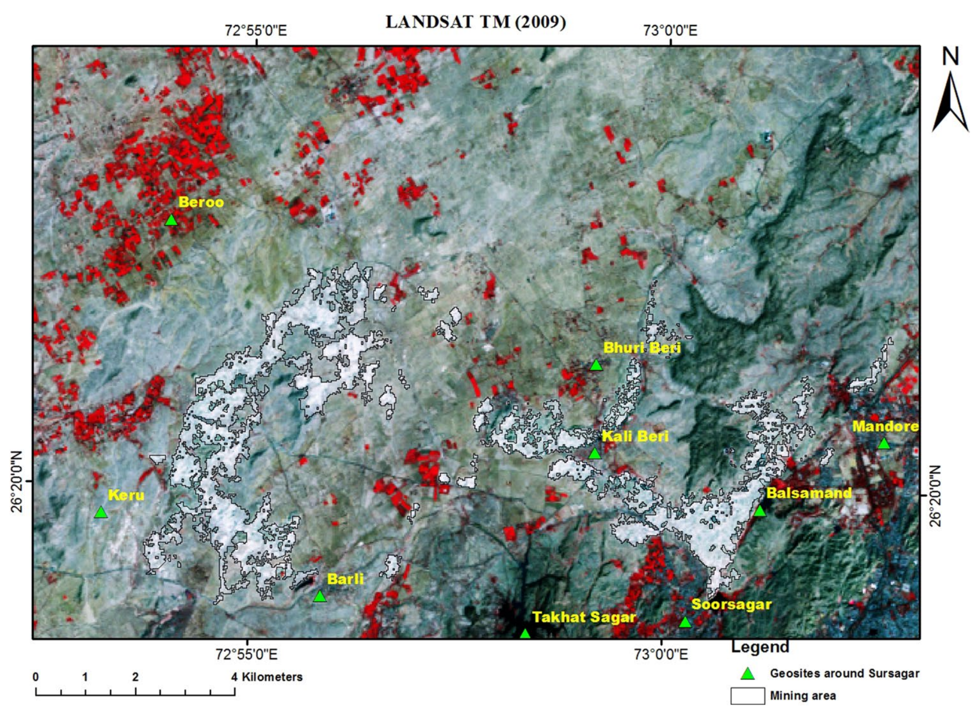

Fig. 15 Landsat TM Image showing 14.49 sq km Mining area in the year 2009 in new areas of Barli, Keroo, Kali Beri and Beroo in the SSF landscape of Jodhpur

rate (Fig. 18), the universally outstanding geoheritage sites of the SSF landscape (54 sq. km) will be exhausted in the next couple of decades. The study shows that these areas are characterized by great scenic beauty of landscape with great cultural and aesthetic values (Mathur et al. 2021) and are on the verge of damage and even extinction in future.

Discussion

The landscape of SSF of the northern part of KSR represents a kind of plateau with the horizontal disposition of siliciclastic rocks. This area is also known for deposits of world-fame Jodhpur sandstone designated as HSR

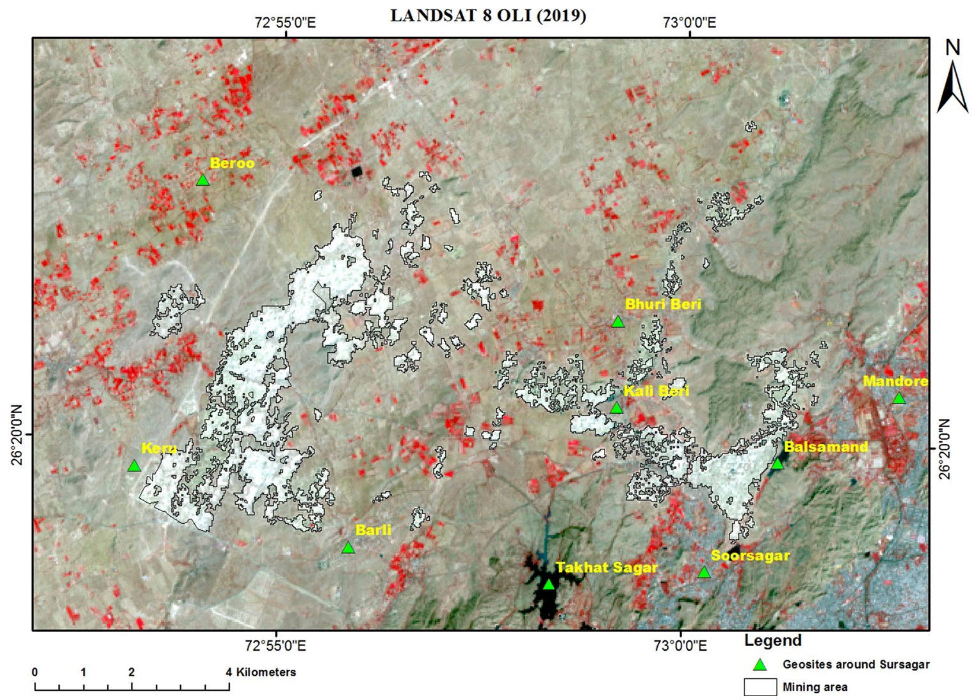

Fig. 16 Landsat 8 OLI Image showing 16.79 sq. km mining area noticed in the year 2019 extended in all areas of the SSF landscape of Jodhpur

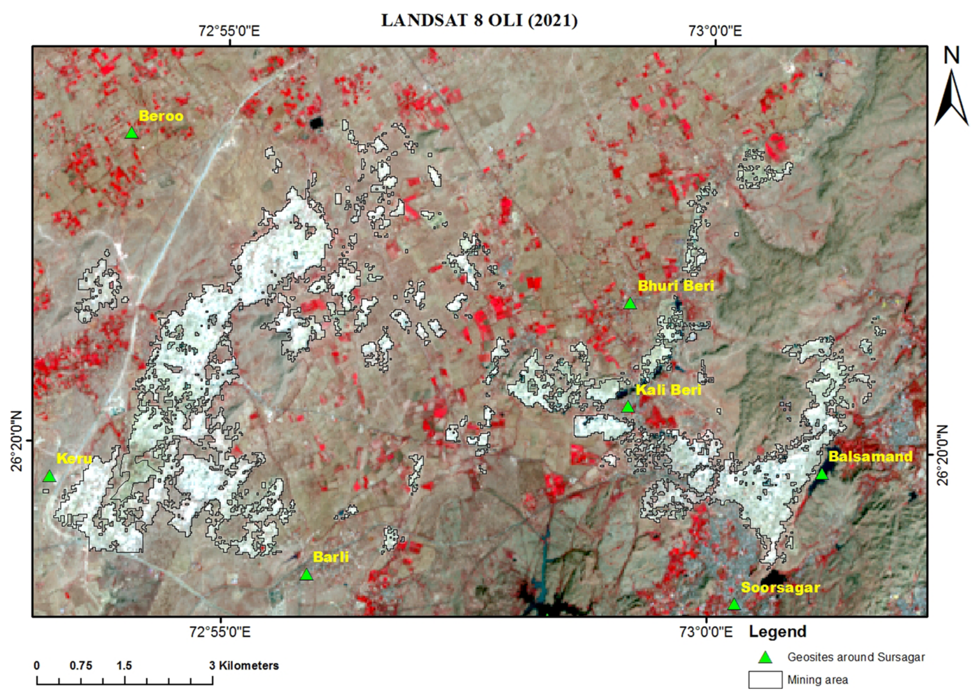

Fig. 17 Landsat 8 OLI Image showing 16.92 sq. km mining area noticed in the year 2021 on the SSF landscape of Jodhpur

of India (Singh and Mathur 2014; Kaur et al. 2020). The sandstone mining in Jodhpur has been witnessed since the thirteenth century during *Pratiharas* dynasty. Geological data from the magnificent outcrops of MIS and SSF represent about two million years old earth history of the Cryogenian and Ediacaran periods. The basement of rocks of MIS (Cryogenian) of the study area proved to be of global significance as analogous geoheritage sites are known only from Seychelles, Oman and Madagascar which were parts of the Indian plate during the Cryogenian period (Kochhar 2001). At the country level, unique and rare volcanic features of MIS have been declared as the National Geological Monuments of India with its interface with JG showing national importance. Features and structures of rocks of MIS and SSF with unconformity between them facilitated the establishment of sequence

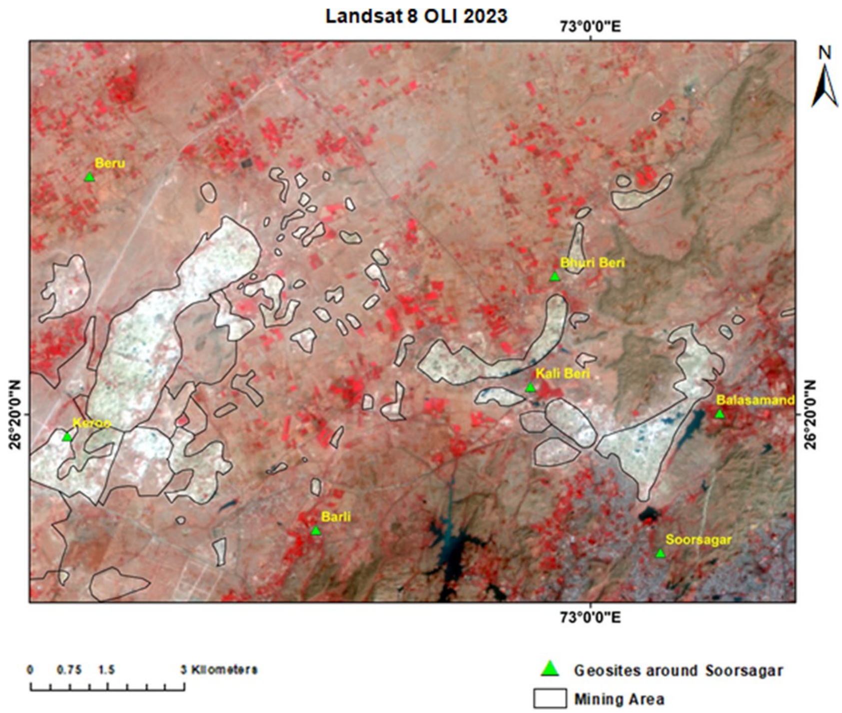

Fig. 18 Landsat 8 OLI Image of the year 2023 showing 22.12 sq. km mining area on the SSF landscape of Jodhpur

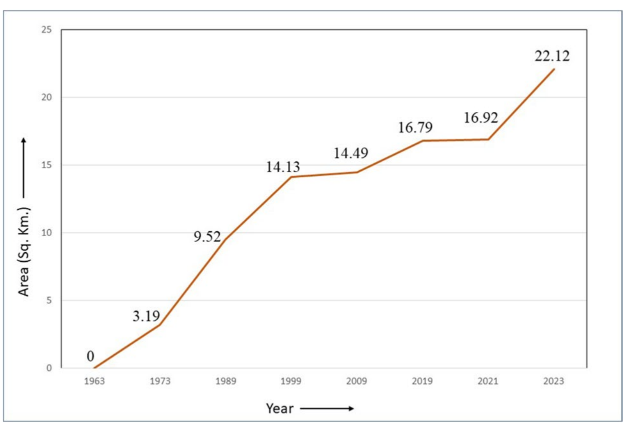

Fig. 19 Graph showing progressive increasing growth in mining area from the year 1963 to 2023 in SSF landscape

stratigraphic framework of the Cryogenian-Ediacaran periods. The siliciclastic sequences of SSF in the study area is represented by the subsequent opening and evolution of the Ediacaran Sea in which large-scale and well-developed shoreline to the distinct suite of coastal sedimentary landscapes were developed (Chauhan 1999 and Mathur et al. 2019a, b). The representation of textbook-style preservation of sedimentary structures especially ripple marks with rich assemblage of fossils bearing shallow marine facies of SSF showcases a unique Ediacaran paleo-ecosystem in the landscape. These features also significantly provide an understanding of the geodynamics and paleogeographical setting of the Ediacaran Sea. Although similar rocks are known from many places in India, the relative diversity in the form of treasure of sedimentary structures appears to be regionally unique and of national significance.

The geomorphological type is linked to a well-shaped Butt and Mesa landscape of SSF indicating the influence of fluvial systems. The paleontological type heritage is linked to the presence of a rich assemblage of Ediacaran fossils. Such oldest and most complex Ediacaran fossils are unique on the national scale as only three more localities are known from India. A diverse and rich assemblage of Ediacaran fossils (Raghav et al. 2005; Kumar and Pandey 2009; Sharma and Mathur 2014; Parihar et al. 2015, 2019; Mathur et al. 2020a, b, 2021) also represents stimulation and proliferation of primitive multi-cellular life on the earth's hydrosphere (Meert 2003). These Ediacaran fossils also add to our understanding of the origination and evolution of early complex life on the Earth along with the palaeogeography, stratigraphy, environmental, and taphonomic distribution of the soft body animals before radiation event of the Cambrian earth history (Maheshwari et al. 2004). The similar sedimentary-type geoheritage is known from three more localities in India and only six such occurrences at the international level (Kumar 2012; Mathur 2021), making the SSF landscape an important geological entity in the world of immense scientific value.

The archaeological geoheritage of Jodhpur is represented by the thirteenth century-old oldest HSR (Jodhpur sandstone) mines at Mandore-Balsamand areas showing ancient patronage of India. The unique geo-monuments constructed by HSR provide additional heritage values to the landscape of geotourism significance. Among these geo-monuments, *Mehrangarh fort*, *Umed* Palace, hundreds of traditional water bodies (TWB; Singh and Mathur 2014); Clock Tower, cenotaphs and temples are additionally enhancing the cultural values. Among TWB (locally known as *Jhalras* and *Baories*) in the study area are not only the representation of rich hydrogeological knowledge of the local community but also showcase remarkable architecture, civil engineering, groundwater harvesting, and conservation system of medieval times of India (Singh and Mathur 2014).Concerning the above discussions, the assessment of seven types of classical geoheritage of SSF landscape is of high rank and not only attracts geoscience educators and researchers but is of great scientific and geotourism values. The outstanding SSF landscape endowed with world-class geoheritage values that are endangered and damaged by extensive mining activities is a serious geo-environmental problem and is of great concern to the geological fraternity. The assessment of periodic threat and damages in the landscape of SSF clearly suggest that out of the 54 sq. km sandstone lease area (DMG website), more than fifty percent area has already vanished is a great loss to humanity and the nation rather than to our mother Earth. To protect them, geopark concept can prove to be the best tool for their conservation and management. Additionally, the combination of cultural and historical tourism with geotourism can be a mutually beneficial innovative idea in the Geopark on SSF landscape that will certainly contribute to the sustainable socioeconomic development of the region,

Geoconservation

Scientifically, geoconservation is a complex problem (Brilha 2016; Mathur 2021). In India, the geoscientific community, administration and Government have not recognized the significance and importance of geoconservation of their world-class geoheritage. Hence, India needs strong geoconservation policies and guidelines to protect significant geoheritage sites. In the absence of such policies, alternatively, geodiversity can be linked with biodiversity. It is a universal fact that most biodiversity is developed on abiotic landscapes having geodiversity. In India, the conservation of biodiversity is governed by the Biodiversity Act, of 2002 which was framed to declare Biodiversity Heritage Sites (BHS) and their conservation (BHS Report 2002). Accordingly, BHS are well-defined areas that are unique, ecologically fragile ecosystems. The act is enforced by the National Biodiversity Authority (NBA) of the Ministry of Environment, Forest and Climate Change, Government of India. Similarly, a National Geoheritage Conservation Authority may be formed to conserve significant geodiversity in India.

Since biodiversity and geodiversity are integral parts of the ecosystem and both are complimentary to each other, thus, alternatively geoconservation can also be governed by the Biodiversity Act, of 2002 in India by simply making the amendment to include geodiversity. Since abiotic natural geoheritage and archaeological heritage (geo-historical-cultural) are the non-replaceable and priceless assets of the Earth and humanity. Truly, natural geoheritage cannot be developed as it requires millions of years to build by geological processes. Similarly, rebuilding of magnificent archaeological heritage is also a difficult task, rather impossible in the present time. The damage, deterioration, destruction or disappearance of these most prized assets (geoheritage) is a loss to all of us and most importantly to future generations of the world. Thus, significant geoheritage of the SSF landscape with existing tourism facilities can be protected and conserved through a proposed Geopark at the northern part of Jodhpur. Further, it will create a more balance among geoheritage conservation, public education, tourism, and socioeconomic 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. The proposed Geopark would be beneficial for scientific research and education (training, study tours and camps for students). Further, it will certainly contribute to promoting tourism through geotourism for sustainable socioeconomic development. The recreation, infotainment, cultural/ historical activities, and visits would be other common uses and benefits of the proposed Geopark for the socioeconomic development of the region through geotourism.

Conclusion

Characterization and assessment of the landscape of rocks of basement MIS and SSF at the northern part of KSR in Jodhpur clearly manifested the presence of seven types of geoheritage of regional, national, and global significance. Geologically, the spectacular landscape represents two critical periods (Cryogenian-Ediacaran) of the Earth's history. This landscape has several unique strato-type sections showing land and Sea interaction and providing an understanding of significant geological processes of 200 million years of Earth's history. Rocks of SSF of JG preserve copybook style sedimentary structures and a rich assemblage of fossils significantly shows complex early biogenic activities of shallow *Ediacaran* Sea of great scientific values. The sandstone mining in Jodhpur has been witnessed since the thirteenth century during the *Pratiharas* dynasty with geo-monuments of additional archaeological values representing ancient patronage of India. Thus, the knowledge that corresponds to the geoheritage types of the landscape is of educational and geotourism values with the potential to become a unique natural laboratory for all sorts of visitors and for the advancement of sciences. Thus, the landscape of SSF is an undeniable potential site for being developed as a National Geopark and/or UNESCO Global Geopark in the country. Further, it will create a more balance among geo-heritage conservation, public education, tourism, and socio-economic development of the region. For geo-conservation, remaining mining areas of high geoheritage indices can be protected under the proposed Geopark territory. It can help in the mitigation of negative mining-related anthropogenic influence on unique geoheritage and promotion of tourism in the landscape of the northern rural part of Jodhpur.

Acknowledgements The authors are highly grateful and express their sincere sentiments of gratitude to HH Shri Gaj Singh Ji for his esteemed encouragement and support for geological works related to geoheritage and geotourism aspects of the Marwar region, India. The authors are grateful to the anonymous reviewers for providing thoughtful comments, suggestions, and guidance to improve the quality and content of the paper. The authors are highly gratified to Mr. Jagat Singh Ji, and Mahendra Singh Ji of MMT, Jodhpur, for their invaluable help. The authors are grateful to Prof. K.L. Srivastava, Honourable Vice Chancellor of JNVU, Jodhpur, Prof. S.R. Jakhar, Head, Department of Geology, JNVU, Jodhpur, Prof. R.P. Choudhary, Head, Department of Mining Engineering, MBMU, Jodhpur and Dr. Shruti Kanga, Head, Department of Geography, Central University, Bathinda, for providing encouragement and facilities for the present work. It gives us immense pleasure from the bottom of our hearts to express sincere thanks to Dr. V. S. Parihar, Dr. S. L. Nama (JNVU, Jodhpur) and Mr. Virat Arora for their local support and fieldwork.

Authors' Contribution All authors have made equal contributions.

Funding The work was not funded by any organization.

Declarations

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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