




# The Unique Geoheritage of the Kachchh (Kutch) Basin, Western India, and its Conservation

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## Abstract

The Kachchh Basin is a peri-cratonic rift basin in the Gujarat state of Western India which exposes a vast range of geological features which are of great importance for basic and applied research by geoscientists. The fossil-rich stratigraphy of the Kachchh Basin represents the past 200 million years of geological history from the Jurassic Period to the present day, including through the Neogene Period. Both Mesozoic and Cenozoic sequences are highly fossiliferous with a variety of mega, macro, and microfossils, including invertebrate, plant, trace, and vertebrate fossils. Crucially, the Kachchh Rift Basin demonstrates a uniquely well exposed, syn to post-rift tectono-sedimentary sequence formed from the Late Triassic to the Early Cretaceous during the break up of Eastern Gondwanaland. The basin is bounded by reactivated primary faults forming tilted horsts and half-grabens. Tilted-up edges of the uplifted fault blocks are represented by uplifted hilly ranges, whereas the intervening subsiding blocks are the geomorphological expression of the low-lying Rann and Banni plains (mudflats, marshes, and grassland). This activity was followed by an inversion cycle initiated in Late Early Cretaceous following the aborting of the rift and is active in the present neotectonic cycle. Thick Deccan Trap lava flows and basic intrusive bodies indicate associated deeper crustal and mantle processes associated with this rift basin evolution. Easily accessed, well-exposed continuous sedimentary sequences with scanty vegetation provide a unique window of opportunity to looking into the geological past of this unique landscape which has preserved the evidence of the evolution of life both in near shore, coastal, and terrestrial environment, as well as a rare opportunity to understand a history of syn/post-rift-fill sedimentation, volcanism, and tectono-geomorphical evolution. More recently the terrain has become a hotspot amongst the planetary scientists as it provides a terrestrial analogue for Lunar and Martian landscapes. These and many other features justify why the unique geological heritage of the Kachchh Basin should be conserved for posterity not only for geoscientists from all over the world but also for local communities and visitors who could learn from its 200 million year history. We therefore propose that the landscapes of the Kachchh Basin should be conserved as a National Geopark in India to achieve such ambitions, and we believe that in this, they have an immense potential to achieve many of the UN's Sustainable Development Goals. It is proposed to create 9 geo-stations (for administration) and 75 geosites grouped under these stations within the proposed Kachchh Geopark.

**Keywords** Geoheritage · Geopark · Geotourism · Kachchh Rift Basin · Rann · India · Tectonics

## Introduction

Sedimentary successions which represent a wide range of spatial and temporal changes in the sedimentation process, including in relation to tectonic, volcanic activity, and faunal and floral assemblages, are a very important aspect of geological heritage and hence deserve protection, especially if they are well-exposed. Geoheritage includes geological features (e.g. structural, stratigraphical, palaeontological, and economic) which provide knowledge about the Earth's evolution or the history of Earth sciences and can be used for research, teaching, or as reference localities, not just regionally but also

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globally. A section or outcrop of such a geological heritage could be a rare or single site at which the occurrence of a rare or unique fossil, mineral, or structure is noted or any other geological or geomorphological feature which is well developed or preserved at its place of occurrence. There is a strong need of legal protection and conservation for this naturally provided heritage, usually through a combination of various international, national, and regional laws (Dauvin et al. 2004). In 1972, UNESCO established the World Heritage Convention regarding the protection of the world's cultural and natural heritage, with multifaceted definitions of natural heritage for protection that could be ecological or geomorphological/geological. The evaluation and importance of the Earth's heritage and its wise management for future generations have become significantly considerations in recent years due to the development of the concepts of geodiversity and biodiversity (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). Crucially, geoheritage is also allied to the historical, cultural, aesthetic, and religious heritage of humanity (Brocx and Semeniuk 2007).

During the early history of geology and palaeontology, the conservation of geological sites and materials was rarely an issue for the developing science, as new localities with 'new' fossil assemblages were continually being discovered (Page 2018). However, as many well-known geological localities were subjected to damage in the later nineteenth century, due to the processes of urbanization and industrialization by the mid-twentieth century, a general awareness of the need for some form of site protection had been developed (Page et al. 1999). In most countries, however, it took until the late twentieth century for this awareness to evolve into conservation systems and networks of protected sites (Page and Wimbledon 2009). These geologically important sites that need to be conserved as geological features, and fossils that they yield, are a natural heritage that can be important for understanding the science and the sequence of changes and events that have taken place through geological time. Conserving geologically important sites by developing their recreational and touristic potential can also be crucial for educational and economic purposes (Page 2018). In particular, over the past few years, there has been a significant surge in interest in the conservation of geoheritage through the establishment of geoparks and geotourism worldwide. Geotourism can be defined as sustainable tourism with a primary focus on experiencing the Earth's geological features in a way that fosters environmental and cultural understanding, appreciation, and conservation and is locally beneficial. It is a form of tourism in which the elements of the landscape and its evolution together create a tourist experience that is richer than the sum of its parts, attracting visitors with diverse interests (Dowling and Newsome 2006, 2010). Geotourism activities

have the potential to raise the profile of the Earth Sciences, including activities that could fund research and generate employment opportunities (Kelley et al. 2019).

In many countries, there has been a systematic effort to protect geological and geomorphological features, through the identification and documentation of significant sites as 'geosites' (Panizza and Piacente 1993; Wimbledon et al. 1995; Wimbledon 1996; Panizza 2001; Reynard 2004; Carobene and Firpo 2005, etc.). The conservation of such sites is environmental management and includes an appraisal of their sustainability, hazard aspects, and geodiversity (the combined geological, geomorphological, pedological, and hydrological features) (Sheth et al. 2017). Geological features are a treasurable natural heritage and need to be protected like natural forests and other habitats and the wildlife that relies on them. However, unlike many such habitats, many geological features which are a record of Earth history on which the modern landforms and environments have developed cannot be recreated. Such heritage sites are a natural wealth for the country of their occurrence and need to be protected from destruction by human activity.

As a result, a concept of 'Geopark' evolved from the later 1980s in order to protect the geoheritage sites and manage them for the benefit of and in collaboration with local communities, leading to a surge in interest in the conservation of geoheritage in recent years and the establishment of geoparks and geotourism programmes worldwide. 'Geoparks' are unified geographical areas where sites and landscapes of international geological significance are conserved and managed with a holistic approach to protection, education, and sustainable development (UNESCO 2016). Crucially, according to the UNESCO model, they are also territories that combine the conservation and promotion of geological heritage with sustainable local development (Zouros 2004). 'Geoparks' have proven to be admirable tools to educate a general public about the Earth sciences, as they combine conserving geological heritage with improving such understanding and promoting regional economic development (Patzak and Eder 1998; Eder 1999; Kelley et al. 2019). The possibilities for teaching Earth sciences activities in these areas are diverse, and they can provide the support necessary for teachers and researchers to work with teaching and learning (Fornaro and Fernandes 2018). The 'Geoparks' concept also allows us to be able to introduce geosciences into the cultural sphere; contributing to the notion that human culture is not independent of nature (Menegat 2009). In the past 20 years, beginning with the foundation of the European Geopark Network in 2000, the establishment of Geoparks globally as part of a Global Geopark Network (GGN) has been supported by UNESCO from 2015. In parallel with UNESCO designated 'Global Geoparks', many countries, such as Germany and Korea, have also continued to develop national Geopark networks, which reflect the same principles of education, community

participation, and sustainable development. Crucially, all geoparks can play a significant role in the economic development of local or rural areas through geotourism.

A categorized system for geoconservation (i.e. the conservation of a geological heritage), geo-education, and geotourism consists of a geosite at the smallest spatial scale, geotopes confines at larger scales, and a geopark typically at the largest scale (Eder 2008; Ieleniz 2009; Joyce 2010; Moufti and Németh 2013, 2016). A geopark would typically be a nationally protected area covering a number of geological heritage sites of particular importance, rarity, or aesthetic appeal and achieves its goals through conservation, education, and sustainable development of geological heritage through geotourism (Dowling and Newsome 2010). Crucially, geoparks can exist at various scales and national network, and UNESCO Global Geoparks are just one system through which such goals can be recognized and achieved.

India has a high potential for the establishment of Geoparks. The vast outcrop of Precambrian rocks in Central and Southern India, well-exposed Gondwana basins, coastal rift basins, and orogenic belts of Himalaya and Assam-Arakan on the North and North-East borders of the Indian plate have enormous scope for the formation of Geoparks (Chauhan et al. 2016a). However, in India, very little has developed so far in this regard, and the concept of ‘geopark’ is still in the nascent state—although the Geological Survey of India (GSI) has carried some groundwork for setting up such areas by identifying 26 geosites across the country. Surprisingly, no such site has been identified by the GSI in the Kachchh Basin of Gujarat state (Western India) despite its rich and famous geological heritage. The Kachchh Basin, extending over the entire district of the Kachchh and a part of the Banaskantha district, represents one of the finest geoheritage sites not only in Gujarat but in the whole of India and merits for a place amongst the important geoheritage sites of the world.

In this paper, we discuss the unique geology of the Kachchh Basin and describe its rich geoheritage to demonstrate that the basin is virtually a ‘natural museum’ of geology, a 3D model for marginal rift basin evolution, and a natural field textbook of geology. Heritage geosites under various sub-disciplines of geology are described in this paper to aid students, teachers, research scholars, geoscientists, and mining and petroleum geologists from India and abroad (Table 1). Crucially, the geoheritage and landscapes of the Kachchh Basin also have the potential to help, benefit, and improve the economic and hence social and infrastructural situation of local communities, including through meeting a range of the United Nation’s achieve UN Sustainable Development Goals, through the development of geotourism. We propose here that the Kachchh Basin should be established as a National Geopark with 75 geosites grouped under 9 geo-stations selected after extensive field study (Table 1).

## Geology and Geoheritage of the Kachchh Basin

Although the Kachchh Rift Basin (KRB) is famous for its unique stratigraphy, its structural features and tectonics are equally fascinating (Biswas 1993). The structural style of the KRB is defined by east-west oriented tilted horst blocks with intervening half-grabens, bordered on the north by the Great Rann Graben (GRG), a graben along the northern rift shoulder of the Nagar Parkar horst (Figs. 3 and 4a, b) (Biswas 1980, 2005). Towards the south, the GRG is followed by the Island Belt Uplift (IBU) which is a south tilted horst with its footwall facing the GRG and hanging wall forming the Banni Half-Graben (BHG) against the footwall of the Kachchh Mainland Uplift (KMU) (Figs. 3 and 4a, b). The KMU is a south tilted horst block that formed the Gulf of Kachchh Half-Graben (GOKHG) against the Saurashtra Horst (Figs. 3 and 4a, b). The latter is the southern rift shoulder of the KRB along the North Kathiawar fault (NKF) (Figs. 3 and 4a, b). In the eastern part of the basin, a third north tilted horst block, the Wagad Uplift (WU), bounded by South Wagad fault (SWF), is located *en echelon* between the IBU and the KMU (Fig. 4a, b). Its northward tilt formed the Rapar Half-Graben (RHG) (Fig. 4a, b).

All the four master faults along the footwalls of the uplifts and the two boundary faults along the rift shoulders are sub-vertical normal faults bounding basement fault blocks which were reactivated primordial faults with a Neo-Proterozoic structural trend (Biswas 2016b; Fig. 4a, b). The basement fault blocks were covered by rift-fill sediments which formed a ductile layer (Fig. 3). The only basement outcrop (having nepheline syenite and related rocks) in the KRB is exposed in Meruda Hill in the middle of the Rann mudflat (Biswas and Deshpande 1968; Thakkar et al. 2020b). During post-rift structural inversion, the ductile layer formed marginal flexures over the tilted upward edges of the uplifts (Biswas 2016b). Repeated movements, mostly strike-slip, along the master faults during different stages of the inversion cycle complicated the marginal flexures into narrow deformation zones with complex folds and associated faults (Bhattacharya et al. 2019; Biswas 2016b; Kothiyari et al. 2016c). The uplifts are, therefore, bordered by narrow deformation zones along their respective footwalls (Biswas 2016b). While the structural lows—i.e. grabens and half-grabens—are covered by Pleistocene-Holocene sediments, the structural features are well exposed in the uplifts, displaying the structural style with folds and faults of several orders (Figs. 3 and 4a, b). In addition, syn-rift igneous activity and post-rift volcanic activity make the structural history more interesting. Thus, the structure and tectonics of the Kachchh Basin presents an ideal 3D model of a peri-cratonic rift basin in a volcanic passive margin, in this case the Western Continental Margin of India. This geology is extensively exposed and with its characteristic intergrading marine and fluvio-deltaic rift-fill sediment

**Table 1** List of proposed 75 prospective geosites, grouped under 9 Geo-stations, for the Kachchh Basin

Geo-station	Geosite no.	Name of the geosite	GPS location	Geological aspect can be studied
1. Bhuj	1	Bhujiya Hill	23° 14' 48.30" N 69° 41' 14.68" E	Igneous activity, sedimentology, structural geology
	2	Khari Gorge	23° 15' 3.25" N 69° 37' 48.88" E	Sedimentology, ichnology, neotectonic and palaeoclimate
	3	Kodki Fault	23° 14' 37.57" N 69° 34' 58.63" E	Structural geology, igneous activity, sedimentology
	4	Kodki Mahadev Temple	23° 13' 54.16" N 69° 33' 24.73" E	Structural geology and sedimentology
	5	Fakir Wadi Section	23° 11' 39.10" N 69° 36' 24.95" E	Structural geology, sedimentology, palaeontology
	6	Tapkeshwari Hill	23° 10' 52.27" N 69° 40' 0.81" E	Geomorphology, structural geology, tectonics, stratigraphy, sedimentology, palaeontology, hydrogeology
	7	Gangeshwar Temple	23° 11' 36.86" N 69° 43' 36.37" E	Neotectonics, palaeoclimate, palaeontology, stratigraphy, sedimentology, structural geology
	8	Khatrod hill	23° 10' 50.11" N 69° 48' 11.44" E	Neotectonics, tectonic geomorphology, stratigraphy, palaeontology
	9	Khari River Section near Rudramata Dam	23° 19' 20.06" N 69° 40' 15.69" E	Stratigraphy, sedimentology, structural geology, ichnology
	10	Jhurio Hill, Badi Nala	23° 25' 44.16" N 69° 33' 52.38" E	Stratigraphy, sedimentology, structural geology, palaeontology, tectonic geomorphology
	11	Habbo Hill	23° 22' 34.44" N 69° 50' 26.72" E	Stratigraphy, sedimentology, palaeontology, structural geology, igneous activity, tectonic geomorphology
	12	Kas Hill, Lodai Dam	23° 22' 46.18" N 69° 54' 25.14" E	Tectonic geomorphology, stratigraphy, palaeontology, structural geology, igneous activity
	13	Nadapa China Clay area	23° 17' 33.53" N 69° 55' 38.65" E	Stratigraphy, sedimentology, mining Geology
	14	Vidi Section	23° 4' 24.56" N 70° 1' 24.96" E	Igneous activity, sedimentology, stratigraphy, K-T boundary
	15	Chakar-Kotada River	23° 5' 20.26" N 69° 44' 11.58" E	Sedimentology, stratigraphy, igneous activity
	16	Palar Dhuna Water Fall	23° 16' 5.81" N 69° 23' 3.77" E	Geomorphology, igneous activity
	17	Geological Museum, K.S.K.V. Kachchh University, Bhuj	23° 12' 52.38" N 69° 39' 18.99" E	Geological specimens (ore, minerals, rocks, fossils collected from Kachchh Basin, Aravalli Craton, Himalaya, Deccan plateau, South India, etc.)
	18	Jhuran River and Jawahar Nagar road section	23° 21' 13.47" N 69° 59' 29.13" E	Stratigraphy, sedimentology, palaeontology
19	Ler Section	23° 11' 23.17" N 69° 45' 39.59" E	Stratigraphy, sedimentology, structural geology, palaeontology	
2. Mandvi	20	Mandvi Beach	22° 49' 31.57" N 69° 20' 16.41" E	Sea level changes, coastal geomorphology, neo-ichnology,
	21	Khojachora bentonite field	23° 0' 51.82" N 69° 23' 34.11" E	Economic geology
	22	Gadhsisa Bauxite Field	23° 5' 2.82" N 69° 22' 39.79" E	Economic geology
	23	Dahisara Road Cutting Section	23° 4' 38.05" N 69° 30' 50.72" E	Sedimentology
	24	Dhunai Quarry Section	23° 4' 1.29" N 69° 30' 49.08" E	Igneous activity and mineralogy
	25	Punadi-Asambiya Field	22° 59' 56.46" N 69° 25' 6.75" E	Sedimentary processes, chemical weathering, economic geology
3. Naliya	26	Naliya River	23° 16' 21.55" N 68° 49' 28.75" E	Stratigraphy, sedimentology
	27	Khari Nadi section	23° 25' 45.00" N 68° 49' 40.00" E	Sedimentology, stratigraphy, palaeontology
	28	Waior village	23° 25' 15.70" N 68° 41' 59.93" E To 23° 25' 32.68" N	Stratigraphy, sedimentology, palaeontology

**Table 1** (continued)

Geo-station	Geosite no.	Name of the geosite	GPS location	Geological aspect can be studied
			68° 41' 59.19" E through river bed	
	29	Rakhadi River A	23° 28' 44.77" N 68° 40' 48.91" E	Stratigraphy, sedimentology, palaeontology, fuel geology
	30	Rakhadi River B	23° 29' 16.95" N 68° 41' 46.06" E	Stratigraphy, sedimentology, palaeontology, fuel geology
	31	Harudi Cliff	23° 31' 36.03" N 68° 41' 8.63" E	Stratigraphy, sedimentology, palaeontology, fuel geology
	32	Kakdi River	23° 34' 35.54" N 68° 38' 38.59" E	Stratigraphy, sedimentology, palaeontology, igneous activity
	33	Kankawati River sections	23° 6' 24.50" N 69° 2' 31.77" E	Stratigraphy, sedimentology, palaeontology
	34	Ber-Nani River Section	23° 27' 11.53" N 68° 37' 24.35" E	Stratigraphy, sedimentology, palaeontology
4. Narayan Sarovar	35	Koteshwar-Pinjor Pir	23° 42' 41.32" N 68° 33' 13.24" E	Sedimentology, coastal geomorphology, palaeoclimate and sea level changes
	36	Panandhro Lignite Field	23° 42' 24.19" N 68° 46' 38.84" E	Sedimentology, stratigraphy, economic deposits, palaeontology
	37	Chher Nani	23° 47' 36.29" N 68° 40' 46.15" E	Geoarchaeology, coastal geomorphology, palaeoclimate and sea level changes
5. Lakhpat	38	Lakhpat Fort	23° 49' 32.04" N 68° 46' 23.02" E	Stratigraphy, palaeontology, geomorphology, geo-archaeology
	39	Ghuneri Hill	23° 48' 9.90" N 68° 49' 40.70" E	Stratigraphy, sedimentology, structural geology, palaeontology
	40	Ukra Hill	23° 45' 30.78" N 68° 51' 39.15" E	Sedimentology, stratigraphy, palaeontology
	41	Katesar Hill	23° 46' 21.31" N 68° 52' 47.19" E	Sedimentology, stratigraphy, palaeontology, geo-archaeology
	42	Sahera-Mundhan Hill section	23° 46' 9.15" N 68° 55' 3.64" E	Sedimentology, stratigraphy, palaeontology, structural geology, tectonic geomorphology
6. Matanumadh	43	Matanomadh	23° 32' 44.25" N 68° 57' 0.35" E	Stratigraphy, igneous activity, planetary science
	44	Helipad Section of Matanomadh River cliff	23° 31' 42.49" N 68° 56' 36.27" E	Stratigraphy, sedimentology, palaeontology, fuel geology
	45	Amyu	23° 39' 35.31" N 68° 59' 12.51" E	Stratigraphy, sedimentology, palaeontology
	46	Jara Hill	23° 41' 43.19" N 69° 1' 0.09" E	Stratigraphy, sedimentology, palaeontology, tectonic geomorphology, volcanic activity, structural geology
	47	Jumara Hill	23° 41' 34.39" N 69° 4' 11.52" E	Stratigraphy, sedimentology, palaeontology, structural geology, geomorphology
	48	Kaya Dongar Hill (Manjal Dome), Nara Road	23° 38' 2.53" N 69° 8' 27.80" E	Stratigraphy, sedimentology, palaeontology, volcanic activity, structural geology
7. Nakhtrana	49	Keera Hill	23° 35' 4.63" N 69° 14' 34.86" E	Stratigraphy, sedimentology, palaeontology, structural geology, geomorphology, igneous activity
	50	Dhinodhar Hill	23° 27' 16.60" N 69° 20' 31.05" E	Geomorphology, igneous activity
	51	Nirona river	23° 26' 40.32" N 69° 29' 13.86" E	Geomorphology, stratigraphy, sedimentology, structural geology
	52	Vithonia Hill near Vithon	23° 19' 31.40" N 69° 20' 35.75" E	Geomorphology, igneous activity
	53	Netra Inter-trappean beds	23° 25' 25.31" N 69° 2' 48.83" E	Igneous activity, K-T boundary, sedimentology
	54	Kaliya Dhrow Bedrock River	23° 23' 13.95" N 69° 28' 32.77" E	Sedimentology, tectonic geomorphology, stratigraphy
8. Khavada	55	Simri Wandh Nala	23° 52' 19.50" N 69° 49' 22.03" E	Structural geology, stratigraphy, palaeontology, sedimentology
	56	Bandi River	23° 51' 58.86" N	

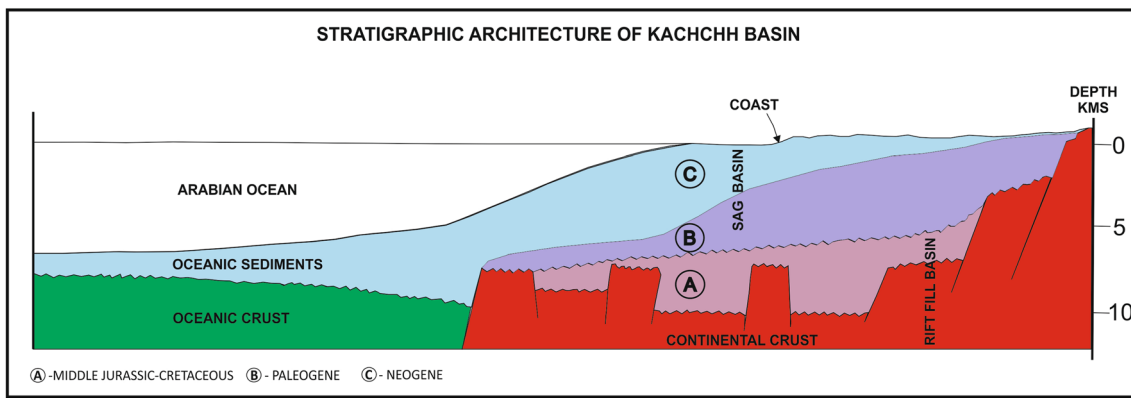
**Table 1** (continued)

Geo-station	Geosite no.	Name of the geosite	GPS location	Geological aspect can be studied
			69° 48' 19.35" E	Stratigraphy, palaeontology, geomorphology, quaternary climates and tectonics
	57	Goradongar Hill	23° 51' 9.57" N 69° 46' 12.28" E	Geomorphology, structural geology, stratigraphy, palaeontology, sedimentology
	58	Kaladongar Hill	23° 56' 13.73" N 69° 48' 51.97" E	Stratigraphy, palaeontology, geomorphology, structural geology, sedimentology
	59	Kuar Bet	23° 59' 20.09" N 69° 44' 26.66" E	Stratigraphy, palaeontology, geomorphology, structural geology, sedimentology
	60	Nir Wandh	23° 54' 7.48" N 69° 56' 27.66" E	Igneous activity
	61	Sadhara Hill	23° 45' 18.94" N 69° 54' 39.54" E	Stratigraphy, palaeontology, geomorphology, structural geology, igneous activity, sedimentology
	62	Allah Bund (prior permission is required from the BSF Headquarter)	24° 7' 34.10" N 69° 7' 2.79" E	active tectonics, palaeoclimate, sedimentology, palaeoseismology
	63	Vigakot (prior permission is required from the BSF Headquarter)	24° 13' 7.25" N 69° 11' 48.84" E	Geo-archaeology, active tectonics
9. Rapar	64	Kanthkot-Tramau River	23° 29' 29.96" N 70° 29' 42.95" E	Stratigraphy, palaeontology, sedimentology, igneous activity
	65	Kanthkot Fort temple	23° 29' 4.81" N 70° 27' 42.46" E	Stratigraphy, palaeontology, structural geology, sedimentology
	66	Bharodia	23° 33' 26.39" N 70° 24' 27.36" E	Stratigraphy, palaeontology
	67	Dholavira-Arch	23° 53' 13.90" N 70° 12' 52.88" E	Geo-archaeology
	68	Dholavira-Geol	23° 55' 23.30" N 70° 13' 35.81" E	Stratigraphy, sedimentology, geomorphology, palaeontology, sedimentology
	69	Palaswa	23° 26' 13.21" N 70° 59' 22.27" E	Palaeontology, sedimentology
	70	Mardak Bet	23° 23' 19.69" N 71° 5' 13.76" E	Gemology, geomorphology, structural geology, sea level changes, sedimentology
	71	Bhachau Road Section	23° 17' 37.56" N 70° 22' 53.68" E	Stratigraphy, sedimentology, igneous activity
	72	Gangta Hill	23° 44' 24.38" N 70° 29' 49.77" E	Stratigraphy, sedimentology, geomorphology, structural geology, palaeontology
	73	Rapar-Chitrod road section	23° 23' 50.57" N 70° 43' 1.37" E	Stratigraphy, sedimentology, geomorphology, structural geology
	74	Mouana Dome	23° 52' 38.86" N 70° 52' 43.65" E	Stratigraphy, sedimentology, geomorphology, structural geology, palaeontology, volcanic activity
	75	Cheriya Bet	23° 56' 11.40" N 70° 20' 43.30" E	Sedimentology, stratigraphy, basement conglomerate, geomorphology

package, superimposed by a transgressive marine sediment package in a marginal sag basin (Fig. 1).

The Mesozoic rift-fill sediment package is exposed in the interior highlands and records the tectono-sedimentary evolution of the KRB through a complete rift cycle comprising pre-rift, syn-rift, and post-rift sedimentation processes. The Paleogene-Neogene sediment package in the post-rift sag basin is exposed in peripheral plains and consists of an on-lapping/off-lapping transgressive-regressive system tract, disconformably overlying the

seaward tilted Mesozoic rift-fill package (Fig. 1). The marine Mesozoic and Cenozoic strata are highly fossiliferous, containing rich assemblages including macro invertebrates, vertebrates, as well as micro- and nannofossils and trace fossils. This rich palaeontological heritage, especially the ammonite faunas, has drawn the attention of the palaeontologists and stratigraphers internationally since the nineteenth century (Waagen 1873-1875; Cox 1940; Rajnath 1942; Fürsich et al. 2013, 2020; Bhosale et al. 2021), and the basin is famous for Mesozoic



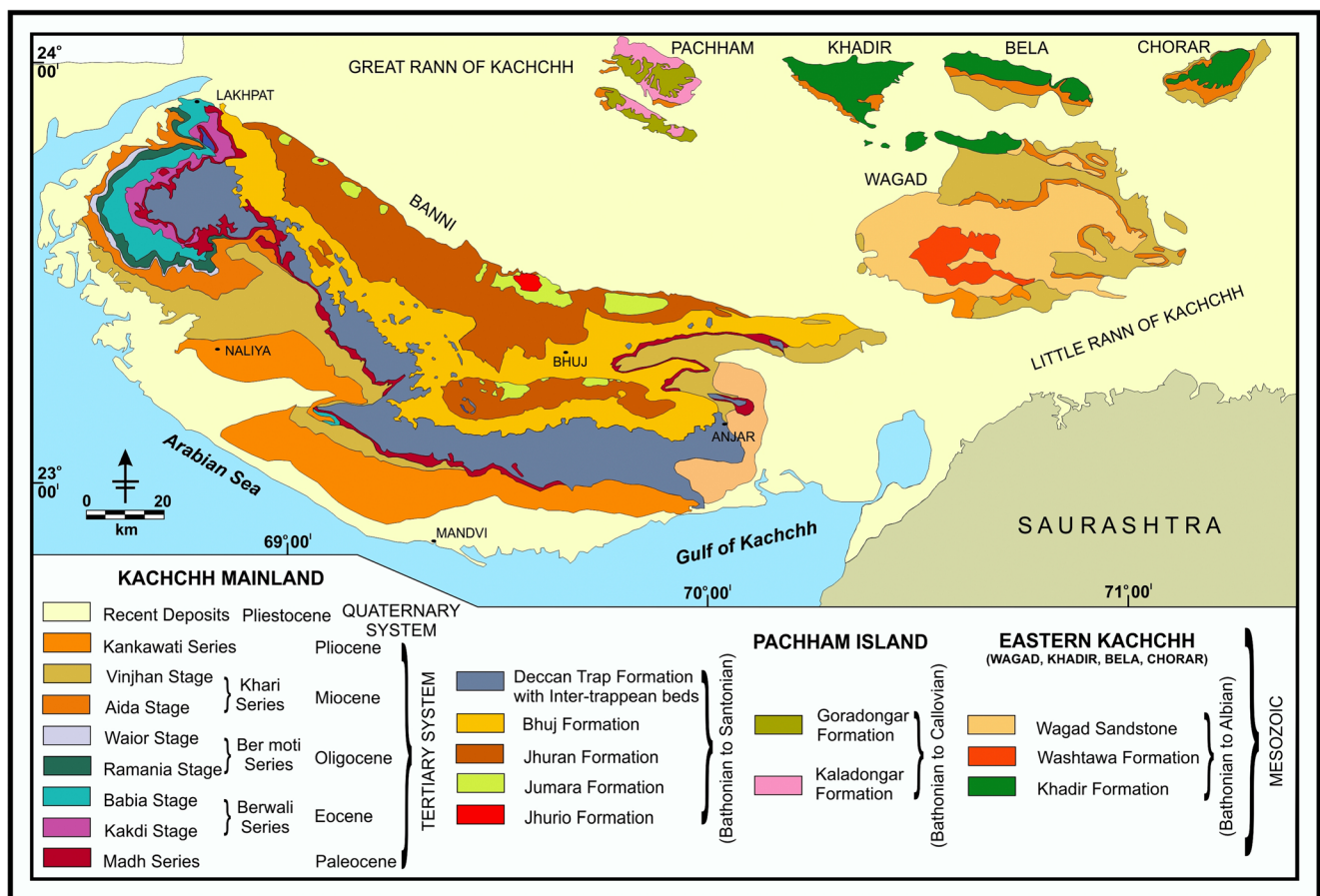
**Fig. 1** A theoretical model (not to scale) of the history of the Kachchh Basin, an ideal example of peri-cratonic rift basin with two distinct sedimentary packages: (1) older Rift-fill package deposited over faulted basement and (2) younger package deposited in post-rift sag basin with

landward on-lapping system tracts over the older package. Both are extensively exposed for learning of all parameters of geology. Key: (a) Mesozoic, marine/non-marine, Rift-fill sediments, (b) Paleogene marine transgressive sediments, (c) Neogene marine transgressive sediments

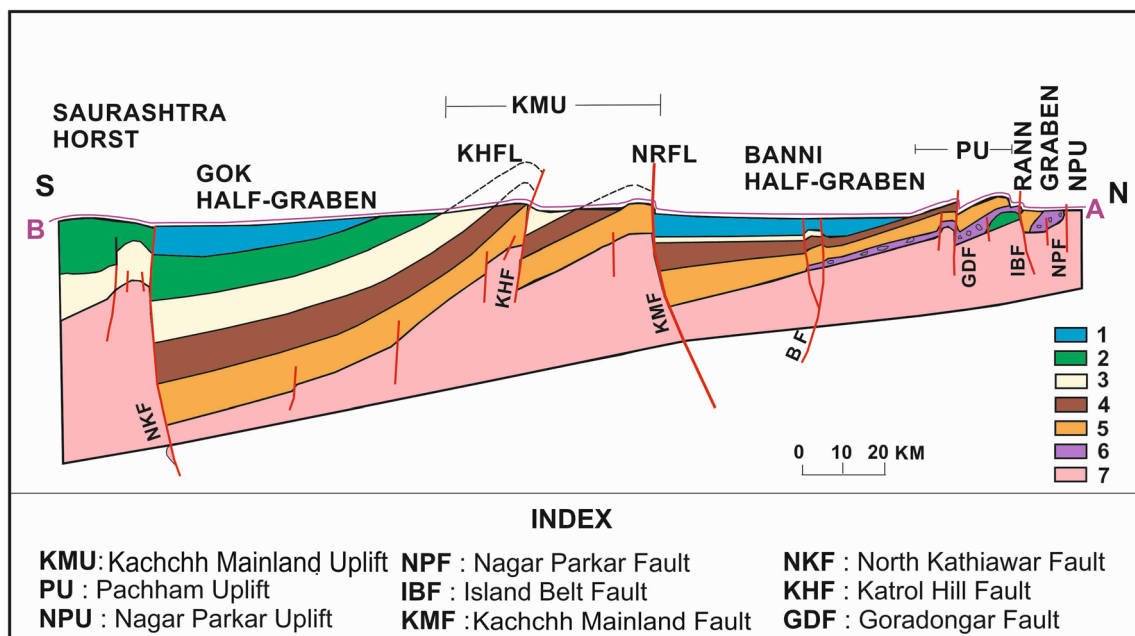
(Middle Jurassic to Lower Cretaceous), Paleogene-Neogene, and Quaternary stratigraphy (Figs. 1 and 2) (Biswas 2016a; Thakkar et al. 1999, 2001; Maurya et al. 2003a, 2003b). Late Cretaceous, Deccan Trap lava flows are exposed in the southern peripheral plain of the Mainland uplift and separate these Mesozoic and

Cenozoic sediments, forming a ‘basement’ for the latter sediments (Figs. 2, 3, and 4a).

A semi-desert environment, with scant vegetation, and bed-rock terrains with extensive rock exposures and easy logistics, including good road connectivity, facilitate easy accessibility to the majority of the sites for research and educational



**Fig. 2** Geological map of the Kachchh Basin showing three distinct lithostratigraphic divisions. (1) Mainland of Kachchh, (2) Pachham Island, and (3) Eastern Kachchh (modified from Biswas & Deshpande 1970)



**Fig. 3** N-S Geological cross-section (along the line A–B in Fig. 4a) across the Kachchh Basin showing intra-rift faulting, tilted-blocks, marginal flexures over fault blocks (NRFL, Northern Range Flexure; KHFL, Kathol Hill Flexure), and half-grabens. Key: (1) Cenozoic (including

Quaternary), (2) Deccan Trap and Intrusives, (3) Lower Cretaceous, (4) Upper Jurassic, (5) Middle Jurassic, (6) Lower Jurassic, (7) Precambrian (vertical scale exaggerated) (after Biswas 2005)

activities. Excellent outcrops in cliffs along rivers and conjugate streams developed sub-parallel to the dip, almost at regular intervals, as well as numerous road sections, provide field classrooms for studying and teaching structural geology, stratigraphy, palaeontology, and sedimentology (Figs. 5 and 6). Many such sections have become important reference sections for students, researchers, and innovative scientific scholars from all over the world. In the context of geoheritage, the KRB can be compared to a natural textbook of geology where any aspect of the science can be taught and studied, as introduced below.

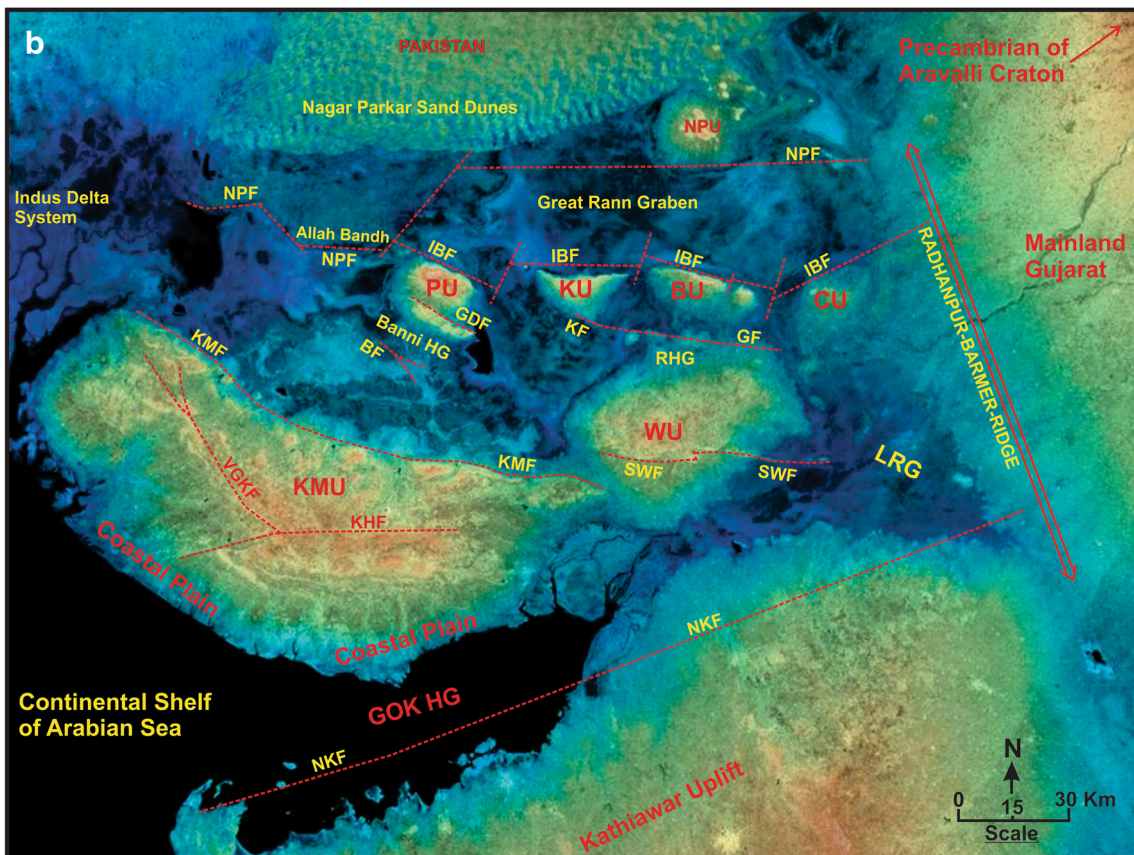
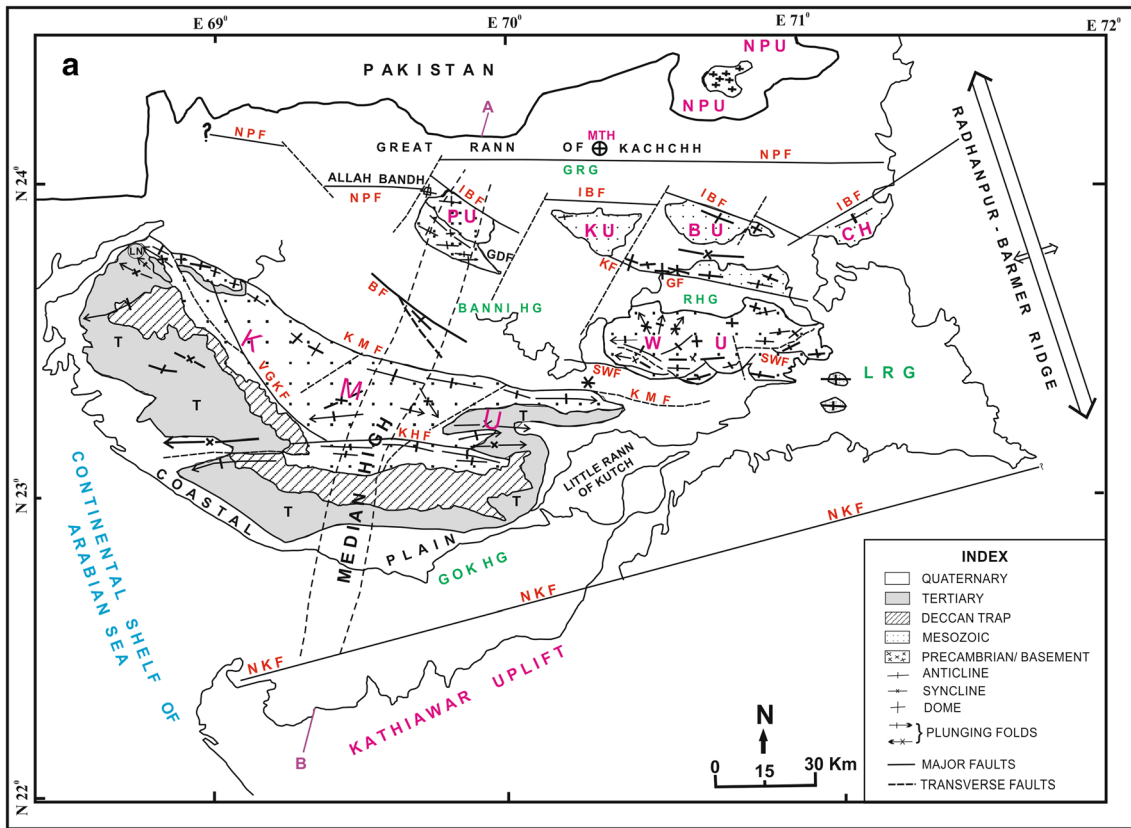
## Stratigraphy

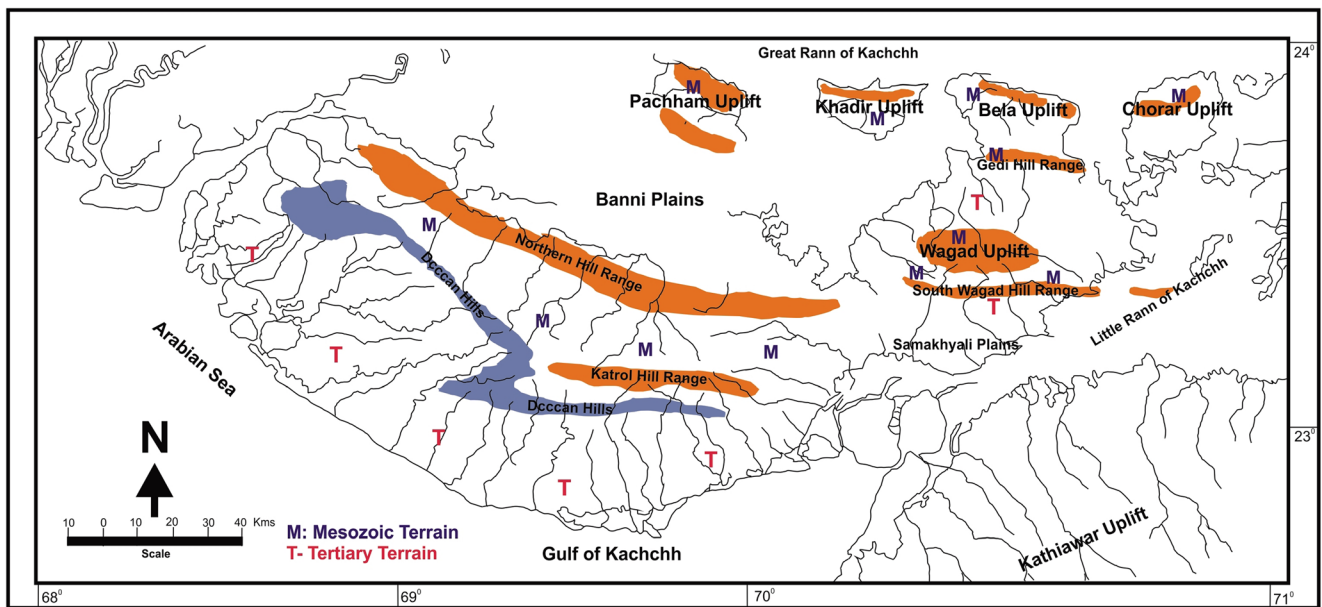
The KRB consists of three broad sedimentary assemblages which can be grouped under the (i) Mesozoic, (ii) Paleogene-Neogene, and (iii) Quaternary (Fig. 2). The Mesozoic sequences are a rift-fill deposit ~2500-m thick and dominated by siliciclastics derived from felsic rocks and shallow marine carbonate rocks mixed with arenaceous and argillaceous sediments. These deposits encompass the Middle Jurassic to Lower Cretaceous (Biswas 2016a; Chaudhuri et al. 2020) (Fig. 7 and Fig. 8). The lower part is a transgressive marine deposit which partially covers alluvial fans and flood plain deposits, which from the Middle Oxfordian grade upwards into a regressive marine and fluvio-deltaic deposits of latest Jurassic-Early Cretaceous age (Desai and Biswas 2018).

Paleogene and Neogene deposits of the KRB are extensive and have been deposited on many earlier formations during transgression (Raju 1974, 1991, 2011). Paleogene and Neogene marine sediments, which are around 900-m thick, were deposited in a post-rift marginal sag basin, as discussed above (Biswas 2016a) (Figs. 9 and 10). The earlier Cenozoic succession provides an outcrop analogue for reservoir rocks of the Western Offshore oil field, and the Miocene section of the Kachchh Basin is considered as the outcrop extension of the Mumbai offshore reservoir, providing an opportunity to examine the reservoir rocks of Mumbai High at the outcrop scale (Shekhar et al. 2019). Certain Paleogene and Neogene sections of the Kachchh Basin are also important chronostratigraphical reference sections (Shekhar et al.

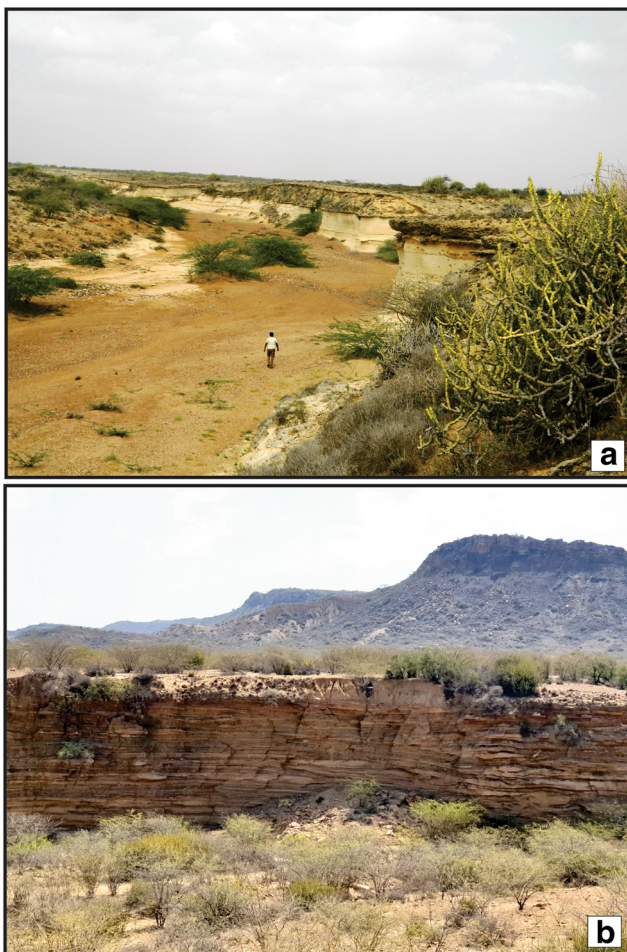
**Fig. 4 a** Tectonic map of the Kachchh Basin with all uplifts and structures (after Biswas 2016b). NPU, Nagar Parkar Uplift; PU, Pachham Uplift; KU, Khadir Uplift; BU, Bela Uplift; CU, Chorar Uplift; WU, Wagad Uplift; KMU, Kachchh Mainland Uplift; NPF, Nagar Parkar Fault; IBF, Island Belt Fault; Banni HG, Banni Half Graben; BF, Banni Fault; SWF, South Wagad Fault; KMF, Kachchh Mainland Fault; KHF, Kathol Hill Fault; NKF, North Kathiawar Fault; GRG, Great Rann Graben; GOKHG, Gulf of Kachchh Half-Graben; GDF, Goradongar Fault; GF, Gedi Fault; RHG, Rapar Half-Graben; LRG, Little Rann Graben; VGKF, Vigodi-Gugriana-Khirastra Fault; KF, Kakindia fault; LN, Lakhpat Nose. A–B: line of section (Fig. 3). **b** SRTM view of the Kachchh Basin showing geomorphical features—uplands, Rann, and coastal plains correlated with uplifted and subsided blocks as controlled by major and minor structural elements in the basin (modified after Biswas 2016b)







**Fig. 5** Drainage map of Kachchh showing sub-parallel rivers across the southern and northern Mainland on either sides of a central watershed. The radial drainage pattern is compatible with elliptical/domal uplifts

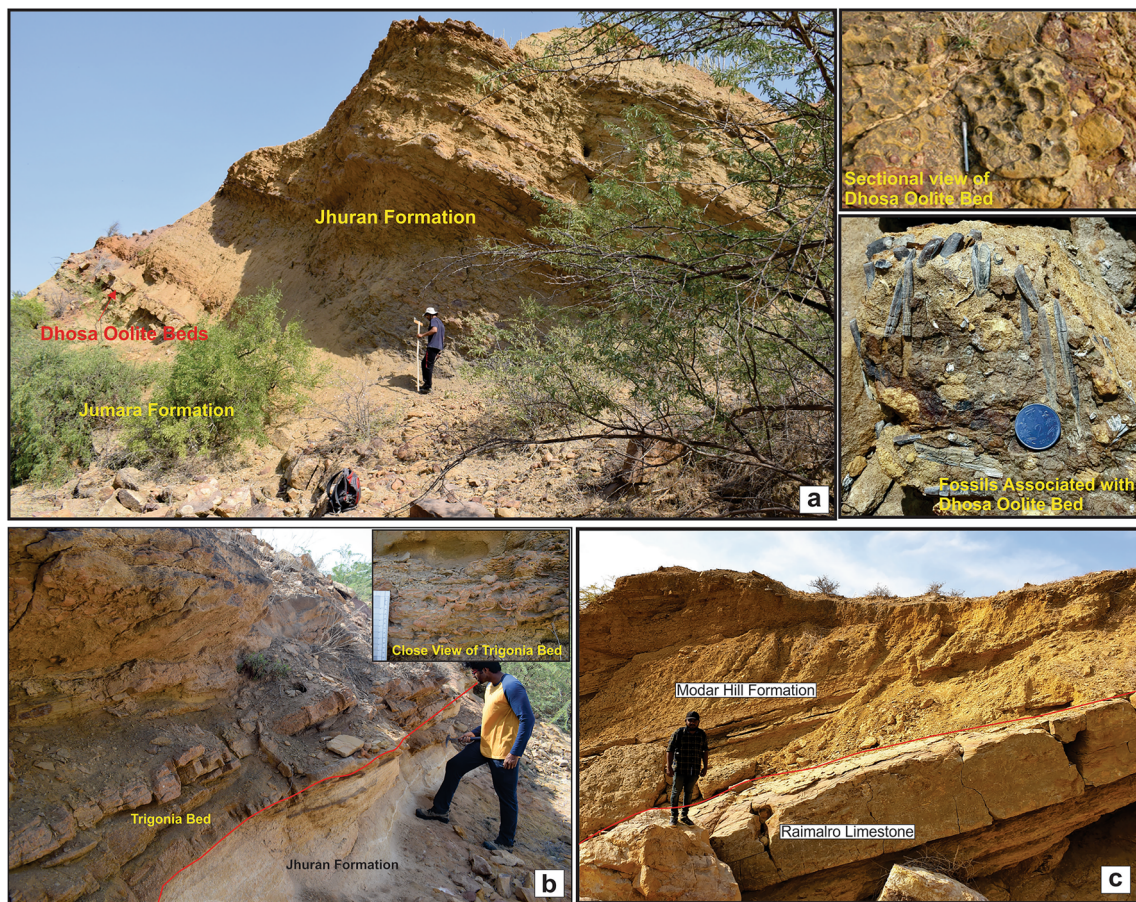


**Fig. 6** Typical landscapes of Kachchh. (a) Rakhadi River Canyon in a Cenozoic terrain exposing a Paleogene sequence. (b) Upper Jurassic sequence exposed in river and hill sections (foreground, Jara River cliff section; background, Jaramara Scarp section)

2019), the Miocene of the Waior section, in particular, having the potential to be recognized as a Global Boundary Stratotype Section and Point (GSSP), at least at a regional level in India (Raju 1974, 1991, 2011) (Fig. 21a). Marine transgression started in Late Paleocene and continued cyclically until the Mid Eocene, on-lapping over the Deccan Trap and exposed Mesozoic rocks with a strong disconformity (Biswas 2016a). Transgression over the Mesozoic deposits continued after a break in the Later Eocene until the Mid Miocene. It has been suggested that the evolution of a carbonate ramp and associated palaeoenvironments during the Eocene-Oligocene occurred simultaneously with Palaeo-Tethys carbonate ramp sedimentation (Banerjee et al. 2018). The sea finally regressed during Late Miocene-Pliocene times.

Mesozoic rift-fill sediments were deposited in three intra-rift sub-basins described previously, namely, the GRG, BHG, and GOK HG, from north to south, causing lithofacies variation which resulted in three rock-stratigraphic groups, the Mainland, Pachham, and Eastern Kachchh Groups. Each group is exposed only in the back slopes of the respective tilted blocks (Figs. 1, 2, and 3). Almost the entire sequence of the Paleogene-Neogene marginal sag basin deposits is seen in the coastal peripheral plain of the KMU (Fig. 2). The sub-parallel drainage system across the back slopes of the uplifts has exposed excellent sections in the sequence showing characteristic litho- and biofacies and key stratigraphic features, such as formation boundaries, hiatuses, unconformities, and well-defined marker beds which are crucial for regional correlation across the basin (Figs. 5, 7, 8, 9, and 10).

The Quaternary of the KRB is represented by both degradational (incised valleys, strath terraces, badland



**Fig. 7** Stratigraphical contacts in the Mesozoic sedimentary package: (a) Dhosa Oolite beds at the top of the Jumara Formation (Oxfordian) and the overlying Jhuran Formation (Kimmeridgian); Gangeshwar Dome, south of Madhapar village, Central Kachchh Mainland (close-up of Dhosa Oolite shows diverse lithoclasts and fossils depicting significant

depositional changes linked to tectonic activity, (b) Trigonia Marker Bed above the Jhuran Formation: Ghuneri Dome, Western Mainland Kachchh indicating the Jurassic-Cretaceous boundary, (c) Contact of Raimalro Limestone (Bathonian) and Modar Hill Beds (Callovian) in the Goradongar Formation at Pachham Island

topography, etc.) and aggradational sequences. Because of the current arid to semiarid climate, however, most fluvial processes in the region are relatively dormant. As a result, aggradational landforms are scant and limited to the valleys proximal to pediment zones. The aggradational landforms primarily identified by Biswas (1971) and Merh and Patel (1988) are restricted to the coastal Quaternary and the Rann of Kachchh (Biswas 1971, 1987). Thakkar et al. (1999, 2001) for the first time described Quaternary sequences within the rocky mainland and recognised three major episodes with alluvial and colluvial fan deposits of the Early Pleistocene, sandy sheets of miliolites with boulders, and pebbles from the Mid Pleistocene and fluvial sand, silt, and clay with some aeolian deposits of Late Pleistocene and Holocene age (Fig. 11). The various episodes of Late Pleistocene and Holocene sedimentation that took place along various river courses in Mainland Kachchh, the Island belts, and Wagad have been documented and are important for reconstructing the history of climate and tectonics spanning the last 100 ka (Figs. 11 and

18c, d) (Maurya et al. 2003a, 2003b, 2003c, 2008, 2013; Khonde et al. 2011, 2017a, 2017b; Chowksey et al. 2010; Das et al. 2016a, 2016b, 2017; Prizomwala et al. 2014a, b, 2016a, 2016b, 2019; Patidar et al. 2007, 2008; Kundu et al. 2010; Bhattacharya et al. 2013a, b, 2019; Ngangom et al. 2012, 2017, Ngangom and Thakkar 2016; Makwana et al. 2019; Sane et al. 2020; Durga Prasad et al. 2021).

### Sedimentology

Extensive exposures of rocks within the hills, rivers, and coastal belt provide plenty of scope for detailed palaeo-sedimentological studies in a context of an outdoor natural laboratory. Stratigraphic successions, formation boundaries, strata geometry, sedimentary structures, lithofacies, and their ‘vertico-lateral’ variation are well displayed in cliff sections along rivers and in road cuttings and enable sedimentologists to determine the depositional processes and depositional environment represented (Fig. 12). The Mesozoic and

**Fig. 8** Examples of Mesozoic stratigraphical sections: (a) Jumara Formation (Oxfordian)—shales with oolitic marlstone bands (on the top of the hill), exposed in on the northern flank of the Jhurio Dome, Northern Mainland Kachchh, (b) transgressive and regressive sequences of Late Jurassic, Jhurio Formation exposed in the deeply incised valley of Khari River in the Katrol Hill Range, (c) deltaic deposits of Early Cretaceous age (Bhuj Formation) exposed in a road section near Bhuj town, (d) contact of Late Cretaceous Deccan Trap on the top and underlying Early Cretaceous Bhuj formation exposed at Chakar-Kotada River (e) railway crossing near Viri village, South of Anjar town, exposing Inter-Trappean Beds of fossiliferous and cherty limestone with dinosaur bones and eggs—top of bed marks the K/T boundary

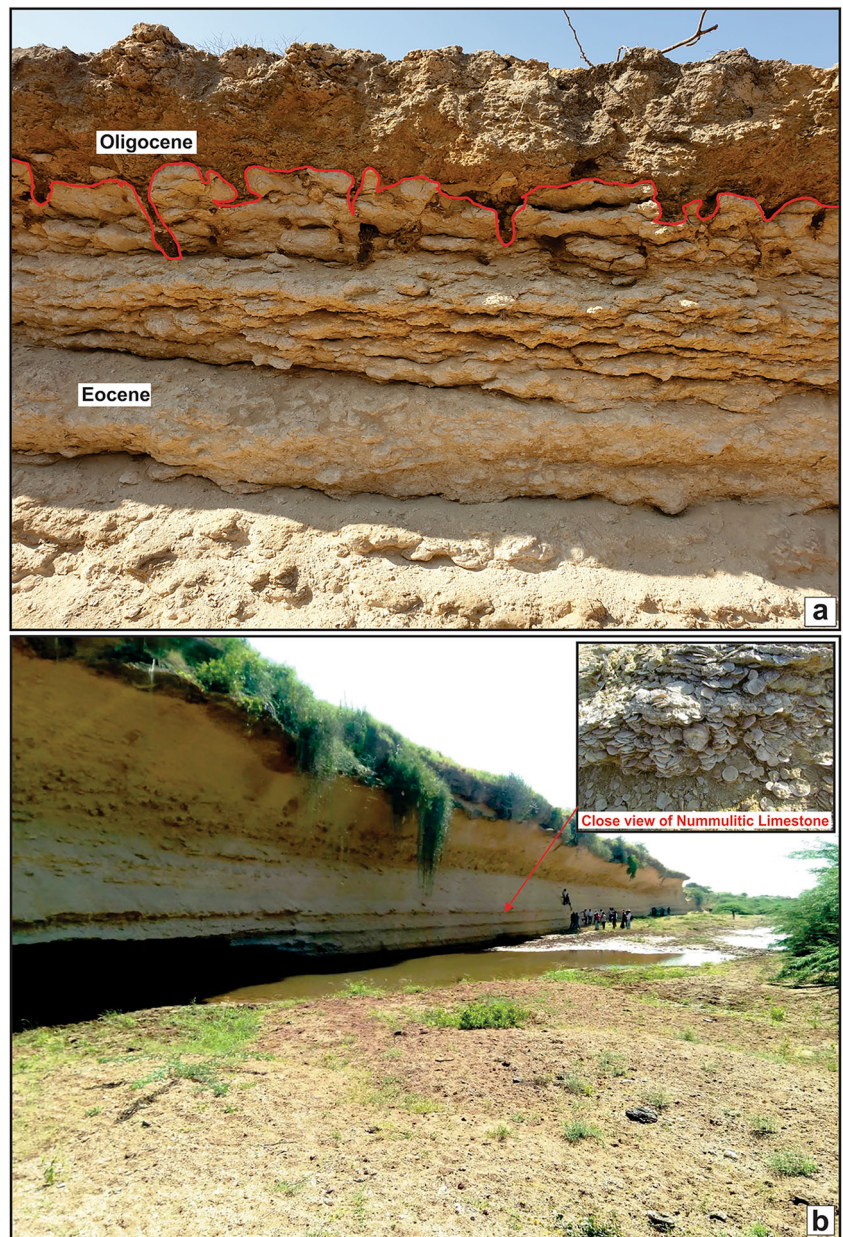


Paleogene-Neogene sediments were deposited in various sedimentary environments such as marine, fluvial, deltaic, aeolian, and lacustrine settings resulting in well-preserved sedimentary structures diagnostic of the depositional environment, such as cross-bedding, ripple marks, lamination, stratification, fining and coarsening upward sequences, soft sedimentary deformation, palaeo-channels, clastic dykes, erosional surfaces, etc., all of which can be studied in detail (Fig. 12). Continuous exposures of formation successions and marker beds in lateral continuity are an added advantage for sedimentological studies in the KRB.

## Palaeontology

The KRB is recognized as one of the most important Jurassic fossil localities in the world, especially for fossil ammonoids (Fig. 13, 19 a,b), thanks to the famous monographs of Wynne (1872), Waagen (1873-1875), and Spath (1924, 1927-1933) and intensive modern studies, including by J. Krishna and D.K. Pandey as reviewed by Fürsich et al. (2013, 2020). In particular, Middle and Upper Jurassic assemblages provide a global reference for the Indo-Malgach (ammonoid) bioprovince (Page 2008). In addition, the palaeoecology and biofacies of the sequence have been intensively studied by

**Fig. 9** Paleogene stratigraphical sections: **(a)** cliff section on the Rakhadi River showing the unconformable contact between Middle Eocene (Lutetian-Bartonian) and Oligocene (Rupelian), **(b)** cave developed in massive foraminiferal (nummulitic) Middle Eocene limestone (grainstone). These limestones form excellent oil and gas reservoirs in the Western Offshore fields



F.T. Fürsich and collaborators (see also Fürsich et al. 2013, 2020). Fossil-rich Mesozoic and Cenozoic formations of the Kachchh Basin were deposited in a large range of environments, e.g. aeolian, fluvial, lacustrine, and marine, which supported a wide diversity of animals and plants, including vertebrates (e.g. ichthyosaurs and dinosaurs in the Jurassic and shark, giraffe, elephant, whale, rhinoceros, snakes, birds, crocodiles, and fish in the Cenozoic), macro invertebrates (e.g. molluscs, corals, sponges, crustacea, etc.), ichnofossils, plant fossils (e.g. a Cretaceous flora), and micro-fossils (e.g. spores/pollen, foraminifera, ostracoda, etc.) (Fig. 13). The large variety of well-preserved trace fossils (Figs. 7, 8, and 13) recorded and classified from both Mesozoic and Cenozoic strata of the KRB have been of especially importance for the interpretation

of palaeoenvironments and the depositional history of the basin. In addition, rich assemblages of plant fossils from the Lower Cretaceous Bhuj Formation correlate these deposits with Upper Gondwana (Fig. 13).

Notable vertebrate occurrences include a complete skeleton of an *ichthyosaur* from the Late Jurassic which has significant implications for Gondwanan palaeobiogeography (Prasad et al. 2017) and a Mid Miocene (~14 Ma) assemblage from Palasava village indicating a warm, humid/wet, and tropical to sub-tropical environment and the presence of a forest in the vicinity of a riverine-estuarine system (Kapur et al. 2019). The latter highlights the significance of the Neogene palaeontology of the region in palaeoenvironmental, palaeoecological, and biostratigraphic terms and is linked to

**Fig. 10** Paleogene and Neogene Formations: (a) Lower Eocene lignite deposits exposed in excavations at the Gujarat Mineral Development Corporation Mine near Panandhro, Western Kachchh, (b) river section exposing Eocene *Nummulitic* deposits, Oligocene marine inner shelf (open marine limestone and black shale lagoonal) deposits and Miocene as marine foreshore deposits near Matanomadh village (inset view shows kerogene-rich shale due to a lateral change from Oligocene limestone facies to H<sub>2</sub>S-rich black shale and possible petroleum source rock)



global eustatic sea level changes. The Neogene fauna of the KRB is correlated with those of a regression cycle in the Tagus Valley succession of Portugal and with the vertebrate assemblage of Middle Siwalik of the Himalayas (Kapur et al. 2019). The Paleogene-Neogene limestone belt from Lakhpat to Naliya is particularly significant for its rich content of foraminifera, including *Nummulites* which are popularly known as *Nand nu Nanu* and *Lakhpat ki paisa* meaning ‘the god’s currency’, as well as ostracoda (Fig. 9). *Nummulites*, in particular, have been studied extensively for their biostratigraphic value as well as their evolutionary development and depositional environments (Saraswati 1994, 1995; Reuter et al. 2013; Sengupta et al. 2015). These limestones are also packed with many other fossils such as bivalves, gastropods, crab, and fish remains. Vertebrate, invertebrate, and many other fossils including the Jurassic ichthyosaur mentioned above are housed in the Geological Museum of KSKV Kachchh University in Bhuj (Fig. 13). However, the semi-desert condition and sparse vegetation and extensive outcrops make it easy to observe many fossils in the field, meaning that educational and research studies can benefit from this ‘natural museum’ which attracts geoscientists from all over India and abroad.

### Heritage of Structure and Tectonics

The KRB is situated in a critical area of the global tectonic framework and is tectonically very active even in

modern times, as evident from repeated earthquakes (Biswas 2014). The structural style of the basin is defined by tilted horst blocks along E-W master faults with intervening grabens and half-grabens (Figs. 3 and 4a, b). Like any other major rift basin, the KRB underwent a first-order tensional cycle when the rift structures were formed, followed by an inversion cycle when the rifting was aborted. Tensional stress prevailed during the rift phase, while compressive stress dominated during the initial stage of inversion causing up-thrust along the master faults resulting in block tilting and consequent marginal flexuring of a ductile sediment carapace. During northward drifting of the Indian Plate, horizontal stress was induced, and the fault kinematics changed to strike-slip movement, trans-tensional during the drift stage, changing to transpressional after plate collision (Biswas 2005, 2016b). Transpressional stress prevails during the present cycle as well (Kothyari et al. 2016c). First-order geomorphological features and repeated earthquakes are the evidence for these processes. Several episodes of tectonic movements with changing stress pattern deformed the marginal flexures into complicated folds and generated a network of faults. The complex structure associated with igneous intrusions bears testimony to several episodes of tectonic movement and igneous activity. A unique structural style was thus formed, and almost all types of fold and faults



**Fig. 11** Examples of Quaternary processes, including: (a) Hinterland Quaternary deposits near Gangeshwar Mahadev temple, Madhapar, within the main axes of Katrol Hill (the hills in the background are the E-W trending Katrol range exposing Jurassic strata); the hinterland valley is filled by Late Pleistocene sandy biomicrites (with *Miliolites*), overlain by the colluvial, fluvial and aeolian formations exposed in the incised sections, (b) the flat Rann surface—a vast Quaternary basin with paleo-mudflats overlain by the fluvial deposits forming ‘bets’ (i.e. islets) (Bhediya bet in the Rann of Kachchh)

are exposed in hill and river/road sections, often in three dimensions making them ideal for study. For students of structural geology, such models are highly illustrative (Fig. 14).

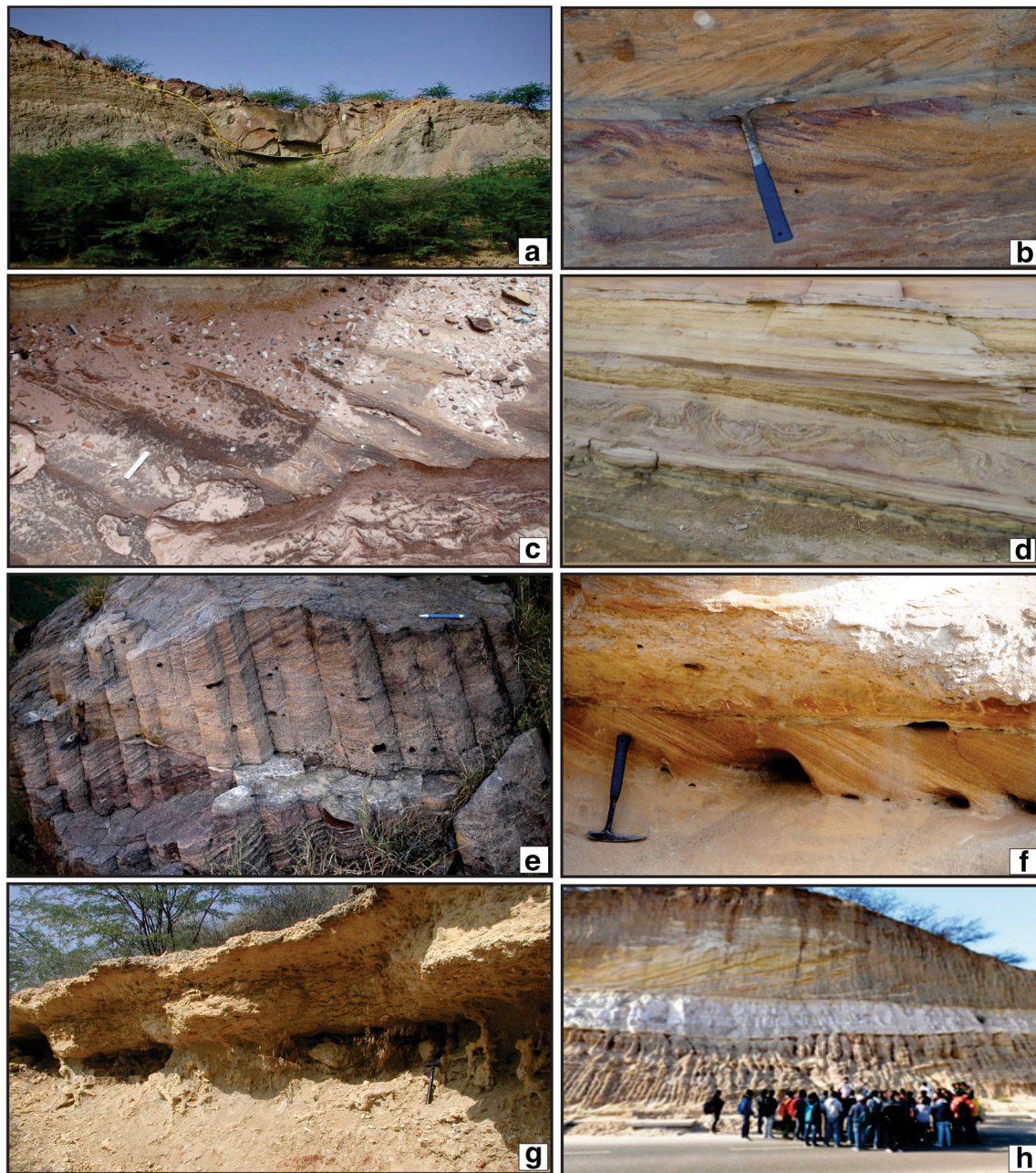
### Igneous Activity

The Kachchh Basin experienced two phases of igneous activity: (1) Late syn-rift plutonism and (2) post-rift volcanism when the Indian Plate passed over the Reunion hot spot during the Early Cretaceous. The syn-rift activity is represented by intrusive bodies such as large plugs, laccoliths, sills, and dykes of basic and ultra-basic rocks with mantle xenoliths (Fig. 15) (Ray et al. 2016; Sen et al. 2016; Karmalkar et al. 2000). All these intrusive bodies are associated with folds and related faults. The post-rift volcanism is the part of Deccan Trap volcanic activity at the northern fringe of the Deccan volcanic

province. The Kachchh Basin is the only place in Western India where the volcanoes are exposed as eruptive centres (Fig. 15b) indicating that the hot-spot-related Deccan Trap flows are of central eruption and not ‘fissure’ eruption style as previously believed (Biswas and Deshpande 1973). Volcanoes are of a low profile shield-volcano type which become covered by their own flows and are exposed only where the covering flows above the craters are eroded as seen in many places in the Kachchh Basin. Trap flows are commonly alkaline olivine and tholeiitic basalt, while some of the intrusive bodies associated with the northern island belt are typical alkaline complex types with diorite and syenite with lamprophyres (Sen et al. 2016). Rift-related intrusions are common in all major rift basins in the world including the Indian Gondwana basins. The ultramafic rocks were sourced from an asthenospheric melt as a result of mantle arching and fracturing which forms a rift pillow in the sub-crust below the crustal rift basin (Ziegler 1992; Biswas 2005). The exposures of intrusive bodies trap flows, and volcanoes of Cretaceous age in the KRB that are rare heritage sites should be conserved for future study and education (Fig. 15).

### Geomorphological Significance

The landscape of the KRB is characterized by isolated rocky uplands surrounded by vast low-lying plains comprising palaeo-mudflats, salt playas, coastal mudflats with salinas, and grassy lowlands (Fig. 4b). The morpho-tectonics of uplands demonstrates first-order topography indicating prevalent active tectonism. The Kachchh region is, therefore, an excellent example of a tectonically controlled landscape whose physiographic features are the manifestation of the Earth’s movements along the tectonic lineaments (Biswas 1971, 1974) (Fig. 17). Taking into consideration the factors of altitude, slope, and ruggedness of relief, the KRB can be divided into four main physiographic units from north to south, viz., the Rann, the low-lying Banni Plain, the Highlands with hilly terrains, and the Southern Coastal Plains (Figs. 2 and 4a, b). There are six highlands with marginal hill ranges followed by gentle slopes: the Kachchh Mainland Uplift in the south, the Wagad Uplift in the east, and the Pachham Uplift, Khadir Uplift, Bela Uplift, and the Chorar Uplift in the north forming an E-W chain of small highlands (Fig. 4a, b). These four small highlands amidst the surrounding plains of Banni and Rann look like islands and were indeed islands during the Late Neogene-Quaternary periods when the low land areas were inundated by the sea. Even today, during the monsoon, all these highlands become temporarily surrounded by water, recreating an island like topography. Hence, these four highlands are referred to as ‘Islands’ and form an E-W chain collectively known as the ‘Island Belt’ (Biswas 1971) (Fig. 4b), which are part of a previously continuous E-W south sloping fault-



**Fig. 12** Examples of sedimentary structures in the Kachchh Basin: (a) Paleo-channel in the Jhuran Formation (Upper Jurassic) exposed in the Khari River section, (b) 2D view of Herringbone cross-stratification in sandstones of the Bhuj Formation (Lower Cretaceous) exposed in Tapkeshwari caves, near Bhuj, (c) wave ripple marks in Late Jurassic sandstones, exposed in Khari River section near Rudramata Bridge, (d) soft sediment deformation structures in the Late Jurassic Rudramata Shales, exposed by Khari River, (e) columnar joints developed in Early Cretaceous sandstone of the Bhuj Formation accompanied by basic igneous dykes in which such joints are also common, near Kodki Village, (f)

torrential cross-bedding commonly seen in the Lower Cretaceous Bhuj sandstone in the Khari cliff section near Bhuj, (g) highly bioturbated Miocene limestones with dissolution cavities, Kankawati River section (dissolution cavities between burrows have created the secondary porosity which has made such limestones the main oil reservoirs in the offshore Bombay High oil field), (h) road cutting section on the Bhachau-Samakhyali highway exposing mega-cross bedding, stratification, channel deposit and sand-bar deposits in the Lower Cretaceous sandstone and shale beds of the Bhuj Formation

bounded ridge which was broken into four segments by wrench faulting (Fig. 4b).

The landscape of the KRB is characterized by these rugged highlands with hill ranges having steep escarpment face along the footwall on the faulted northern side and a gentle back

slopes towards the south along the hanging wall. In north tilted Wagad highland, the topography is reversed, however. Fault controlled hill ranges are bound by major E-W trending longitudinal faults (Fig. 4a, b) which played a pivotal role in sculpturing the landscape. These faulted hill ranges are mainly



characterized by narrow deformation zones following the escarpment face with various types of folds such as domes, half domes, brachy-anticlines, and plunging anticlines. The escarpment faces are sheared monoclinical flexures over the faulted edges forming cuestas along the foot of the scarps. Mesozoic and Cenozoic climatic, sea level changes, tectonic processes, and chemical weathering resulted in the development of a wide range of geomorphological features (e.g. present and palaeo-mudflats, beaches, stabilized and coastal dunes, wave-cut cliffs, caves, knick points, fault scarps, incised and deformed Holocene sediments, strath terraces, and gorges) of which ‘textbook’ examples can be studied in the field (Figs. 16 and 17).

### Significance of Neotectonics and Palaeoseismic Studies

The Quaternary tectonic activity within the KRB is also manifested by the presence of geomorphological markers and palaeoseismic features associated with tectonic elements (Chauhan et al. 2016b). Most geomorphological features depict the younger tectonic events of the Basin and provide the opportunity to study morphotectonic features along fault zones (Figs. 17, and 18). The youthfulness of the topography in terms of climate and tectonics is characterized by these young features, such as fault scarps, receding scarps, deep bedrock gorges, caves, canyons, triangular facets, mountain fronts, deep valley incisions, warpings, gullied surface, meanders, offsets, deflected and anastomosing drainages, and knick points, whilst depositional features such as salt flats, alluvial and colluvial fans, debris deposits, valley fill miliolites, and coastal dune deposits are equally important as young features (Figs. 16, 17, and 18). Quaternary tectonic activity along various faults of the KRB is also confirmed by using Neotectonic, tectono-geomorphic and paleoseismic, GIS, and remote sensing techniques (Thakkar et al. 1999, 2001, 2012a, b, 2020a, Thakkar 2018a, b; Rajendran and Rajendran 2001; Maurya et al. 2003a, b, c, 2008, 2013, 2016; Patidar et al. 2007, 2008; Malik et al. 2008, 2017; Prizomwala et al. 2014a, b, 2016a, 2016b, 2019; Goyal et al. 2015; Kothiyari et al. 2015, 2016a, b, c, 2018, 2019, 2020a, 2020b, 2020c; Das et al. 2016a, b, 2017, 2019, 2020; Padmalal et al. 2019; Bhattacharya et al. 2019; Dumka et al. 2019; Shaikh et al. 2019, 2020; Kandregula et al. 2020; Lakhote et al. 2020a, b; Mishra et al. 2020; Rajendran et al. 2020). Quaternary climate and sea level processes also resulted in fluvial, aeolian, and marine erosional and depositional features in the Kachchh landscape, and Quaternary sediments are found along the coast, and the Rann exposes some spectacular evidence of sea level changes. (Figs. 16, 17, and 18).

The seismically active region of the KRB with Quaternary deposits potentially has well-preserved evidence of past earthquakes. In recorded history, the region has undergone many

devastating earthquakes, for instance, the 325 BC Makran earthquake and tsunami, 1030 AD Brahminabad earthquake, 1668 AD Debal earthquake, 1819 AD Allah Bund earthquake, and 1845 AD and 1956 AD Anjar earthquakes (Brune 1996; Nelson 1846; Jacob 1860; Williams 1958; Lisitzin 1974; Chung and Gao 1995; Johnston 1996; Iyengar et al. 1999; Bilham 1999; Rajendran and Rajendran 2001; Rajendran et al. 2001, 2002, 2008). After the 2001 Bhuj (Gujarat) earthquake, geologists focused more on the recurrence period of major earthquakes in the Kachchh Intra-plate Basin by exploring palaeoseismological features using the 2001 earthquake-induced deformation features as analogues of past intra-plate earthquakes. In particular, they found evidence of the 1819 Allah Bund source as various ground deformation and soft sedimentary deformation features (Rajendran et al. 2001, 2002, 2008, 2020; Tuttle et al. 2001; McCalpin and Thakkar 2003; Thakkar and Goyal 2004; Thakkar et al. 2012b). Consequently, the KRB is also very important for palaeoseismologists to help understand the characteristics of large intra-plate earthquakes, and measures may be taken to preserve some of the large earthquake-induced liquefaction sites where craters and sand blows are reported and preserved, for instance, in the flat Banni and Rann surfaces (Maurya et al. 2006; Thakkar et al. 2012a, Thakkar 2018a, b).

### Sea Level Climate and Geo-archaeology

The period of last two decades of research in the KRB is notable for revelations about Quaternary processes, characteristics, and their significance in a global context owing to its immensely thick Quaternary sediments in Rann and Banni, as well as sediments in the coastal region and hinterland fluvial sediments along the Bedrock Rivers (Figs. 2 and 11). The Great and Little Rann salt flats exposed in the area of around 23000 sq. km have sediments with the potential sediments to understand an uninterrupted history of Holocene sea level and climate change (Figs. 2 and 11) (Merh 2005). These areas are a vast natural factory for rock production, as a slowly subsiding graben receives sediments from the sea and northern Himalayan Rivers as well as being an excellent example of a recent inland, intra-continental sedimentary basin (Fig. 11b). The tide-dominated coastline of the Gulf of Kachchh has also preserved excellent depositional and erosional landforms, for example, typical relict tidal-flat deposits sandwiched between fluvial sediments indicate frequent changes in land-sea interactions. In places, relict intertidal flats are preserved in the spit-sheltered locations. Such locations have low tidal amplitudes and restricted wave activity and have deposited fine, cohesive deposits in a low energy environment but now occur at various elevations compared to the present-day tidal amplitude (Sharma et al. 2020).

There are around 19 major archaeological sites distributed along the coast and in the Great Rann of Kachchh (GRK), and it has been suggested that Holocene sea level exerted an important influence in sustaining ancient coastal communities (Lawler 2011). In particular, the decrease in mid-Holocene sea level enabled some populations to exploit the exposed coastal lowland environments for sustenance, migration, and trade (Stanley and Warne 1997; Fleming et al. 1998), and there is, therefore, a possible link between the sea level changes and the contemporary human history along the proximity of the coast and inland of the KRB (Rawat 2015). The largest archaeological site is located near Dholavira village at the western tip of the triangular Khadir Island. Dholavira is one of the most famous Harappan cities located in the KRB and was amongst many important centres of maritime and inland trade for the Indus Valley civilization (Fig. 19c to f). Owing to the palaeoshoreline, along the margin of the Great Rann of Kachchh, it had been a favoured location for Harappan settlements along with the southern Gulf of Kachchh region (Gaur and Vora 1999, 2007).

Ngangom et al. (2017) has established that the arid landscape of the eastern Great Rann of Kachchh has responded to the changing intensity of the Indian Summer Monsoon (ISM) during the last 5 ka and which supports an earlier suggestion that the decline of the Harappan civilization was unrelated to the existence of a major fluvial system (Tyagi et al. 2012). Instead, a gradual decline in the ISM after 5 ka and before 2 ka could be the major driver for the abandonment of the Harappan civilization in Eastern Great Rann of Kachchh. In addition, Sarkar et al. (2020) in their recent studies at Vigakot and Karim Shahi, which are further west than Dholavira and on the northern border of the Rann and southern fringe of the Thar desert, state that the Early Iron Age to Early Historic and Historic to Mediaeval settlements at Karim Shahi and Vigakot provide new insights into a continued demographic decline and redistribution subsequent to the post-urban Harappan period. One of the least discussed aspects of such studies is archaeoseismology, and Bisht (2011) documented three major seismic episodes during the third-millennium BC identifying three collapse levels in the ruined Dholavira fort. Despite various studies of archaeological sites in the Kachchh region, a full understanding of the cause and factors of Harappan migration are yet to be established (Sarkar et al. 2016; Khonde et al. 2017b; Rajesh et al. 2020). Ancient anchor stones and old coins found buried in Rann sediments around Pachham Island and adjacent Kuar Bet suggest that in archaeological times when the Great Rann of Kachchh was inundated by the sea forming a gulf, overseas traders used to visit India, docking their ships at these places. It is clear, therefore, that climatic changes affecting the ISM are likely to have had a major affect in the decline of the civilization. By virtue of its

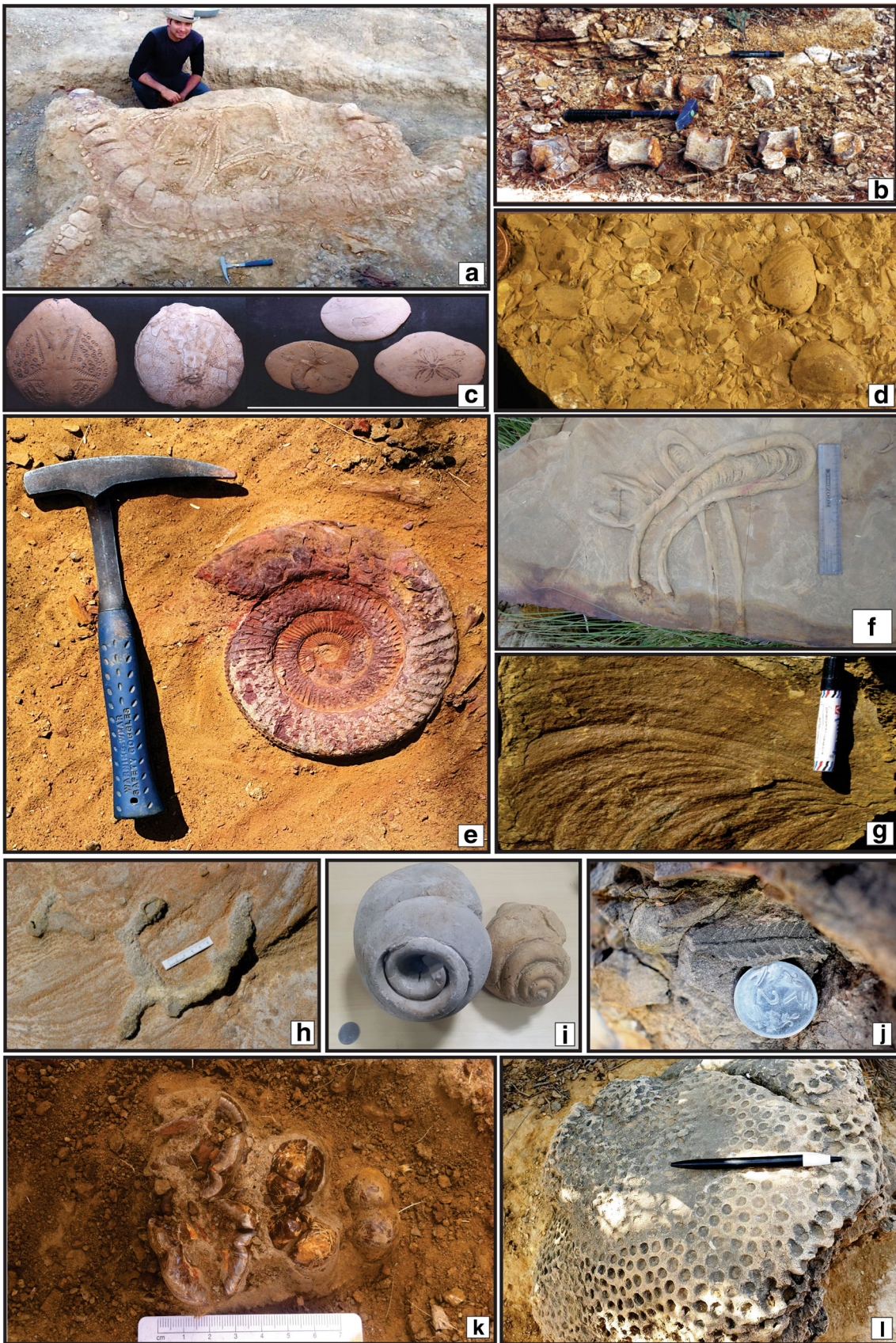
**Fig. 13** Diverse assemblages of Mesozoic and Cenozoic fossils from the Kachchh Basin, a famous region for palaeontological studies: (a) Middle Jurassic (Callovian) marine vertebrate (ichthyosaur) found in Kas Hill Range, near Lodai Dam, Kachchh Mainland (now in the Geological Museum of KSKV Kachchh University, Bhuj), (b) Dinosaur Bones from the Middle Jurassic, Kuar Bet, Kachchh, (c) Echinoids in Fulra/Nummulitic Limestone of Eocene age, (d) Bivalves from the Oxfordian, Jumara Formation (Upper Jurassic), (e) Ammonite from the Middle-Upper Jurassic Kanthkot Member, Wagad, (f) *Rhizocorallium* burrows (ichofossil), flagstone member of the Middle Jurassic, Goradongar Formation, Pachham Island, (g) *Zoophycos* burrow seen in the Jumara Formation, Jumara Dome, western Mainland Kachchh, (h) *Ophiomorpha* burrows in the Jhuran Formation (Upper Jurassic), Jhuran River section, Jawahar Nagar, (i) Gastropods from Eocene limestone, near Matanomadh, (j) *Ptilophyllum* plant fossil seen in the Lower Cretaceous, near Mota-Jakh Temple, (k) upper molar of an elephant-like mammal (Gomphother) in the Miocene sediments at Palasava, eastern Kachchh (now preserved with around 1000 other Miocene vertebrate fossils, including snake, shark, elephant, giraffe, rhino and crocodile) in the Geological Museum of KSKV Kachchh University, Bhuj), (l) a fragment of coral from a bioherm which in the Coral Limestone Member of the Maniyara Fort Formation (Lower Oligocene), exposed in Waior River bed, western Kachchh

typical landscape, excellent preservation potential for archaeological sites, and rich cultural heritage, the Kachchh peninsula has the potential to qualify as being one of the important archaeological heritage regions in India (Fig. 19c to f).

### Kachchh Landscape and Planetary Science

Analogue studies of the Moon and Mars applicable to the Earth provide many new insights into the role of different geological processes pertaining to their formation and evolution. These studies also help to develop approaches and techniques for future planetary missions. The KRB is one such unique geological setting where one can begin to understand several Lunar and Martian climatic and tectonic processes through their analogues, and hence scientists from India and across the world are attracted to the Kachchh landscape and geology for studying planetary science (and the Indian Space Research Organization—ISRO—has funded a number of research projects to help understand the Martian landscape through analogue studies in the KRB and other parts of India).

Bhattacharya et al. (2016) have reported an analogue terrestrial locality hosting jarosite in the Matanomadh area of western Kachchh (Fig. 20a). The detailed analysis suggests that the presence of hydrous sulphate and its phyllosilicate phases at Matanomadh area is similar to the geological environment of many of the identified jarosite localities on Mars (Fig. 20a, b). This terrestrial analogue study is potentially important for the understanding of the effects of hydrous alteration in early Martian landscapes and how Mars subsequently dried over the time. Notably,





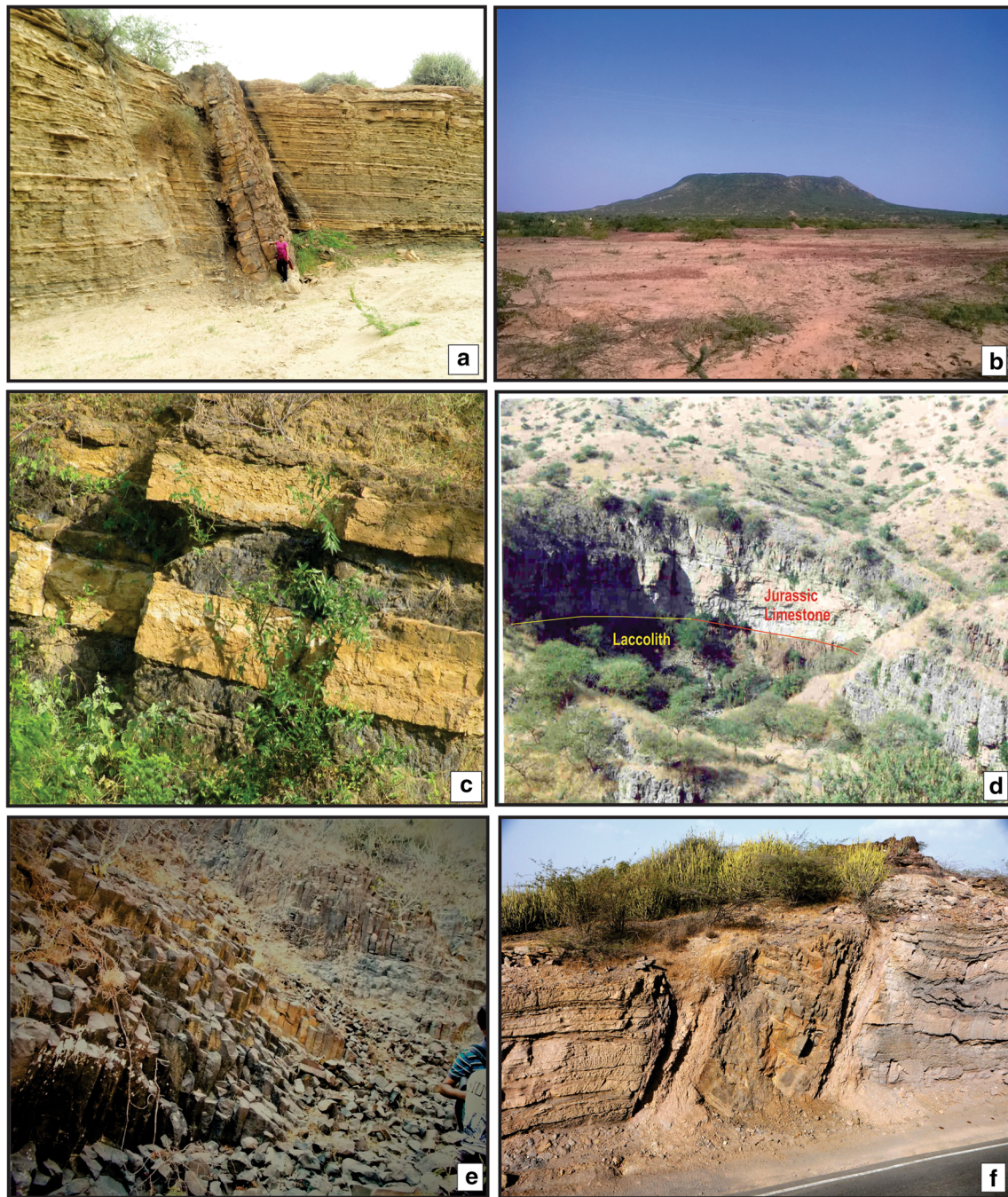
**Fig. 14** Examples of second and higher-order structures commonly seen in the Kachchh Rift Basin: (a) normal Fault displacing sandstone and shale beds of the Lower Cretaceous Bhuj Formation in the Bhuj-Kodki Road section, (b) folded and faulted flagstone beds of Middle Jurassic, Goradongar Formation at Simri Nala near Simri Wandh, Pachham Island, (c) exposed fault plane and fault scarp in Upper Jurassic sandstone (Jhuran Formation) at Gangeswar Dome, South of Madhpar Village, (d) Katrol Hill fault exposed in the Fakirwadi-Walakhawas section, Shivparas Dome, 6 km south of Bhuj (shows razor-sharp hairline trace of Katrol Hill Fault between folded Oxfordian (Upper Jurassic) Jumara Formation on the left, and homoclinal Albian (Lower Cretaceous) Bhuj Formations to the right), (e) Thrust Fault in Middle-Upper Jurassic sequences on the eastern flank of Habo Dome, (f) small scale strike-slip

faults in Middle Jurassic sequences (Goradongar Formation) at Paiya Dome, Paiya Village, Pachham Island, (g) exposed normal fault plane and associated structural features in Lower Cretaceous sequences (Bhuj Formation) at Ratiya Nala near Ratiya Village, (h) faulting and related folding of Middle-Upper Jurassic strata (Jumara Formation) in the Katrol Hill Fault zone, Jadura Nala, South of Bhuj, (i) Flexured Miocene strata near Waior village, (j) steeply dipping northern limb of the large scale Kaladongar anticline near the Island Belt Fault (which covered by Holocene, Rann sediments to the North), (k) horst-like structure between two normal faults in the Katrol Hill Range at Tapkeshwari Hills, (l) high angle reverse fault displacing Eocene strata in the Kachchh Mainland Fault Zone on the northern flank of Ghuneri dome

one of the planned field excursions of the postponed 36th International Geological Congress in India was entitled: “A walk on Mars: Jarosite localities of Kachchh, India” and reflects the international (even interplanetary) scientific importance of the area.

In 2015, the Indian, Physical Research Laboratory (PRL) in Ahmedabad organized the 15th PLANEX Workshop on ‘Mars and Moon: Remote Sensing and Analogue Studies’ which included a 2-day field trip in

the KRB, which included the Matanomadh jarosite locality and various volcanic craters and plugs such as Dhinodhar and Vithonia, which are also important for Martian and Lunar analogue studies (Fig. 20c). The latter sites are important as it is hypothesized that Lunar and Martian volcanism was dominated by fissure type eruptions, similar to those producing terrestrial flood basalts. Lava-water interaction on Mars is presumed to have led to the development of structures such as columnar joints (HiRISE



**Fig. 15** Examples of exposed volcanic and plutonic intrusive bodies in the Kachchh Basin: (a) basalt dyke cutting through Jurassic sequences (Jhuran Formation) in the Jara River, near Jara Village, (b) Volcanic Plug, Varar Village, (c) Doleritic sill intruded into Upper Jurassic sequences, Kaswali River section near Nadapa Village, (d) Gabbro laccolith in the

core region of Habo Dome, exposed in Dhrang Nala, South of Dhrang Village, (e) columnar joints in basalt flows of the Deccan Trap, core area of Dhinodhar Hill shield volcano, (f) Dolerite dyke intruded along a fault in the Lower Cretaceous, Bhuj Formation (contact metamorphism can also be seen in the section), Bhuj-Kodki Road

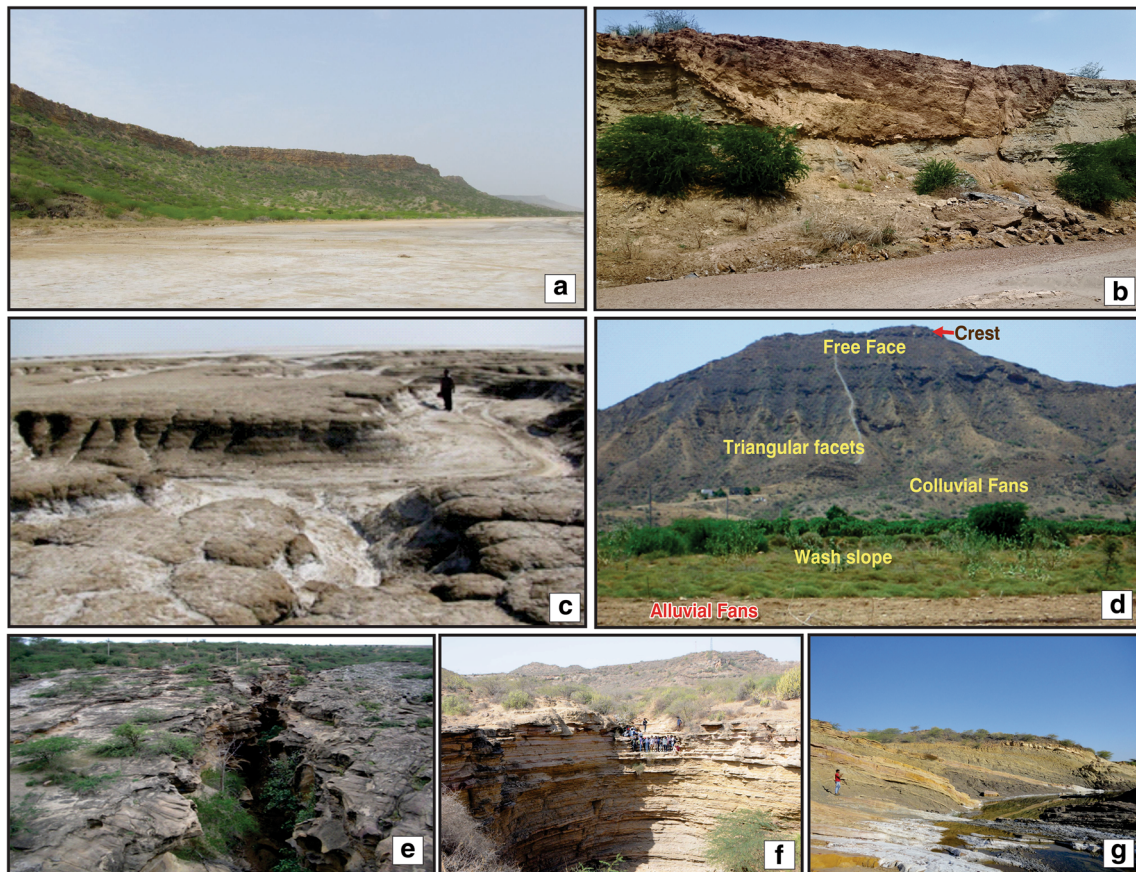
observations) similar to the columnar joints found in the Dhinodhar plug basalt—which would also indicate the presence of near surface water on early Mars (i.e. the morphometric similarity of the joint patterns between Martian and terrestrial basalts at Dhinodhar suggests the possibility that contraction cooling of lava prevailed on early Mars) (Fig. 20c, d, e).

The Luna crater in the Banni plains near the Hajipir pilgrimage site is in arial view similar to several impact craters and landscapes on Mars and the Moon and adds more value to the Kachchh Basin as a potential landscape analogue for Mars and Moon (Fig. 20f—and in recent years, this site has been on a list of Martian analogues studied by the planetary scientists from NASA). Karanth



**Fig. 16** Examples of geomorphological features of the Kachchh Rift Basin: (a) coastal stabilized and moving sand dunes at Pinjor pir, Narayan Sarovar, (b) erosional caves resulting from physical (wind) and chemical weathering processes in calcareous sandstone beds of the Bhuj Formation, Tapkeshwari temple, (c) panoramic view of the western tip of Kachchh Mainland facing the Kori Creek near Lakhpat, showing the geomorphological expression of the contact between Paleogene-Neogene (foreground) and Quaternary (background) palaeo-mudflat surface, (d) stabilized coastal dunes adjoining the estuary and creeks facing the open Arabian Sea near Nani Chher village, western Kachchh, (e) an

ideal beach profile: open sea-active beach-beach bar-beach/ sand ridges parallel to the beach at Layja beach, (f) an example of a palaeo-coastal erosional profile showing wave-cut cliff and palaeo-abrasion ramps in Khadir (Jurassic) sandstone, near Fossil Park, Khadir Island, (g) An active Barkhan-type coastal sand dunes system at Modhwa beach near Mandvi, showing the intense activities of SW monsoon winds, (h) mushroom-shaped sandstone remnants north of Khadir scarps within the Great Rann of Kachchh, showing wave erosion of coastal cliffs which are now abandoned as isolated mushroom-rocks projected above the Rann surface (near Cheriya bet, Khadir Island)



**Fig. 17** Examples of morphotectonic features of the Kachchh Basin and evidences of neotectonic activity: (a) Khadir Island escarpment face (steep IBF scarp facing vast salt-covered palaeo-mudflat of the Great Rann of Kachchh to the north), (b) Strath-terrace showing hanging Quaternary palaeo-channel exposed in the present-day Khari River valley (an indication of neotectonic activity in the Mainland), near Palara Village, (c) Gully erosion on a raised Holocene surface, Allah Bund, western Great Rann of Kachchh, (d) Fault scarp (around 150 m high) along the KHF, exposing typical neotectonic features associated with a

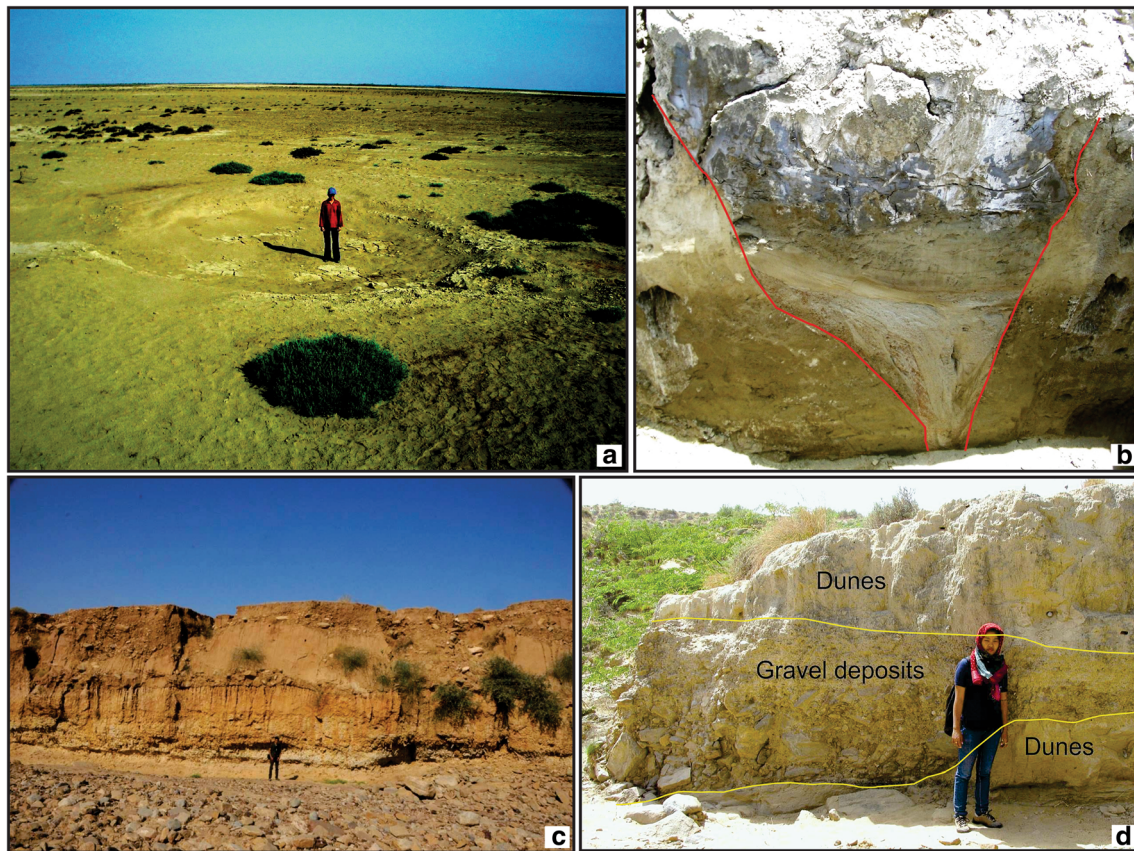
resurgent young fault (Katrol Hill Fault), Ashapura/Khatrod-Dongar, Katrol Hill Range, near Kukma Village, (e) Gorge cutting down through the Holocene peneplained surface of Cretaceous, Bhuj Formation along Khari River, near Bhuj, (f) Knickpoint (around 35 m high) along the Katrol Hill Fault near Tapkeshwari, south of Bhuj, (g) Canyon cut into Upper Jurassic, Jhuran Formation, controlled by neotectonic activities along the Kachchh Mainland Fault and associated transverse faults, near Nirona Dam

et al. (2006) reported glassy objects comparable to tektites and fragments of dark, heavy, and magnetic lumps from the site confirming that it is indeed an impact crater. In addition, the gullies that are the most common fluvial features that have formed over the last few Gyr of Martian history (Carr 2012) have a potential analogue in the uneven and ‘bouncy’ topography with minor gullies developed in Jurassic shales near Jara village in the western Kachchh region and in Paleogene shales near Kanmer village in the Eastern Kachchh region (Fig. 20g, h). The salt flats of the Great Rann of Kachchh also have potential analogues on Mars, with the processes of salt crystal formation and microorganisms in the hypersaline waters providing evidence to support the potential presence of primitive life on the Martian surface a few billion years ago (Fig. 20i). It is established that the salts exist on Mars (Clark and van Hart 1981; Trumbo et al. 2019), and it

has been suggested by Clark (1979) that residual brine pockets might still be present in cavities within salt bodies on Mars, at least partially isolated from the atmosphere. In addition, below its icy crust, Europa hosts a salty, liquid-water ocean in connection with a rocky seafloor, making it an exciting place to understand potential habitability elsewhere in the solar system (Anderson et al. 1998; Kivelson et al. 2000; Zimmer et al. 2000; Trumbo et al. 2019). Hence, the salt flats and playas of the Ranns of Kachchh also contribute to the regions as a research hotspot for Planetary Science.

### The Geopark and Geotourism Potential of the Kachchh Basin—a Discussion

The UN Sustainable Development Goals (SDGs) aim to eradicate global poverty, end unsustainable consumption patterns,



**Fig. 18** Examples of stratigraphical and morphological evidence of Quaternary climates and tectonics in the Kachchh Basin: (a) a large liquefaction crater formed during the 2001 Bhuj earthquake, 8 km north of Umedpur village in the Rann of Kachchh, (b) a trench wall view showing a funnel-shaped liquefaction pipe with its opening choked by blocky clay (Thakkar et al. 2012a, b, Thakkar 2018a, b) (c) cliff section in

the Bandi River in Pachham Island, an incision in the gentle back slopes of Kaladungar cuesta hill—note the massive debris flow deposits (Quaternary) resting on the Paleogene-Neogene sandstones, (d) debris flow deposits with gravels and pebbles overlain and underlain by the dune sands at the Kuran River section

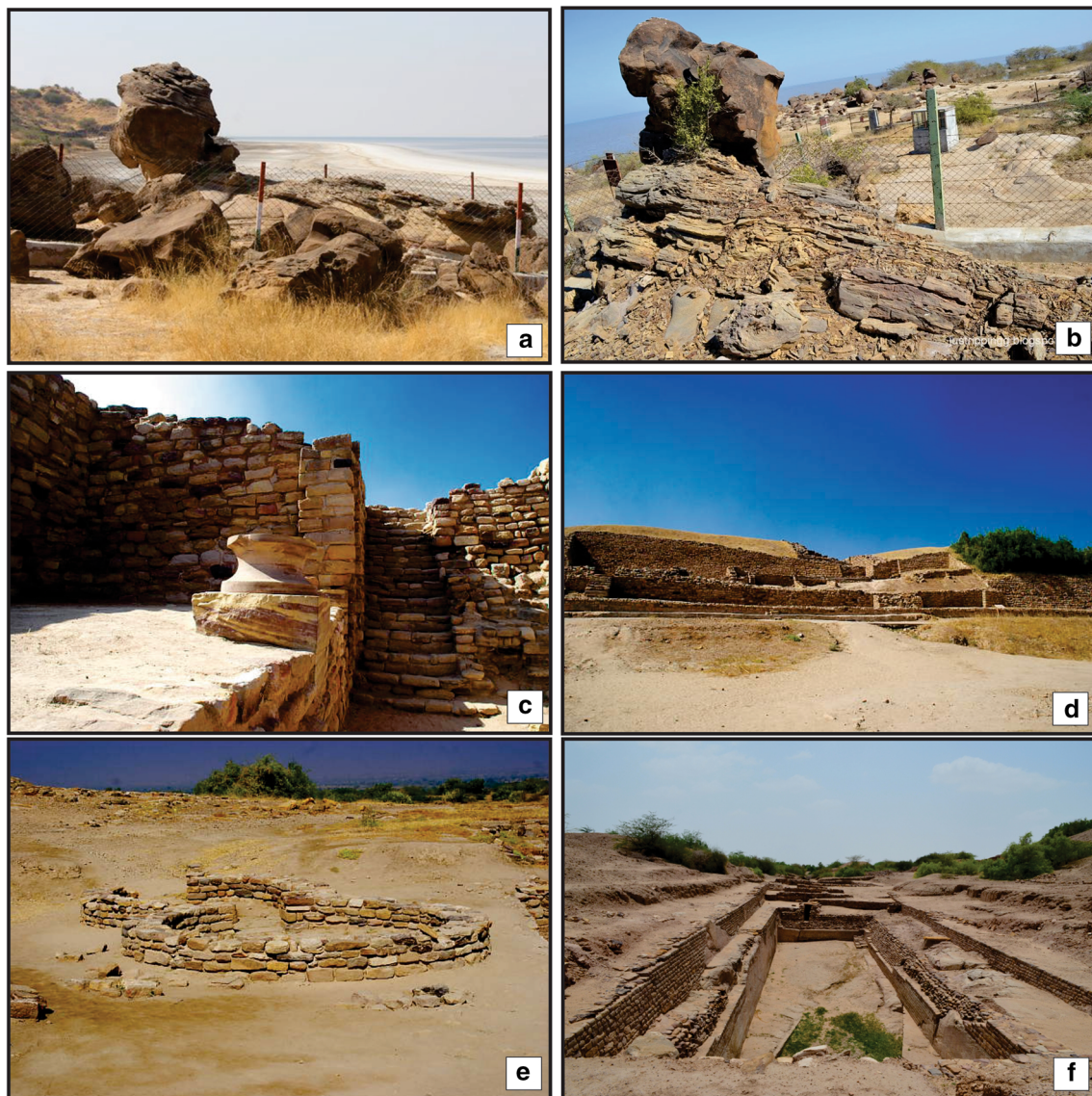
and facilitate sustained and inclusive growth, social development, and environmental protection (Gill 2017; United Nations 2015). Geology can play a fundamental role in achieving the SDGs by identifying many areas where there is fundamental link between Earth science understanding with community benefit. Of the total of 17 agreed SDGs, 11 key aspects are geological. These indispensable elements include agrogeology, climate change, energy, engineering geology, geohazards, geoheritage and geotourism, hydrogeology and contaminant geology, mineral and rock resources, geoeducation, and geological capacity building (Gill 2017). As a result, the landscapes of the KRB have an immense potential to achieve many UN Sustainable Development Goals, and the establishment of a geopark and promoting geotourism in the areas will help achieve such goals.

The surface regolith on which agriculture is sustained develops on the bedrock over a geological time scale. Soil development in any area depends on geology and climates, and as the landscapes of the KRB have diverse lithological and

geomorphological units, these produce different soils which delineate climate, tectonics, and ecological zones. Cretaceous fluvial and deltaic sequences produce good soils and aquifers and hence have good agriculture productivity. Areas of basalt produce black cotton soil suitable for extensive horticulture development. Most marine formations of Jurassic and Paleogene-Neogene, however, provide sandy soils, the latter often with high salinities resulting in a poor development of crops. The soils of the Banni plains have a good moisture retaining capacity but are poor in water yield and a high amount of inherent salinity due to their origin from the palaeo-mudflats—nevertheless, they are one of the most distinct areas for traditional wheat farming (Singh and Kar 2001).

Owing to the bedrock terrain, the usable groundwater is restricted to Cretaceous sandstones and some Pliocene formations, while the thin alluvial cover is confined to structurally subsided blocks, and further structural and lithological control on groundwater is discernible. Groundwater is the prime source of irrigation, and domestic water as rainfall is scanty





**Fig. 19** The Harappan civilization archaeological site at Dholavira and the geology of the surrounding area of the Kachchh Basin: **(a)** ‘Fossil Park’ with a variety of invertebrate fossils and large sections of fossil wood (Middle Jurassic, Khadir Formation), at the western tip of Khadir Island—the large sandstone blocks are the eroded remnants of the northern limbs of anticlinal structures against the IBF which is buried under the sediments of the Rann, **(b)** large wood fossils (Middle Jurassic period) at

Dholavira Fossil Park, **(c)** interior of the 3-storied Harappan Fort (a large city of the Indus valley civilization) with staircase and entrance, **(d)** view of the outer wall of the Dholavira site, **(e)** an extraordinary circular residential structure dating from a later phase of the civilization—similar earthquake resistant structures are still found in Kachchh and are termed as ‘Bhunga’, **(f)** ancient water reservoir dug near the Dholavira Fort for water supply—an example of ancient ‘rainwater harvesting’

and erratic. Though the government has provided long distance irrigation canals and pipeline systems from the Sardar Sarovar Dam on Narmada River, local check dams and earthen dams often prove to be the best solutions. Water supply, however, is often problematic, and viable solutions are yet to be developed. The latter include regulating the extraction of groundwater for irrigation through a combination of community awareness and government action, but the depth of wells is increasing, and higher capacity pumps are installed. In addition, extraction by industry should be better accounted for

and controlled. Massive artificial recharge and rainwater harvesting campaigns are needed, crucially involving local communities (Saha and Gor 2020).

Due to its geographical position along the trajectory of Indian Summer Monsoon winds, the KRB receives fairly constant winds throughout the year especially in coastal and hilly tracts. This wind energy is now being successfully harnessed, and the Kachchh region has become a wind power hub of India. In addition, excepting a few days of monsoon a year, it receives intense sunlight all year round the year, and the area

is also becoming a solar hub for the country. Significant numbers of private sector companies are investing in otherwise unused land in the Great and Little Rann of Kachchh for solar power plants, some of which may become the largest on the globe. The Kachchh Basin region therefore is developing as a

major area for non-conventional energy resources, such as wind, solar, and even tidal wave production in the future.

The Kachchh Basin region can also serve as an important zone for critical geohazard studies. It is a seismically sensitive region and falls under the category zone V of the seismic



**Fig. 20** Examples of various identified and possible location for analogue studies in planetary science: (a) the Matanomadh locality from where Bhattacharya et al. (2016) reported jarosite, (b) field photographs of study showing of basalt spheroids and a saprolite horizon with abundant clay boulders containing jarosite, (c) satellite image of Dhinodhar Plug (a volcanic plug)—one of the eruptive centres of Deccan Trap, (d) columnar

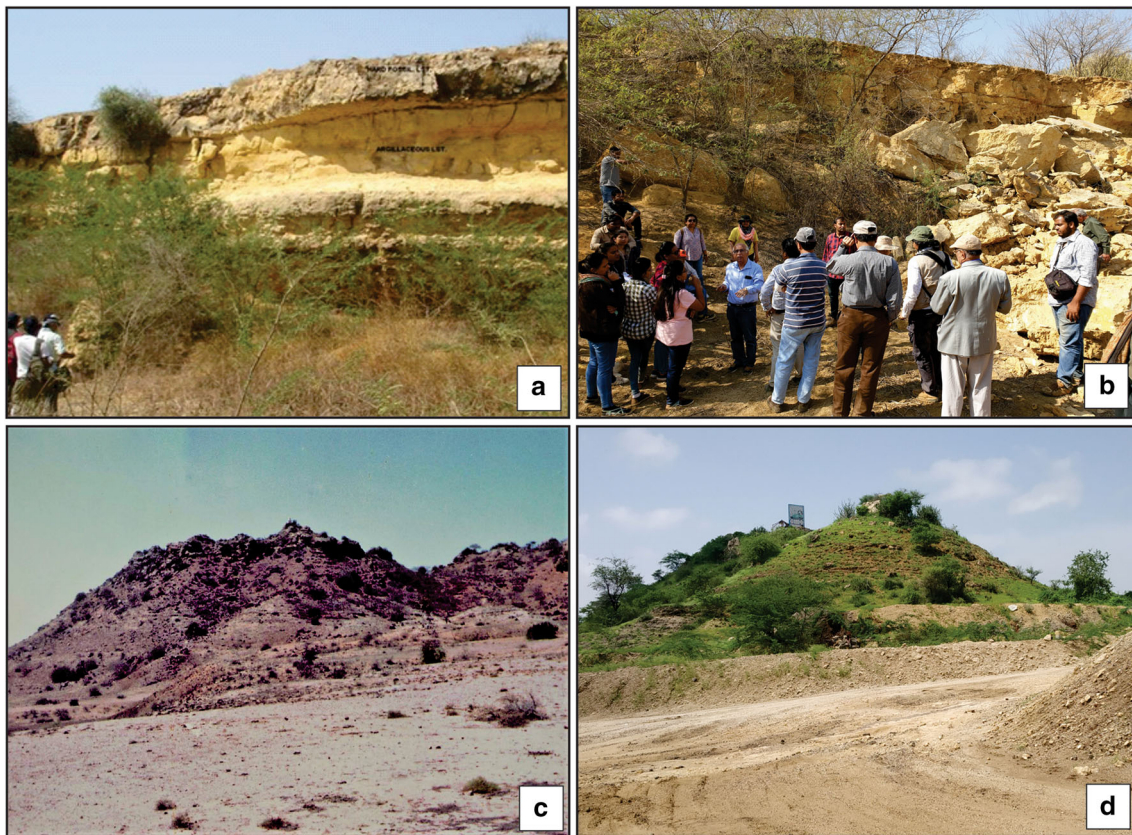
joints exposed in the core area of Dhinodhar Plug, (e) Surface view of columnar joints, (f) Satellite image of Luna impact crater, (g) photograph showing bumpy topography with small gullies in Mesozoic shale formations near Jara Village, (h) bumpy topography with small gullies in Cenozoic shale near Kanmer village, (i) salt flats (including salt crystals) of the Great Rann of Kachchh

zonation map of India. The 2001 Republic Day earthquake is one of the largest calamities the Kachchh region has ever faced, but many historical earthquakes and tsunamis have jolted the land in the last millennium. Other geological and climatic hazards occurring frequently in the Kachchh region include cyclones, droughts, storms, and floods. A major revenue generator of the state of Gujarat comes from the mineral resources of the Kachchh district as both Mesozoic and Cenozoic sediments provide economically important minerals such as bentonite, bauxite, gypsum, china clay, and laterite, whilst basalt and the Eocene fossiliferous limestone and lignite are good sources of cement, building materials, and fuels. In recent years, the discovery of offshore oil and gas reserves in the KRB by the Oil and Natural Gas Corporation (ONGC) would also significantly enhance the economy of the region.

Carneiro et al. (2004) stated that geological awareness virtually does not exist in students who have only completed basic education (elementary and middle school levels), and hence the society is generally not sensitive towards the Earth and its values. Crucially, practical classes and especially field excursions are fundamental to teaching sciences such as geography, geology, and oceanography (D'Aquino and Bonetti 2015), and hence geoparks can contribute the necessary elements for the necessary outside activities for education (Gill 2017). Unfortunately, in India, geology is not an independent subject at the school level, and hence the majority of the population have an inadequate knowledge of the Earth sciences (Shekhar et al. 2019). Hence, it is essential to make local communities aware about the significance of geology of their area, and the concept of geoparks, and how indeed the subject is relevant to their lives (Gonggrijp 1999; Page 1999; Fassoulas 2003; Weber 2003; Andrasanu 2005). As discussed, the KRB in Western India has an enormous potential for such education, as it exposes many geological features which are not only fundamental to the geological sciences but could also create the basis for the development of geoparks, with the development of geotourism based on its rich geoheritage. In particular, the KRB Palaeo-rift Basin serves as an excellent field laboratory for geoscience education owing to its continuous marine sedimentation from the Middle Jurassic, with interspersed non-marine and igneous phases demonstrating 'textbook' features, such as sedimentary structures, transgressive and regressive sequences, rich assemblages of invertebrate, vertebrate, and plant fossils, tectonic features and igneous rocks, encompassing tholeiitic, alkaline, and alkaline olivine suites, plus residual weathering minerals and rocks related to hydrocarbon prospects. The basin is also a nucleus of research for Geo-Archaeology, Planetary Science for Martian and Lunar analogue studies, geohydrology, geohazards, engineering, and mining geology, and some of the Mesozoic and Cenozoic sections include globally important stratigraphic reference sections.

The Department of Earth and Environmental Science of the KSKV Kachchh University, Bhuj (India) is actively promoting all the criteria of the UN SDGs and has been practicing geological capacity building since its establishment in 2008. The department has an important geological museum for Western India with over 4000 geological specimens (rocks, minerals, and fossils) from the KRB, as well as from the Precambrian of Rajasthan, the orogenic belt of Himalaya, the volcanic province of Maharashtra, and the Singhbhum Precambrian of Eastern India. It is well known for its field-based teaching to graduate and doctoral students from all over India. The faculties of the department organize frequent seminars, workshops, conferences, and field training for geological, environmental, and ecological capacity building throughout the year. Every year, the department also assists students, researchers, and eminent scientists from various colleges, universities, and research institutes (including from NASA, ISRO, INSA, etc.) and professional organizations (ONGC, Carin, Fugro, Cell, BG., etc.) including through field courses and lectures as well as museum visits. It also provides Earth science teachings to the young people of the region through delivering voluntary lectures and activities, including through the Government of India sponsored INSPIRE programme. Master students of the department are also involved to get involved in such activities and hence benefiting from interactions with eminent scientists, experts, and industrialists in their respective fields. The faculties and research students of the department frequently undertake educational campaigns in schools, local communities, and for district administrators and the media to promote the potential of the region for geotourism and the formal establishment of a geopark.

The authors MGT and GC have also made representation to the District Magistrate for Kachchh to ensure that the rules for sustainable mining made them aware of the potential of a geopark to develop geotourism and related activities as an alternative way of gaining economic benefit from the geology of the region. SKB and MGT have also officially requested that the Chief Minister and the state tourism department establish the KRB as a national geopark and to promote geotourism in the Kachchh region. Initial successes include the establishment by the District Magistrate and the state tourism department of a Fossil Park and a fossil interpretation centre in Khadir Island near Dholavira. MGT is also responsible for designing a large size tableau of ichthyosaurs, stegosaurs, ammonites, and other Jurassic fossils, as well as collecting a representative selection of such fossils, for the new interpretation centre. SKB is a retired director of the Keshava Deva Malaviya Institute of Petroleum Exploration (KDMIPE) (the research and development wing of ONGC) and has worked on the Kachchh Basin for over six decades—and is still actively working on Geology of Kachchh at the age



**Fig. 21** Examples of the threat posed by mining and quarrying to geoheritage sites: **(a)** section north of Waior village in its original condition as a 12m high cliff section and internationally famous type section of the Waiorian Stage of Indian regional chronostratigraphy (Chattian, Upper Oligocene—the section shows yellow, bedded and bioturbated limestone interbedded with thin calcareous shale, rich in foraminifera such as *Miogypsina* and *Spiroclypeus* as well as macro- and

ichnofossils), **(b)** present view of the same Waior cliff after destruction by quarrying for cement production, **(c)** Babia Hill, near Panandhro, western Kachchh, an excellent outcrop of Eocene-Oligocene limestone topped by a palaeo-coral reef, in the upper part of the type section of the Middle Eocene Fulra Limestone—as originally seen, **(d)** present-day view of the same Babia Hill, with only top visible, due to burial by spoil produced by lignite mining

of 85. With the team of fifteen geologists, SKB took 15 years to map the entire Kachchh Basin, finally producing a definitive geological and tectonic map of the Kachchh and Saurashtra regions of Western India (published by KDMIP-ONGC). As a token of his goodwill for future geologists, he has donated his lifetime collections on the geology of the Kachchh Basin, which includes publications, geological literature, books, maps, diagrams, research papers, reprints, literature notes, notes on short courses, and even a geological hammer. These collections are displayed in the ‘BISWAS CORNER’ of the geological museum of K.S.K.V. Kachchh University and represent a unique geological archive, providing a tangible link between the long history of fundamental geological studies in the region to ongoing research today—and hence an invaluable source for developing the context for a geopark.

With its rich geoheritage of international importance, as documented above, and its unique landscape, the KRB has the potential to be a model geopark in India with high prospects

for promoting geotourism and community-related sustainable development projects, for instance, promoting the famous Kachchh embroidery works and other traditional craft activities.

Summarising the current situation of the KRB in the context of developing a geopark and geotourism, the following ‘SWAT’ analysis is useful to help identify priority areas for activity:

**Strength** The Kachchh Basin has rich and diverse geological heritage of global significance and high scientific value and has been an important work centre in India for geologists since the early nineteenth century.

**Weakness** A lack of a national or regional geoheritage conservation policy and governmental implementation, combined with a lack of rigorous control of mining operations and monitoring and slow decision-making processes, currently makes it difficult for the conservation and protection of geoheritage to be systematically achieved.

**Opportunities** The region has a good infrastructure and network of roads, accommodation, and transport facilities. The services of the local branch of the Gujarat State Geology Department in Bhuj could be utilized for the management and conservation of identified geosites (Table 1), as well as to monitor (and hence help regulate) mining operations and develop and guide tours. Maps and literature are available from the ONGC and the GSI. The Department of Science and Technology of the Government of India is already considering a project proposal for the preparation of field catalogues, guide maps, and multi-media CDs for geo-tourists and visiting geoscientists. With proper planning, geotourism will enhance the value of the state and regional tourism industry, which presently focuses mainly on the local festivals, handicrafts, and cultural activities. Crucially, the Department of Earth and Environmental Science in the K.S.K.V. Kachchh University, Bhuj, can provide academic and research planning and trained manpower to assist with various geoheritage-focused projects.

**Threats** Unregulated mining, construction, and other anthropogenic activity with complete disregard to geological heritage can be a major threat to specific sites (Fig. 21). This problem is compounded by a lack of intervention by the State Geology and Mining Department and Gujarat Mineral Development Corporation to regulate such activities. This is due to lack of awareness about the scientific, educational, and even aesthetic values of the geosites. In addition, local communities often remain unaware and hence insensitive to such issues and hence needs to be educated about the geological values they have inherited from nature.

## Conclusion

The Kachchh peri-cratonic, Palaeo-rift Basin in Western India is nature's geological museum and a vast outdoor laboratory for Earth scientists. Once destroyed, it cannot be recreated; hence, such a geoheritage needs to be protected from damaging human activities and included in sustainable development plans as proposed by the UN and UNESCO. Without this intervention, the nation could lose key aspects of this captivating expanse of landscape and its unique geoheritage which has the potential to become India's first national geopark. Crucially, the landscapes of the KRB have an immense potential to achieve several of the UN's Sustainable Development Goals through developing key aspects of its geology for educational and touristic purposes. Though the district is the largest in India by its area, the logistics and communication in the Kachchh region are suitable for easy access to the geological sections and sites by road connections as well as

cross-country driving, especially during the winter season which is the most best for field visits and general tourism.

The many important geological heritage sites discussed in this paper indicate that the basin area is de facto a natural text book for teaching, learning, and researching on almost any discipline of geology, environmental science, and ecology and even has some features of importance to planetary science. These heritage features are spread all over the basin, and visitors need to be taken to different areas to demonstrate different aspects of this rich geological heritage. Hence, the entire district of the Kachchh could be declared as a national geopark in India.

The key purpose of this paper is to create an awareness amongst state and central government authorities about not only the need to protect natural geological sites as geological monuments and national parks in India, for future generations to study geology and learn from, but also to raise the profile of geotourism as a way to achieve sustainable economic development. Over the last two decades, the Government of Gujarat has undertaken various initiatives for industrial and economic development (e.g. Vibrant Gujarat) and tourism developments (e.g. the Rann Festival, Statue of Unity, Ahmedabad river front, etc.), but it now has the possibility to take the lead in establishing the concept of Geoparks in India by declaring the Kachchh Basin as India's first National Geopark. In this way, not only will geoscientists, researchers, and students have opportunity to continue to study such exemplary features in the field, so will local communities through school and adult education programmes and initiatives, leading to both social and economic benefits.

Crucially, the Department of Earth and Environmental Science in the K.S.K.V. Kachchh University, Bhuj, is in a position to take a lead in promoting such developments and activities. Varieties of geological features, such as rock types, sedimentary structures, fossils, folds and faults, intrusive bodies, and volcanic flows, as well as scenic views will also attract the more general tourist attention, promoting an interest in geology and geotourism. New geological studies and educational programmes, as well as the raising of awareness of geology within general visitors, will help ensure that future generations are more aware of the contribution of geology and geological sciences to their own lives, something which is only really possible within the context of a geopark.

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