



Geological heritage and geotourism potential of Udaipur region, Rajasthan, India

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Abstract

The Rajasthan state of India is always been a region of diversity in its geology, geomorphology, flora, fauna, ethnology, history, civilization, post-Christ historical, industrial, and war-defense development. The area of unending climatic changes from fertile lands of the Himalayan fed Vedic Saraswati, pre- and post-Indus civilization to long-run aridity in the Thar Desert made the Rajasthani people with incredibly strong minds. The Pb-Cu-Zn and other dozens of metals and innumerable non-metals of the Aravalli region one of the oldest orogenic regions of the world have enriched the treasures of all the Indian empires from 4000 BC until today. Udaipur and the surrounding area focused here are a small part of Rajasthan but housed almost all kinds of geological features; viz., Precambrian orogenic, collision tectonics, ophiolite suites, carbonatites, huge deep-water sediments to shallow shelf carbonates, miogeosynclines, and ancient global oxidation events, as well as the events about algal blooms in the world, are remarkably preserved in this small region which we classified into four different traverses with 27 geological heritage sites. The micro, macro, and mega structures, drawn and described in almost all books of structural geology and metamorphic and igneous petrology, are classically exposed in the Udaipur region that merits its place among the best geoparks of the world. Several geological exposures of this region have given prolific knowledge to a number of renowned geologists in India as well as the world. We propose this region to be conserved for future geologists, researchers, and students, as well as for common curious tourists.

Keywords Geological heritage · Micro–macro-mega tectonic structures · Aravalli region · Udaipur · Rajasthan

Introduction

The Earth is a dynamic planet and has a diverse climate and geological history which has been preserved within the rocks (Santangelo and Valente 2020). There are several outcrops/successions globally which represent that a wide range of spatial and temporal changes in the sedimentation processes, tectonic and volcanic activities, metamorphism, and faunal and floral assemblages are very important aspects of geological heritage and hence deserve protection, especially if they are

well-exposed. Geological heritage may refer to regionally or globally referenced section/outcrop/location which has preserved the geological features that provide information about the Earth's evolution or the history of Earth sciences and can be utilized for research, education, and also for the geotourist attraction (Reynard and Brilha 2018; Bentivenga et al. 2019; Chauhan et al. 2021). Geological heritage is a natural wealth for the country of its occurrence and also a valuable natural resource for long-term development; hence, its accurate identification, assessment, and protection are essential (Chauhan et al. 2021; Mikhailenko et al. 2021). Several studies have addressed issues affecting geological heritage, particularly with the identification and assessment of geosites which are crucial for the conservation and enhancement of the geological heritage (Wimbledon 2011; Bentivenga et al. 2019). The term “geosite” refers to a location that possesses significant geological or geomorphological features that should be preserved or are currently protected (Panizza and Piacente 1993; Wimbledon et al. 1995; Wimbledon 1996; Panizza 2001; Reynard 2004 etc.). The geosites provide an understanding of the internal and

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exterior geological phenomena that occur on the Earth, and studies of the geosites are also important in raising awareness of the importance of geological heritage protection and enhancement among local and national groups. Furthermore, proper documentation of geosites is required for the development of relevant regulations and the creation of databases for the protection and better understanding of geological heritage, as well as for territorial planning (Palladino et al. 2013; Bentivenga et al. 2015; Cook and Abbott 2015; Bentivenga et al. 2019).

The World Heritage Convention was developed by UNESCO to protect the world's cultural and natural assets, with a wide range of classifications of natural heritage for protection, including ecological, geomorphological, and geological. Due to the development of the ideas of geodiversity and biodiversity, the evaluation and relevance of the Earth's legacy, as well as its conservation for future generations, have become key considerations in recent years (Brilha 2002; Zouros 2004, 2005; Stace and Larwood 2006; Carcavilla et al. 2007; Zouros 2007; Panizza 2009; Zouros and McKeever 2009; Zouros et al. 2009). Conventionally, the concept of a "Geopark" emerged in the late 1980s to protect and manage geological heritage sites, and many countries have begun developing their own UNESCO-designated "Global Geoparks" as well as "National Geopark networks." As a result, almost all geoparks could play a significant role in the economic development of local or rural areas through geotourism.

The landscape of India has preserved a variety of geological features/formations ranging from Precambrian to the present with various significant geological heritage sites that display unique geomorphology, geological features, formations, rock types, fossils, geological boundaries, or tectonic discontinuities, processes, structural features, landscapes, and mineral deposits (Chauhan et al. 2021; Wadhawan 2021). However, in India, compared to other countries, the geological heritage, protections of geosites, geopark, geotourism, and geo-conservation concepts are yet to be established systematically, and the same can be achieved by the identification and assessment of geological heritage sites. In the last couple of decades, the Geological Survey of India (GSI), INTACH, and Earth Scientists identified and evaluated several geological heritage sites from various terrains of India, and they have reported the same in the form of media, news articles, reports, booklets, books, monographs, and research papers (Mazumdar 2007; GSI 2012; Singh and Anand 2013; Swarna et al. 2013; Sheth et al. 2017; Shekhar et al. 2019; Chakrabarty and Mandal 2019; Mathur 2020; INTACH 2016, 2021; Wadhawan 2021; Chauhan et al. 2021; Biswas and Chauhan 2021; Singh et al. 2021; Bho-sale et al. 2021; Ghosh et al. 2021; Tripathi 2021; Saurabh and Sudhanshu 2021; Muduli et al. 2022; Prabhakar and Radhika 2022; Mandal and Chakrabarty 2022; Chavan et al. 2022; Nayak and Karuppannan 2022; Thakkar et al. 2022;

Prizomwala et al. 2022; Kaur et al. 2022; Verma et al. 2022; Pandey et al. 2022; Joshi et al. 2022). However, considering India's geological diversity, it is crucial to find, investigate, and evaluate an increasing number of geological heritage sites in India.

Therefore, in the present paper, we have highlighted various geological heritage sites from the Udaipur region and surrounding areas of Rajasthan State, India. The Udaipur region is one of India's most important tourist hotspots due to its rich history, culture, medieval architectural marvels, geography, geomorphology, biodiversity, and ecology. The Udaipur is a tourist destination famed for its Rajput-era palaces, history, culture, and gorgeous landscapes. Maharana (King of Mewar Region) Shri Udai Singh relocated his capital from Chittorgarh to a rich valley region that became known as Udaipur in 1553 (Brian 2012). Because of its sophisticated lake system, Udaipur is known as the "City of Lakes" as it is surrounded by seven lakes, namely, Fateh Sagar Lake, Pichola Lake, Swaroop Sagar Lake, Rangasagar Lake, Doodh Talai Lake, Udaisagar Lake, and Badi Lake. Importantly, all the lakes are included in the National Lake Conservation Plan (NLCP) of the Government of India's rehabilitation initiative. Apart from the lakes, Udaipur is recognized for its medieval forts and palaces, museums, galleries, natural settings and gardens, architectural temples, and traditional fairs, festivals, and buildings. The tourist attractions listed above, as well as many others, keep the Udaipur region busy with tourists throughout the year. In contrast to well-known tourist destinations, the Udaipur region and surrounding area of Rajasthan state have preserved several well-exposed geological heritage sites of Archaean-Proterozoic stratigraphy, igneous and metamorphic petrology, structural geology, paleontology, geomorphology, sedimentology, and economic geology, including REEs. The world-class Makrana marble and red sandstones used for making the Taj Mahal, Kutub Minar, and other Mughal and British monuments were mined from here. Several student groups, researchers, geological government officials, and mining and mineral company executives visit Udaipur and the surrounding area each year to study field geology and training purposes.

The State Government of Rajasthan has pioneered various projects to develop tourism products such as great forts, palaces, temples, and other heritage properties. A few projects are (1) in 1982, the palace on wheels luxury train, (2) Pushkar fair, (3) heritage properties repurposed into tourist sites, (4) the launching of "Rajiv Gandhi Tourism Development Mission" in the year 2001, and (5) Mewar (Gangaur) Festival Udaipur, which marked the beginning of a new era in Rajasthan's tourism growth. Further, to provide a planned and focused approach to tourism development, Rajasthan launched the "Tourism Policy of Rajasthan" in 2001, making it one of the first states in the country to do so.

Over the last several years, there has been a substantial increase in global interest in geological heritage conservation through the construction of geoparks and geotourism. Geotourism is defined as sustainable tourism that focuses on experiencing the Earth’s geological features in a way that promotes environmental and cultural awareness, appreciation, and conservation while also being useful to the local community. It is a type of tourism in which the landscape’s aspects and evolution work together to create a tourist experience that is more than the sum of its parts, drawing tourists with a wide range of interests (Dowling and Newsome 2006, 2010). Activities related to geotourism have the potential to improve the visibility of Earth sciences, including activities that could fund research and create jobs (Kelley et al. 2019). In India, though the idea of geotourism is in its initial phase, the Udaipur region fortunately has a lot of potential in it. Unlike many other pioneering tourism efforts, the Rajasthan State Government may take a leading role in the implementation and development of geotourism in the state by promoting the Udaipur region as a tourism hotspot. The purpose of this paper is to highlight the geoheritage sites of the Udaipur region and surrounding area in order to raise awareness and increase the appeal of Earth science to the local community, as well as to draw the attention of concerned authorities to develop geotourism in the Udaipur area, which will, in turn, boost the region’s economy and employment opportunities through conservation and development of the geological heritage sites. Furthermore, the material presented in this study will be of great use to interested scientists, researchers, students from schools/colleges/universities, visitors, and mining and mineral sector geoscience specialists working in the Udaipur region and allied terrains areas.

Geology of the Udaipur region

The district of Udaipur is located in southern Rajasthan, between the latitudes of 23° 45' 00" and 25° 05' 30" and the longitudes of N73° 00' 00" and E74° 33' 18" (Fig. 1). The stratigraphy of Udaipur contains Archean basement rocks from the Mangalwar gneiss complex (MGC) of the Bhilwara Supergroup, post-Aravalli intrusives, Aravalli Supergroup rocks, post-Delhi intrusive, Delhi Supergroup rocks, and recent alluvium. (after Roy and Kroner 1996; Roy 1988a, b) (Fig. 2). The entire region is surrounded by the Precambrian Aravalli Mountains (Fig. 3). The MGC is the oldest Precambrian succession in the region with more extensive occurrences of primary sediment. The lowermost Aravalli Supergroup and the Archean MGC are separated by a fine-grained mica deposit known as “pyrophyllite” or sericite schists, which indicate the unconformity between them. According to Roy and Paliwal (1981) and Pandit et al (2008, 2012), these sericite schists are “paleosols,” which reflect a weathering profile that evolved at the top of Archean granites and gneisses. Detailed investigations and tectonic stratigraphic analyses by numerous pioneer workers on the Archaean–Proterozoic Contact (APC) unconformity have enabled the unconformity to be recognized in Jhamarkotra, Rajasthan. The Aravalli Supergroup, which consists of metavolcanics and metasedimentary rocks, is unconformably overlain by the MGC granites and gneisses. The quartzite outcrops in the region serve as a marker horizon, with siliceous veins as the most prominent feature, indicating the presence of highly deformed rock formations in the area. The formation rests on a granite gneiss surface with stromatolitic phosphorite that

Fig. 1 Geological map of SE Rajasthan showing the distribution of the major tectonostratigraphic units of the Aravalli Mountains and neighborhood (Modified after Heron 1953; Gupta et al. 1997; Roy and Jakhar 2002)

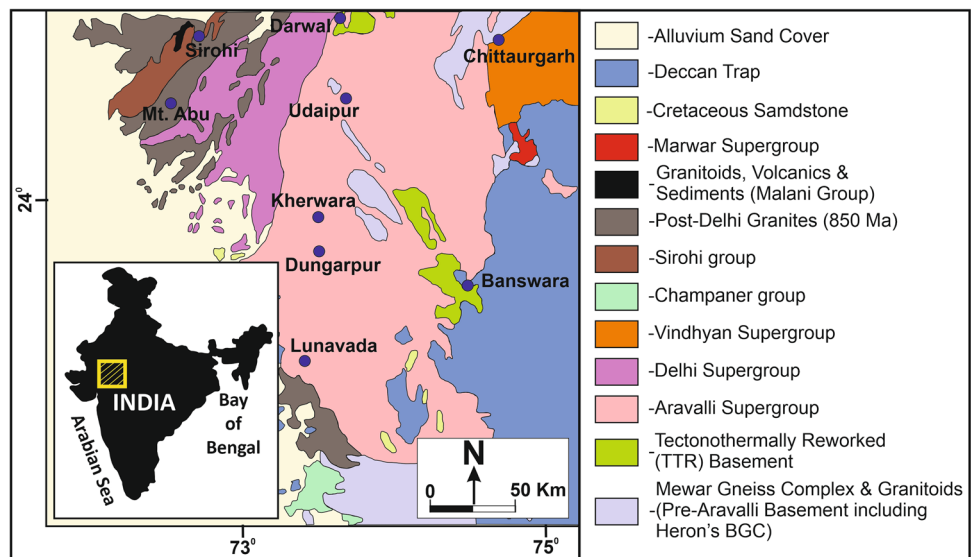
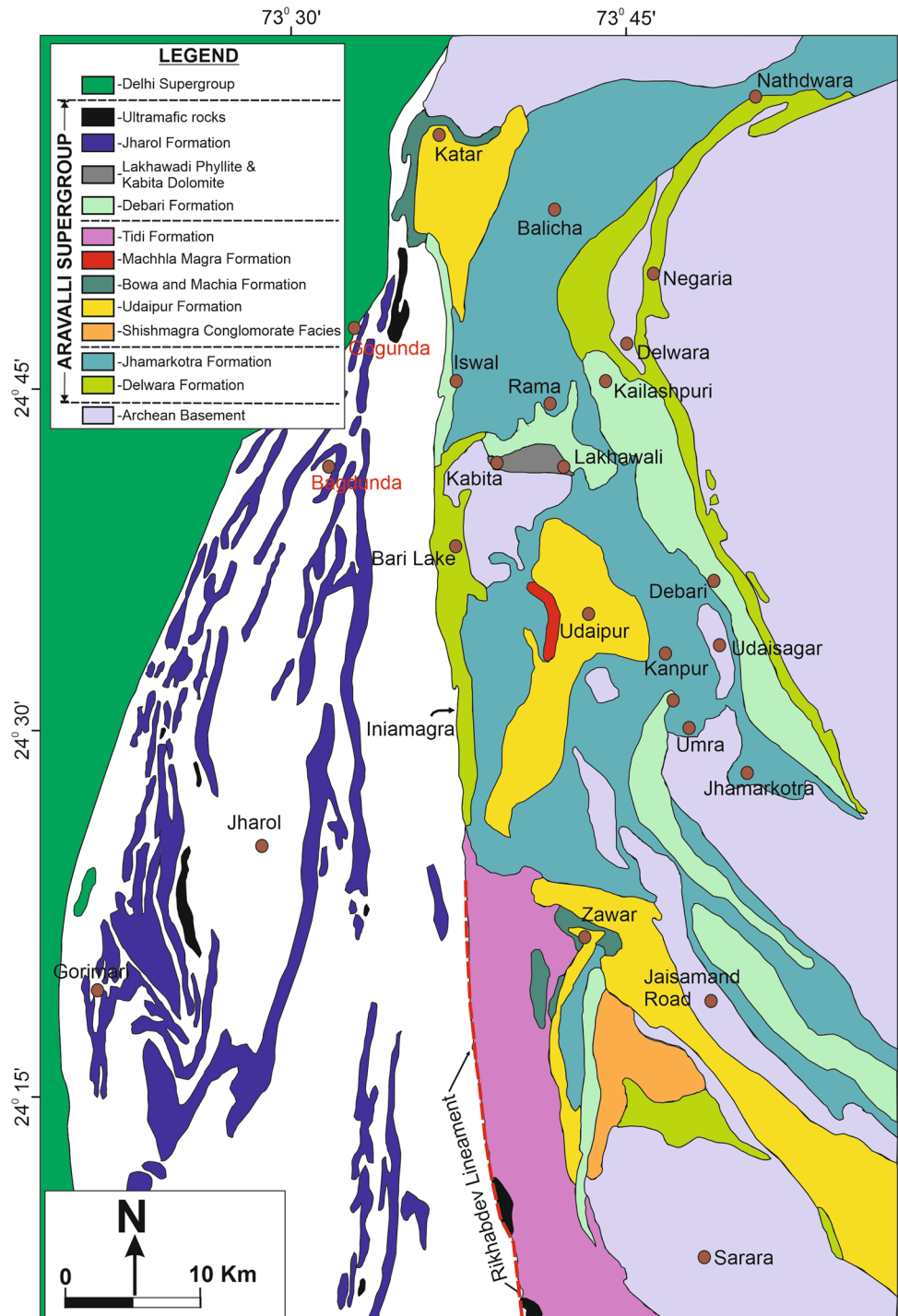


Fig. 2 Geological map of the region around Udaipur (modified after Heron 1953; Roy et al. 1988)



is slightly deformed (Roy 1988a, b; Roy et al. 1993). In the Udaipur region, the general physiographic gradient is to the south and southeast. With heights ranging from 1313 to 350 m above mean sea level, the Rocky Hills, which are the parts of the Aravalli range, cover the most northwest to the central sector of the area and are considered ideal runoff zones (Fig. 3). Udaipur region is recognized for its undulating terrain with a series of folded

Aravalli hill ranges stretches in a NE-SW orientation in the western part of the region. A typical plain of gneisses and granites with no alluvial cover can be found to the east of the Aravalli mountains. The drainage system of the region is well-developed with some major rivers like Jakham, Som, Wakal, Sei, Sabarmati, Gomti, and Berach. These rivers receive their water during the monsoon and flow more freely in the rainy season. The rivers Jakham,

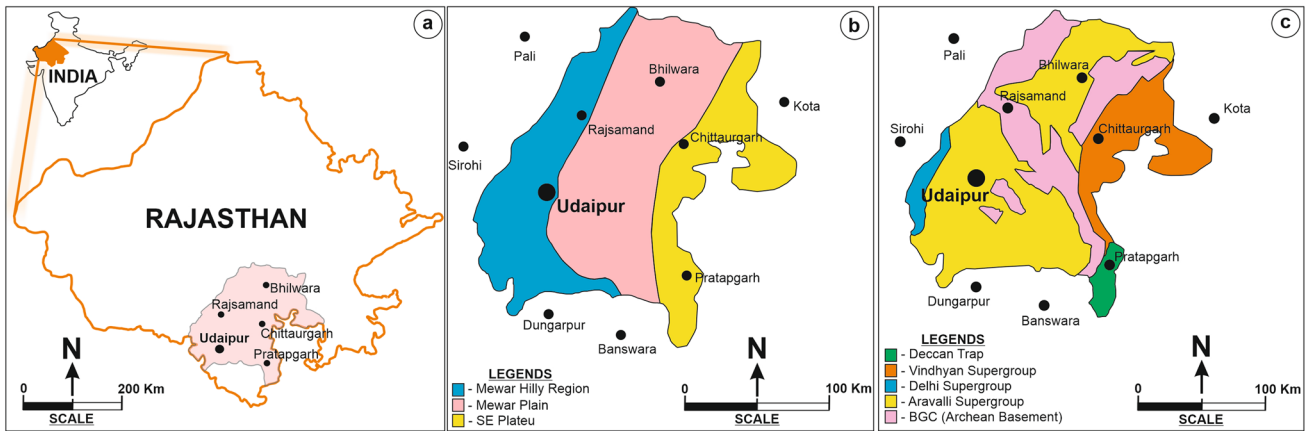


Fig. 3 a Map of Rajasthan showing the Mewar region, Rajasthan (inset: map of India showing Rajasthan state) (source: <https://en.wikipedia.org/wiki/Mewar>). b Map showing physiographic set up of

the Mewar region. c Simplified geological map of the Mewar region (after Wiszniewska et al. 2020)

Gomti, and Som drain the region’s southeastern plains. In the district’s southwest, the Wakal, Sabarmati, and Sei rivers flow through the valley region of the Aravalli hills. These rivers have been dammed at various points around the area, resulting in the development of many artificial lakes.

Some of the region’s most valuable mineral belts are found in the rocks of the Aravalli Supergroup. Among the most notable are the Jhamarkotra rock phosphate, Daroli limestone, Babarmal pink marble, and Zawar lead–zinc deposits. Green marble can be found in post-Aravalli rocks, particularly ultrabasics, which are also talc-host rocks. Lead–zinc, copper, rock phosphate, soapstone, limestone, barytes, and marble are among the metallic and non-metallic minerals found in the region. In the realm of gemstones, the region has shown the potential of emeralds (Sinha-Roy, 2000).

The Aravalli craton in the Udaipur area features an array of Proterozoic fold belts inside a reworked Achaean basement complex. Two examples are the Paleoproterozoic Aravalli fold belt and the Mesoproterozoic Delhi fold belt. Fold belts, which are marked by significant crustal dislocations and ductile shear zones, are described by resurgent tectonics (Figs. 1 and 2). The southern Aravalli ranges near Udaipur are delimited by two major NW–SE striking lineaments: Jaisalmer–Barwani lineament (L) and Bundi–Khatu–Sakhi lineament (M). The Aravalli fold belt is further divided to the north of Udaipur by a notable dislocation zone known as the Banas dislocation zone (BDZ). Structurally, the area has been subjected to three episodes of deformations, i.e., F_1 , F_2 , and F_3 (Chauhan et al. 1996; Roy and Jhaxhar 2002). Out of these, the second deformation is the most dominant one. The first deformation is less conspicuous due to superimposition by F_2 folds. The first deformation is invariably associated with axial planar schistosity (S_1) which is

mostly observed parallel to bedding planes (S_0) indicating the isoclinal nature of first folding. The second deformation (F_2) is observed as open to isoclinal, upright folds trending NNE–SSW. S_2 cleavages developed axial planar to these folds and are at an angle to S_1 schistosity except at the hinge of the folds. The third deformation (F_3) is less penetrative and is observed at a few places striking ESE–WNW with the vertical axial plane. Among linear structures (intersections lineations) are the most common features due to superposed deformation. Early lineations are deformed as a result of later deformations preserved in different rocks. Lineations are also marked by small-scale fold axes, mullions, and boudins.

Physiographic features and landform of the Udaipur region

The hilly areas of the Aravalli range, the Mewar plains, and the southeastern plateau are among the most conspicuous topographic characteristics of the Mewar region (Fig. 3). The Aravalli range is one of the oldest folded mountain ranges in India and the world. The hill range stretches for around 670 km from Delhi in the north to Gujarat in the south passing majorly through Rajasthan (Kohli 2004). The Aravalli range of Rajasthan is separated into four sections: (i) northeastern Aravalli range, (ii) central Aravalli range, (iii) southern Aravalli range or Mewar hilly region and Bhorat plateau, and (iv) Abu block. The “Mewar Hilly Region of Southern Aravalli Range” comprises the western and northwest parts of the Mewar region (about 17,007 sq km). Based on the lithology and overall morphology, the southern Aravalli range is further divided into four zones: (i) zone of structural hills on granite, (ii) zone of dissected hills on carbonate rocks, (iii) zone of folded hills on quartzites,

and (iv) zone of arcuate hills on quartzites, conglomerate, and greywacke (Gupta et al. 1997). Jarga of Udaipur district is the highest peak in the Mewar region with an elevation of 1431 m, followed by Kumbhalgarh, Rajsamand (1224 m), Kamalnath, Udaipur (1001 m), and Sajjangarh, Udaipur (938 m). The highest section of Mewar hilly region lies between Gogunda and Kumbhalgarh, having an average elevation of around 900 m and due to their flat disposition, gives an appearance of the plateau, known as the “Bhorat Plateau” (Gupta et al. 1997).

Geodiversity and geological heritage sites of the Udaipur region

Rajasthan is the largest state of India in terms of area and is home to diversity. The state is broadly divided into nine regions based on language and culture. These include Marwar, Mewar, Dhundhar, Matsya, Hadoti, Shekhawati, Merwara, Vagad, and Mewat. These regions are equally rich in their heritage and artistic contribution. For centuries, the Mewar region was ruled by Rajputs and was founded in 566 CE by Guhaditya, the founder of the Guhil dynasty. This area holds a major tribal population in Rajasthan including *bheel*, *meena*, and *garasiya*. Mewar or Mewad is a region in the south-central part of Rajasthan state and mainly includes the districts of Bhilwara, Chittorgarh, Pratapgarh, Rajsamand, Udaipur, Pirawa Tehsil of Jhalawar district, and some parts of Madhya Pradesh and Gujarat (Fig. 3). The region lies between the Aravalli range to the northwest, Ajmer to the north, Gujarat and the Vagad region of Rajasthan to the south, the Malwa region of Madhya Pradesh state to the southeast, and the Hadoti region of Rajasthan to the east. Metallic minerals include ores of lead, zinc, copper, silver, and iron and are important metallic mineral resources. A large number of non-metallic minerals are being found and exploited in the Mewar region. These include asbestos, kyanite, garnet, pyrophyllite, soapstone (talca), calcite, dolomite, baryte, mica, quartz, feldspar, clays, ochres, silica sand, rock phosphate, wollastonite, limestone (for cement), limestone (for lime), brick earth, murrum, granite, marble, sandstone, quartzite, slate, phyllite, and serpentinite and are the important building and dimensional stones found in the Mewar region.

There are a number of natural and man-made geological heritage sites in and around the Udaipur region that have particular geological or geomorphological significance. As well as its inherent geological characteristics, it may also have cultural or heritage significance. In the present study, we have chosen twenty-seven geological heritage sites from the Udaipur area covering 4–5 outcrops around each site. The geological heritage sites are grouped under four road traverses for ease of field visits and geotours (Table 1).

Figure 4 shows the location of various geological heritage sites with respect to various road traverses. We have discussed below the geological significance and details of each geological heritage site grouped under each road traverse.

Geological heritage sites along Udaipur-Gogunda-Jaswantgarh-Kumbhalgarh road traverse

This traverse covers the northwest portion of the Udaipur area and discusses a total of nine geological heritage sites (Table 1) (Fig. 4). The exposed rock formations in this area comprise the Archean basement, Aravalli Supergroup, and Delhi Supergroup. Along this route, a variety of metamorphic and igneous rocks are exposed. The exposed geological structures of varying scales enable geologists to understand various deformational episodes that have happened since the Archean era. In the following section, we are discussing the exposed geological features of each geological heritage site of this traverse.

Ahar River granites (Archean granitoids) (24° 40' 35" N: 73° 38' 19" E) (11 km NW of Udaipur, NE of Thur-ki-pal, village Thur)

Granite and granite gneiss bodies exposed in and around Kabita, Thur Ki Pal/Jamuniya Ki Naal, and adjacent areas occupying a triangular area northwest of Udaipur city are named Ahar River Granite (ARG) by Crawford (1970). These basement granite and granite gneisses (Archean) occur as intrusives within the older Archean basement rocks. The Ahar River granite is surrounded by the Paleoproterozoic rocks of the Aravalli. Roy (1988a, b) confirmed the basement status of the ARG on the basis of sedimentological grounds and similar tectono-stratigraphic relationship of the basal succession of the Aravalli Supergroup both with the ARG near Udaipur and with the Mewar gneiss complex rocks southeast of Nathdwara. The ARG is a coarse-grained, massive, leucocratic rock except along the outcrop margins. It ranges in composition from alkali granite to granodiorite to tonalite, with a minor amount of ferromagnesian minerals. The enveloping Aravalli metasediments form a continuous sequence starting with greenschist (metavolcanics) and quartzite (locally conglomerate) along the granite contact. The rocks of the Delwara Formation of the Lower Aravalli Group are traceable along the western margin of the ARG known as “Bari Volcanics” in this region (Roy, 1993). Wedges of conglomerate (granite carbonate mixite) and quartzite have developed at the base of the carbonate—horizon along the eastern fringe of the outcrops of the ARG belonging to the Jhamarkotra Formation of the Lower Aravalli Group (Roy 1988a, b). The granite

Table 1 Details of the geological heritage sites of the Udaipur region

Road traverse	Geological heritage site number	Location coordinates	Geological aspects can be studied	Geological age	Geological/archeological, cultural features
1. Udaipur-Gogunda-Jashwantgarh-Kumbhalgarh road traverse	1a. Ahar River granite (Archaean granitoids)	24° 40' 35" N 73° 38' 19" E	Basement granitoids, Mewar gneissic complex (MGC) (APC) and basal volcanics	3.3–2.5 Ga Achaean	Paleosols, Sheared contact, and tectonic mélange, basement cover relationship
	1b. Archaean-Proterozoic contact (APC)	24° 42' 03" N 73° 38' 16" E		Archaean and Lower Aravalli	Deformed structures, folds, and cleavages in metavolcanics
	1c. Jhamarkotra Formation	24° 43' 04" N 73° 38' 01" E	Early F ₁ folds; S ₀ and S ₁ ; L ₁ lineations	Jhamarkotra Formation, Lower Aravalli	S ₀ , S ₀ /S ₁ , F ₁ folds, micro-faulting, bedding cleavage relationship, and evidences of reducing environment in carbonaceous phyllite
	1d. Jharol Formation	24° 44' 14" N 73° 33' 26" E	Roofing slab quarry, early F ₁ , F ₂ folds; S ₀ , S ₁ , and S ₂ ; lineations	Deep-water facies (Jharol formations)	Chronological study of S ₁ , S ₂ , L ₁ , L ₂ , F ₁ , and F ₂ folds and deformation of lineations
	1e. Kaliguman lineament near Shiv temple	24° 44' 13" N 73° 33' 19" E	Kaliguman lineament and ultramafics	Deep-water facies (Jharol formations)	L ₁ , L ₂ , F ₁ , and F ₂ fold, deformation of lineations and interference patterns, fold profile study in ultramafics
	1f. Majam village	24° 42' 33" N 73° 32' 29" E	Hb schist, L ₁ , L ₂ , F ₁ , and F ₂ fold, deformation of lineations	Deep-water facies (Jharol formations)	Interference patterns: crescent, hook, dome, eyed, and mushroom patterns, and F ₂ folds, cleavages, joints, and faults
	1 g. Northeast of Modi village	24° 47' 31" N 73° 34' 06" E	Quartzite, talc-chlorite schist, and green marble quarry	Ultramafics and deep-water facies rocks	F ₁ , F ₂ fold, boudins, and its dislocation controlled by folds, controlled mineralization of talc
	1 h. South of Jashwantgarh, opp. Hotel Raj	24°46'53" N 73°28'09" E	Delhi Supergroup	Delhi and post-Delhi intrusive	Calc-silicate rocks intruded by granite and pegmatite, boudinization
	1i. Kumbhalgarh fort	25° 09' 10" N 73° 35' 12" E	Delhi Supergroup	Delhi and post-Delhi intrusive	Calc-silicate rocks intruded by granite and pegmatite, Boudinization and folds, tourist place and national park

Table 1 (continued)

Road traverse	Geological heritage site number	Location coordinates	Geological aspects can be studied	Geological age	Geological/archaeological, cultural features
2. Udaipur-Chittorgarh-Kota-Bhilwara road traverse	2a. Tulsi Namla, east of Udaipur (paleosol site)	24° 36' 43.34" N 73° 50' 7.20" E	Archaean Proterozoic contact (APC) and basal quartzite	2.5–2.15 Ga	Unconformity and paleosol, great oxidation event (GOE)
	2b. Near Debari power house, east of Udaipur	24° 36' 37" N 73° 49' 22" E	Basal Debari conglomerate	1.5 Ga	Strain analyses of pebbles and sedimentary structures
	2c. NE of Udaipur between Rundera and Kikwas villages	24° 38' 59.37" N 74° 3' 38.02" E	Carbonatite	2273 to 950 my	REE deposit
	2d. Bojunda Village, Chittorgarh	24° 50' 20.5" N 74° 35' 00.8" E	Bhagwanpura limestone	Lower Vindhyan	Bojunda stromatolites park
	2e. Berach River, Chittorgarh	24° 54' 13" N 74° 37' 22" E	Great boundary fault (GBF)	Post Vindhyan	Ductile deformation, folds, cleavages, striation, and lineations
	2f. Menal gorge, between Chittorgarh and Kota	25° 5' 58.38" N 75° 9' 52.24" E	Sandstone	Upper Vindhyan	Deep gorge, water fall and temples, mini Khajuraho, ancient Shiv temple
	2g. Maharami Padmini Palace, Chittorgarh fort	24° 52' 44" N 74° 38' 42" E	Kaimur sandstone	Upper Vindhyan	Historical place, palace, and fort
	2h. Bijoliya	25° 10' 26" N 75° 20' 55" E	Lower Bhandar Group	Upper Vindhyan	Prehistoric paintings, weathering structures, sedimentary structures, etc
	2i. Tiranga hill, Pur-Banera iron ore deposit, near Bhilwara	25° 19' 59" N 74° 32' 34" E	Tiranga hill, Pb–Zn–Cu and Fe deposit	Lower Proterozoic	Ancient mining of Pb–Zn–Cu–Fe, structural control of mineralization
	2j. Rampura–Agucha lead–zinc deposit, Gulabpura, Bhilwara	25° 49' 50.67" N 74° 44' 24.84" E	Largest Pb–Zn mine in India	3.2 to 2.5 Ga	Open and underground mines, ancient civilization
	2k. Rajpura–Dariba mines, Udaipur–Fatehnagar road	24° 56' 33.3" N 74° 07' 46.3" E	Rajpura Dariba Group Pb–Zn–Cu–Ag deposit	Bhilwara Supergroup	Ancient mining and geological monument of world-class gossan
	3. Udaipur-Zawar-Kherwara road traverse	3a. Zawar mines area, Udaipur	24° 21' 03" N 73° 41' 47" E	Tiri River section near Ram-anath temple	Aravalli Formation
3b. Near Ramanath temple, Zawar mines road		24° 20' 57" N 73° 41' 51" E	Ancient mining and smelting	765 ± 100 BCE	Archaeological study
3c. Keshariyajee, Obri, and Kherwara on Udaipur–Ahem-dabad road		23° 56' 52.00" N 73° 38' 23.00" E	Green marble mines	Post Aravalli	Marble mining, the only green marble in India

Table 1 (continued)

Road traverse	Geological heritage site number	Location coordinates	Geological aspects can be studied	Geological age	Geological/archeological, cultural features
4. Udaipur-Jhamarkotra-Mamadev traverse	4a. Mamadev village on Udaipur-Jhamarkotra-Jagat road	24° 25' 52.51" N 73° 52' 16.54" E	Oldest Archaean rocks, (BGC)	3.3 Ga	Folded gneisses, banded Gneisses, and famous Jagat temple
	4b. Jhamarkotra mines, Jhamarkotra, Udaipur	24° 28' 39.47" N 73° 50' 10.56" E	Jhamarkotra Formation, Aravalli Supergroup	2.5–2.15 Ga	Largest and high-grade phosphorites mines
	4c. Stromatolite fossil park	24° 28' 29.72" N 73° 52' 2.27" E	Jhamarkotra Formation, Aravalli Supergroup	2.5–2.15 Ga	Different species of cyanobacterial stromatolites, host rock, and deformation of stromatolites
	4d. Jhameswar Mahadev temple, Jhamarkotra-Jagat road, Udaipur	24° 28' 26" N 73° 52' 08" E	Recent deposits in the river in the cave temple	Recent deposit	Stalactite and stalagmite, cave temple, and natural valley

suffered extreme post-crystalline deformation during the earliest deformation of the Aravalli (cover) rocks and the granite–cover contacts are marked by prominent ductile shear zones. The granite near its contact with the metasediments and metavolcanics shows mylonitisation (Fig. 5a) accompanied by extensive fluid-assisted mineralogical changes along these high-strain zones. As a result, granite has been locally transformed into phyllitic rocks (ultramylonitic phyllonite) showing prominent mylonitic foliations and lineations (Roy and Jakhar, 2002). Besides this, the interface between the basement and cover sequences is also marked by the presence of paleosol in the area. The paleosol occurs as pockets of white mica and high aluminous rocks (Fig. 5b). The “granite” body, consisting dominantly of massive, coarse to fine-grained, grayish-green leucogranitoid, includes a number of inclusions of amphibolite and metasedimentary rocks.

Archean–Proterozoic contact (APC) (24° 42' 03" N: 73° 38' 16" E) (Jamuniya Ki Nal, 12 km north of Udaipur city on NH76)

Archean-Proterozoic contact/basal Aravalli quartzite/basal volcanics are exposed here. The contact between the basal Aravalli formations with Ahar River granite/Mewar gneiss is well-exposed. The basal Aravalli formations include metabasalts (basal volcanics) with thin bands of dolomite, quartzite, and conglomerate (local), representing the Delwara Formation of the Lower Aravalli Group. The mineral assemblages of the metamorphosed basal volcanics suggest greenschist to amphibolite facies metamorphism. At the contact zone here, high aluminous rocks are noticeable with narrow lenticular pockets of white mica aggregate representing paleosol between the Archaean basement rocks and the basal Aravalli formations (Fig. 5b). The zone of occurrence of high-aluminous pockets, therefore, forms an important lithostratigraphic unit, especially due to their very specific stratigraphic position at the interface of the basement and the Aravalli Supergroup (Pandit et al. 2008, 2012). The longest dimension of the white mica deposits ranges between 10 and 20 m, whereas the widest zones are usually between 2 and 10 m. The paleosol is considered as a marker of erosion-related unconformity or APB in the region. Basal volcanics are showing deformation. Because of intense deformation, pebbles in the conglomerate have been stretched into sheets and well-developed mylonitic foliations can be seen in the rocks. The Delwara Formation includes metabasalts with thin bands of dolomite and quartzite. For the study of the superposition of deformation, these metavolcanics (chlorite schist) exhibit beautiful F_2 folds and S_1 and S_2 cleavages (Fig. 6a to f).

Fig. 4 Map of Udaipur region and the surrounding area showing locations of geological heritage sites and road connections (mentioned in Table 1)

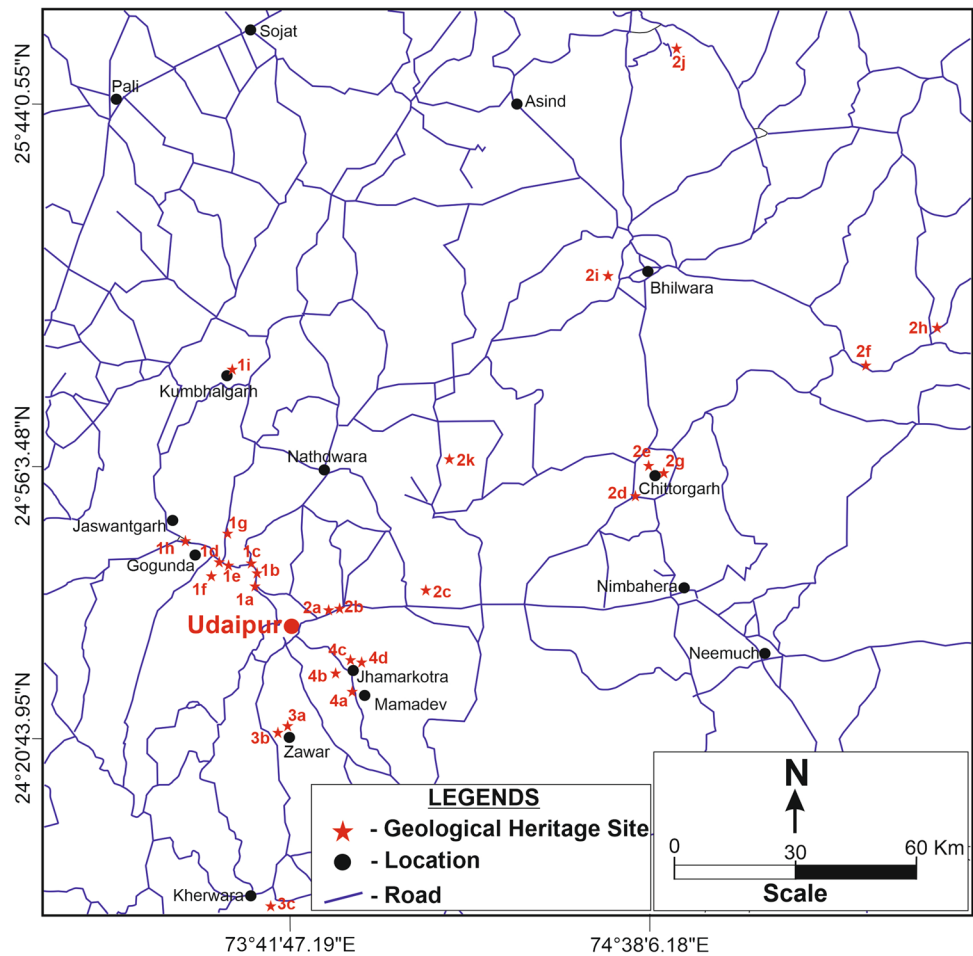
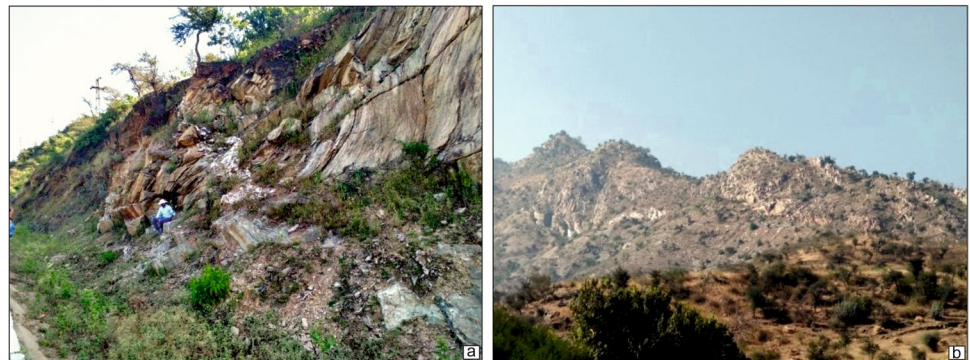


Fig. 5 a The granite near its contact with the metasediments and metavolcanics shows mylonitisation. **b** Pockets of paleosol (white mica and high aluminous rocks) mining below the Basal quartzite ridge



Aravalli Formation (Jhamarkotra Formation) (24° 43' 04" N: 73° 38' 01" E) (location: 1 km towards Iswal from Ghasiar temple on the south side of the road)

The passage from the basal Delwara Formation of quartzite-metavolcanic association to the next higher dominantly carbonate succession appears which is gradational in nature. The dolomitic rocks have developed extensively in the shelf region of the Udaipur sector. Outcrops of dolomitic rocks form high castellated ridges, which virtually encircle the

valley of Udaipur. The carbonate rocks are dominantly dolomitic in composition showing rapid changes in facies to orthoquartzite, ferruginous dolomite, manganese-bearing dolomite, carbonaceous phyllite (black shale facies), and phyllitic dolomite (Fig. 7a). It also passes to argillaceous phyllite, which contains intercalations of dolomitic limestone. Carbonaceous phyllite exhibits bedding (S_0) and S_1 cleavages, which are axial planar to the F_1 folds. In the Aravalli region, it is very rare to find F_1 folds, and these can be studied well in this road-cutting section (Fig. 7a to d).

Fig. 6 **a** Folded earlier schistosity (S_1) by an open upright fold (F_2) with axial planar schistosity (S_2) and recumbent folding. **b** Shear cleavages (S_2) cutting at right angles to the cleavages (S_1) at F_2 fold hinge in metavolcanics. **c** Folded earlier schistosity (S_1) by an open upright fold (F_2) with axial planar schistosity as crenulation cleavages (S_2). **d** Inclined plunging F_2 fold. **e** and **f** Shear cleavages (S_2) cutting at right angles to the cleavages (S_1) at F_2 fold hinge in metavolcanics at Jamunia kinal, NW of Udaipur

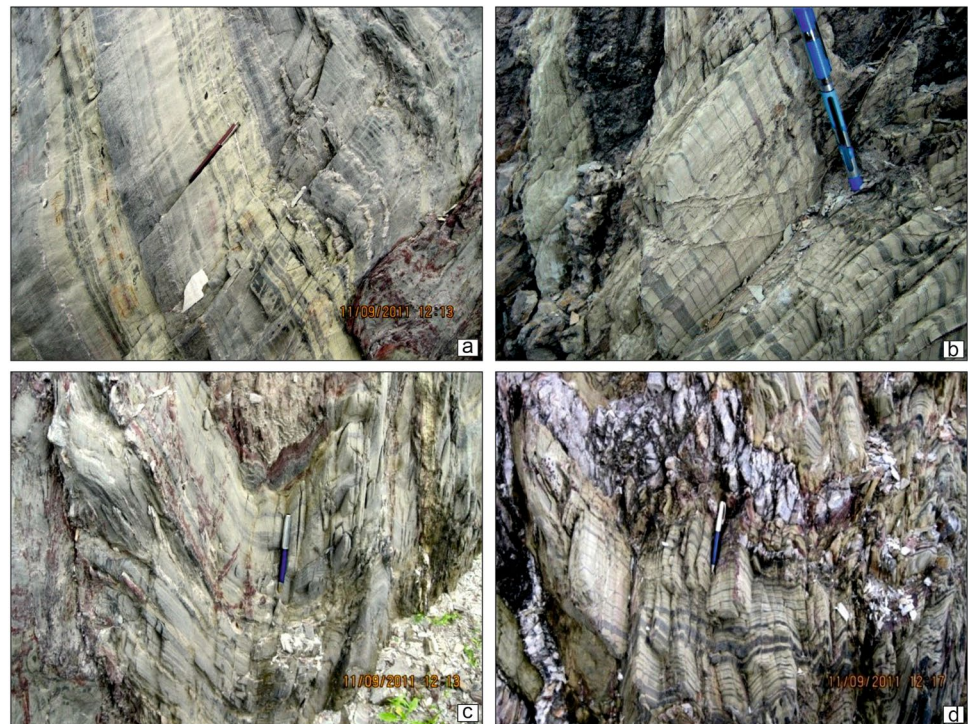


Aravalli Formation (Jharol Formation) (24° 44' 14" N: 73° 33' 26" E) (location: 6 km before Gogunda on Iswal-Gogunda road)

This is an ideal site for the identification of bedding/lamination (S_0), axial plane cleavage (S_1 and S_2), superposed folding, fold hinge, intersection lineation (L_1 and L_2), down-dip lineation, two generations of folds F_1 and F_2 , interference patterns, fold profiles, folded early lineations, superposed folding and deformation of lineations, identification of S_2 cleavage, and L_2 lineations can be studied with practical training on the spot. The site is exposed by the small hillock located at the roofing slab quarry near a bridge at the above-mentioned GPS location on Iswal-Gogunda road.

This is a classical place to understand the superposed deformation and unfolding of it, fold profile study on competent and incompetent rock, and fold classification exercise. The first folding event (F_1) is characterized by tight to isoclinal folds (Fig. 8a) with varying axes and shallow dipping axial traces. Bedding parallel cleavage S_0/S_1 in quartzite and quartz schist indicates the isoclinal nature of F_1 , the intersection of bedding, and first cleavages. F_1 folds have been superposed by N-S to NNE-SSW trending, open to isoclinal, upright F_2 folds (Chauhan et al. 1996), and have imposed pervasive upright cleavage in the Upper Aravalli phyllite (Fig. 8b). Fold mullions (Fig. 8c) and cleavages, joints, and small-scale first-generation folds can be studied at this location (Fig. 8d) (Sharma et al. 1988).

Fig. 7 **a** Bedding plane (S_0) in carbonaceous phyllite near Ghasiar in the Highway road cutting, note the cleavages (S_1) at an angle to it. **b** Stripping lineation (parallel to pen; L_1) on S_1 cleavage plane. **c** and **d** Vertically plunging F_1 fold, note the bedding plane (S_0) and cleavage (S_1) right angle to each other at the fold hinge



Kaliguman lineament (Jharol Formation) (24° 44' 13" N: 73° 33' 19" E) (location: 5 km before Gogunda on Udaipur–Gogunda road to the NE of Shiv temple)

Ultramafic rocks represented by serpentine, talc-tremolite schist, and chlorite schist occur along two regional lineaments, i.e., Rikhabdev lineament and Kaliguman lineament (Bakliwal & Ramasamy, 1987). Along Kaliguman lineament, the outcrops occur from Sempala to Gogunda. The ultramafic rocks along with their envelopes have undergone metamorphism to greenschist facies. The main mineral assemblages are (1) serpentine-talc-chlorite, (2) serpentine-talc-dolomite, (3) serpentine-tremolite-talc-chlorite, (4) serpentine-anthophyllite talc, and (5) dolomite-talc-tremolite chlorite schist. Long narrow bands of phyllite, quartzite, and limestone are frequently associated with ultramafic rocks that are in various stages of serpentinization and alteration and are associated with quartzite (recrystallized chert), ultramafic Braccia, and carbonates. Deformation of associated quartzite in chlorite schist exhibits beautiful deformation. Strongly developed L_1 lineation in quartzite (Fig. 9a and b) and early cleavages (S_0/S_1) are deformed by the F_2 open upright fold. Various exercises on fold morphology, fold profiles, and deformation of lineations can be done for better understanding (Fig. 9c and d). Small-scale structures “S” and “Z” folds are also well-exposed (Fig. 9e). Interference of F_2 and F_3 forming eyed fold is also traceable (Fig. 9f) (Sharma et al. 1988).

Majam village, Bagdunda (Jharol Formation) (24° 42' 33" N: 73° 32' 29" E) (location: 7 km from Gogunda on Gogunda-Jharol road (Nallah section))

Identification of bedding, axial plane cleavage, folding, fold hinge, intersection lineation, superposition of folds, small-scale faulting, and interference patterns are all possible at this location. Various structures can be seen with crystal clear outcrops of quartzite, mica schist, and hornblende schists exposed in the nallah section north of Majam village (Fig. 10a to f) (Sharma et al. 1988).

Ultramafics, Jharol Formation, northeast of Modi village (24° 47' 31" N: 73° 34' 06" E) (location: 6 km from Gogunda on Gogunda-Lossing road-talc mining area on the road side)

The outcrop of ultramafic intrusion representing the part of “Kaliguman lineament” is exposed at this site with about 150-m wide intrusive body deformed and co-folded with the Aravalli metasediments. These ultramafic rocks are represented by serpentinite and talc-chlorite schist. Low-to medium-grade metamorphism and intense deformation have obliterated the original mineralogy and texture of these rocks. The ultramafics are relatively more altered (serpentinized) and are hosts for talc and asbestos deposits of Gogunda which are considered as Syn to post–Aravalli intrusions (Chauhan et al. 2004a, b; Roy et al. 1998).

The talc mineralization is structurally controlled by F_2 deformation, and it is developed along the cleavage plane

Fig. 8 **a** First-generation isoclinal fold (F_1) plunging south-westerly in mica schist. **b** Deformation of early cleavage (S_1) and lineations (L_1) over an open upright fold (F_2). **c** Fold mullions (F_1) exposed over first-generation cleavage plane. **d** Cleavages, lineations, and joints in mica schist



which was boudinized during the first deformation and later relocated by F_2 deformation. The talc deposit follows the same structural pattern as seen on small scale, exhibiting participation of boudins in F_1 and F_2 deformation. The talc chlorite schist exhibits the development of crenulation cleavages (Fig. 11a). F_2 fold hinges have been deformed by F_3 fold forming dome and basins (Fig. 11b), i.e., doubly plunging fold. Early isoclinal folds of the competent garnet-rich layer in talc-chlorite schist exhibit coaxial folding (Fig. 11c), which is displayed by the local outcrop pattern around Modi village (Chauhan et al. 2004a, b). The talc mining is also following the hinge zones of the small-scale fold (“S” and “Z” shape) developed due to the major F_2 fold (Fig. 11d). The development of boudins and their deposition by later folding are beautifully exposed (Fig. 11e and f).

South of Jaswantgarh, opp. Hotel Raj on NH-76 (road-cut) Delhi Supergroup, Calc-silicate rocks intruded by granites and pegmatites (24° 46' 53" N: 73° 28' 09" E) (location: 8 km from Gogunda on Gogunda-Pindwara Highway on NH-76)

Calc-silicate rocks of Delhi Supergroup have been intruded by granites and pegmatites (post-Delhi intrusion) exposed in the road cutting (south side) on NH-76 after bifurcation to Jaswantgarh road. Isolated boudins trails can be traced which have been formed due to the layer parallel stretching of the competent rocks surrounded by the incompetent ones. At the necking point of these boudins the force, acting right angle to these layers can be noted due to the bending. (Fig. 12a to d)

Fig. 9 **a** and **b** First-generation lineations (L_1) plunging south-westerly in quartzite. **c** and **d** Deformation of early cleavage (S_1) and lineations (L_1) over an open upright fold (F_2). **e** Small-scale structures exhibiting S-shaped folds. **f** Eyed fold in fine-grained quartzite formed due to superposed folding



Kumbhalgarh fort (Delhi Supergroup, Kumbhalgarh formations) (25° 09' 10" N: 73° 35' 12" E) (location: 75 km from Udaipur)

The geology around the Kumbhalgarh fort is occupied by the rocks of the Delhi Supergroup, which is represented mainly by quartzite and calc-silicate rocks. No mineralization of economic importance is seen near this place. Occasionally, the rocks around the fort are also intruded by granites/pegmatites of younger age. The structural features like coaxial folding in the calc-silicate rock, development of boudins in the calc-silicate rock possibly due to stretching in the fort exposures, and occurrence of F_2 folds of competent calc-silicate rock are well-exposed (Fig. 13a to d).

The Kumbhalgarh fort, a historical and popular tourist spot, is one of the rarest forts of India that have never been attacked and never captured by a single enemy in its

history (Fig. 13e). It has the longest wall on the hill ridges with a total length of almost 36 km and merits second after the Great Wall of China in terms of length (Fig. 13f). It is also the birthplace of the King of Mewar, Maharana Pratap. Kumbhalgarh is a small town in the Rajsamand district of Rajasthan, and the fort was built during the fifteenth century by Maharana Kumbha. Standing majestically on an 1180-m high ridge in the Aravalli range and representing the past glory of the Rajput rulers, the fort wall is not in a regular straight pattern, but it runs through mountain cliffs and valleys. It has steep ascend and descent throughout its length, while the wall has stairs and walkways at places. It is surrounded by Kumbhalgarh national park which contains a thick forest with various flora and fauna including the endangered species of panthers and leopards.

Fig. 10 **a** First-generation isoclinal fold (F_1) of quartzite in mica schist. **b** Deformed first-generation fold hinge by F_2 fold. **c**, **d**, **e**, and **f** F_2 folds with crenulation cleavages and crenulated compositional layering. **g** Small-scale F_2 fold profile for conducting the exercise on deformation and faulting chronology. **h** Folded boudins in the hinge zone of F_2 fold, exhibiting a crescent shape. **i** Deformation of early cleavages (S_1) and folds (F_1). Note the Hook-shaped interference pattern. **j** Eyed and mushroom-shaped interference pattern

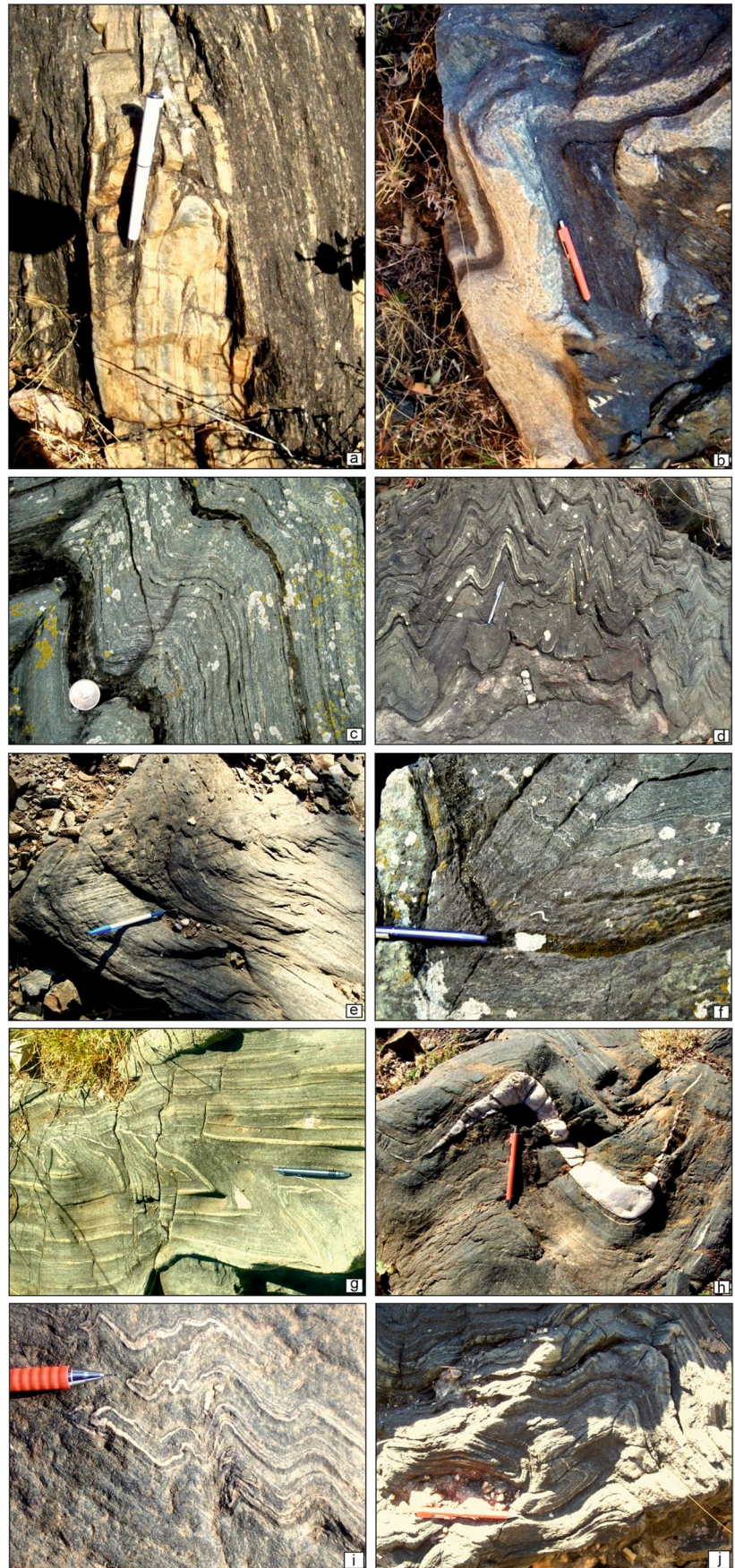


Fig. 11 **a** Development of crenulation cleavages (S_2) in talc-chlorite schist, near Modi village in quarry. **b** F_2 fold hinges have been deformed by F_3 fold, forming a doubly plunging fold. **c** Early isoclinal folds of a competent garnet-rich layer in talc-chlorite schist exhibit coaxial folding (F_1). **d** Talc mining NE of Modi village of isolated boudins of talc mineralization and its disposition similar to **e** and **f**. **e** and **f** Participation of boudins in the F_2 deformation which is followed by the talc mineralization in the area



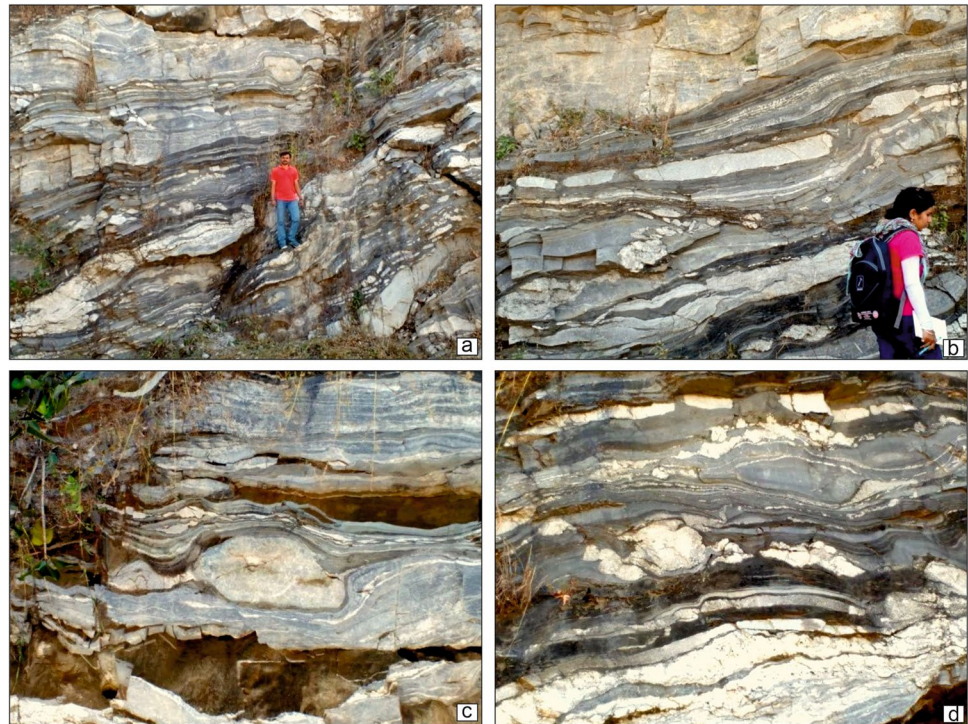
Geological heritage sites along Udaipur-Chittorgarh–Kota-Bhilwara road traverse

The above-mentioned traverse covers the east and north-east portion of the Udaipur area and discusses a total of eleven geological heritage sites (Table 1) (Fig. 4). The exposed rock formations in this area comprise of Archean to Proterozoic era. Along this route, a variety of metamorphic, igneous rocks, and sedimentary rocks are exposed making the number of geologically important sites, viz., stratigraphic, structural, paleontological, sedimentological, and geomorphological features, and economic mineral deposits including REE are classically exposed. In the following section, we have discussed the exposed geological features of each geological heritage site on this traverse.

APC–Tulsi Namla: Archaean-Proterozoic contact/basal Aravalli quartzite/paleosol (24° 36′ 43.34″ N: 73° 50′ 7.20″ E) (location: 300 m south of Tulsi Namla, 16 km east of Udaipur-NH-76)

Several fine-grained sericites bearing pelitic, schistose lithologies occur along the Archean (banded gneiss complex)–Proterozoic (Aravalli Supergroup) contact (APC) (Fig. 14a) in the Udaipur valley to the NW of Indian craton. These Al-rich lithologies (subsequently metamorphosed) have been described as “paleosols” (Fig. 14b), developed over a 3.3-Ga-old Archean gneissic basement, and are overlain by Paleoproterozoic Aravalli quartzite (Fig. 14c and d). The paleosol was developed between

Fig. 12 a, b, c, and d Development of boudins in calc-silicate rocks. Boudins trail exhibiting layer parallel extension of the granite/pegmatite intrusion (Post Delhi). Note: The necking of boudins, one can understand the bending mechanism



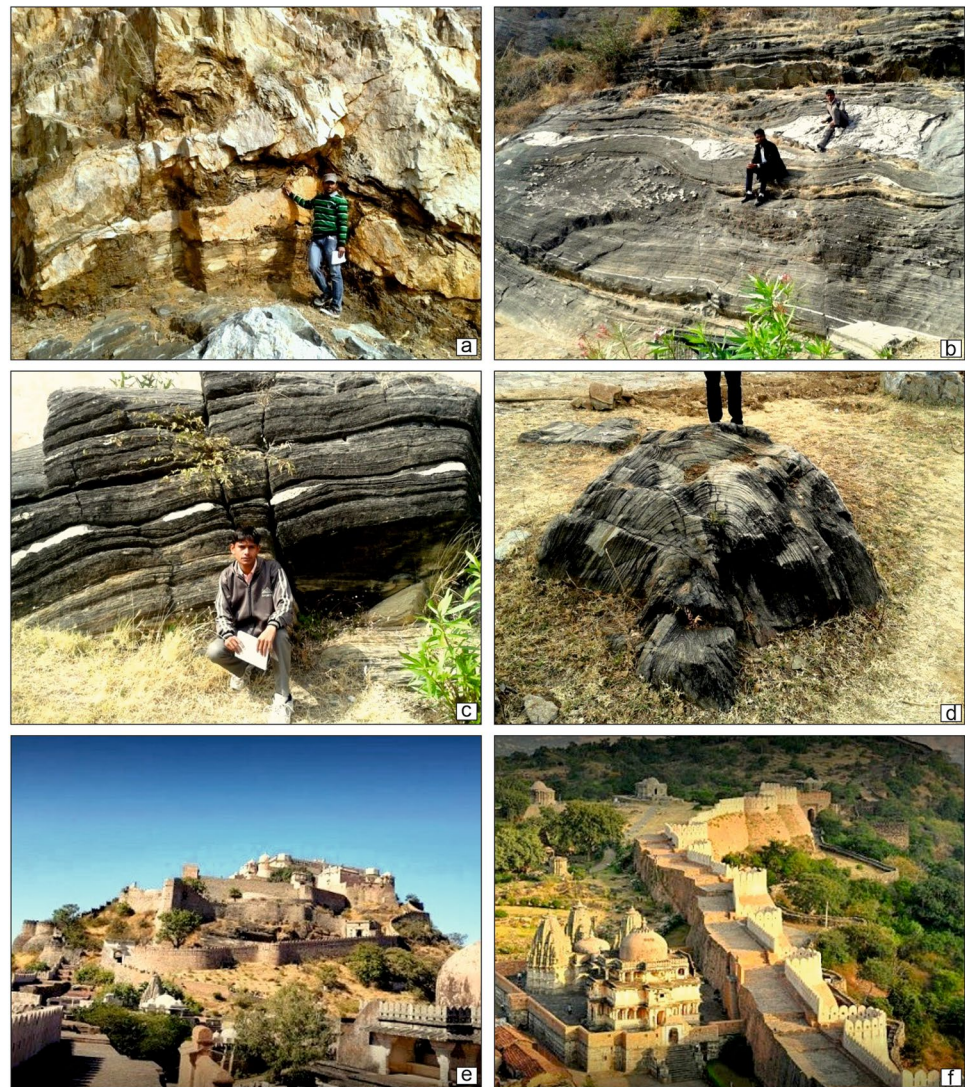
2.5 and 2.1 Ga, coincident with the globally recognized great oxidation event (GOE) (Pandit et al. 2008). These paleosol sections were interpreted to have developed under a reducing environment; however, the finding of a “ferricrete” zone in the upper part of the Tulsi Namla section (east of Udaipur) has led to an alternative suggestion of oxygen-rich conditions during paleosol development (Pandit et al. 2008). The Tulsi Namla paleosol section shows all the features characteristic of a complete paleosol section described in other Archean cratons. The paleosol includes sericite schist with kyanite (Fig. 14b) as the prevalent Al-silicate in the lower part of the profile, while chloritoid and Fe-oxides typify the Fe-rich upper part. Alumina has remained immobile during the weathering process, while Fe and Mn show a decrease in the lower part of the section and an abrupt rise in the upper part, in the ferricrete zone. The field and geochemical data indicate that the Tulsi Namla section is an in situ weathering profile and at least the upper part shows evidence of oxidizing conditions. The weathering interval can be inferred by the stabilization of the craton at 2.5 Ga and the deposition of rift-related sequences of the Aravalli basin (Delwara Formation) at 2.15 Ga. The Udaipur paleosols, especially in the eastern flank, represent the complete Archean–Paleoproterozoic paleosol sections in India (Pandit et al. 2008). The green varieties of white mica contain more than 0.3% Cr indicating contribution from mafic/ultramafic rocks in the basement (Pandit et al. 2008, 2012).

Debari conglomerate (24° 36' 37" N: 73° 49' 22" E) (location: 10 km east of Udaipur city near Debari power house, on Udaipur–Chittorgarh NH76)

At this location, Polymictic conglomerate can be seen with an arkosic matrix having stretched pebbles of different clasts lithology e.g., quartzite, quartz veins, granitic, gneissic and phyllitic material, cherty quartzite, etc (Fig. 15a to f). These conglomerates belong to the Debari Formation of the Upper Aravalli Group (~ 1500 my). The clasts have been deformed into ellipsoids (Fig. 15d). The deformed pebbles with their long axes define down dip stretching lineation (Fig. 15a). These rocks are in contact with either metavolcanics of the Delwara Formation or with the Basement rocks. Heron (1953) recorded the conglomerate being a basement bed for Aravallis, probably accumulated on a somewhat irregular surface of the “eroded gneisses”; hence, it is absent in places or may have been eliminated by thrusting along the unconformable margin.

The polymictic conglomerate-arkose-quartzite horizon, occurring linear band from Kailaspuri in the north to Salumber in the south (Sharma et al. 1998), is an important stratigraphic marker horizon within the AFB, marking the base of the Debari Group and is designated as Debari conglomerate. The presence of a boulder bed at the base along with a finely laminated greenschist matrix at places suggests a depositional environment similar to dropstone (Sinha-Roy et al. 1998). Moreover, lateral facies variations to carbonate, repeated phyllitic interbands, presence of

Fig. 13 **a** Coaxial folding in the calc-silicate rock on the way to Kumbhalgarh. **b** and **c** Boudins developed in the calc-silicate rock due to stretching in the fort area exposures. **d** F2 folds of competent calc-silicate rock exhibit open upright fold (F_2) geometry in the fort area. **e** and **f** Kumbhalgarh fort and view of the wall and temples as per the details given



ripple marks, trough cross-bedding, and graded bedding in metasedimentaries of this horizon suggest an intertidal near-shore environment of deposition (Sharma et.al. 1998). These beds belong to the Debari Formation of the Upper Aravalli Supergroup (~ 1500 my).

Newania carbonatites bodies: (rare igneous rock) (24° 38' 59.37" N: 74° 3' 38.02" E) (location: 40 km NE of Udaipur between villages Rundera and Kikawas)

The Newania carbonatite occurrence is located about 40 km NE of Udaipur between villages Rundera and Kikawas. Carbonatites are considered as rare igneous rocks which contain more than 50% of carbonate minerals and less than 10% SiO₂. The carbonatite body is about 3 km long and trends northwest and intrudes into 2.95 Ga old Untala granite gneisses of the banded gneissic complex (Fig. 16a and b). Rajasthan has only four occurrences of carbonatites, i.e., (i) Sarnu–Dhandali in Barmer district, (ii) Mer–Mundwara in Sirohi district, (iii)

Newania in Udaipur district, and (iv) Bhamni in Barmer district. In Newania, there are mainly two types of carbonatites, i.e., magnesiocarbonatite and ferro-carbonatites (Tantkar et al. 2019). Due to the complex mineralogical and chemical composition, carbonatites are one of the valuable sources for many important minerals. Carbonatite contains the highest concentration of REE of any igneous rock and is, therefore, a good target for REE exploration. It has been reported that there were multiple phases of carbonatite intrusions in the area with different ages of carbonatite bodies which have been reported, i.e., 2273 Ma, 1551 Ma, 1473 Ma, and 950 Ma.

Bojunda stromatolite park (24° 50' 20.5" N: 74° 35' 00.8" E) (location: 110 km east of Udaipur near village Bojunda before Chittaurgarh)

Background of Vindhyan Supergroup The Vindhyans cover a large part of Peninsular India, an area of about 104,000 sq. km and spreading over part of Bihar, Madhya Pradesh, and

Fig. 14 **a** Mining pit of paleo-sole from where pyrophyllite has been extracted. Note the foliation of basement rock dipping towards younger formations. **b** The paleosol includes sericite schist with kyanite as the prevalent Al–silicate mineral in the lower part of the profile. **c** Basal Aravalli quartzite dipping easterly towards the Basement which is pebbly at the base. **d** Further west this quartzite becomes fine-grained and associated with phyllitic rock. Note the transverse Fault across the strike of the rocks



Rajasthan from Dehri-on-Son in Bihar to Choti-Sadri south of Chittaurgarh in Rajasthan. Vindhyan rocks of Rajasthan have a comparable thickness of about 3200 m and form the main Vindhyan basin occupying an area of 24,000 sq. km. The basements for the Vindhyan rocks are pre-Aravalli rocks, referred to as the Bhilwara Supergroup which comprises shale, slate, and phyllite intercalated with dolomite / limestone and quartzite. The contact between two sequences is that of distinct composite unconformity marked by Khairmalia amygdaloidal andesite, Khardeola conglomerate, or by a mega lineament called the great boundary fault (GBF).

Stromatolites are structures produced by blue-green algae and are known as the impression of one of the earliest forms of life on earth. The best exposure of the stromatolites in Stromatolite Park near Bojunda village, about 6 km SW of Chittorgarh city on either side of the Chittorgarh–Udaipur state highway and west of Saras dairy plant (Fig. 17a to d). The park is spread over an area of about 8 acres and was declared a national geological monument in 1976. The stromatolites of different species are exposed within the massive Bhagwanpura limestone of the Lower Vindhyan age. Lithologically, the Bhagwanpura limestone represents a repetitive succession of limestone and conglomerate.

Great boundary fault (GBF) (24° 54' 3" N: 74° 37' 22" E) (location: Berach River, near Hotel Padmini, Chittaurgarh)

The GBF is an important dislocation zone in southeastern Rajasthan (Fig. 18d). The geological and structural setting indicates that the GBF, a reverse fault, is also an imbricate fault zone that sliced the Vindhyan and pre-Vindhyan rocks. The trace of the GBF is curvilinear, and it appears to be a rotational fault with the hinge located nearly 20 km south of Chittorgarh. These features indicate that the GBF is related to indentation tectonics caused by the impingement of the Bundelkhand massif with the Vindhyan cover rocks on the Precambrian terrain of Rajasthan, as a result of regional crustal deformation of the Indian plate after the collision and jamming of the Indian and the Asian plates. In this context, the GBF has a regional crustal significance in the tectonic development of the NW Indian plate segment in Late Tertiary and Quaternary times, and likely, this fault zone is still active.

Ductile shearing along the great boundary fault The great boundary fault manifests itself as a northeast striking tectonic lineament that cuts the Precambrian crust in Rajasthan for a strike length of more than 400 km. Great boundary fault zone (GBFZ) is characterized by the occurrence of numerous, meter scale ductile shear zones, two groups of

Fig. 15 **a** and **c** Polymictic conglomerate with flattened pebbles may define “flattening fabric” (X – Y section) with stretched pebbles. **b** Lineation is defined by stretched pebbles in a conglomerate (X – Z section). **d** and **e** Bedding plane defined by stretched pebbles in a conglomerate (Y – Z section). **f** Steeply dipping conglomerate with stretched pebbles (X – Y section) dipping westerly

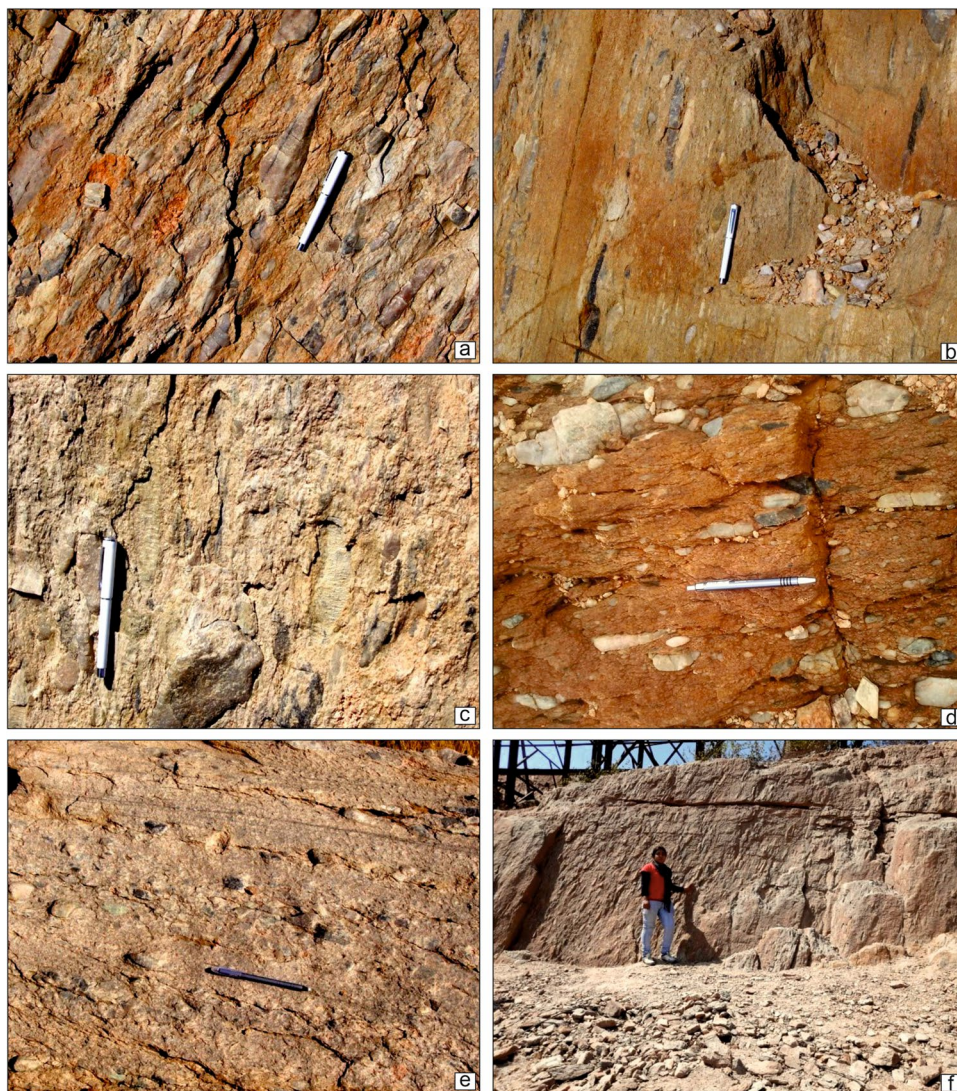
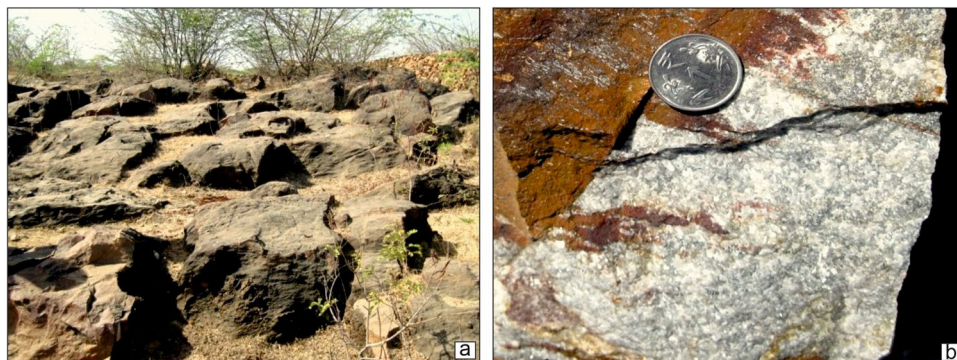


Fig. 16 **a** Carbonatite exposures in the field. **b** A close view of carbonatite sample from Newania



successively developed mesoscopic folds, F_1 and F_2 , and the intense nature of F_2 folding (Fig. 18a). Here, we focus on the nature of deformation within the GBFZ that cuts through the Nimbahera shale beds exposed in the Berach River section.

It is noteworthy that GBFZ in the Berach River section cuts through Vindhyan rocks rather than following the contact between the Berach granite and Vindhyan sedimentary rocks. The outcrop pattern within the GBFZ is controlled

Fig. 17 **a** and **b** Stromatolites, a vertical section at Bojunda, at right angles to the bedding plane (S_0). Note the convex surface (top), i.e., right side up. **c** and **d** Stromatolites: top view section, i.e., bedding plane, at Bojunda exhibiting circular to elliptical sections of the stromatolites on bedding plane surface (S_0)

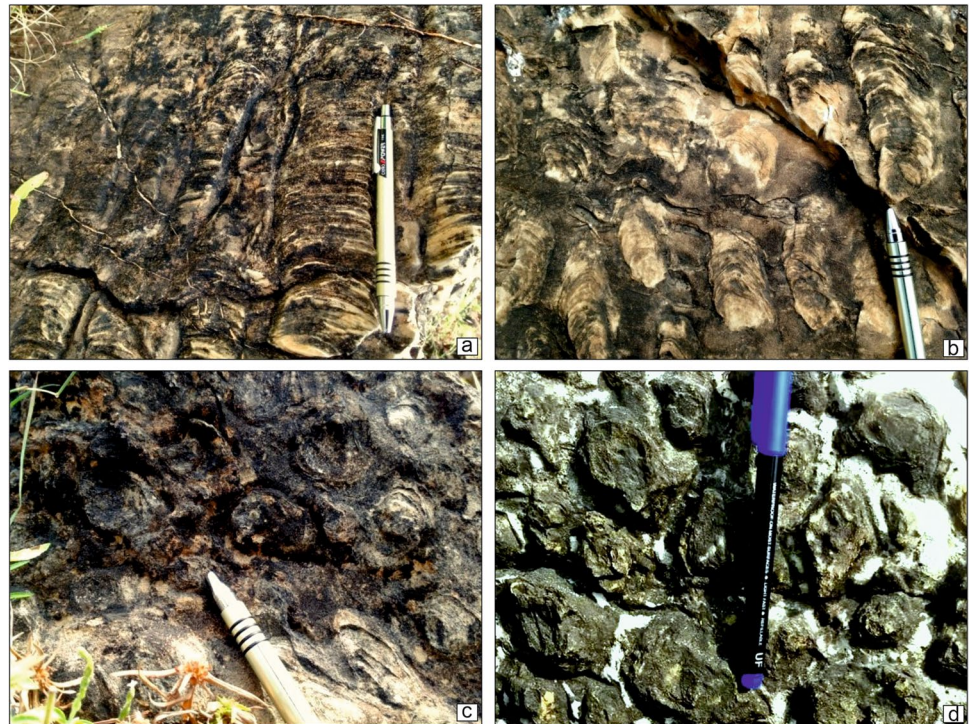
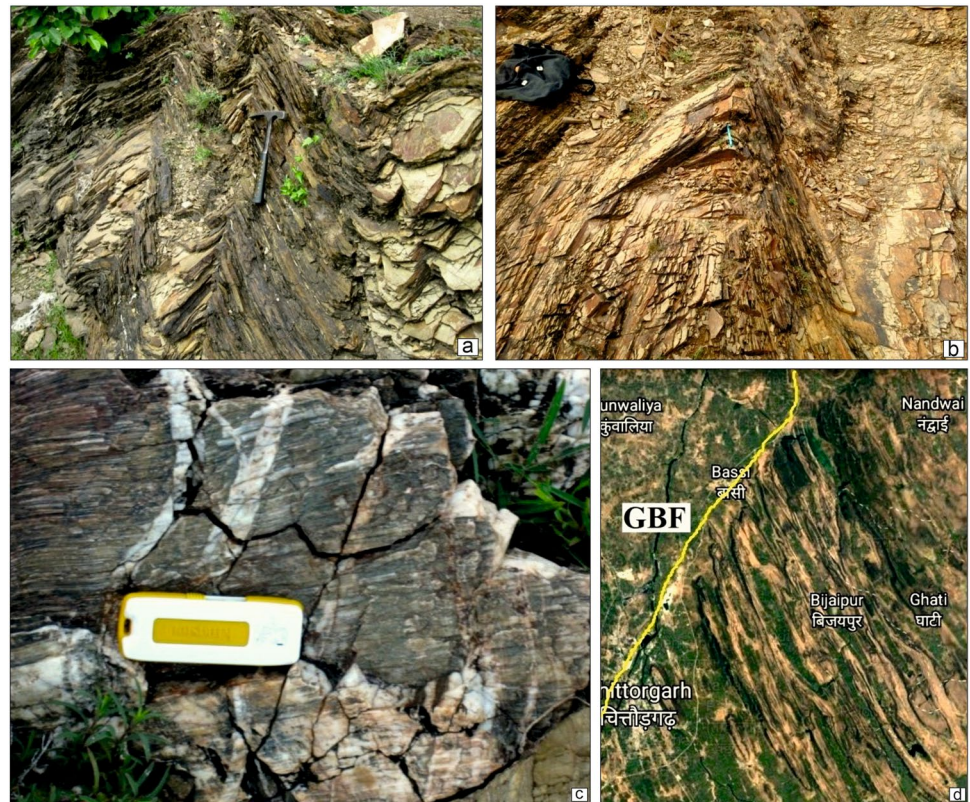


Fig. 18 **a** Sharp-hinged, chevron folds (F_2) developed in the shale, Berach River section, Chittaurgarh. **b** An open upright F_2 folds that plunge at a low angle towards NE. **c** Striations developed due to flexural slip folding. **d** Google image showing GBF zone



by characteristically open to gentle and upright F_2 folds that plunge at a low angle towards NE and/or SW. Many of these folds define periclinal domes and basins, and the

individual fault hinge line (Fig. 18b) commonly bifurcates at a moderate angle. Several lines of evidence such as the direct relationship between the thickness of beds and wavelength

of folds, the branching of hinge lines, the reversal in sense of shear offsets at the opposite limbs, and the orthogonal relationship between the hinge line and striation under fold limbs (Fig. 18c) implies that these folds were developed by flexural slip mechanism due to layer parallel compression. The tectonic evolutionary histories of GBF consist of an early event of ductile shearing and a late event of successive reactivation by brittle faulting (Srivastava and Sahay 2005).

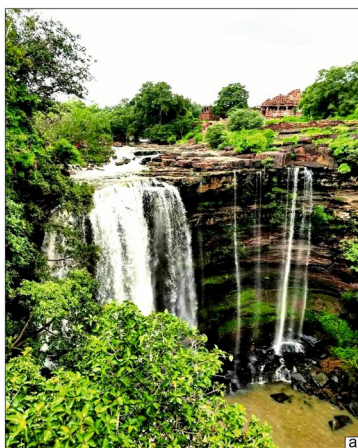
**Menal gorge, Begu Tehsil (25° 5' 58.38" N: 75° 9' 52.24" E)
(location: 90 km from Chittorgarh on the way to Chittorgarh-Kota highway)**

A typical geomorphological feature, the gorge with a deep narrow passage and steep rocky sides is present at Menal in Begu Tehsil of district Chittorgarh. This is one of the most popular picnic spots during the monsoon season and is also known as “mini Khajuraho” in Rajasthan. Menal is situated about 90 km from Chittorgarh on the Chittorgarh-Kota highway and is famous for its ancient temples, waterfalls, and beautiful forests. A gorge with ~ 45m depth within the sandstone beds of Bhandar Group (Upper Vindhyan Supergroup) is present here which becomes a waterfall and creates a picturesque scene during the rainy season (Fig. 19a).

Kaimur sandstone, Upper Vindhyan (24° 52' 44" N: 74° 38' 42" E) (location: lake near Maharani Padmini Palace, Chittorgarh fort)

The Chittorgarh fort sandstone belongs to the Kaimur Group of the Vindhyan Supergroup. This sandstone is generally thickly bedded and grayish or pinkish-white in color and fine to medium-grained in nature. Sedimentary structures like current bedding, ripple marks, and mud cracks are seen at places. Sheared zone and tension gashes are also observable (Fig. 19b).

Fig. 19 a Menal waterfall. b Tension gashes in sandstone bed exhibiting shearing near Padmani Palace, Chittorgarh fort

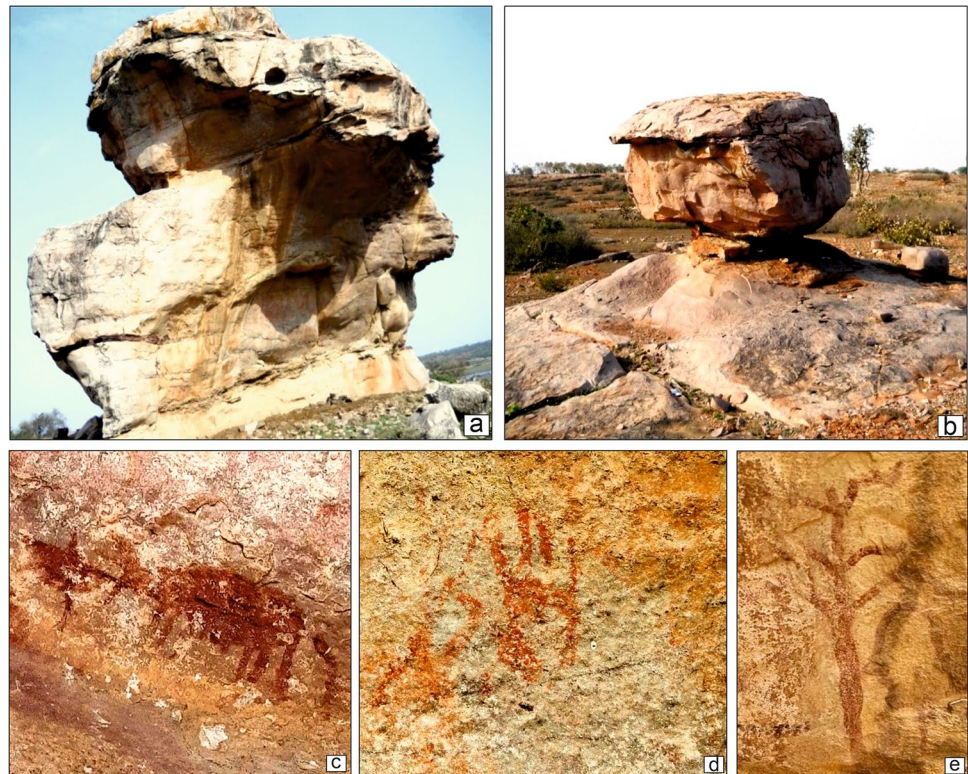


Rock pedestal and rock paintings, Bijoliya (25° 10' 26" N: 75° 20' 55" E) (location: 90 km from Chittorgarh on the way to Chittorgarh-Kota highway)

Bijoliya area comes under Mandalgarh tehsil of Bhilwara district and is located at 90 km from Chittorgarh on Chittorgarh–Kota National Highway. It is the second-largest sandstone-producing area in the state of Rajasthan. The area mainly comprises sandstone and shale belonging to the Lower Bhandar Group (Bundi Hill Sandstone) of the Vindhyan Supergroup. In sandstone units of the Bijoliya area, many depositional, soft-sediment deformation and weathering, and erosional structures are present. These include different types of bedding and laminations, ripple marks, cross-bedding, parting lineation, load casts, slump structure, rain print, flute casts, Liesegang rings, pedestal rock, tafoni, and spheroidal weathering (Nagar et al. 2017).

The pedestal rocks are more commonly reported in arid regions, while these rocks are exposed in this semi-arid regions. These rock pedestals are of hard, massive, grey sandstone of the Bhandar Group (Upper Vindhyan) exposed on the uplands about 3 km from Bijoliya town, on the way to Bundi (SH No. 29) (Fig. 20a and b). More than 20 rock pedestals of various sizes and shapes are found here with some having tafoni cavities of variable size and depth. Interestingly in two of the large-sized pedestal rocks, several paintings of the prehistoric period are reported. The rock paintings probably made by prehistoric humans depict animal figures, geometric designs, body parts, and hunting scenes (Fig. 20c to e). Few of them are in a highly fragmented, faded, or in a such poorly preserved state that it is very difficult to make out the precise subject matter of the paintings. The main feature of these rock paintings is that it contains figures of a hunting scene, elephant, wild animals, hand impressions, and plant drawing. Apart from these, an epitaph was also found, possibly written in *Brahmi* script, but got damaged due to rains. The majority of the pictographs are monochrome; i.e., red to reddish-brown

Fig. 20 a and b Rock pedestals at Bijoliya. c, d, and e Pre-historic rock paintings within pedestal rocks at Bijoliya



color was used. The paint is found to be made by grinding the red ochre or hematite (*geru*). Some sticky substances such as animal fat or gum or resin from trees might have been used while mixing rock powder with water. There is ample proof of the fact that the early human and prehistoric civilizations existed in the Hadoti region (including in the Bijoliya area) of Rajasthan. There is no documentation about the precise ages of these rock paintings; however, few of the rock paintings were supposed to belong to the Upper Paleolithic period, and a few have been of the later historical period. Similar representations of human figures and hunting scenes associated with animal figures have been assigned to the later phases of the Mesolithic period. The bull figure and plants probably belong to the agriculturists and cattle keepers phase. The manuscript on the rock in *Brahmi* script possibly belongs to the period between the third century BCE and the fifth century CE.

Tiranga Hill: Pur Banera iron ore deposit (25° 19' 59" N: 74° 32' 34" E) (location: 7 km NW of Bhilwara town on Bhilwara–Meja Dam road)

The area is known for multi-metal deposits and constitutes the part of Pur-Banera mineralized belt of the Bhilwara district (Bheemalingeswara et al. 1986). Presently iron ore mining is going on at Tiranga hill, but earlier, the area was known for copper and silver mining as large numbers of old workings and slag heaps are present in the area (Fig. 21f).

At Tiranga, the Pb–Zn–Cu mineralization occurs within the metamorphosed banded iron formation (BMQ) (Fig. 21a) of the Lower Proterozoic formation of the Bhilwara sector. The BMQ in the area is folded and lies within the garnet-mica-schist and calc-gneisses (Fig. 21b). Here, the richer part of mineralization is structurally controlled and found especially within the cores of synformal F_2 folds (Fig. 21c) in BMQ bands. Looking at the higher concentration of iron in BMQ, M/s. Jindal SAW Limited is mining iron ore and established a beneficiation and pellet set-up plant integrated with a beneficiation plant near village Pur, which is about 12 km from Bhilwara city (Fig. 21e and f). Jindal SAW Ltd. is upgrading the iron ore (ROM) from about 28% Fe to a concentrate of 65% Fe by way of magnetic separation and other separation methods as the ore is mostly magnetite along with banded magnetite quartzite. The magnetite concentrate thus produced is being used for manufacturing of pellets (Fig. 21f). The Pur-Banera belt is having a reserve of 522 million tonnes of 30 to 40% Fe.

Rampura–Agucha lead–zinc deposit (25° 49' 50.67" N: 74° 44' 24.84" E) (location: 10 km southeast of Gulabpura in Bhilwara district)

Rampura–Agucha is the largest lead-zinc mine in the country and the second-largest zinc mine in the world with a production of 3.9 million MT in the year 2020. It stands apart as a world-class ore body with a zinc-lead reserve grade

Fig. 21 **a** Metamorphosed and folded banded iron formation (BMQ). **b** Banded hematite in calc-silicate rocks at Tiranga hill. **c** Folded hematite quartzite with old workings, note the concentration of mineralization in the hinge zone of the F_2 fold. **d** Folded hematite quartzite. **e** Hematite quartzite with malachite staining. **f** Iron pellets (magnetite concentrate) from Pellet Plant, Bhilwara



averaging 14.2%. The total reserve is 39 million MT, and mineral resources are 45.8 million MT as of March 2020. Rampura-Agucha is located in the Bhilwara district, 220 km from Jaipur, and 10 km southeast of Gulabpura on NH 79. The mine is owned by Hindustan Zinc Limited (HZL) and has the world's largest deposits of zinc and lead. Rampura-Agucha was commissioned in 1991 as an opencast mine. Presently, the mining is going on with a combination of open-pit mines and also underground mines (Fig. 22a to d). The mine is highly mechanized with state-of-the-art technology.

The deposit forms a part of pre-Aravalli BGC (3.2 to 2.5Ga) consisting of gneisses, schists, and intrusives of acidic and basic igneous rocks. Graphite-mica-sillimanite

gneiss/schist forms the host for economic mineralization and has a strike extent of about 1400 m. The ore zone is massive, wider in the middle section with tapering ends on either side along the strike. The economic minerals occurring in this deposit are sphalerite, pyrite, pyrrhotite, and galena. The genesis of mineralization remains unclear, but presently, it is interpreted as a volcanogenic massive sulfide that has later been subjected to high-grade metamorphism and tectonic disturbances. The total ore reserves have been estimated to be 61.10 million tonnes with 1.57% Pb, 13.48% Zn, and 9.58% Fe (Gandhi 2000). Ancient mine working, vast slag spread, and mine debris in the vicinity of the deposit bear testimony to ancient mining and smelting activities. Three archaeological mounds treasuring the history of ancient

Fig. 22 a, b, and c Rampura–Agucha open cast mine. d Rampura–Agucha underground mine



civilizations have been identified (Tiwari and Kavdia 1984; Roy et al 2004).

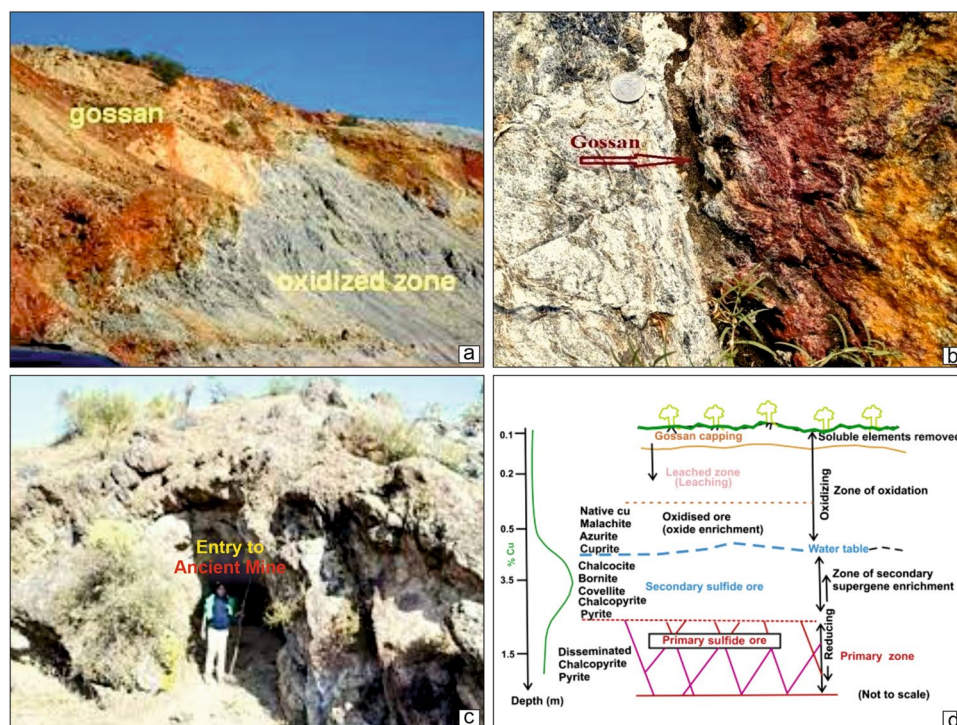
Rajpura–Dariba deposit, ancient mining, and Gossan exposure (24° 56′ 33.3″ N: 74° 07′ 46.3″ E) (location: 75 km from Udaipur city on Udaipur–Fatehnagar road)

Rajpura–Dariba area of Rajsamand district has a unique geological feature called “Gossan” which is of importance to geologists due to its diagnostic characteristics to locate sulfide minerals beneath the surface. It is a capping of the oxidized cellular mass of limonite and gangue over aggregated sulfide materials. Here, a spectacular in situ zone of gossan is found in the form of a ridge cap between Dariba and Rajpura villages (Fig. 23a and b), having a strike length of 4.5 km and width ranging from 2 to 40 m. It is a unique world-class gossan formation that acts as the principal guide and indicator of the base metal mineralization of Zn–Pb–Cu–Ag deposits in this area (Fig. 23d). The gossan here is intensely oxidized, weathered, decomposed rock consisting of erosion-resistant iron oxides and quartz, giving it a reddish-brown, orange, or yellow color. The Rajpura–Dariba multi-metal deposit was discovered based on this gossan. The Rajpura–Dariba belt has been grouped under the Rajpura–Dariba stratigraphic group, which is a part of the Bhilwara Supergroup. Geological Survey of India (GSI), in collaboration with Hindustan Zinc Limited, has declared the Rajpura–Dariba Gossan a Geological Monument in 1977 for the protection and preservation of this geoheritage.

Rajpura–Dariba Pb–Zn belt, located about 75 km north-northeast of Udaipur, is one of the best-studied mineral belts in Rajasthan. The mineralized belt constitutes the central segment of a spindle-shaped, curvilinear supracrustal belt that occurs within the basement gneisses of BGC. The rock types exposed in this belt are quartzites, siliceous dolomites, calc-pelites, garnet, staurolite, and kyanite-bearing meta-pelites. Lead and zinc deposits of various grades occur in dolostone and graphite mica schists. The main ore minerals are sphalerite, galena, pyrrhotite, pyrite, and chalcopyrite (with subordinate tetrahedrite, fahlore, and arsenopyrite).

GSI has reported ancient workings, heaps of mine debris, and slag coupled with extensive gossan zones which served as guides for exploration of the zinc and lead sulfide mineralization in Rajpura–Dariba. Ancient miners carried out both underground and opencast mining for many centuries. A large number of narrow openings provided ventilation and sunlight for the underground. Timber was used for mine support and the carbon dating of which gave an age of 2100–2500 years B.P. pointing it to be mined in the historical period too (Deb et al. 1989; Gandhi 2000) (Fig. 23c). The Rajpura–Dariba Pb–Zn deposit is considered a shallow marine synsedimentary deposit that is later modified (recrystallized and remobilized) by metamorphism (Mishra 1985). Sindesar Khurd deposit is an extension of the Rajpur–Dariba deposit, where Pb–Zn mineralization occurs in the metamorphosed volcanoclastic, argillaceous, and calcareous sediments. Minerals like sphalerite, galena, pyrrhotite, and pyrite

Fig. 23 **a** and **b** Gossan exposures at Rajpura-Dariba mines. **c** Ancient mining at Rajpura-Dariba mines. **d** Vertical profile diagram of the secondary enrichment



have been noticed occurring as fine-, medium-, and coarse-grained minerals as disseminations, bands/layers, veins, and massive ore.

Presently, Hindustan Zinc Limited is mining for the recovery of lead-zinc ores. The mining is being done through the underground mining method by using the blast hole stopping method, and the stops are backfilled with cemented tailings. The ore is crushed underground before being hoisted to the surface. It is then crushed again and milled before undergoing a flotation process to produce the concentrate. Total reserves are 20.4 million MT, and mineral resources are 38.5 million MT with a reserve grade of 6.8%.

Geological heritage sites along Udaipur-Zawar-Kherwara road traverse

This traverse covers the southern portion of the Udaipur area and discusses a total of three geological heritage sites (Table 1) (Fig. 4). The exposed rock formations in this area comprise of Aravalli Formation. Along this route, a variety of metamorphic and igneous rocks are exposed. The route comprises various geological heritage sites where a variety of stratigraphic, structural, economic mineral deposits, and geoarchaeological sites are classically exposed. In the following section, we discuss the exposed geological features of each geological heritage site of this traverse.

Zawar mines area, Tiri River Sect. (24° 21' 03" N: 73° 41' 47" E) (location: 32 km south of Udaipur, near Ramanath temple and Tiri River section, Zawar mines)

The lead-zinc-bearing rocks of the Zawar mines area show the classic development of small-scale structures resulting from superposed folding and ductile shearing. The most penetrative deformation structure noted in the rocks is schistosity (S_1 and S_2) axial planar to a phase of folding (F_1 and F_2) (Fig. 24a). The lineations, which are parallel to the hinges of F_2 folds (Fig. 24b), have vertical or very steep axial planes. The deformation of F_2 folds into hook-shaped geometry and the development of another set of axial planar crenulation cleavage are the main imprints of the third-generation folds (F_3) in the region. Younger generation recumbent and reclined folds with kink bands are also present which represent F_4 and younger generations.

Zawar mines show excellent development of folds, cleavage, intersection mullions, and fold mullions in the quartzose layer (Fig. 24b) within phyllite and also crenulations or fracture cleavages (S_2 , S_3 , and younger generations; Fig. 24a to d). Orientations of quartz-filled fracture cleavages locally simulate a "ladder vein" type appearance (Fig. 24e to h). Fanning and refraction of axial planar cleavage are also noticed in the quartzose phyllite (Fig. 24a). Sigmoidally oriented quartz gash veins in quartzose phyllite are also observable (Fig. 24h). The complex outcrop patterns observed in the rocks of the Zawar

Fig. 24 **a** Refraction of S_2 cleavages in F_2 fold hinge in phyllite, Zawar. **b** Mullions in the phyllite at Ramanath temple, Zawar. **c** and **d** F_2 folds in the phyllite, Zawar. **e**, **f**, and **g** Tension gashes (ladder veins) formed at the hinge of F_2 folds in the phyllite at Ramanath temple, Zawar. **h** Tension gashes formed at an angle to the S_0/S_1 , the main mineralization also follows the same trend in dolomite, Zawar



area are presumably due to the differential behavior of fault-bounded zones during the early and later folding phases (F_1 and F_2). The entire belt of the Aravalli Supergroup in the Udaipur and Lunavada sectors is characterized by a low to very low grade of metamorphism (Roy 1988a, b; see also Sharma 1988).

Ancient mining and smelting activity (24° 20' 57" N: 73° 41' 51" E) (location: 32 km south of Udaipur, near Ramanath temple, Udaipur-Zawar mines road)

- Old Smelting Sites at Zawar Village

Ancient mining Ancient mine openings are visible in almost all mine areas and are mostly in the form of open stopes, trenches, chambers, galleries, shafts, inclines, and open-pit mines (Fig. 25a). Once the ore was located at the surface, based either on the presence of gossan or surficial exposure of mineralized veins, the ancient miners followed its downward extension along the dip and pitch of the ore shoot. One of the deep old workings in Zawar mala is erroneously known as “Pratap Khan”, (Fig. 25b) with a false narrative of it being a hiding place of Rana Pratap Singh (1572–1597 CE), who resisted the Moghuls and was forced to hide in these mines from the armies of Akbar, in order to wage his “guerilla” war. It is more likely that during the period of exile, Rana had these mines worked in order to extricate him from some serious financial difficulties and also to meet the economic strains of war.

Beneficiation Is an important intermediate step in transforming natural ore into metal, and it normally involves two principal stages, viz., crushing and mineral separation. After having mined the ore, it was necessary to prepare it for smelting. The presence of heaps of rock fragments, of more or less uniform size, around the entrances of the mines throughout the Aravalli range, indicates that the crushing of the ore was done in the immediate vicinity of the mine site. The unearthing of iron hammers, pestles, and stone hammers in and around the mining centers indicates that they were used for crushing the ore. In the Zawar valley, such mortars have also been observed in the valley area where the smelting was done. After crushing, the richer portion of the ore was separated from the gangue by hand picking. At Zawar, Dariba, and Agucha, manual beneficiation of both lead and zinc minerals could have been possible. The low level of lead in smelting retort residues (Fig. 25c and d) at Zawar

Fig. 25 **a** Ancient mining and old workings in the East Mochia Hill, Zawar. **b** Ancient mining and old workings in the Zawar mala hill (*Pratap Khan*), Zawar. **c** Remnant of ancient smelting furnaces, Zawar. **d** Retorts used for smelting, Zawar. **e** and **f** Remains of houses made up of used retorts



confirms an efficient mechanical removal before smelting zinc (Craddock et al. 1985).

At Zawar, lead was smelted on a small scale at about 500 BC, possibly as a by-product of zinc mining (Craddock et al. 1989). There is an evidence to suggest that argentiferous galena was roasted prior to smelting. Lead ores are readily reduced, and a roasting stage may not have been considered necessary. The early furnaces were of clay-lined stone. Before zinc ore could be smelted, it was necessary to drive off the sulfur and thus convert zinc sulfide to oxide. The sphalerite ore, separated manually from other Zawar sulfides, was roasted in air to convert sulfides to oxides; probably in specially built ovens, the remains of which have so far not been found. The calcined ore, together with reducing agents and necessary fluxes such as dolomite, charcoal, and salts (borax), was then used to fill the retorts (Fig. 25d). A complete retort is cylindrical and tapers at one end, resembling an aubergine (brinjal) (Gandhi 2000).

The production estimates, based on the debris around Zawar, are quite impressive. A furnace block could have produced between 20 and 25 kg of zinc per day, depending upon the furnace type and on the retort capacity, and thus, an overall production through fifth or sixth centuries of the order of 60,000 tons has been estimated (Craddock et al. 1990). The radiocarbon dates show that the deep mines in Rajasthan in general, and of Zawar in particular (Fig. 25a and b), were worked predominantly more than 2000 years ago, i.e., around the Mauryan period. Despite this, the available evidence is that the earliest zinc smelting was around 840 ± 130 BP, which only suggests that the earlier mined zinc ore was probably carried away from Zawar and mixed with copper to produce brass directly by the cementation process. The industrial phase of zinc production probably began at Zawar sometime in the twelfth century, and this production was expanded considerably in the fourteenth century when Rana Lakha of Mewar (1382–1397) re-established the mine at Zawar for the production of lead, zinc, and silver (?). The temple inscriptions, the fort, and the dilapidated township in the Zawar valley are believed to belong to the late fourteenth to early fifteenth centuries. Zawar (Jawar) village, some 32 km south of Udaipur, is believed to be of much earlier origin than when discovered in the time of Maharana Lakha (1382–1421). They yielded silver, tin, copper, lead, and antimony. These riches added to Mewar's prosperity during Lakha's reign and funded the rebuilding of many temples and palaces destroyed when Ala-Ud-Din-Khilji sacked Chittaur in 1303. When Maharana Pratap Singh-I (1572–5197) retired to the hills during the Mughal scourge of Mewar, faithful *Bhils* of the region saved his family by carrying them in wicker baskets and concealing them in the mines of Zawar, where they guarded and fed them. Bolts and rings are still preserved in trees around Zawar to which baskets were suspended,

often being the only cradles for the royal children, which kept them out of the reaches of tigers and wolves. Later, the mines were abandoned, then re-opened, and worked for lead and zinc, which they still yield. It is also the location of several Hindu temples dedicated to Jawar Mata, Shiva, Vishnu, and Jain temples.

Production of zinc on an industrial scale continued for further fourth to fifth centuries, i.e., even after the arrival of the British in the country. It has also been stated in Ain-I-Akbari that zinc was made in the mid-eighteenth century at Zawar. Tod (1829) recorded that considerable revenue came to the state from the zinc mines at Zawar, until the late eighteenth century. The technological skill and ingenuity typified in the once flourishing industry decayed into oblivion, presumably, by famines and a series of feudal wars between the Rajputs of Mewar and Moguls/Marathas in the middle of the nineteenth century. The archaeological study by the British Museum, London, M.S. University of Baroda, and Hindustan Zinc Limited in 1983, has proved that at Zawar zinc was produced by the distillation process for the first time in the world. The American Society of Metals (ASM International) recognized Zawar as an "International Historic Landmark" in 1988. According to their description made at the site "At this site are preserved the Zinc retorts distillation furnaces and remnants of related operation. The village artifacts together with temple ruins attest to the success of this metallurgical technology. This operation first supplied the Zinc for the making of the brass instrument in Europe, a forerunner of the industrial revolution" (Fig. 25e and f). The carbon dating of ancient mining and smelting samples yielded the earliest age of 765 ± 100 BCE (Ranawat 2016a, b).

Rikhabdev lineament and ultramafics: (23° 56' 52.00" N: 73° 38' 23.00" E) (location: green marble mines area, near Kesariyajee, Obri, and Kherwara)

Ultramafic rocks represented by serpentinite, talc-tremolite schist, and chlorite schist occur along two regional lineaments, i.e., Rikhabdev lineament and Kaliguman lineament (Bakliwal and Ramasamy, 1987). Along Kaliguman lineament, the outcrops occur at three localities, viz., (i) west of Khankat, (ii) in the valley near Undithal, and (iii) from Sempala to Gogunda. Along the Rikhabdev lineament, the outcrops have the greatest development from Rikhabdev to Kherwara and further south in Dewal, Dungarpur, and Bhi-chiwara. Geologically, it is serpentinite but has acquired a name in the marble industry due to its easy block ability, ability to take an excellent polish, and low hardness. The serpentinites of the region are ultramafic rock bodies that have undergone metamorphic changes up to the stage of serpentinitization and occur as deep green, massive serpentinite which is suitable for use as dimensional and decorative stones. Rikhabdev–Kherwara rocks occur as large, irregular

lensoid bodies, some of which are more than 5 km in length along the strike. Large size blocks up to $3 \times 1.5 \times 1.5$ m in size are excavated (Fig. 26a to f). The important locations of green marble mines are Dhelana, Khanmin, Bilkhai, Bhadawa, Masaron ki Obri, Pipaldara, Saru, and UgmanaKotra.

Geological heritage sites along Udaipur-Jhamarkotra traverse

This traverse covers the southeast portion of the Udaipur area and discusses a total of four geological heritage sites. The exposed rock formations in this area compromise Archean eon to the recent deposits. Along this route, a variety of metamorphic and igneous rocks are exposed. The route comprises various geological heritage sites where a variety of stratigraphic, structural, and economic mineral deposits and paleontological and weathering feature sites are classically exposed. In the following section, we are

discussing the exposed geological features of each geological heritage site of this traverse.

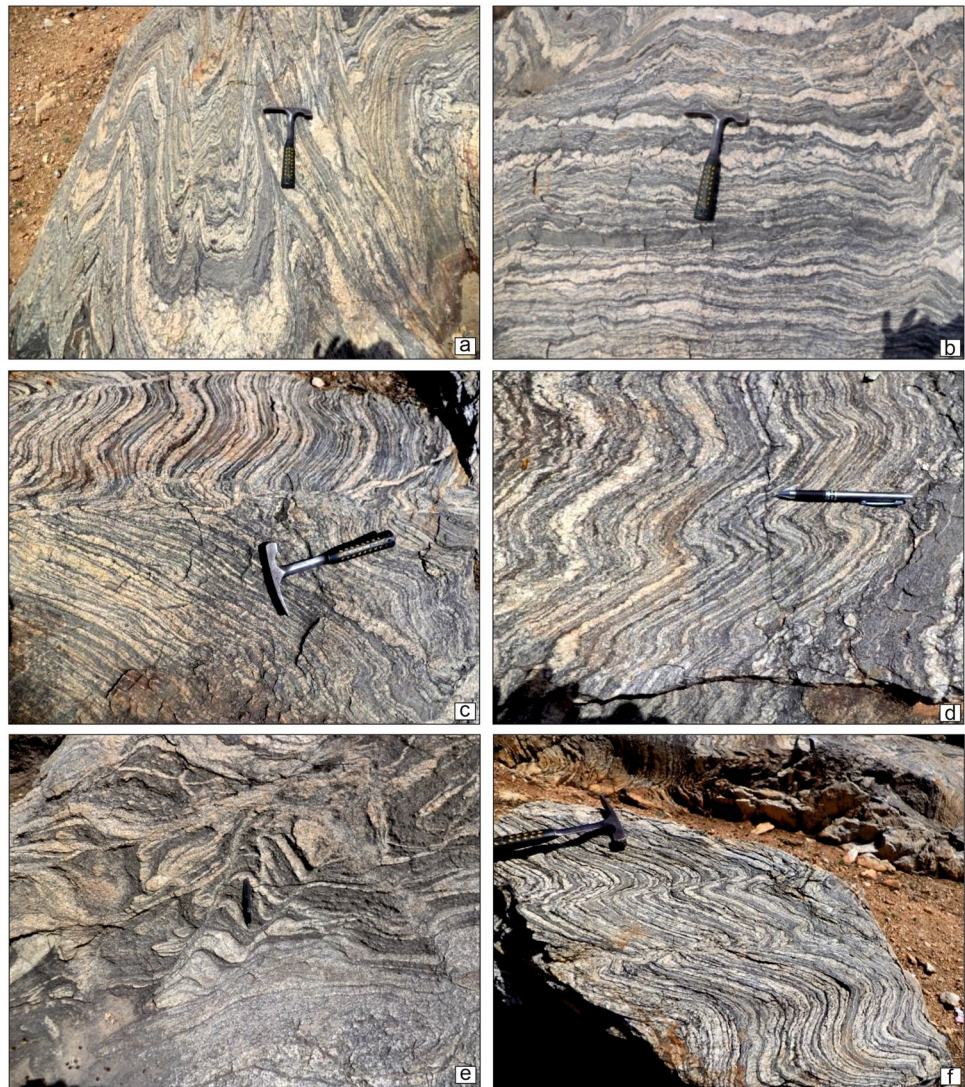
TTG basement gneisses (oldest Archean rocks, Mewar gneissic complex) ($24^{\circ} 25' 52.51''$ N: $73^{\circ} 52' 16.54''$ E) (location: 30 km on Udaipur-Jhamarkotra-Jagat road, near Mamadev village)

Near Mamadev village on Udaipur-Jhamarkotra-Jagat Road, scattered outcrops of biotite-gneiss, one of the oldest rocks in the country is exposed (Fig. 27). The gneisses show a prominent banding marked by alternate light (quartz-feldspar rich) and dark (biotite-rich) layers. There are a few small, irregular bodies of mafic (hornblende-rich) enclaves within the gneisses. Gopalan et al. (1990) reported 3.3 Ga Sm/Nd isotope ages for gneisses. The single zircon mean age of the same rocks is estimated at 3.28 Ga (Roy and Kroner 1996; Weidenbeck et al. 1996).

Fig. 26 a, b, c, d, and e Green marble mines near Keshariyajee, Obri, and Kherwara. f Green marble polished slab



Fig. 27 a, b, c, d, e, and f Banded gneisses exposures (basement rocks) near Mamadev village, exhibiting folding of compositional layering



Jhamarkotra mines (24° 28' 39.47" N: 73° 50' 10.56" E) (location: Jhamarkotra mines, 24 km east of Udaipur)

It is the biggest and highest-grade phosphorite deposit in the country and probably the longest mine in the world (Fig. 28).

The rock phosphate occurs in the metasedimentary rocks of the Aravalli Supergroup. It is of algal origin occurring in between siliceous, ferruginous, and cherty dolomitic limestone resting over basal quartzite and gritty quartzite which unconformably rest over the banded gneissic complex of

Fig. 28 a View of Jhamarkotra open cast mines. b East–west mining block exhibiting the benches on the foot wall at Jhamarkotra open cast mines, Udaipur



pre-Aravalli age. The deposit extends over a strike length of 16 km in a horseshoe shape with an average thickness of 15 m. A reserve of 77.0 million tonnes of rock phosphate has been proved that out of these, 17 million tonnes is of + 30% P_2O_5 grade and the rest is of 12 to 30% P_2O_5 .

Stromatolite fossil park (24° 28' 29.72" N: 73° 52' 2.27" E)
(location: 25 km southeast of Udaipur on Udaipur-Jagat road near Jhameswar temple)

The stromatolitic fossil park is situated close to the world-famous Jhamarkotra rock phosphate mines which illustrate the species of the cyanobacterial stromatolites that trapped the phosphate in their edifices during deposition (Fig. 29a to d). The most common of the species namely is *Columella columnaris*. The fossil park has been developed on a hillside close to the Jhameswarji temple. The host rocks of the stromatolites are dolomitic carbonates, which immediately overlie the quartzite. Stromatolites are biogenic sedimentary algal structures. At the hill near Jhameswar temple, various varieties, shapes, and sizes of stromatolites are present in the fossil park. The blue-green algae flourishing in the shallow marine basin were responsible for these stromatolitic structures and phosphate deposition. These unique algal stromatolite fossils are about 1800 million years old and occur in the dolomitic limestone of the Jhamarkotra Formation of the Lower Aravalli Supergroup. The Geological Survey of India has declared it a National Monument for Stromatolites. Paleogeographically, Roy and Paliwal (1981) and Chauhan (1979) described the stromatolite occurrences as an indicator of paleo-shorelines along which the cyanobacterial colonies grew abundantly. In many places, the deformation of stromatolitic-bearing dolomite and vein quartz along with stromatolitic-bearing dolomite can be also seen (Banerjee 191, Roy and Jakhar 2002).

The host carbonate formation shows rapid lithofacies changes to ferruginous and manganiferous (locally) dolomite, dolomite arenite, black shales, argillaceous dolomite, and quartzite. Residual weathering of the carbonate rocks has resulted in the extensive formation of silcrete, fercrete, and cave breccias. Phosphorites are restricted entirely to biothermal/biostromal stromatolites. Banerjee (1971) recognized five different modes of phosphorite occurrences: (1) columnar algal stromatolitic phosphorite; (2) laminar algal phosphorite; (3) reworked conglomeratic or brecciated phosphorite; (4) massively bedded phosphorite; and (5) disseminated and nodular phosphorite. Besides these, phosphorite also occurs in botryoidal and powdery forms. Columnar phosphatic stromatolites are the most common form present at Jhamarkotra. In the simplest form, these columnar stromatolites look like a series of inverted tubes made up of phosphatic laminae, with dolomite occupying the intercolumnar zones. Columns show their growth

perpendicular to the bedding plane. Excellent examples of columnar phosphatic stromatolites growing perpendicular to bedding planes can be observed in the fossil park. Excellent examples of deformed columns of stromatolites can be seen in national stromatolite fossil park (Fig. 29).

Stalactite and stalagmite (24° 28' 26" N: 73° 52' 08" E)
(location: Jhameswar Mahadev temple, Jhamarkotra on Udaipur-Jagat road)

A stalactite (Greek stalactites) is from the word for “drip” and meaning “that which drips” is a type of speleothem (secondary mineral) that hangs from the ceiling or wall of limestone caves. It is sometimes referred to as dripstone. A stalactite is an icicle-shaped mass of calcite attached to the roof of a limestone cavern. Groundwater trickling through cracks in the roofs of such caverns contains dissolved calcium bicarbonate. When a drop of water comes in contact with the air of the cavern, some of the calcium bicarbonate are transformed into calcium carbonate, which is precipitated out of the water solution and forms a ring of calcite on the roof of the cavern. By repetition of this process, the length and thickness of the stalactite are increased. A stalagmite is a cone of calcite rising from the floor of a cave. Stalagmites and stalactites are often found in pairs; the stalagmite is formed as a result of further evaporation and precipitation from the solution after the trickle of waterfalls from the stalactite. Stalactites and stalagmites often meet each other to form solid pillars. Curtains of dripstone sometimes form when water drips from the ceiling of a cave along joint planes. Since stalactites, stalagmites, and curtains of dripstone form only in the presence of air, their existence in a cave indicates that the cave was above the water table while the dripstone was forming (Fig. 30).

Conclusions

Every state or region has various unique geological and geomorphologic features which constitute its geodiversity and geoheritage. Over the time, the development process obliterates many of these features. Udaipur region of Rajasthan state is having distinctive geodiversity and geoheritage of Aravalli and Delhi fold belts of Archean and Proterozoic eons; there is a little realization of the significance of these geological features. It houses all possible geological features that exist on earth. The picturization of all possible features found in and around the Udaipur region in this work proves its uniqueness to act as a geopark having 27 geoheritage sites. There is a need to develop and conserve these geological identities and understand the scientific value of the features and landforms. There is a dire need to identify stakeholders who will actively protect these sites and sensitize

Fig. 29 a, b, c, and d Varieties of stromatolitic phosphorites at Stromatolitic Fossil Park, Jhamar kotra, Udaipur. e and f Deformation of stromatolitic bearing dolomite. g, h, i, and j Deformation of vein quartz along with stromatolitic bearing dolomite. Note the beautifully folded phosphatic and non-phosphatic layers, shear cleavages (S_2), and drawn-out hinges due to extreme flattening

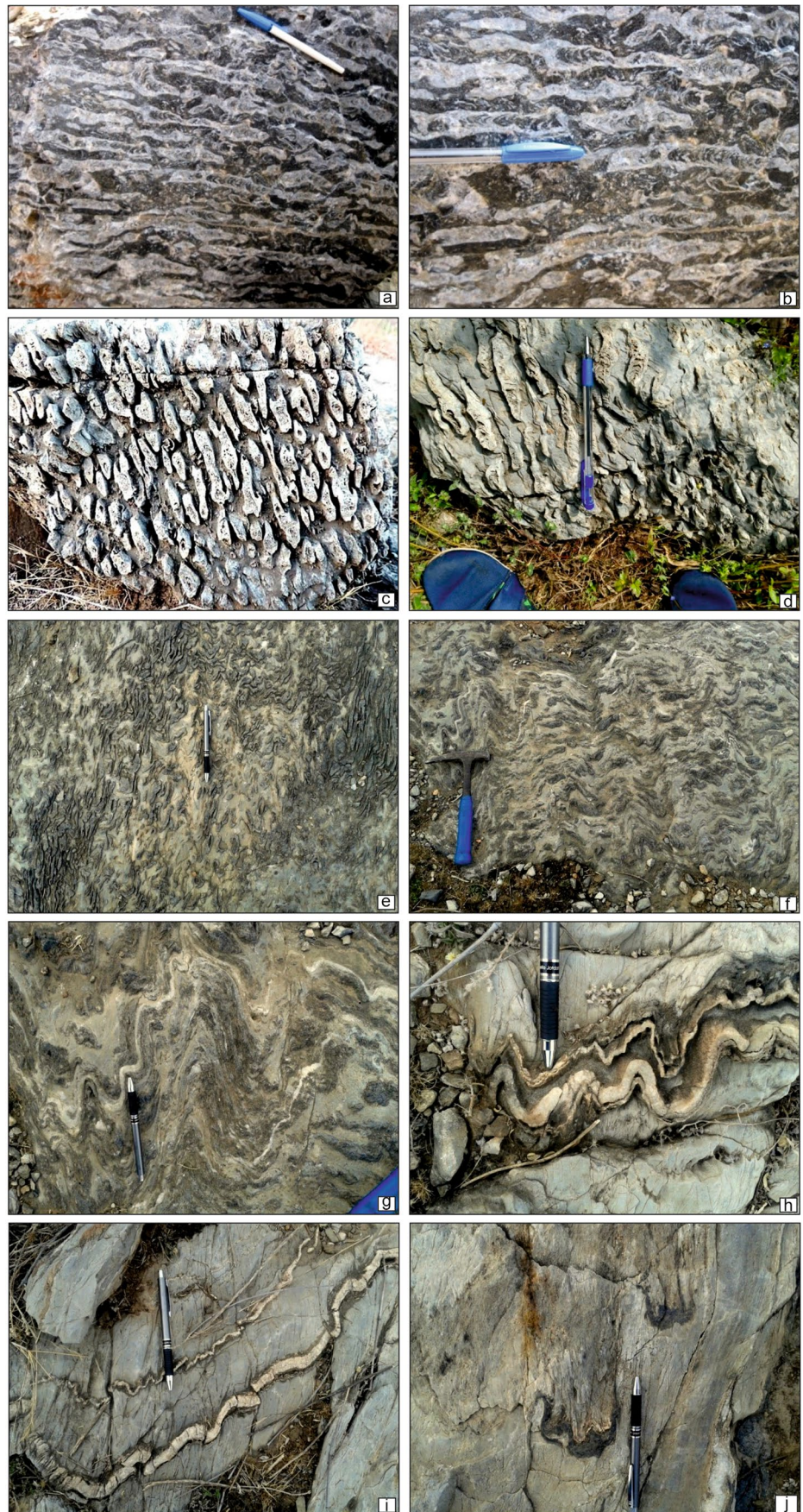


Fig. 30 **a** Jhameshwar Mahadev cave temple. **b** Stalactite and stalagmite in the temple



local administrations, tourism departments, and the public at large about these neglected heritages. Simple measures of protection, raising visibility and awareness, can make a significant difference. With such efforts, the future geoscientist of India and the world would have very basic knowledge of understanding the natural geological and climatic processes happened since the beginning of this planet.

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Declarations

Conflict of interest The authors declare no competing interests.

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