



# Geosites of the Early Cretaceous (Bhuj Formation) Based on Their Ichnological Values: Insights from the Kachchh Basin, Western India

Suruchi Chauhan<sup>1</sup> · Bhawanisingh Desai<sup>1</sup>

Received: 15 June 2022 / Accepted: 30 November 2022 / Published online: 17 December 2022  
© The Author(s), under exclusive licence to International Association for the Conservation of Geological Heritage 2022

## Abstract

Geoheritage studies have become increasingly important in recent years because of their ability to build an inventory of potential, established and endangered geological heritage. It is a worldwide endeavour to locate and preserve geological heritage for educational, tourism and conservation objectives. The Kachchh Basin is universally acknowledged in India for its rich palaeontological treasures of the southern Tethys margin. Several outcrops of low-dipping Mesozoic strata provide valuable information about the area's geological history. Since many decades, national and international students of earth sciences, geomorphology, geophysics, petroleum and reservoir engineering and mineral exploration have visited the Kachchh Basin for educational and training purposes. The basin reveals exceptional outcrops bearing evidence of Mesozoic life and its evolutionary fingerprints. The outcropping Cretaceous sediments of the basin extend offshore, producing economic quantities of hydrocarbons. Thus, it has become essential to preserve and protect Cretaceous sedimentary sequences for teaching and training purposes. We have identified three important geoheritage locations that should be preserved for the future. These three sites are (a) Tapkeshwari ichnosites, (b) Hill Garden ichnosites and (c) Ghuneri Dome ichnosite. The selected geoheritage sites displayed lateral stratigraphical continuity, outstanding textbook-type examples of (a) different trace fossil assemblages, (b) physical sedimentary structures and (c) dual-porosity petrophysical characteristics. Therefore, these sites offer a unique opportunity to study the wave-dominated deltaic ichnology of the Cretaceous clastic sequence and the effect of bioturbation on the petrophysical parameters.

**Keywords** Bhuj Formation · Early Cretaceous · Ichnosites · Ichnological values · Geoheritage

## Introduction

Geoheritage studies are an important trend in modern geological research that aims to compile an inventory for documenting and future conservation (Wimbledon, 1999, 2011). Despite all of the efforts, there are still several concerns that must be addressed. Thus, one of the current endeavours is identifying and categorising geoheritage sites. Lesser-known but geologically rich locations must play these roles. The term palaeontological geoheritage refers to the many features that distinguish palaeoenvironments. These scientists defined them as facies,

palaeontological, ichnological, taphonomic events and geoarchaeological characteristics. While physical sedimentary structures and body fossils are widely recognised as determinants of sedimentary rocks, biological reworking (bioturbation) is almost completely ignored. Dinosaur footprints are all examples of bioturbation (Mateus and Milan 2009), Tunnels made by burrowing trilobites (Neto de Carvalho and Baucon 2016), soil displacement caused by plant roots (Alonso-Zarza et al. 2008) and trails made by insects (Minter et al. 2007). The overall material of sediment that organisms have reworked tends to replace the primary fabric of the deposit as a result of bioturbation (Taylor et al. 2003; Baucon et al. 2020).

Trace fossil records disclose their producers' behaviours and ecological conditions, individual and group activities, evolutionary trends and taphonomic windows, all of which contribute to our understanding of the evolution of life and the Earth's memory. In Kachchh, several important ichnological sites are known to the public and described (Fursich 1998; Bhosale et al. 2021; Desai 2016; Desai and Chauhan 2021). They are included in education, geoparks, museum

This article is part of the Topical Collection on Indian Geoheritage: From the Precambrian to the Present

✉ Bhawanisingh Desai  
bhawanigd@gmail.com; bhawanisingh.desai@spt.pdpu.ac.in

<sup>1</sup> Department of Petroleum Engineering, School of Energy Technology, Pandit Deendayal Energy University, Raisan, Gandhinagar, Gujarat, India

collections, nature walks and the National Inventory of the Geological Heritage (Chauhan et al. 2021). In the Kachchh Basin, Early Cretaceous strata are widely exposed across the region. However, from an ichnological standpoint, the Ghuneri Dome, Hill Garden road cut section and Tapkeshwari section are three notable places that preserve great burrows.

Almost as ancient as the reconstruction of trace fossils is the use of trace fossils (ichnofossils) to rebuild sedimentary environments in the geological record (Hasiotis et al. 2013). The objective of the study was to characterise the trace maker so that the information gained from existing trace makers may be added annually to the trace maker's records. Several ichnologists have used the ichnofacies concept (Seilacher 2007). Simultaneously, a great deal of work was given to neoichnological research in all significant depositional environments. The results and those of ichnological experiments have advanced the field of study. Several studies have provided excellent compilations for delineating processes and depositional environments based on their trace fossil contents (Buatois and Mángano 2011; Knaust and Bromley 2012).

In the region under investigation, the interaction between organisms and sediment led to the discovery of bioturbated textures (ichnofabric) (Baucon et al. 2020). Bioturbation is acknowledged as affecting the quality of hydrocarbon deposits and aquifers (Singh et al. 2022a, b a, b). Furthermore, we have demonstrated the significant need to make all ichnological data usable for hydrocarbon exploration and its influence on the prediction of porosity and permeability (Singh et al. 2022b). This work examines ichnosites, their values and their vulnerabilities, explicitly referring to three ichnosite from the Bhuj Formation (Lower Cretaceous). Previous research paid less emphasis to the components of ichnoheritage. These sites require analysis, which leads to a better appreciation of the proposed geoheritage type and the distinctive geological characteristics of the Kachchh Basin, western India, which, despite its apparent distinctiveness, is not well acknowledged by the international research community. Thus, our goal is to create an inventory of the various ichnological sites in the Kachchh region of western India to document and protect these critical resources.

## Geology of the Study Area

Based on the relationships of Mesozoic sediments, four distinct Formations can be identified: Jhurio, Jumara, Jhuran and Bhuj (Fig. 1). The Kachchh Mainland Group sediments were deposited in the Gulf of Kachchh Half-Graben. The Bhuj Formation is named after Bhuj region and consists of massive nonmarine sandstone rocks with a more or less homogeneous composition (Biswas 1987, 2016b). These rocks account for roughly three-quarters of the KMU's entire Mesozoic outcrop (Biswas 1987,

2016b). The Bhuj Formation, dominated by sandstone, is divided into three members: Ghuneri, Ukra and Upper (Biswas, 1977). The Ukra Member is a wedge-shaped transgressive unit only exposed in the basin's western part (Desai 2013). Ghuneri and Upper members, on the other hand, are well exposed from the basins proximal to the distal part. When mapped from east to west, the thickness of the Ghuneri Member increases significantly (Chauhan et al. 2022). The Ghuneri Member is 168 m thick in the east and 535 m thick in its type area in the west (Biswas, 1977). Except for a few scattered plant-rich shale horizons and rare shell lenticels, the Ghuneri Member is predominantly unfossiliferous.

The Ghuneri Member (Bhuj Formation's lower member) is composed of a cyclic repetition of ferruginous or lateritic bands, shale and sandstones (Desai and Chauhan 2021; Biswas 1977, 1987). The outcrop's upper portion stretches from Bhachau in the east to Ghuneri in the west, occupying lowlands between the mountain ranges (Biswas 1993). The sandstones of the Bhuj Formation and the Deccan Trap flows are extremely well exposed in road cutting. The Early Cretaceous strata are made of shale and sandstone alternations with coarsening-upwards sequences and varying bioturbations (bioturbation index 1–6), demonstrating bioturbation repetition within the Bhuj Formation. Sedimentary features in the research region include plane laminations, trough cross-stratification, soft sedimentary deformation structures and some microfaults with varying grain sizes and colours. The colour and composition changes are caused by chemical weathering. The particle size of the sandstone varied greatly. Some of the rocks are fragile and weathered. These sedimentary units have been intensely bioturbated. A closer examination reveals a unit of bioturbated shale or siltstone that coarsens and thickens vertically. Bioturbation intensifies gradually until it reaches its maximum. The trace fossils form two distinct fair weather and storm weather ichnoassemblages developed within a wave-dominated deltaic environment. Thus, asymmetrical cyclic bioturbated units of Ghuneri Member offer better insight into the ichnology of the Early Cretaceous wave-dominated deltaic environment (Chauhan et al. 2022). This deposit belongs to the Lower Cretaceous period (Valanginian to Albian) (Chauhan et al. 2022; Desai and Chauhan 2021; Biswas 1977, 1987).

The research area contains ichnofossils, plant fossils (such as Cretaceous flora) and microfossils (such as spores/pollen, foraminifera, ostracoda). The wide range of well-preserved trace fossils documented and categorised from strata of the Kachchh mainland have been of particular significance for understanding palaeoenvironments and the basin's depositional history. In addition, abundant trace fossil assemblages from the Early Cretaceous Bhuj Formation link these deposits to Upper Gondwana.

**Fig. 1** Lithostratigraphic classification of the Bhuj Formation, Kachchh Basin (modified after Biswas 2016a, b)

Ma		Stage	Formation	Member
72.1-61.6	Late Cretaceous to Tertiary	Maastrichtian-Danian	Deccan Traps	Basalt flows
100.3		Early Cretaceous	Bhuj Formation	Upper Member: Massive sandstone
~113	Aptian			Ukra Member: Green Glauconitic shale/ferruginous bands with fossils
~125	Hauterivian to Barriasian			Ghuner Member/Lower Member Bioturbated sandstone/shale with Plant fossils
~145.0	Late Jurassic			Jhuran Formation
~152.1		Upper Member: Fossiliferous sandstones, shales, hard calcareous sandstones		
~157.3		Kimmeridgian	Middle Member: mainly shales, fossiliferous with sandstones interbeds Lower Member: sandstone/shales/arenaceous limestones with fossils	

**Economic Significance of the Kachchh Cretaceous Sediments**

The Cretaceous sediments of the Kachchh Basin are famous for their economic aspects. They include commercial quantities of (a) coal–Ukra coal deposits, (b) kaolinite mineral deposits (Jawahar nagar and Nadappa mine deposits), (c) clean quartz deposits (Bhuj-Mundra road quarry deposits) and (d) sandstone as building and ornamental stones. Several open-cast quarries of these deposits can be seen spread across the basin. In addition to these economic deposits, the groundwater in the sandstone of the Bhuj Formation is of excellent quality because most agricultural farms are situated in the Bhuj Formation.

Several hydrocarbon-producing basins surround the Kachchh Basin, and efforts by the government of India and oil companies have provided commercial quantities of hydrocarbons from the offshore region. These offshore hydrocarbon-bearing reservoirs are extended onshore, where the majority of data on the stratigraphic characteristics of the Mesozoic sections in the offshore area is provided by cores and well logs, which are commercially and industrially

valuable. Kachchh Mesozoic sediments are well correlated across the onshore-offshore profile (Jyotsna et al. 2022), and the basin has 898 MMTOEs of hydrocarbons in place, of which 727 MMTOEs (80%) are attributable to offshore Mesozoic sediments and 36 MMTOEs (4%). As reported by exploratory wells offshore, the Cretaceous Bhuj Formation extends offshore with similar reservoir sedimentology (DGH 2015; Jyotsna et al., 2022). In Offshore Kachchh, exploratory wells discovered commercial quantities of natural gas in the Cretaceous layers (Bhuj Formation, Wandrey 2004; DGH 2015). The Lower Cretaceous Bhuj Formation accounts for approximately 30% (270 MMTOE) of in situ conventional hydrocarbons, according to estimates of hydrocarbon reserves (DGH 2015; OALP-V round Broucher). The petrophysical analysis of Ghuner Member outcrop samples indicated a dual-porosity and permeability network, with porosities ranging from 15 to 21% and permeabilities ranging from 21 to 403 mD, respectively (Singh et al. 2022a, b a, b). The source rocks of the Mesozoic petroleum system in the Kachchh Basin are organic-rich, mature Jurassic and Early Cretaceous shales (Jyotsna et al. 2022). These shales have a total organic carbon (TOC) level between 2 and 3%.

Potential reservoir rocks in the Kachchh offshore are Jurassic and Lower Cretaceous sandstones and Late Cretaceous limestones; sandstones have a porosity of 25% and a permeability of 30 mD (Wandrey 2004; Jyotsna et al. 2022).

## Method and Material

Abundant trace fossils were recorded as a result of a detailed analysis of the established locations in the field. According to the present level of ichnological knowledge, they were examined. Although the identification and systematic description of ichnospecies are not yet complete, significant ichnogenera have been identified. This basic information is sufficient to interpret ichnofacies and reconstruct paleoenvironmental conditions. The ichnological data and associated interpretations substantially contribute to our understanding of the Cretaceous geology of the Kachchh Basin.

According to the proven abundance of trace fossil assemblages, both places seem unique and may thus be classified as ichnosites. However, the latter must be carefully described. Various strategies have been suggested for similar problems. These methodologies represent substantial advancements in the study of geoheritage, although these solutions are often only applicable to certain tasks or applications in specific socioeconomic circumstances.

This was proposed by Ruban (2020) and tested at numerous geosites with early Cretaceous paleogeographic values. This suggests that its use in this study is consistent with regional geoheritage studies. Uniqueness (Global, National, regional or local), number of geoheritage types (classification in Ruban (2020)), accessibility (accessible in a populated area, easy in a remote location or complex), vulnerability (no danger, potential danger, partially damaged or destroyed), need for interpretation (absent, basic geological knowledge needed, professional required geological knowledge, needed scientific analysis) and scientific significance (international, national, regional or local).

## Ichnological Importance

The use of trace fossils (ichnofossils) in reconstructing sedimentary environments in the geological record is almost as old as trace fossil reconstruction itself. Many early researchers tried to identify the trace maker to apply knowledge learned from current trace makers to the fossil record. Many research projects have adapted and used the concept of ichnofacies, and its bounds have been questioned (Seilacher 2007). Concurrently, great effort was given to neoichnological investigations in all significant habitats, and the results, coupled with those of ichnological experiments, have raised the whole field of study. They understood

the close interaction between organisms and sediment led to the discovery of bioturbated textures and the development of the concept of ichnofabric. Finally, ichnology is a helpful tool in stratigraphy and reconstructing evolutionary patterns and mass extinctions. Bioturbation is also becoming more widely recognised as a determinant in the quality of hydrocarbon reservoirs and aquifers. We have also realised the importance of bringing all ichnological data to a level where sedimentologists can utilise it (Ekdal et al. 1984; Curran 1985). Sedimentologists can benefit from compilations that incorporate all central depositional systems in trace fossil content and use in evaluating depositional settings. (Knust 2012).

## Ichnosite of the Early Cretaceous Bhuj Formation

The current research identified three ichnologically important ichnosites in the Kachchh mainland. An almost continuous rock outcrop covers the whole mainland through hills, river cuts, domes and road cuts (Fig. 2). The sites are categorised according to education, entertainment and historical criteria and the organisation and supervision of field visits. When outcrops are continuous, it is easier to trace geological and ichnological characteristics from one ichnosite to the next.

The present findings indicate that exposing hundreds of square metres of early Cretaceous strata detail provides an opportunity to analyse the early sediments, which correlate to a hiatus phase. The geological/ichnological characteristics observed at the potential locations are described in the following section. The selected ichnosites (Tapkeshwari-, Hill Garden- and Ghuneri-type sections) are located east to the west on the Kachchh mainland (Fig. 2).

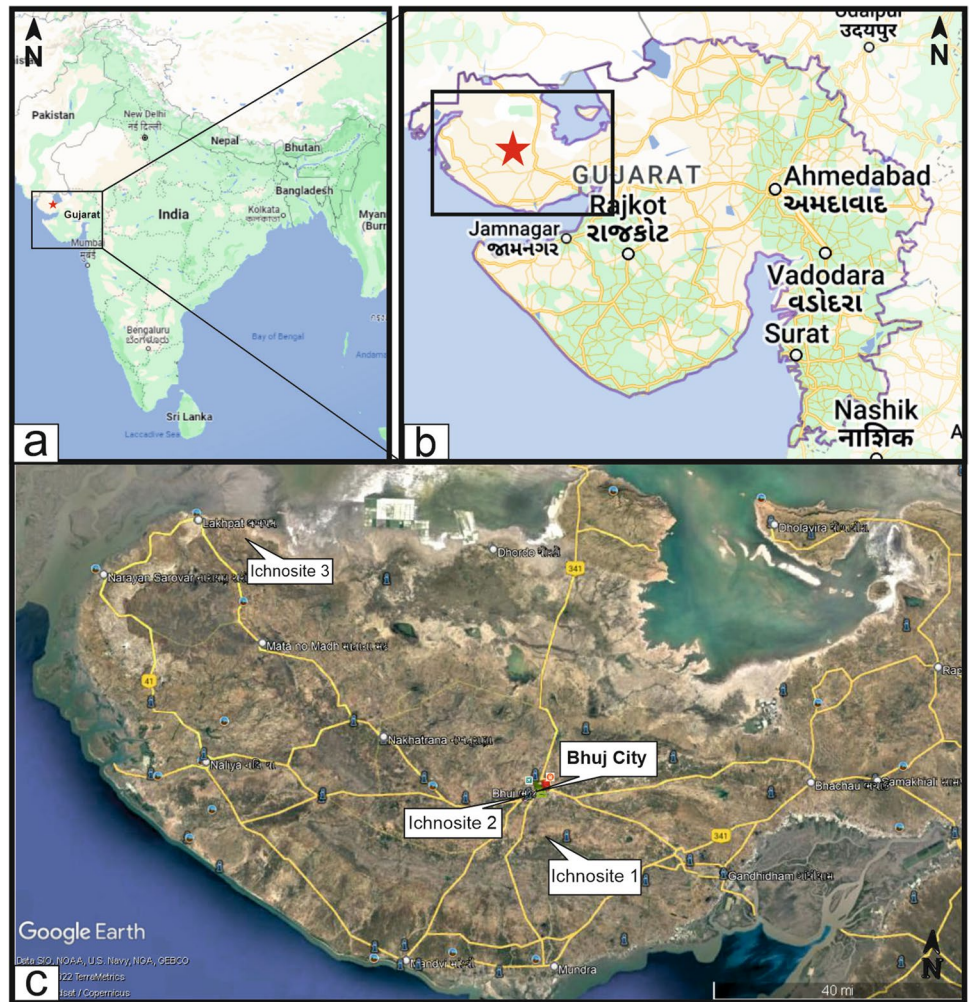
## Tapkeshwari Ichnosite

The proposed Tapkeshwari ichnosite (23°10'54.99"N; 69°40'00.39"E) is near Bhuj town. The geosite lies approximately 8 km southwest of the city centre on the Mundra-Bhuj route to Tapkeshwari road (Fig. 3). All major roads and local transit services in Bhuj are easily accessible from the site. The Jurassic and Cretaceous strata underpin the site. The Jhuran Formation (Upper Jurassic) underpins the bottom portion of the site, while the Ghuneri Member of the Bhuj Formation underpins the top part (Lower Cretaceous).

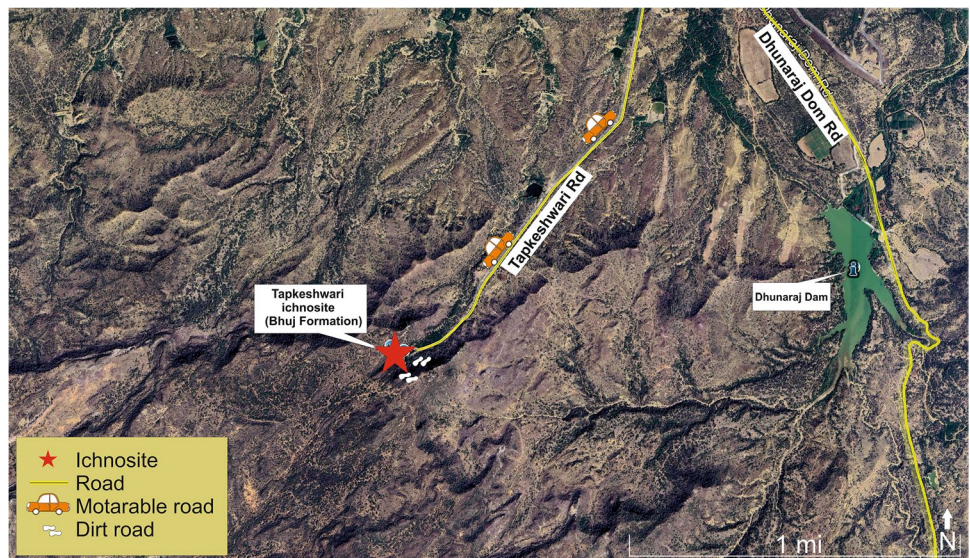
The sediments include moderate to low variety trace fossils, such as *Diplocraterion*, *Skolithos Pylonichnus* and *Polyladichnus* in the ferruginous, coarse- to medium-grained sandstone deposit (Fig. 5). The extensive vertical structure of suspension feeders suggests moderate to high wave energy in shallow marine environments of deltaic deposits of Ghuneri Member the Bhuj Formation sediments. The fossils display ichnofabric from the middle to the lower tier.



**Fig. 2** Location of the Kachchh Basin within India. **a** Indian subcontinent showing the position of Gujarat state on its western side. **b** Location of the Kachchh district within Gujarat State. **c** Google Earth image of the Kachchh Basin showing the major road connection with Bhuj and the location of the studied ichnosites



**Fig. 3** Google image showing the location of the Tapkeshwari ichnosite well connected with the Bhuj City road





Ripple marks, planar cross-bedding, massive bedding and parallel bedding are the geological features found at the ichnosite (Fig. 5). The site features a long, thick and broad channel-cutting body (Fig. 5). The shape of the channel body demonstrates a deltaic distributary deposit (Gibling 2006). The presence and absence of trace fossils and sedimentary structures explain the depositional environment. There are no visible fossils in the channel body. However, the channel body's top portion has excellent trace fossils that may have formed during the postdeposition time.

The location is well-known and popular among travellers. Because of the sunrise/sunset viewpoint and the sandstone caves, temples with a long history, Rao Vijay Rajji constructed Tapkeshwari Temple approximately 450 years ago on a rocky hill. This is a popular tourist and spiritual site in Bhuj, where tourists and devotees enjoy nature. Peaceful surroundings (Fig. 4).

This region is always packed with academicians and researchers investigating various geological fields (Fig. 5). Sedimentologists can determine the boundary between the Bhuj and the Jhuran Formation here. Palaeontologists

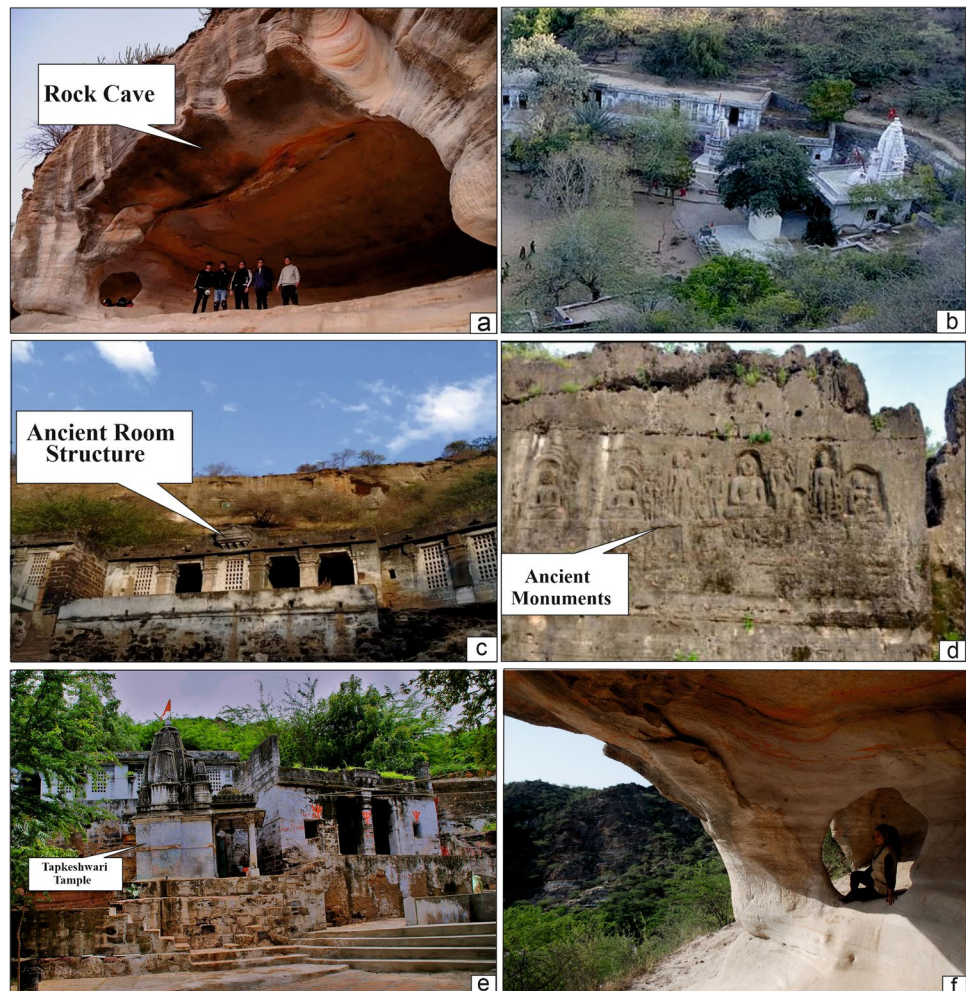
examine trace fossils, while structural geologists may investigate host-like structures between two normal faults in the Katrol Hill range. Identify the erosional and weathering processes of the cave and other hydrological and geomorphological aspects (Biswas and Chauhan 2021). This site is crucial for geology students and researchers. There are several suitable old structures for archaeological investigation here, representing the history and culture of the preceding decade.

The following reasons for this site's consideration and conservation as a geological heritage, connectivity, viewpoint, historical buildings and natural rock caves will contribute to establishing a self-sustainable local economy.

### Hill Garden Ichnosite

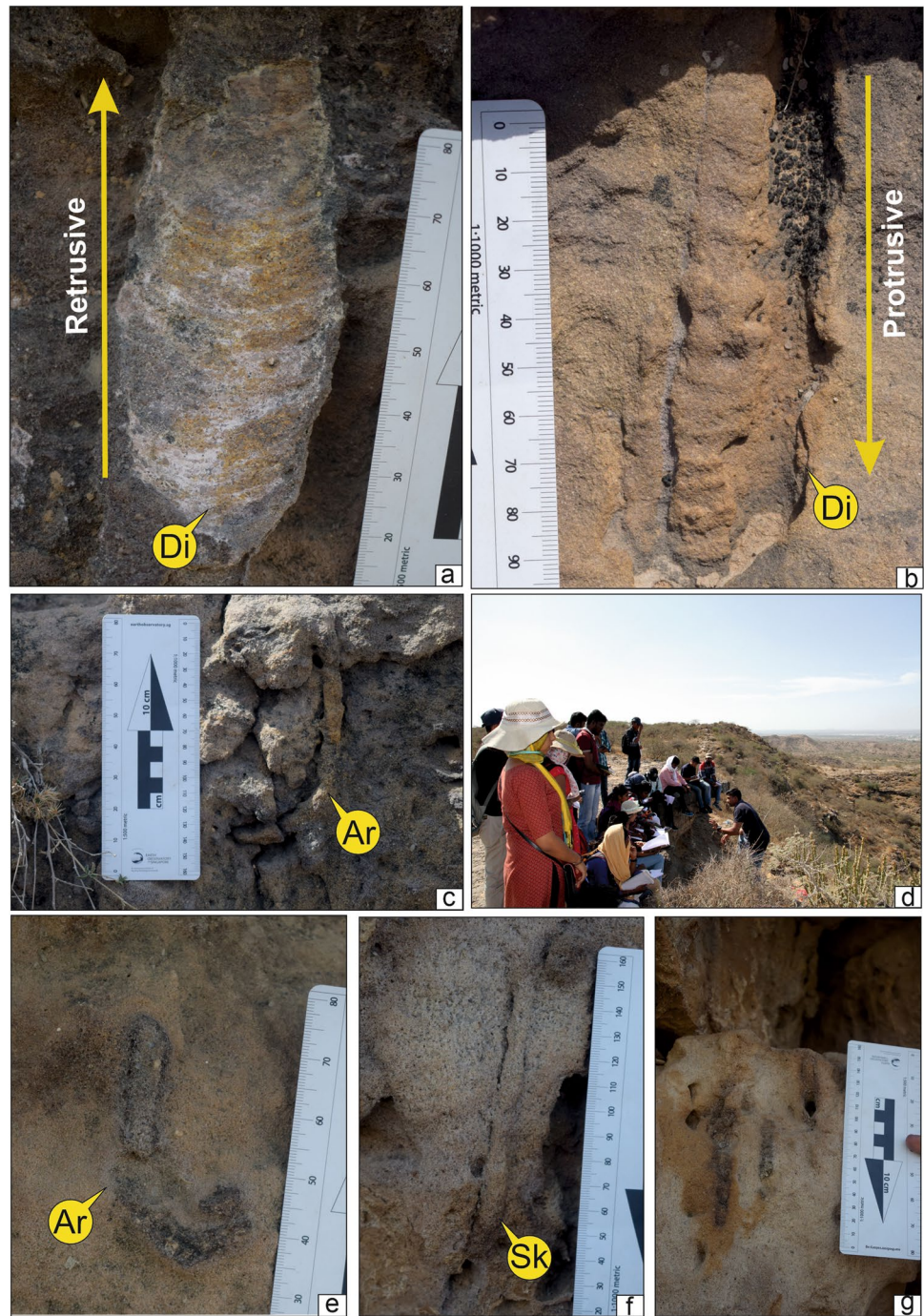
The proposed Hill Garden ichnosite ( $23^{\circ}14'20.52''N$ ;  $69^{\circ}38'24.89''E$ ) comes under Bhuj town, the district headquarters of Kachchh district. The geosite is located  $\sim 3$  km southwest of the city centre on a ring road (Figs. 6, 7), connecting to all the major roads and transport services of Bhuj town. The site has a unique feature where thousands of

**Fig. 4** Details of the Tapkeshwari ichnosite. **a** A massive rock cave formed in the sandstone of the Bhuj Formation. **b** Top view of the Tapkeshwari temple and associated buildings in the vicinity of Ichnosites. **c** Ancient temple and associated rooms of religious significance. **d** Rock cut-carvings on the walls of the temples and monuments. **e** A 450-year-old Goddess Tapkeshwari Temple. **f** Naturally, formed caves in the sandstones above the temple; this site is also famous as a filming site for many Bollywood movies





**Fig. 5** Trace fossils present in the Tapkeshwari site. **a–b** Well-developed sprites of *Diplocraterion*. **c** A ‘U’-shaped *Arenicolites* in coarse-grained sandstones. **d** Student attraction to studying geomorphological and geological features. **e** The thick limb of *Arenicolites* developed in sandstone. **f** Vertical burrow of *Skolithos*. **g** Diagenetically altered trace fossils



*Diplocraterion parallelum* are preserved in the sandstone quarry cuttings with the rare occurrence of *D. bicalvatum* and *Skolithos* (Fig. 8).

The trace fossils belong to the Ghuneri Member of the Bhuj Formation (Lower Cretaceous). The vertical section of the geosite starts with multiple, thickly bedded bioturbated sandstones (mainly *Skolithos* and *Pylonichnus*), followed by minor siltstone layers that are overlain by the massive sandstone with a dense post depositional colony of *Diplocraterion* (Fig. 8). The trace fossil colony shows moderate- to

deep-tier ichnofabric with a maximum depth of 50 cm and shows protrusive and retrusive behaviour (Fig. 8). The geosite also shows sedimentary structures such as planar and trough cross-bedding and parallel laminations. The integration of ichnofossils with sedimentary structures shows that organisms colonised the sediments of the delta.

Although trace fossil research in the Kachchh Basin commenced over a Century, the present site has been found in the last few years. The *Diplocraterion* colonisation along the bed boundary holds mysteries to ichnologists. The primary



**Fig. 6** Location of the Hill garden ichnosite within Bhuj city. The site is road cutting along the hill garden road surrounded by other amusement aspects. Note that the star marks the approachable section top that has excellent exposure to trace fossil *Diplocraterion*



threat to the geosite is urbanisation. Since the sandstone of the Bhuj Formation is a good building material, a major part of the section was lost to the sandstone quarrying (Fig. 7). In the future, if the local government decides to widen the road, then the whole section will be lost indefinitely if not protected (Fig. 8).

To conserve and protect a site as a geological monument, connectivity (airport, railway station and local roads), accommodation and other entertainment facilities are necessary, which will help build a local self-sustainable environment. The Hill Garden geosite is connected by all the transportation alternatives mentioned above. Additionally, the geosite is located within a 100-m radius of the Hill Garden amusement park (Fig. 7).

### Ghunerri Ichnosites

Near Ghunerri village lies the Ghunerri ichnosites ( $23^{\circ}47'03.80''\text{N}$ ;  $68^{\circ}50'47.80''\text{E}$ ). The location is 130 km northwest of Bhuj. The location is conveniently accessible from state route 42 to the Lakhpat-Siyot road (Fig. 9). The Lower Cretaceous excellently outcrops in the Ghunerri Village and its surrounding.

This is the most important type section for the Ghunerri Member of the Bhuj Formation, which is a distal part of the Cretaceous deposits. Sandstone, shale and siltstone are present. Trace fossils are abundant and abundantly diverse in this distinct rock type. These are observed vertically, inclined and horizontal traces. Horizontal traces are predominant in siltstone and shale (Fig. 10). This signifies low energy and fair weather. Vertical traces are frequent in sandstone, indicating environments of strong storm-wave energy (Buatois and Mángano, 2011; Knaust and Bromley, 2012). These two kinds of energy levels occur simultaneously, indicating that energy is by wave and current. Displaying

sedimentary structures such massive bedding, cross-bedding, flasar bedding and planar bedding (Fig. 10). These results on trace fossil assemblages and sedimentology show that this site represents the distal part of the wave-dominated delta front deposits.

The location is famous for its geological study, history and culture. Numerous ancient structures and historical temples surround the area. There are places such as the Ghunerri cave Shiva Temple and the Ghunerri Ramdevpir Temple. Materials from these ancient caves were used to construct the Lakhpat fort, Lakhpat Gurudwara and mosque building (Figs. 11 and 12). Seals found in the cave and remains of Brahmi writings indicate that Buddhists subsequently used a temple from the first and second centuries AD (Fig. 11). The remaining structures are straightforward, single cells, perhaps belonging to the collection of 80 Buddhist caves recorded by Hiuen-Tsang near the mouth of the Indus in the seventh century, according to the department of archaeology (Government of Gujarat). These Buddhist caverns are carved in the Cretaceous sediments (Fig. 11).

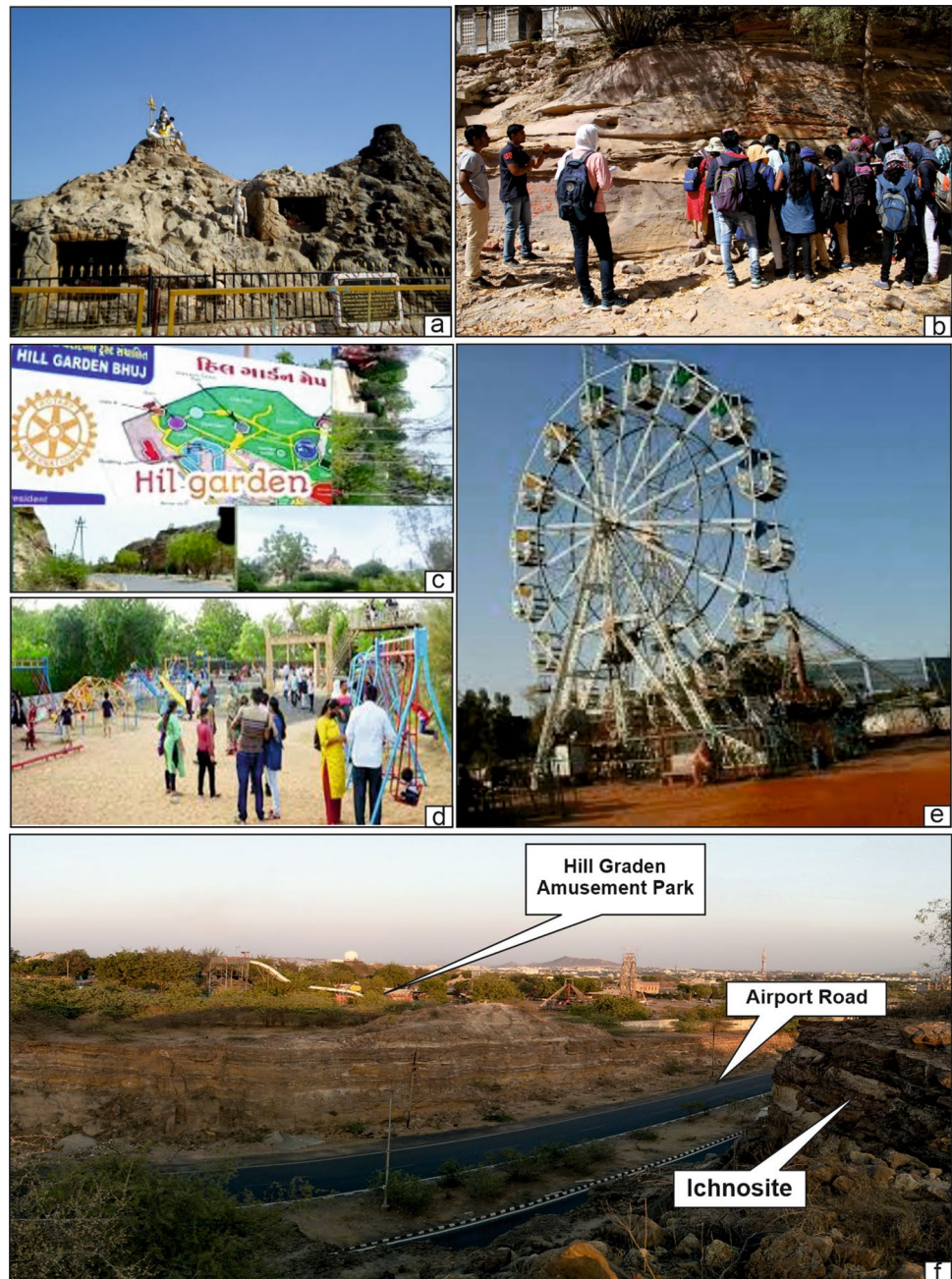
### Geoheritage Values of the Ichnosites

Geoheritage covers geological characteristics of all sizes that are inherently or culturally significant and provides knowledge or insights into the development of the Earth, history and science or may be utilised for study, education or reference (Brocx and Semeniuk 2007, 2019).

Our research focuses on the ichnological heritage of the early Cretaceous. Many of these geosites are now classified as having regional or local significance (Desai 2016). This is particularly true for the following sites, where significant discoveries have been made in recent years: recognising the relevance of conserving the early Cretaceous geoheritage for education and tourism based on its ichnological importance



**Fig. 7** Amusement places surrounding the Hill Garden ichnosites. **A** Religious places in the amusement park. **B** Tech petroleum engineering students studying the section for understanding sedimentary features for reservoir studies. **C** Entrance and detailed map of the amusement park. **D–E** Several amusement rides for children and adults. **F** View from top of the Hill garden ichnosites showing its vicinity and approach from road and its proximity to an amusement park



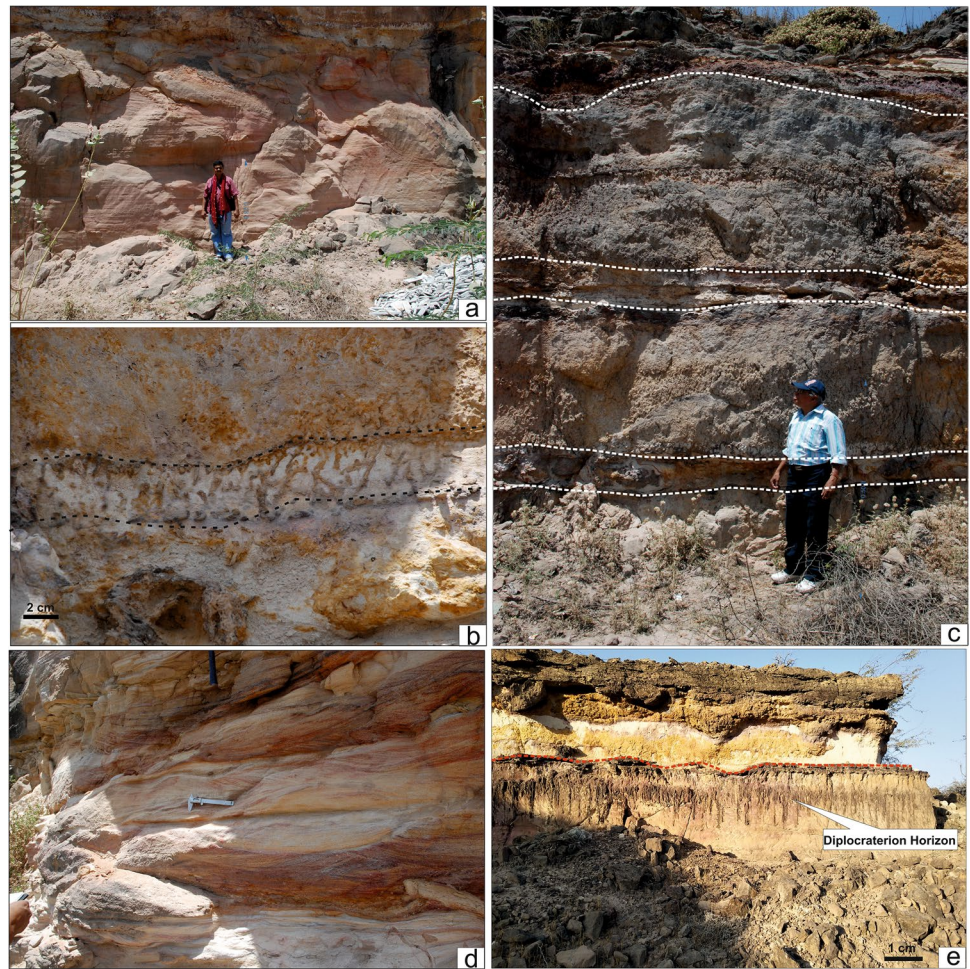
(Desai 2016). Since then, several additional fossiliferous geosites have been scientifically examined and monitored by worldwide teams with the ‘protection and promotion of the fossil deposits of early Cretaceous heritage’ as a particular objective for their research on Mesozoic sediments (Desai 2016). This resource demonstrates the relationships between biostratigraphy, chrono-stratigraphy and litho-stratigraphy provinces and aids in comprehending the environment of the early Cretaceous strata of Kachchh. Its significance lies mainly in its fossiliferous abundance, ichnodiversity and sedimentological facies

(Desai 2016; Desai and Chauhan 2021). Understanding the level of bioturbation and the mineralogical composition of the burrow backfilling and margins is crucial for several applications. Thus, the early Cretaceous ichnological legacy is intended to bolster arguments and provide new tactics for the growth and consolidation of the geo-ongoing ichnosite.

The site is also of cultural significance since it contains first- and second-century monuments, ancient architecture and ancient relics. Additionally, the Cretaceous sandstone is used to construct many structures, which is one of the significant conservation issues of ichnosites.



**Fig. 8** Detailed geological sections of the hill garden ichnosites. **a** Massive sandstone with cross-stratification and bioturbation of the top part (man is 173 cm). **b** Bioturbated zone (dotted line) with the *Glossifungites* ichnofacies surface at the base overlain by the *Polykladichnus* trace fossil zone grading upwards into massive sandstone. **c** Approximately 15 feet of the section with three distinct bioturbated cycles (man is 165 cm). **d** Trough cross-stratification along with channel cross section. **e** The top of the hill garden section shows excellent development of the *Diplocraterion* horizon topped with the omission surface



**Fig. 9** Google image of the Ghuneru dome ichnosite. The road leads to Ghuneru Village and passes through the dome structure



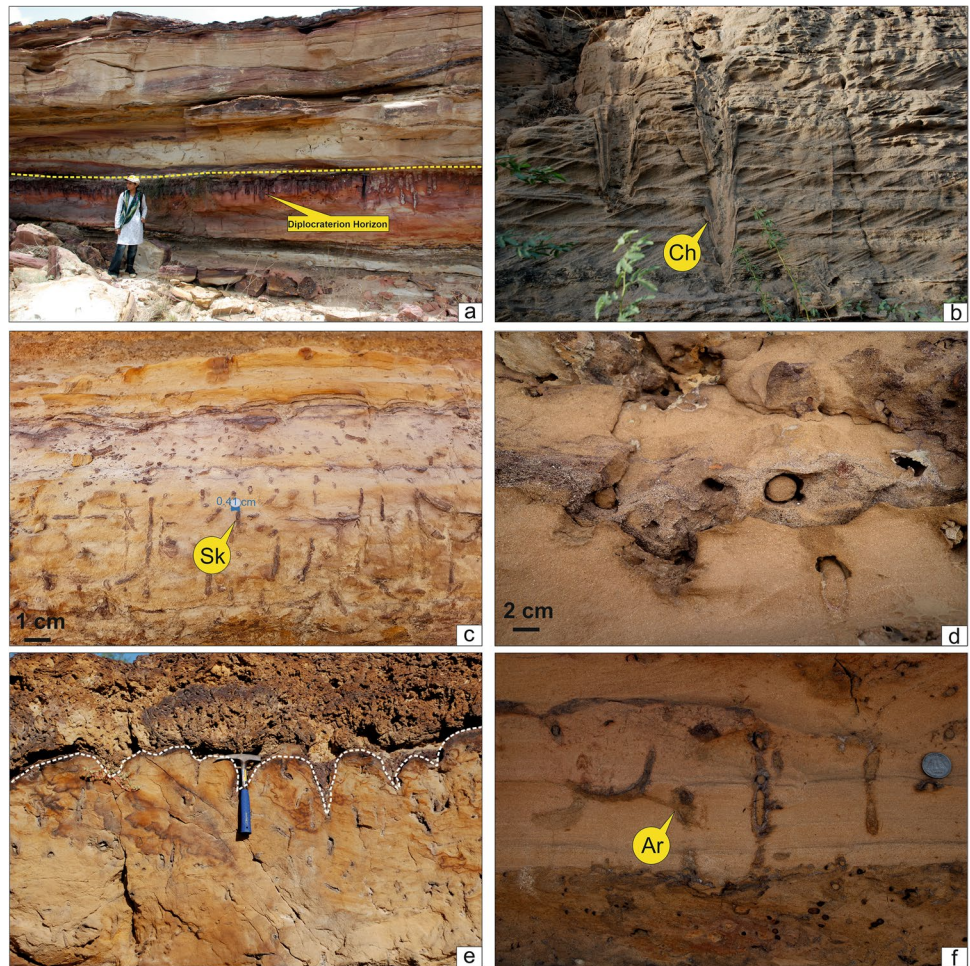
**SWOT (Strength-Weakness-Opportunity-Threats) Analysis**

The analysis helps identify potential opportunities and continue threats to convert them. The SWOT analysis evaluates

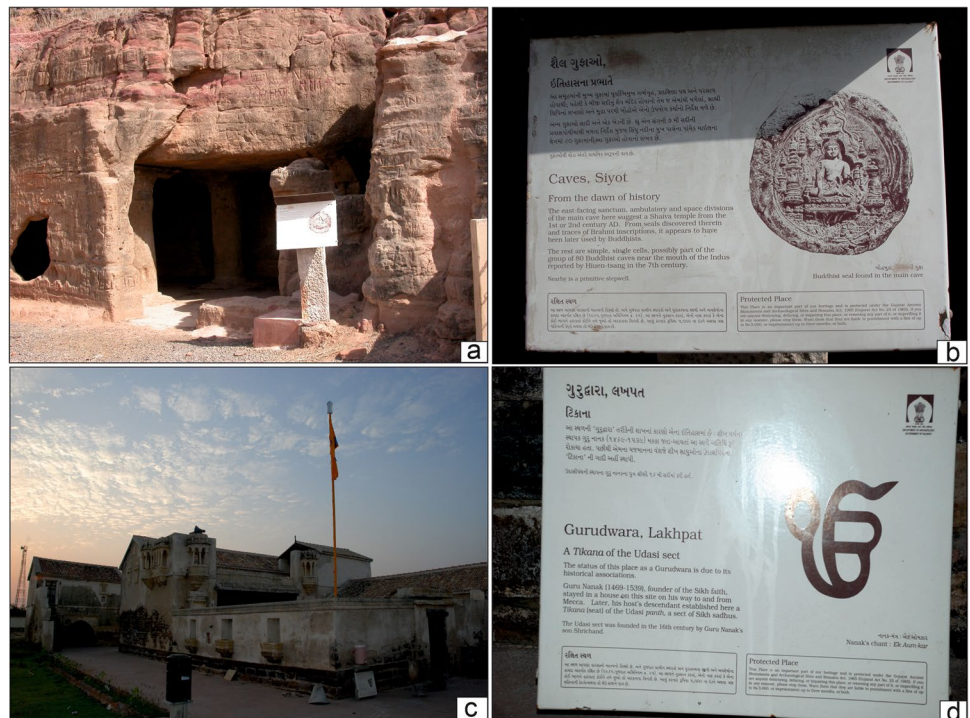
geosites to determine their potential as tourism destinations (Table 1). On this basis, measures may be undertaken to increase the strengths and decrease the weaknesses of internal variables, as well as to maximise the possibilities and minimise the risks posed by external elements (Datta 2020).



**Fig. 10** Ichnology of the Ghuneri Dome area. **a** Upper part of the Ghuneri Member showing thick-bedded sandstone interbedded with thin-bedded shales. Note the excellently developed postdepositional *Diplocraterion* forming a distinct surface. **b** Well-developed large (> 1.5 feet) long *Conichnus conicus*, an equilibrium trace fossil. **c** Moderately bioturbated upper part of the Ghuneri Member showing *Skolithos* burrows. **d** An example of a dual-porosity-type reservoir, where the burrow fill is different than the matrix. **e** Bioturbated sandstone section in the lower part of the Ghuneri Member showing low bioturbated sandstone topped with *Glossifungites* ichnofacies surface (white dotted) overlain by highly bioturbated medium-sandstone. **f** Moderately bioturbated sandstone showing the interrelation of physical sedimentary structures and trace fossils

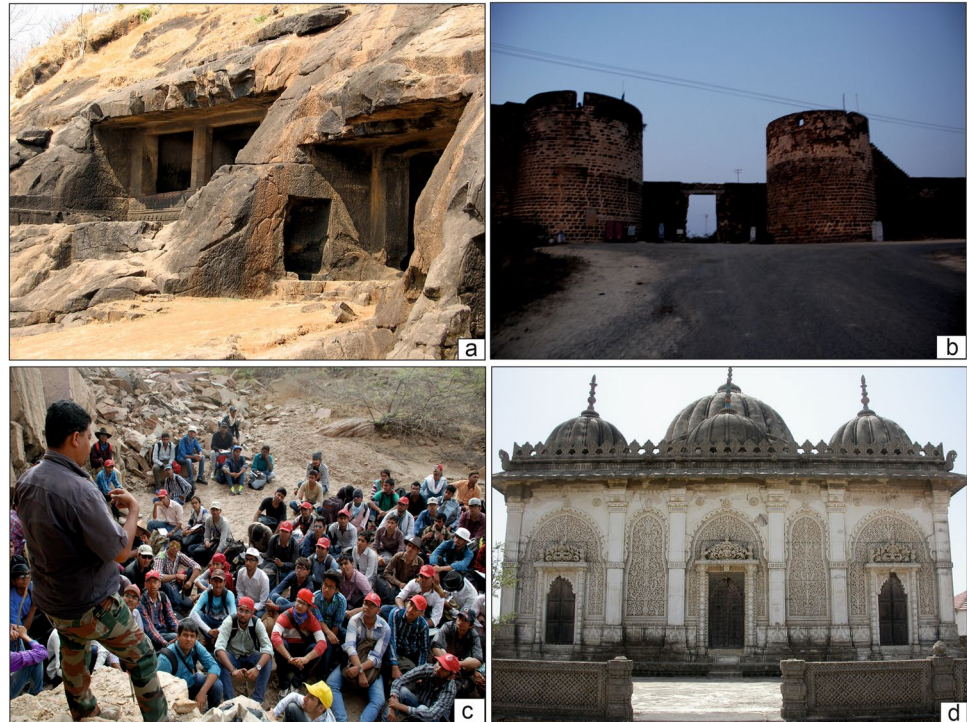


**Fig. 11** Places of tourist attraction near Ghuneri dome ichnosite (**a–b**) A first- and second-century Buddhist cave in the Ghuneri Member sandstone that was visited and well documented by seventh-century Chinese traveller Mr Huen Tsang. Presently preserved by the Archaeological Survey of India (**c–d**), a world heritage site of religious importance. The Lakhpat Gurudwara is world-famous for a historical significance





**Fig. 12** Tourist attraction sites around the Ghuneri dome. **a** Ghuneri Caves near Ghuneri village. **b** Entrance of the Fort Lakhpat: it was a port until the fourteenth to fifteenth century. **c** Author BGD explaining the geological significance to the B. Tech Petroleum Engineering student regarding the sandstone reservoirs around the Ghuneri dome. **d** Intricately carved sandstone forming the mosque structure, preserved inside the Lakhpat Fort



**Table 1** SWOT analysis of the study area

Strength	Weakness
<ol style="list-style-type: none"> <li>1. The first and second-century architecture of the Ghuneri site comprises a temple, caves and sculptures. The Tapkeshwari site is distinguished by its 500-year-old temple and ancient room architecture</li> <li>2. Importance of richness and variety in deltaic ichnology</li> <li>3. Comprehending factors such as shallow marine and deltaic ichnodiversity of the early Cretaceous period, palaeontology, sedimentology and stratigraphy in the context of future researchers</li> <li>4. The ichnosites have a very good communication and transport network</li> <li>5. The locations are popular among local tourists for their sunrise point, rocky cave, amusement park and historical and cultural significance</li> </ol>	<ol style="list-style-type: none"> <li>1. The undervaluing of local culture and the natural environment</li> <li>2. Students and locals lack an understanding of the geological importance of ichnosites</li> <li>3. Lack of attention to geocultural heritage via media, ads, billboards and other means</li> <li>4. Less assistance from the local government and federal government to promote tourism in the region</li> <li>5. There are few links between the geopark and industry</li> </ol>
<p>Opportunity</p> <ol style="list-style-type: none"> <li>1. Promotion of the site may enhance the number of visitors in the region, contributing to the economic growth of the local population</li> <li>2. The opportunity to receive financial support from government funding</li> <li>3. The study region is appropriate for research and instructional tours to boost geotourism</li> <li>4. Restoration of historic buildings and natural heritage locations</li> </ol>	<p>Threats</p> <ol style="list-style-type: none"> <li>1. cultural identity and natural value loss</li> <li>2. Improved organisation of Kachchh's tourism zones and attractions</li> <li>3. Insufficient public administration and private help</li> <li>4. The passage of time—the deterioration and destruction of the legacy</li> <li>5. Uncontrolled development that threatens cultural. Historical and natural assets, as well as the environment</li> </ol>



This study is conducted to enhance the current field data for the planned geosites and the cultural and historical features of the location (Bhosale et al. 2021).

## Conclusion

We can conclude that the Bhuj Formation of the Kachchh Basin is an excellent example of an area that is losing its potential to become a geopark because conservation strategies at the geosites have not been implemented, putting the paleontological heritage at risk. If no urgent conservation actions are taken, all geosites may be destroyed within a human timescale. The ichnosites in the Kachchh Basin, which maintain outstanding Cretaceous-era trace fossils in sandstone and shale, were examined for the first time in this study. Due to the organism's properties, a unique paleoenvironmental reconstruction of the Early Cretaceous Bhuj Formation has been proposed, highlighting its geoheritage worth. Consequently, ichnology may be utilised for study, education, geotourism and reference, which strengthens the geoheritage importance of the Early Cretaceous rocks. Ichnosites 'speak' about ancient species, behaviours and surroundings. This case study enables the identification of trace fossils as a significant geoheritage feature in sedimentary rocks. Thus, it is suggested that scientific research be conducted for evaluation of trace fossils in various ichnosites for conservation conditions, and protected status, as well as their usefulness to larger educational programmes and geotours.

**Acknowledgements** The authors gratefully acknowledge Dr Suraj Bhosale for his help in the field. The authors are thankful to the management of the School of Petroleum Technology, Pandit Deendayal Energy University, for providing support.

**Author Contribution** Suruchi Chauhan: conceptualisation, data collection, data analysis and interpretation and manuscript writing.

Bhawanisingh G Desai: conceptualisation, data collection, data analysis and interpretation and manuscript writing

**Data Availability** The data for the above research is available from the authors on request.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

## References

Alonso-Zarza AM, Genise JF, Cabrera MC, Mangas J, Martín-Pérez A, Valdeolmillos A, Dorado-Valiño M (2008) Megarhizolites in Pleistocene aeolian deposits from Gran Canaria (Spain): ichnological and palaeoenvironmental significance. *Palaeogeogr Palaeoclimatol Palaeoecol* 265:39–51. <https://doi.org/10.1016/j.palaeo.2008.04.020>

Baucon A, Piazza M, Cabella R, Bonci MC, Capponi L, de Carvalho CN, Briguglio A (2020) Buildings that 'speak': ichnological geoheritage in 1930s buildings in Piazza della Vittoria (Genova Italy). *Geoheritage* Sep 12(3):1–22

Bhosale S, Chaskar K, Pandey DK, Lakhote A, Thakkar A, Chauhan G, Bhandari S, Thakkar MG (2021) Jurassic geodiversity and geomorphosite of Kanthkot area, Wagad, Kachchh, Western India. *Int J Geoheritage Parks*. <https://doi.org/10.1016/j.ijgeop.2020.12.008>

Biswas SK (1977) Mesozoic rock-stratigraphy of Kutch. *Quarterly Journal of Geology Mining Metallurgy Society of India* 49:1–52

Biswas SK (1987) Regional tectonic framework, structure and evolution of the Western marginal basins of India. *Tectonophysics* 135:307–327

Biswas SK, Chauhan G (2021) The Kutch Rift Basin—potential location for a National Geopark of India. In: Reddy D(ed) A monograph on potential geoparks of India. Indian National Trust for Art and Cultural Heritage (INTACH), New Delhi, 1–36. Editor. Dr. Rajashekhar Reddy.

Biswas SK (1980) Mesozoic rock stratigraphy of Kachchh. *Quarterly Journal Geological, Mining and Metallurgical Society (India)*, 49(3 & 4), 1–52

Biswas SK (1993) Geology of Kachchh. KD Malaviya Institute of Petroleum Exploration, Dehradun, p 450

Biswas SK (2016a) Mesozoic and tertiary stratigraphy of Kutch\*(Kachchh)—a review. In Conference GSI. pp. 1–24, <https://doi.org/10.17491/cgsi/2016a/105405>.

Biswas SK (2016b) Tectonic framework, structure and tectonic evolution of Kutch Basin, Western India. In Conference GSI. pp 129–150, <https://doi.org/10.17491/cgsi/2016b/105417>

Brocx M, Semenik V (2007) Geoheritage and geoconservation - history, definition, scope and scale. *J R Soc West Aust* 90:53–87

Buatois LA, Mángano MG (2011) Ichnology: organism-substrate interactions in space and time. Cambridge University Press. 358p

Chauhan G, Biswas SK, Thakkar MG, Page KN (2021) the unique geoheritage of the Kachchh (Kutch) Basin, Western India, and its conservation. *Geoheritage* 13(1):1–34

Chauhan S, Bhosale S, Padiya D, Desai BG (2022) Ichnology of Early Cretaceous, cyclic bioturbated Ghuneri Member (Bhuj Formation) From Kachchh Basin, Western India (In press).

Curran HA (1985) Biogenic structures: their use in interpreting depositional environments SEPM special. Publication 35:364

Datta K (2020) Application of SWOT-TOWS matrix and analytical hierarchy process (AHP) in the formulation of geoconservation and geotourism development strategies for Mama Bhagne Pahar: An important geomorphosite in West Bengal. *India Geoheritage* 12(2):1–11

Desai BG (2013) Ichnological analysis of transgressive marine tongue in prograding deltaic system: evidences from Ukra Hill Member, Western Kachchh, India. *J Geol Soc India* 82:143–152

Desai BG (2016) Ichnological events associated with evolution of Kachchh rift Basin, Western India. *Recent Studies on the Geology of Kachchh* 6:114–128

Desai BG, Biswas SK (2018) Postrift deltaic sedimentation in Western Kachchh Basin: insights from ichnology and sedimentology. *Palaeogeogr Palaeoclimatol Palaeoecol* 504:104–124

Desai BG, Chauhan S (2021) Taphonomic pathways for the formation of bioturbated cycles in the Early Cretaceous wave-dominated deltaic environment: Ghuneri Member, Kachchh Basin, India. In *Mesozoic Stratigraphy of India* (pp. 311–332). Springer, Cham.

Ekdale AA (1985) Paleocology of the marine endobenthos. *Palaeogeogr Palaeoclimatol Palaeoecol* 50(1):63–81

Fursich FT (1998) Environmental distribution of trace fossils in the Jurassic of Kachchh (Western India). *Facies* 39(1):243–272

Gibling MR (2006) Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *J Sediment Res* 76(5):731–770

- Hasiotis ST, McPherson JG, Reilly MRW (2013) Using ichnofossils to reconstruct the depositional history of sedimentary successions in alluvial, coastal-plain, and deltaic settings. In IPTC 2013: International Petroleum Technology Conference (pp. cp-350). European Association of Geoscientists & Engineers.
- Jyotsna GDD, Desai BG, Lakshmi Narayan Avadhani V (2022) Identification of reservoir units and their petrophysical characterisation with special reference to Mesozoic Formations, Kachchh offshore Basin. *Western India Arabian Journal of Geosciences* 15(9):1–19
- Knaust D, Bromley RG (2012) Trace fossils as indicators of sedimentary environments. *Newnes* (Eds.)
- Mateus O, Milan J (2009) A diverse Upper Jurassic dinosaur ichnofauna from Porto Dinheiro track assemblage. *Lethaia* 43:245–257. <https://doi.org/10.1111/j.1502-3931.2009.00190.x>
- Minter NJ, Krainer K, Lucas SG, Braddy SJ, Hunt AP (2007) Palaeoecology of an Early Permian playa lake trace fossil assemblage from Castle Peak, Texas, USA. *Palaeogeogr Palaeoclimatol Palaeoecol* 246:390–423. <https://doi.org/10.1016/j.palaeo.2006.10.009>
- Neto de Carvalho C, Baucon A (2016) Giant trilobite burrows and their paleobiological significance (Lower-to-Middle Ordovician from Penha Garcia, Portugal). *Comun Geológicas* 103:71–81
- Ruban DA, Tolokonnikova ZA (2022) New Early Cretaceous geosites with palaeogeographical value from the Northwestern Caucasus. *Heritage* 5(2):871–880
- Seilacher A (2007) Trace fossil analysis. Springer, Berlin, p 226
- Singh A, Jha NK, Mandal PP, Esteban L, Desai BG (2022a) Pore throat characterisation of bioturbated heterogeneous sandstone, Bhuj Formation, Kachchh India: an integrated analysis using NMR and HPMI studies. *Journal of Petroleum Science and Engineering*, 110221
- Singh A, Dcunha J, Desai BG (2022b) Evaluating cementation factor for bioturbated sandstones, Bhuj Formation, Kachchh Basin, India: a novel approach using triple-porosity model. *Journal of Petroleum Exploration and Production Technology*, 1–12
- Taylor A, Goldring R, Gowland S (2003) Analysis and application of ichnofabrics. *Earth-Science Rev* 60:227–259
- Wandrey CJ (2004) Bombay geologic province Eocene to Miocene composite total petroleum system, India (Vol. 2208). US Department of the Interior, US Geological Survey
- Wimbledon WA (1999) GEOSITES—an International Union of Geological Sciences initiative to conserve our geological heritage. *Polish Geological Institute Special Papers* 2:5–8
- Wimbledon WA (2011) Geosites—a mechanism for protection, integrating national and international valuation of heritage sites. *Geologia Dell’ambiente, Supplemento* 2:13–25

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.