Geomorphological Field Guide Book

on

KACHCHH PENINSULA

By

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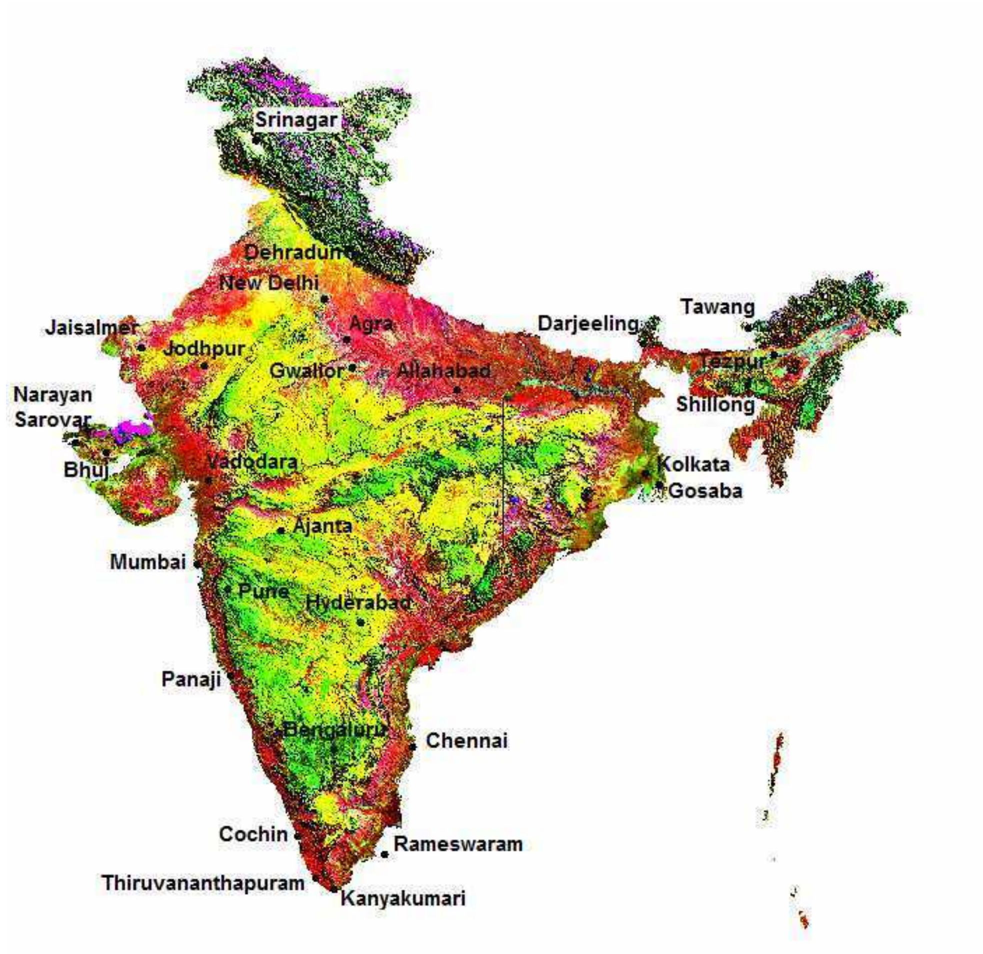


Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.

Geomorphological Field Guide Book on Kachchh Peninsula

Itinerary

Day	Places from - to	Stay
1	Arrival at Bhuj Field visit: Bhuj to Kukma and back	Bhuj
2	Bhuj to Kaladungar and back	Bhuj
3	Bhuj to Dhinodhar, Lakhpat and Narayan Sarovar	Narayan Sarovar
4	Narayan Sarovar to Bhuj	Bhuj
5	Bhuj to Habo Dome, Kas Range and back	Bhuj
6	Depart from Bhuj	

KACHCHH PENINSULA: AN INTRODUCTION

Kachchh district, located at the western extreme of India, lies between 22° and 24° N latitudes and between 68° and 71° E longitudes. It is the second largest district in the country, and has an area of 45612 sq. km. The district is flanked on the south by the Arabian Sea. In the north and the east it is flanked by two vast saline marshes, the Great Rann of Kachchh (~15127 sq. km), and the Little Rann (~4000 sq. km), with few small rocky islands in between (~83 sq. km). In the west lies a vast unfinished delta with tidal creeks and thickets of mangrove (1285 sq. km; Kar, 2011). Between the Great Rann and the hilly central part lies a vast featureless saline plain with patches of halophytic grasses, which is called the Banni (~2525 sq. km). Consequently, large parts of the district are inhospitable. Most of the human habitations in Kachchh district lie especially in the central part of the district, along an elongated tract with rugged hilly terrain and flanked by shallow plains, which is called the 'Kachchh Mainland'. The shape and the broad topographic configuration of Kachchh Mainland resemble that of a tortoise shell, which is possibly why the name 'Kachchh' (a Sanskrit word for tortoise) was given to this land. The district has an arid climate. Its mean annual rainfall is 348 mm, received mostly during the summer monsoon months of June to September, but with high spatio-temporal variability that commonly results in either drought or localized high-intensity rains. Mean summer temperature in May is 42°-43°C, but it often goes up to 45°-47°. Winter is mild due to the nearness of the sea, the mean day temperature during January being 28°-30°C, while the mean minimum temperature at night falls to 7°-10°C. The structural styles, the lithological make-up and the tectonic events have played crucial roles in the geomorphological evolution of the district, as well as in shaping its present landforms. The following summary of our current understanding of the geology and geomorphology of Kachchh district may help to appreciate the landscape of the district.

Geology and Geomorphology of Kachchh

Kachchh is a western marginal peri-cratonic rift basin in India that is oriented E-W at the periphery of the Indian Craton (Biswas, 1987; Biswas et al., 1993; Fig. 2). The palaeo-rift of the Thar and the Southern Indus basin of Pakistan (Zaigham and Mallick, 2000) borders it on the north. To the south occurs another parallel rift basin, the western offshore extension of the Narmada rift, with the Saurashtra horst in between them. The N-S trending Cambay rift basin crosses the above two parallel rifts. Together, the three rifts form an intersecting rift system around the foundered cratonic block of Saurashtra at the trailing edge of the Indian continental plate. The Mumbai offshore shelf extends south of the Narmada rift along the West Coast Fault. This shelf is also rifted and is featured by the N-S trending grabens/half-grabens and horsts.

As mentioned earlier, the landscape of Kachchh Mainland is dominated by a central highland, which is surrounded by lowlands (Fig. 3 to 5). The highland has a rugged hilly terrain with sparse vegetation, exposing the Mesozoic rocks (Middle Jurassic to Early Cretaceous), bordered by thin strips of gently dipping Cenozoic rocks (Paleocene to Pleistocene and Recent), which form the coastal plains. The lowlands are extensive alluvial plains, or mud and salt flats (Rann), and grassy flats (Banni). The marginal hill ranges in the mainland, with escarpments facing the plains are sharp marginal flexures of Mesozoic rocks that are well exposed along the length of the highland.

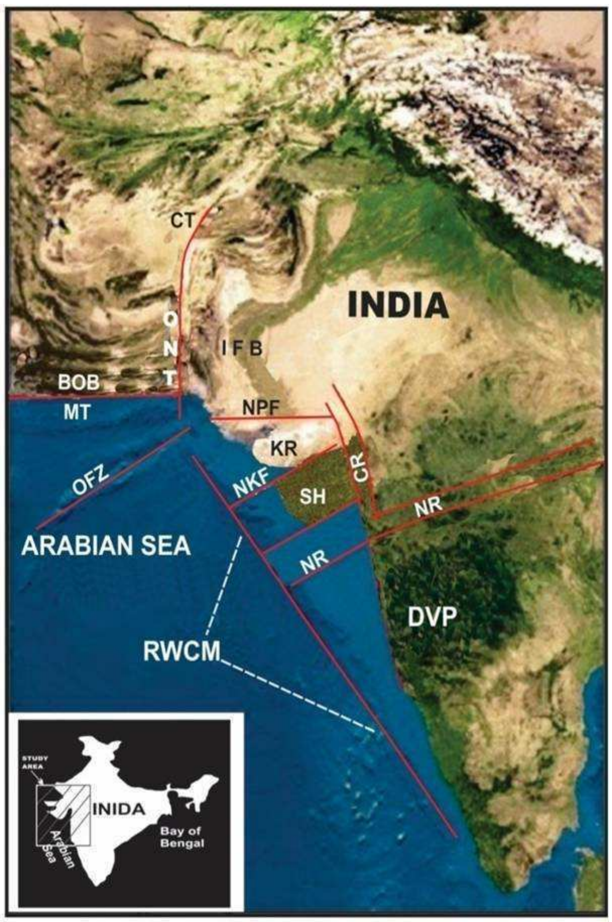


Fig. 2. Rifted western continental margin of India and location of Kachchh Rift (KR). KR is located within intersecting rift complex in the highly tectonised northern part of the WCMI. All bordering rifts are in inversion mode. IFB: Indus Foreland Basin; NPF: Nagar Parkar Fault; NKF: North Kathiawar Fault; CR: Cambay Rift; NR: Narmada Rift; SH: Saurashtra Horst; DVP: Deccan Volcanic Province; CT: Chaman Transfer fault; ONT: Ornachnai Transfer fault; MT: Mekran Thrust; BOB: Baluchistan Orogenic Belt; OFZ: Owen Fracture Zone (Murray Ridge); RWCM: Rifted Western Continental Margin (After Biswas, 1987).

Physiographic Divisions

The Kachchh region provides excellent examples of tectonically-controlled landscapes where the landforms are the manifestations of earth movements along tectonic lineaments of the Pre-Mesozoic basin configuration that was produced by the primordial fault pattern in the Precambrian basement (Biswas, 1971, 1974). Taking into consideration the factors of altitude, slope and ruggedness of relief, Kachchh can be divided into the following four major physiographic units from north to south: (1) the Ranns, (2) the low-lying Banni Plain, (3) the Hilly Region, and (4) the Southern Coastal Plain (Fig. 3). The Gulf of Kachchh between Kathiawar Peninsula and Kachchh Mainland, the Banni grassland between the Mainland and Pachham Island, and the Great Rann of Kachchh between the Island Belt and Nagar Parkar Ridge are the major structural lows. The Gulf of Kachchh shallows eastward, ending up as a mudflat between the Wagad and the Kathiawar highland to the east of the Mainland. This mudflat is called the Little Rann of Kachchh. A description of the four major physiographic units follows.

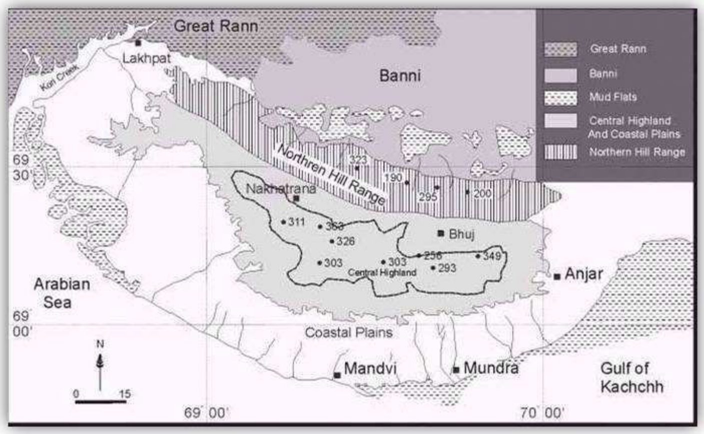


Fig. 3. Major physiographic divisions of Kachchh Mainland (after Biswas, 1982).

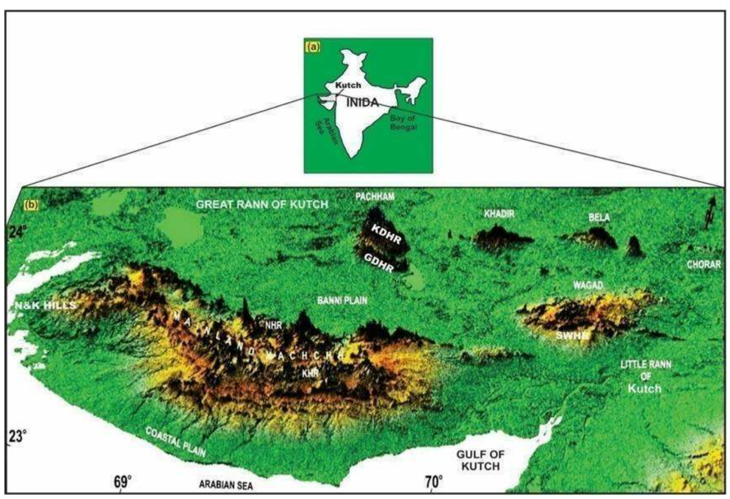


Fig. 4. SRTM DEM of Kachchh landscape. The first order topography is controlled by rift structure. Highlands, surrounded by lowlands, suggest horst and graben features. NHR: Northern Hill Range; KHR: Katrol Hill Range; SWH: South Wagad Hills; KDHR: Kaladungar Hill Range; GDHR: Goradongar Hill Range.

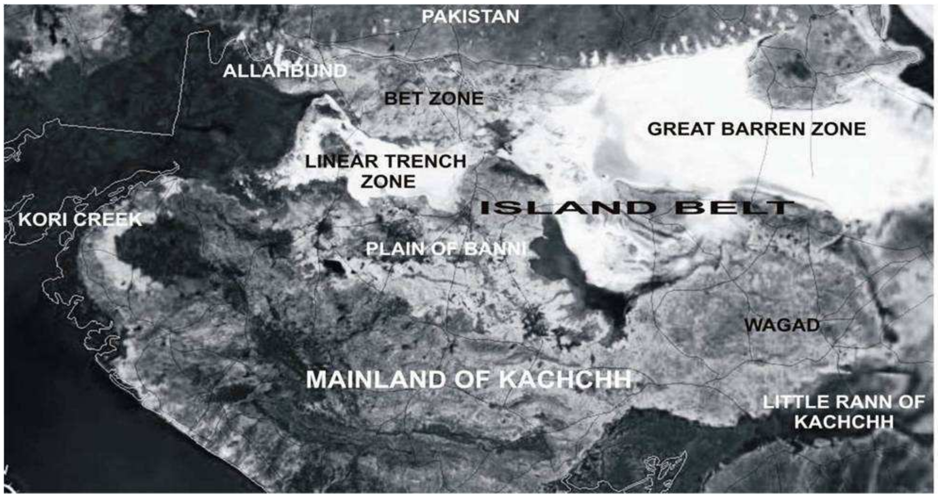


Fig. 5. Image-map showing geomorphology of the Great Ranns of Kachchh (Merh and Patel, 1988).

(1) ***The Ranns***: The Ranns are the most remarkable and unique features of Kachchh, having a flat terrain hardly beyond 3-4 m asl. The Great Rann of Kachchh occurs in the north of the district, while the Little Rann is in the east. As stated earlier, a chain of islands occur within the Great Rann (Fig. 5). The Ranns mostly remain dry, except during the rainy season when it is covered by water. During the dry summer and winter months, much of the Rann surface is covered with salt encrustation. Merh and Patel (1988) identified the following five geomorphic units in the Ranns (Fig.5). These are: (a) Bet Zone (BTZ), (b) Linear Trench Zone (LTZ), (c) Great Barren Zone (GBZ), and (d) Little Rann of Kachchh (LRK).

(2) ***The Banni Plain***: The plain of Banni represents an embayment between the Kachchh mainland in the south, the uplifts of Pachham in the north, and the Wagad uplifts in the east and covers the area ~ 6000 sq km (Fig. 4 and 6). It rises little higher than the surrounding Rann and is covered with green grass and other shrubs. No outcrop is seen within these featureless plains. It receives water from the Mainland and the islands from the north and east respectively during rainy seasons.

(3) ***The Hilly Region***: The hilly areas within the district occur as 'Uplifts', and can be broadly divided into the following three groups: (a) the Island Belt Uplift, (b) the Kachchh Mainland Uplift, and (c) the Wagad Uplift. The Island Belt Uplift consists of four highlands: the Pachham, the Khadir, the Bela and the Chorar highlands, which occur as islands (Bets) within the Great Rann of Kachchh in the north, and form an E-W chain of uplifts. In fact, these four highlands were islands during the Late Tertiary-Quaternary period when the Great Rann was inundated by the sea (Biswas, 1971). The Kachchh

Mainland Uplift occurs in the west, and the Wagad Uplift in the east (Fig. 4 and 6). The Mesozoic (Middle to Upper Jurassic) rocks are exposed in the highlands, bordered by the Tertiary and Quaternary rocks in the southern and western peripheral plains. Early Cretaceous rocks are present only along the southern slopes of the Kachchh Mainland Uplift, overlain by the Deccan Trap volcanic flows, and eastward by the on-lapping Tertiary strata (Fig. 7).

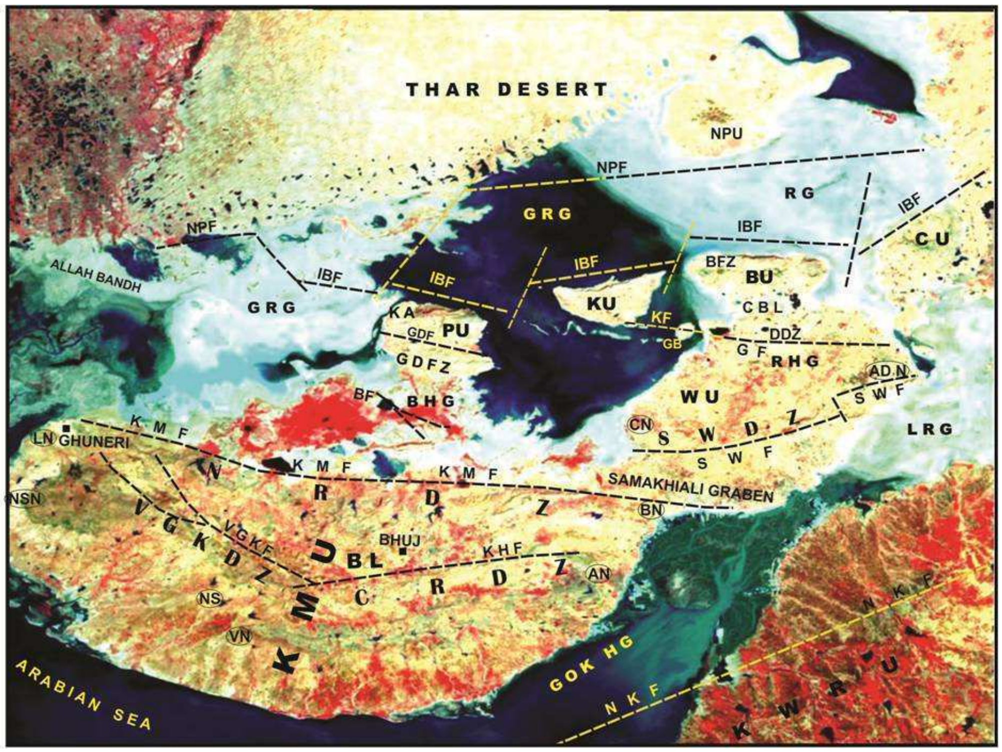


Fig. 6. Morphotectonic map of Kachchh, showing fault-related deformation zones in six uplifts. NPU-Nagar Parkar Uplift , PU-Pachham Uplift, KU- Khadir Uplift, BU- Bela Uplift, CU- Chorar Uplift, WU- Wagad Uplift, KMU- Kachchh Mainland Uplift, NPF- Nagar Parkar Fault, IBF- Island Belt Fault, BHG- Banni Half Graben, BF- Banni Fault, SWF- South Wagad Fault, KMF- Kachchh Mainland Fault, KHF- Katrol Hill Fault, NKF- North Kathiwar Fault, GRG- Great Rann Graben, GOK HG- Gulf of Kutch Half-Graben, GDF- Goradongar Fault, GDFZ- Goradongar Fault Zone, DDZ- Desalpur Deformation Zone, GF-Gedi Fault, BL- Bhuj Low, NRDZ- Northern Range Deformation Zone, RHG- Rapar Half-Graben, SWDZ- South Wagad Deformation Zone, LRG- Little Rann Graben, VGKDZ- Vigodi- Gugriana-Khirasra Deformation Zone, CRDZ- Charwar Range Deformation Zone. KWU- Kathiawar Uplift, KF- Kakindia fault, GB- Gangta Bet. BFZ- Bela Flexure Zone, CBL- Central Balasar Low, LN- Lakhpat Nose, NSN- Narayan Sarovar Nose, AN- Anjar Nose, BN- Bhachau Nose, CN- Chobari Nose, ADN- Adesar Nose.

(a) **The Island Belt Uplift** (IBU) comprises of four south-tilted blocksfrom west to east: the Pachham Uplift (PU), the Khadir Uplift (KU), the Bela Uplift (BU) and the Chorar Uplift (CU; Fig. 4 and 6). The northern boundary of all the Islands is steeper while the gradient is very low towards south.

The Pachham Uplift (PU) is located north of Kachchh Mainland Uplift across the Banni Plain (Fig. 6). The uplift is a NW-SE oriented quadrangular block with southward tilt. It is surrounded in the N and W by mudflats of the Great Rann of Kachchh and in S by the Banni Plain. To the east, a 22 km stretch of Great Rann separates PU from KU. PU is faulted in the middle, forming two parallel south-tilted fault blocks: the Kaladongar Hill in the north and the Goradongar Hill in the south, with a central valley in between, which is covered by alluvium. The central valley, the Dhorawar-Tuganipur syncline, is created by downthrow of the Kaladongar block against the Goradongar Fault (GDF). Like other uplifts, the hill ranges here are deformation zones. The northern margin fault (Island Belt Fault; IBF) is inferred from the sharp edge of the block and truncated marginal anticlines. The southern Goradongar Fault (GDF) is well exposed. It strikes NW-SE, parallel to the inferred IBF. It is a second-order reverse fault associated with rift inversion.

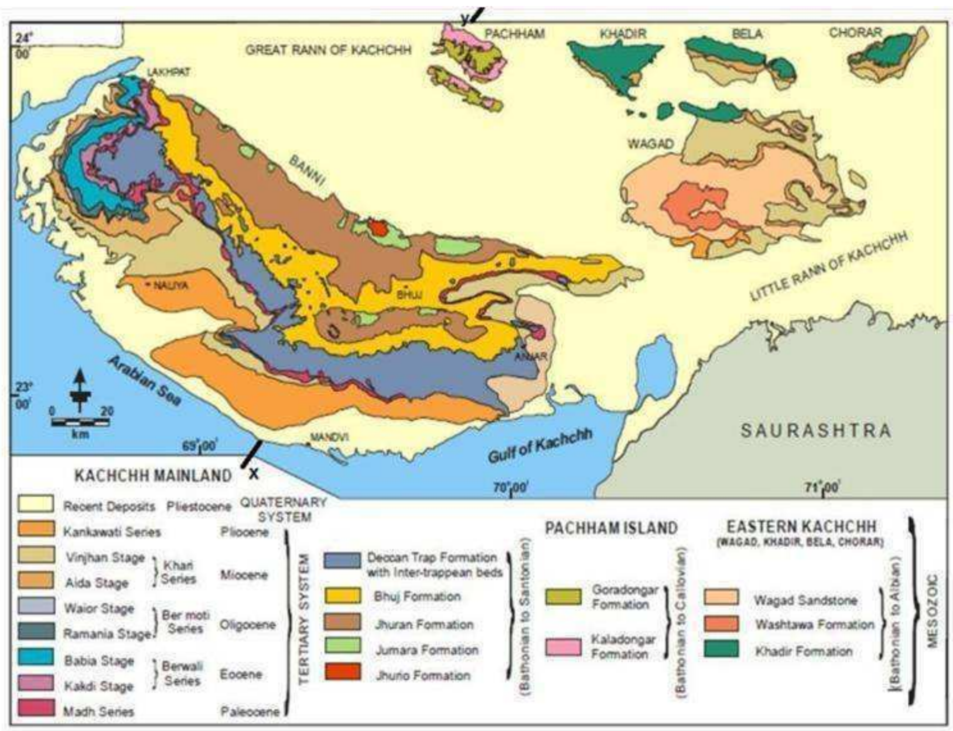


Fig. 7. Geological map of Kachchh (after Biswas and Deshpande, 1970).

The Khadir Uplift (KU) is located to the NE of Kachchh Mainland Uplift across the Banni Plain (Fig. 6). The structure of KU is the simplest of all the uplifts. It is a simple triangular block, sloping down to the south without any marginal folding. The steep northern escarpment is the maximum elevated part of the uplift. The back-slope dips gently (3-5°) to the south. Radial dip pattern on the back-slope suggests a large half-dome structure. This is also indicated by the gently curved southwestern outline of the uplift, cut off by the escarpment on the north. The straight northern escarpment also suggests that it is a receding scarp of the hidden IBF. The outcrop of boulder conglomerates at the foot of the scarp at Cheriya Bet in the north-central part shows apparent reversal of dip. KU back-slope is affected by few small-scale faults, most of which are accompanied by basic dykes. The southern tip of this triangular uplift is bordered by the Kakindia Fault (KF), which continues eastward across a narrow stretch of mudflat from NW-SE to E-W, with a curved trend, and connects with Gedi Fault (GF) between the Wagad Uplift (WU) and the Bela Uplift (BU; Fig. 6). A series of domes occur along this belt. These are, from west to east, the Kakindia Bet, the Kara Bir, the Gora Bir and the Gangta Bet. Apparently, KF is the extension of the GF and the structures are related to Desalpur Deformation Zone (DDZ).

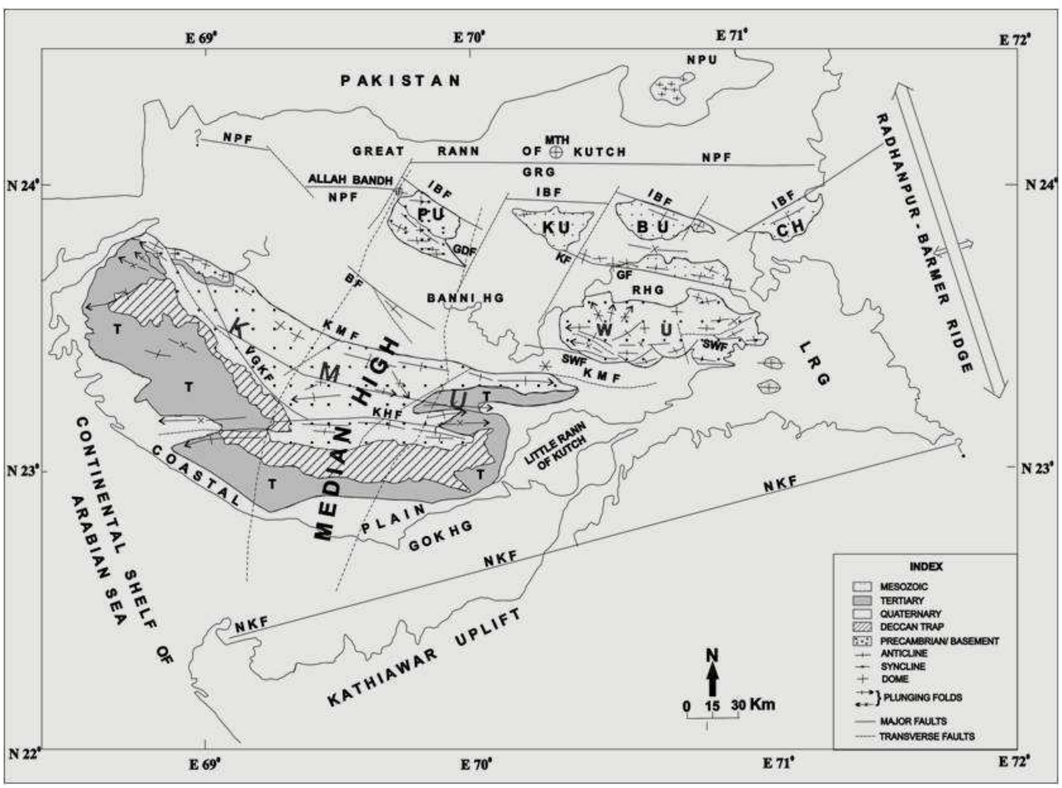
The Bela Uplift (BU) occurs to the north of Wagad Uplift (WU), juxtaposed by Gedi Fault (GF). This uplift is a horst block between the Great Rann Graben (GRG) in the north and the Rapar Half-Graben (RHG) in the south, bound by IBF and GF, respectively. The faulted edges are tilted opposite to each other, forming a central synclinal low, the Balasar Low. The bounding faults are accompanied by deformation zones with chains of folds of varying types and dimensions as seen in all other uplifts. The uplift has three structural zones: (a) The Bela Flexure Zone (BFZ) along the northern margin, (b) the Central Balasar Low (CBL), and (c) the Desalpur Deformation Zone (DDZ) (Fig. 6). BFZ is associated with IBF and DDZ with GF. The tilted edges of the horst with a central low suggest a possible faulting in the middle at the basement level between two oppositely tilted blocks. Bela flexure is a narrow, stretched and elongated anticline. At the eastern end occurs a large dome, Mouana dome, with swarms of basic dykes at the core suggesting presence of a laccolith at depth. Low amplitude faults accompanied by basic dykes are common as in other uplifts.

The Chorar Uplift (CU) is the smallest uplift in the IBU, located at the northeastern corner of Kachchh rift basin (Fig. 6). It is oriented NE-SW as the strike of IBF swings from E-W to NE-SW. It is a domical uplift of very low relief, mostly covered by Tertiary rocks, excepting the elevated and eroded central part. The straight northwestern margin with steeper dips of beds and convex southwestern periphery with radial dips suggest the same structural geometry as in the other uplifts. Due to low amplitude of fading IBF, the fault flexure shows only steep dips and no deformation zone as in the other uplifts.

(b) **The Kachchh Mainland Uplift (**KMU) is the largest uplift in the Kachchh Rift basin. It is a broad-topped oblong upwarp, which is elongated E-W along the Kachchh

Mainland Fault (KMF) in its north. On either sides of the Median High, this uplift plunges towards the Arabian Sea Shelf in the west (Lakhpat and Narayan Sarovar noses) and towards the Little Rann in the east (the Bhachau and the Anjar noses) (Fig. 6 and 8). It is a south-tilted block along the KMF. The E-W strike of KMF curves westward into a WNW-ESE strike, making a concave trend of the northern faulted margin. The back-slope of the uplift slopes gently southward from the Northern Deformation Zone (NRDZ) along the KMF. The slope is featured by small second-order faults and associated folds. The back-slope is faulted in the middle by a major E-W striking Katrol Hill Fault (KHF), which divides the uplift into two south-tilted blocks repeating the stratigraphic sequence.

(c) **The Wagad Uplift** (WU) along the SWF, is located in the eastern part of the Banni Half Graben (BHG), and is the second largest uplift in the basin (Fig. 6). It is an E-W oriented large domical uplift, bound by faults with a central dome and broad peripheral noses, the Chobari Nose (CN) in the west and the Adesar Nose (AN) in the east. This uplift is placed en echelon with respect to KMU, northeast of the eastern plunge of the Bhachau anticlinal Nose (BN). WU is tilted down to the north along the GF. The up-tilted southern edge along the South Wagad Fault (SWF) is a complicated fault zone associated with a complex of faults and folds.



Tectonic map of Kachchh (after Biswas and Khatri, 2002).

(4) The Southern Coastal Plain: This plain borders the Kachchh Mainland, overlooking the Gulf of Kachchh in the south and the Arabian Sea in the west (Fig. 3 and 4). The coastline has been broadly divided into five segments based on geomorphologic variations (Kar, 1993). These are: (a) the deltaic coast to the west of Kori Creek, (b) the irregular drowned prograded coast between Kori Creek and Jakhau, (c) the straightened coast between Jakhau and Bhada, (d) the spits and cuspate foreland complex between Bhada-Mandvi and Mundra, and (e) the wide mudflat coast to the east of Mundra up to the Little Rann.

Regional Geology of Kachchh

The Kachchh basin preserves about 2000 to 3000 m thickness of Mesozoic sediments and about 1000 m thickness of Cenozoic sediments (Biswas, 1977, 1982). The Tertiary rocks are exposed along the coastal belt of southern and western Kachchh, bordering the Mesozoic rocks (Fig. 7). The Quaternary sediments consist of a wide variety of sediments, ranging from marine to fluvial, laccustrine and aeolian deposits. In the coastal plains the late Quaternary deposits mostly consist of alluvium and calcreted or ferricreted loose sediments, covering the older deposits. The exposed Tertiary sediments are mostly littoral to shallow marine shelf sediments, deposited in the peripheral and intervening structural lows that border the Mesozoic uplift areas.

Mesozoic Stratigraphy: The Mesozoic rocks of Kachchh were first mapped by Wynne (1872), who classified the sequence into the upper and the lower Jurassic groups. Waagen (1875) proposed the popular four-fold subdivisions, namely, the Pachham, the Chari, the Katrol and the Umia Series. Rajnath (1942) restricted the term ‘Umia’ only to the lower Umia of Waggen. The upper Umia, made up of non-marine beds with plant fossils, was called by him as Bhuj Series of Middle Cretaceous, or of even slightly younger age. Biswas (1977) recognized three main lithologic provinces within the basin. He classified the rocks of each province separately and named the units according to their strato-types (Biswas, 1977). The litho-stratigraphic sequence of the mainland is divided into four formations, named as the Jhurio (Jhura), Jumara, Jhuran and Bhuj formations (Biswas, 1977, 1981). The major lithological characteristics of these formations worked out by Biswas (1974, 1977, 1982 and 1987) are briefly described below.

Jhurio Formation is a thick sequence of limestone and shales with bands of ‘golden oolites’. The type section occurs in Jhurio hill, in the north-central Mainland. The upper part of the formation is made up of thinly-bedded white to cream coloured limestones (pelmicrite and biomicrite), with thin bands of ‘golden oolite’ (Balgopal, 1973). The middle part is composed of thick beds of grey-yellow weathered shales, alternated with thick beds of golden oolitic limestones. The lower part comprises of thin beds of yellow and grey limestone (Agarwal, 1957; Balgopal, 1973). The physical and biological aspects of the formation indicates littoral to infra-littoral environment. The formation ranges from Bathonian to lower Callovian.

Jumara Formation is thick argillaceous, conformably overlying the Jhurio Formation. It has been named after its type section in Jumara hill to the north of Jumara village and near the Great Rann. The formation is characterized by monotonous olive-grey gypseous laminated shales with thin red ferrugenous bands. The ~300 m thickness of the formation is uniform throughout the area. Local disconformity is observed at places where the Jhuran shales are seen resting over the eroded Dhosa oolite member. The Jumara formation ranges age between Callovian and Oxfordian.

Jhuran Formation comprises of a thick sequence of alternating beds of sandstones and shales. It is divided into four members, the lower, the middle (Rudramata shale), the upper and the Katesar (Biswas, 1977). The lower member consists of alternating red and yellow sandstone and shale. The middle member is mostly shale, comprising of dark grey to black laminated gypseous shales. The upper member is predominantly arenaceous and is composed of red and yellow massive current-bedded sandstones with intercalations of shale, siltstone and calcareous sandstone. Kimmeridgian to Valanginian age is fixed for this formation.

Bhuj Formation is named after its type locality around Bhuj. This formation is characterized by a huge thickness of non-marine sandstones of uniform character. These rocks occupy about 3/4th of the total area of the Mesozoic outcrop in Mainland Kachchh. The lower member is characterized by cyclic repetition of ferruginous or lateritic bands, shale and sandstones. The upper member consists of whitish to pale brown, massive, current-bedded, coarse-grained, well-sorted sandstones. The formation is bounded by the plains of disconformity. In the south, Deccan Trap rests on the eroded undulating surface of this formation. The sediments represent deltaic deposits with distal part of the large Cretaceous delta front towards the west and the proximal part (fluvial) to the east in the direction of the land. Lower Cretaceous (Valenginian to Santonian) time range is fixed for this formation.

The Deccan Trap forms a more or less linear outcrop, extending across the Mainland with a maximum width of about 10 km in the east near the town of Anjar, and gradually tapering westward. Lava flows are dominantly tholeiitic basalts, occupying the southern and southwestern slopes of the central highland. The trappean flows show gentle southerly dips and are believed to be of *pa hoe hoe* type (Biswas and Deshpande, 1973). Six major flows have been reported at the eastern extremity (Dhola Hills near Anjar), where they show alternations of columnar and amygdaloidal basalts, occasionally separated by inter-trappean beds. Associated with the trapppean flows are a number of long, narrow dykes that occur to the N, NW and NE of the lava flow. Most of the dykes occur along transverse faults, extending N-S, NNE-SSW and NNW-SSE. An interesting aspect of the Deccan volcanism in Kachchh is the occurrence of alkaline basalt and its derivatives as plugs, laccoliths and sills within the dome structures in the Mesozoic rocks. The inter-trappeans were deposited in shallow basins and depressions over trappean surfaces, fed by simultaneously formed rivulets. An uppermost Cretaceous age (Maastrichian) is inferred for these inter-trappeans. Laterites form a narrow elongate Paleocene belt, a few hundred meters wide and several hundred kilometers long, sandwiched between the basalts of the Deccan Trap and the Tertiaries, and forms a terrain that is characterized by 10 to 15 m high elongated ridges, separated by broad intermittent valleys.

Tertiary Stratigraphy: Wynne and Fedden (1872) studied these rocks for the first time. Biswas (1974) proposed a revised stratigraphy and established that the Tertiary sediments in Kachchh were deposited on the eroded surface of the Deccan Trap and the Mesozoic sedimentaries. Deposition started with a marine transgression during Lower Eocene and ended in Pliocene. During Paleogene, deposition was restricted to the western part of the Kachchh Mainland, the thickest parts being exposed in the southwestern coastal plain which was the deepest part of the basin. The following is a brief summary of the Tertiary formations as described by Biswas (1974).

Madh Series: The type area of the rocks of this series is the well known village of Mata-no-Madh in western Kachchh. It consists of volcanoclastic sediments deposited in variable environments, ranging from fluviatile to littoral (Biswas, 1974).

Berwali Series: The series is divisible into two stages, the lower consisting of gypseous and ochreous clays and marl containing several varieties of mollusks and foraminifers, and is seen in Kakdi Nadi section (Kakdi Stage), and the upper stage is well exposed in Babia hill in western Kachchh comprising a fossiliferous fragmental limestone with a basal calcareous clay bed (Babia Stage).

Bermati Series: This series forms a well exposed continuous belt south of Lakhpat in northwestern Kachchh. It is divisible into two stages; the lower Ramania stage consists of greenish-grey marl and argillaceous limestone with a basal boundary clayey marl bed deposited in an epineritic environment of a slowly regressive sea (Biswas, 1974).

Khari Series: This series overlies unconformably the Bermoti series and is well exposed in the cliffy banks of the Khari River in southwestern Kachchh. The Khari series is made up of two distinct stages distinguishable. The lower Aida stage is composed of variegated siltstone, the lower 16 m of which is barren, but the upper part contains Lower Burdigalian fossil assemblage. The upper part of the series, the Vinjhan Stage consists of grey to khakhi-coloured gypseous clay with hard marl bands packed with fossils. This stage forms the main bulk of the Lower Miocene of Kachchh. The clays of this stage contain a rich assemblage of Upper Burdingalian fossils. As the Khari series is seen overlapping the Deccan Trap directly, it suggests that this marine transgression was the most powerful one in the history of the Tertiary sedimentation in Kachchh.

Kankawati Series: Well exposed around Kankawati River between Sandhan and Vinjhan, this series consists of grey micaceous and calcareous sandstone, lenticular bands of conglomerate and Khakhi grey clay. The upper part is mainly pinkish hard calcareous grit and conglomerate containing abundant foraminifers. This series has been tentatively assigned a Pliocene age and has been correlated with the Manchhar Series of Sindh-Baluchistan.

Regional Structures of Kachchh

The structure of KR is designed by six major E-W striking intra-rift faults: KMF, KHF, SWF, GF, GDF and IBF, and two rift bounding faults: NPF and NKF, respectively on the north and south (Fig. 8). The basement blocks and the bounding faults are not exposed (Fig. 9). The surface locations of the faults are inferred from the geometry of the marginal flexures which are affected by a zone of parallel late-generation faults. These faults are interpreted to be the upward extension of sub-vertical basement faults which affected the Tertiary strata of the adjacent half-graben (Fig. 9). The common geometry seen in all the uplifts is knee and ankle-bend fold with a short, near-vertical faulted forelimb and a gently dipping, long-back limb. This geometry suggests draping of the ductile sediment layer over the faulted edge of a hard, brittle and tilted basement block. It is assumed that the steep escarpment face and the axis of the knee-bend fold mark the approximate location of the sub-vertical basement fault hidden below the folded sediment layer. This layer is affected by upward propagating faults from the main basement fault. This is confirmed by shearing of the forelimb and juxtaposition of steeply upturned Tertiary strata against the sheared Mesozoic strata of the fore-limb. A zone of parallel, closely-placed sympathetic faults exposed along the foot of the fore-limb scarp helps in tracing the master fault. Following this criteria, the approximate locations of the above mentioned major faults were traced on a map.

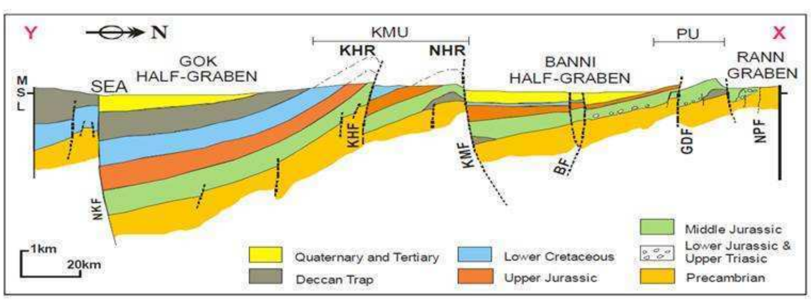


Fig. 9. N-S section across Kachchh, showing fault locations and their subsurface configuration.

Primary Faults

Nagar Parkar Fault (NPF): This fault marks the northern boundary of the rift basin. It is defined by the boundary between basement and rift sediment. However, this fault is not well exposed. The fault is drawn along a prominent geomorphic high, Allah Bandh, in the western part of GRG and the basement outcrop at Meruda Takkar monadnock (Biswas and Deshpande, 1968) in E-W direction (Fig. 7). The Allah Bandh is a ridge of Holocene sediment uplifted during 1819 earthquake. Basement outcrop at Kalinjhar Hill in Nagar Parkar, Pakistan, 60 km NW of Meruda hill confirms that north of the traced fault is a Precambrian terrain. This interpreted location of NPF is further supported by the sharp boundary between the mud flat of Great Rann of Kachchh and the dunes of Thar Desert. This geomorphic boundary is a receded fault line scarp. Outcrop of granite boulder conglomerate in Cheriyabet, north of KU, suggests presence of piedmont conglomerate fan deposit in the narrow graben between the traced fault and IBF. This confirms the traced location of the fault. As discussed earlier NPF is an important transfer fault between rift and foreland basin. It continues eastward across the Cambay basin as Tharad fault along a transverse ridge in line with the Kalinjhar hill of Nagarparkar.

North Kathiawar Fault (NKF): This fault is not exposed. It is postulated approximately along the northern straight edge of the SH mainly on the basis of geomorphology. This southern margin of Gulf of Kachchh is the elevated plateau of Saurashtra which is bound by proven faults in all other sides. The gulf (GOKHG) deepens progressively southwards attaining maximum depth near the plateau. This suggests uplift of the plateau as a horst block against the half-graben. This is supported by the gravity data. It is presumed that the fault is passing offshore along the northern edge of SH. Due to lack of offshore data the fault could not be confirmed. However, progressive thickening of KR sediments in GOKHG towards south and repetition of Lower Cretaceous and Deccan Trap formations are definite indication of the presence of a fault (Fig. 6). On the map approximate location of the fault is shown between Gulf of Kachchh and Saurashtra (Kathiawar) plateau.

Kachchh Mainland Fault (KMF): KMF is the biggest and longest fault in the region and the principal zone of weakness. It extends for 200 km along the northern edge of Kachchh Mainland Uplift (KMU). The fault has a prominent geomorphologic expression. The lofty hills of the northern range appear to rise abruptly from the Banni plain, which is the downthrown side.

South Wagad Fault (SWF): The southern part of Wagad uplift is much faulted and appear to have been shattered and broken into several blocks wedges bounded by faults. These faults have been collectively called South Wagad Fault System. The southern edge of the Wagad uplift is tilted up along this system of faults.

Island Belt Fault (IBF): IBF is not well exposed along the island chain of uplifts, and is concealed under the Rann sediments. The faulting is indicated by steeply-dipping beds of the forelimbs of the drape – folds and the imposing escarpments facing north. At the foot of the northern scarp of Pachham (Kaladongar hills), hard sandstone beds dipping 60°-80° to the north into the Rann sediments indicate the fault. High and erratic dips along the margin of the uplifts bordering Rann indicate faults. The fault appears to have been dislocated by left lateral NE-SW strike-slip faults, which separated Island Belt Uplift (IBU) into four discrete blocks [Pachham Uplift (PU), Khadir Uplift (KU), Bela Uplift (BU), and Chorar Uplift (CU)]. These blocks were rotated anticlockwise and shifted progressively westward as indicated by their axial orientation (Fig. 6).

Secondary Faults

Katrol Hill Fault (KHF): KHF and GDF are the post-depositional later generation faults within the uplifts KMU and PU, respectively. KHF strikes parallel to KMF. To the west it splays out into two faults, one continues to the west in the same strike and the other strikes NW as Vigodi fault and its splay outs – Vigodi – Gugriana – Khirasra – Netra faults (VGKF) (Fig. 6 and 8). The later faults meet the KMF near Lakhpat. The west-striking KHF is dislocated and shifted southward by NE-SW Jarjok fault.

Goradongar Fault (GDF): This Fault brings up the southern part of PU (Goradongar Hills). It is a sub-vertical fault with changing dips as noted in other cases. The associated conjugate fault system and folds are typical of a strike-slip fault. The marginal flexures and oblique folds related to subsidiary faults present a complicated fault and fold pattern of the Goradongar uplift. The Gedi Fault (GF) between Bela horst and Rapar half-graben is in the same alignment as the GDF across the Banni low covered by recent sediments.

Banni Fault: BHG is the south-sloping hanging wall of IBU block with a central arch where MH crosses it. On this arch in the middle of the basin a WNW-ESE striking fault, parallel to IBF, had been mapped by 2D seismic survey (ONGC source). This fault referred to as Banni Fault, is not exposed.

Gedi Fault (GF): The fault separates Bela Horst (BU) and north tilted Wagad block. RHG, sloping north, is the backslope of WU against it (Fig. 6 and 8). GF strikes E-W with upthrow of BU on the north. It shows the same characteristics as seen in other master faults. GF is seen to extend into Gangta uplift. The E-W chain of faulted Karabir, Gorabir and Gangta anticlines in the same alignment as discrete uplifts suggests westward extension of GF. Evidently, it appears that GDF and GF are parts of the same fault.

Transverse Faults

The northern range of the Mainland is affected by innumerable small-scale faults which cut across the flexure irrespective of the individual folds. Several of them form boundaries between adjacent domes or anticlines. In west these faults strike NE-SW separates differently uplifted domes. In central Mainland innumerable small scale faults bunch together to form a wide zone of small scales faults trending NNE-SSW across the Mainland from the Mainland fault in the north to Katrol Hill fault in the south. Faults in almost every direction are noted within this zone. The faults striking NE-SW to NNE-SSW (20°-200° to 40°-220°) are predominant. The eastern and western limits of the domes are marked by N-S transverse faults. The N-S and NW-SE fractures are occupied by basic igneous dykes. The steep scarp marking the KHF is a prominent geomorphic feature of the area. All along the base of the fault scarp, several dissected colluvial fans are encountered (Thakkar et al. 1999). The NNE-SSW, NE-SW, NW-SE and NNW-SSE trending faults exhibit younger fault scarp morphology. This is evident by little or no colluvial deposits along these scarps and absence of gullies or projecting spurs. Moreover, these faults are continuous and never found to cut across by other faults unlike the KHF, which is divisible into several segments by transverse faults cutting across it. The lateral movement along these faults is very conspicuous in the field. Effects of these faults are seen in the form of horizontal shifting of rocks and the E-W trending faults including the Katrol Hill Fault and Kachchh Mainland Fault. The N-S and NW-SE fractures are occupied by basic igneous dykes. The number of transverse faults is greater to the south of Katrol Hill Fault than in the north.

Median High

The most striking feature of the Kachchh basin is the occurrence of a meridianal high in the middle of the basin. This high therefore is called the Median High or Ridge. It has influenced the sedimentation thickness of the Mesozoics. This high passes transversely across both positive and negative element. Structures along this high expose the oldest sediment. They are situated at the highest structural level and show greatest amplitude of the uplift (Fig. 8).

Igneous Activity

Mesozoic sediments are affected by intensive igneous activities. Igneous intrusions are fairly common in all the uplift areas, both in major and minor uplifts. All known forms of intrusive bodies are present and are mainly concentrated in the narrow deformation zones accompanying the master faults. The intrusive bodies are associated with folds and faults as dykes, sills, laccoliths and plugs. The maximum intensity of igneous activity is seen in the northwestern part of Kachchh Mainland Uplift west of Median High and in the northern part of PU (Kaladungar Hill) along the marginal faults, i.e., KMF & IBF. A series of igneous plugs occur along an E-W belt in the central region of KMU, sub-parallel to the rift axis and close to the Katrol Hill Uplift. Some of these plugs are connected to the outliers of Deccan Trap flows capping the hills. Evidently these plugs are the main feeders of Deccan Trap flows, now exposed by erosion. The main Trap province of Kachchh is about 10-20 km to the south, bordering the coastal plain. The Trap flows drape over the tilted eroded surfaces of the Mesozoic rocks and dip parallel to the overlying Tertiary beds. The plugs consist of alkaline basalts with xenoliths of spinel, lherzolite (Karmalkar, et al., 2002) and olivine nodules (De, 1964) indicating that they are derived from upper Sub-Crustal Lithospheric Mantle (SCLM) at a depth of ~40 km. The intrusive bodies occurring as laccoliths, master dykes, massive and extensive discordant plutonic bodies, large sills as well as smaller dykes & sills associated with marginal deformation zone in the western KMU are composed of gabbroic rocks. The massive plugs and dyke swarms at the core of the bordering Kaladongar anticline and large sills associated with the folds in the eastern part of the Goradongar flexure of Pachham Uplift are picrites associated with lamprophyre and diorite. The Trap flows are predominantly tholeiitic basalt. The associations of different groups of mafic and ultramafic rocks are suggestive of different phases of igneous activity viz. synrift stage, post-rift thermo-tectonic stage and inversion stage. During the earlier rift stage mantle derived ultramafic rocks might have sheared the lithosphere by discontinuous stretching. During the later stage the plume (Reunion) related Deccan Trap extrusion took place.

Seismicity of Kachchh

Kachchh lies in the highest zone of seismicity in India (Zone V) and has experienced several large and moderate seismic events during the historical times. The 2001 Bhuj Earthquake (M_w = 7.7) was the most devastating earthquake of recent time, which claimed 20,000 lives. Prior to this earthquake two other large events, i.e., the 1819 Allah Bund Earthquake (M_w = 7.8) and the 1956 Anjar Earthquake (M_w = 6.0) were recorded. It is suggested that owing to its intra-plate setting, the 2001 Bhuj event was an analog of the New Madrid Earthquake of eastern USA (Boudin et al., 2001; Tuttle et al., 2001). Several studies have reported fault plane solution for the 2001 Bhuj Earthquake and the 1956 Anjar Earthquake, which suggest that these took place on south-dipping reverse fault (Chung and Gao, 1995; Negishi et al., 2001). It has also been reported that after the 2001 Bhuj Earthquake, Gujarat region has experienced enhanced seismic activity (Rastogi et al., 2012).

Quaternary Sediments

There are three principal areas in Kachchh, which have witnessed significant Quaternary sedimentation. One is the flat saline Ranns, i.e., the Great Rann of Kachchh and the Little Rann. These flat terrains made up of silt and clay, rich in salt, and occasional sand bodies with no surface exposures of any hard rocks, are the products of marine deposition (Platt, 1962; Biswas, 1974; Glennie and Evans, 1976; Roy and Merh, 1981). The second area is the narrow E-W trending Coastal Plain of southern Mainland Kachchh along the Gulf of Kachchh. The third area is the hinterland Quaternary deposits along the river valleys as terraces and fluvial sand bars, and also along the major fault scarps in the form of colluvial fans, alluvial fans, and valley fills with sandy biomicrites and aeolian miliolite.

Tectonic Geomorphology of Kachchh

The landscape of Kachchh is characterized by rugged hill ranges having a steeper northern side and a gentle back-slope. Fault-controlled hill ranges are flanked to their north by major E-W trending longitudinal faults, i.e., Nagar Parkar Fault, Island Belt Fault, Kachchh Mainland Fault, South Wagad Fault and Katrol Hill Fault. These faults have played a pivotal role in sculpturing the landscape and are the main cause of the cuesta-like topography with a steep northern escarpments and a gentle southern slope (Biswas, 1971). The northern hill range is mainly characterized by various domes, half domes, anticlines, monoclinal flexures and cuestas. Anticlines and domes ranging in elevation between 190 and 388 m are aligned along the southern flanks of the E-W trending faults. At places they are dissected by oblique cutting subordinate faults of varying trends (NNE-SSW, ENE-WSW, N-S and WNW-ESE) along which various present-day rivers have formed their courses (Maurya et al., 2003).

Many streams in the mainland flow across the hills and flexures, forming incised channels, and cutting the uplifted areas marked by upwarps, flexures and half domes, and maintaining their gradient. The faults at some places separate the hill ranges to the south and the Quaternary plains to the north, and is considered to be neotectonically and seismically active. The youthful nature of the steep to sub-vertical fault scarps is attributed to its periodic reactivation. Transverse faults have divided the E-W trending faults into various segments (Maurya et al., 2003). North of the scarp lies gently north-dipping, colluvio-fluvial deposits, which have clasts of boulders to gravel, and appear to merge with the Quaternary and Cenozoic plains at several places.

Drainage Pattern

The drainage pattern in Kachchh Mainland is largely dendritic, and is controlled by the homogeneity in lithology and structure. Around the domes, on the other hand, the drainage pattern becomes radial. Individual streams often show meandering and braided nature, especially in the coastal plain. In the north-flowing streams sharp turns are numerous, which can be explained as stream courses following some pre-existing faults/ weak zones that got reactivated. Such reactivations have also led to the formation of knick points along some north-flowing streams. Significant down-cutting has also taken place along the affected channels (Fig. 10).

The complex drainage pattern of Kachchh Mainland is the result of streams switching or abandoning outlets as they cross the E-W trending master faults. It suggests that there is strike-slip movement along the transverse faults. The NNW–SSE, NNE-SSW and N-S trending trellis, angular and straight drainage patterns that have developed in the area, point to the influence of transverse structures. Further, both the higher and the lower order streams trend in NNW–SSE, NNE-SSW and N-S direction, indicating the influence of recent tectonic activities in the area. The response of streams to the transverse lineaments, fractures and transverse faults is seen in the form of sharp angular turns in their courses and at places as beheading of streams.

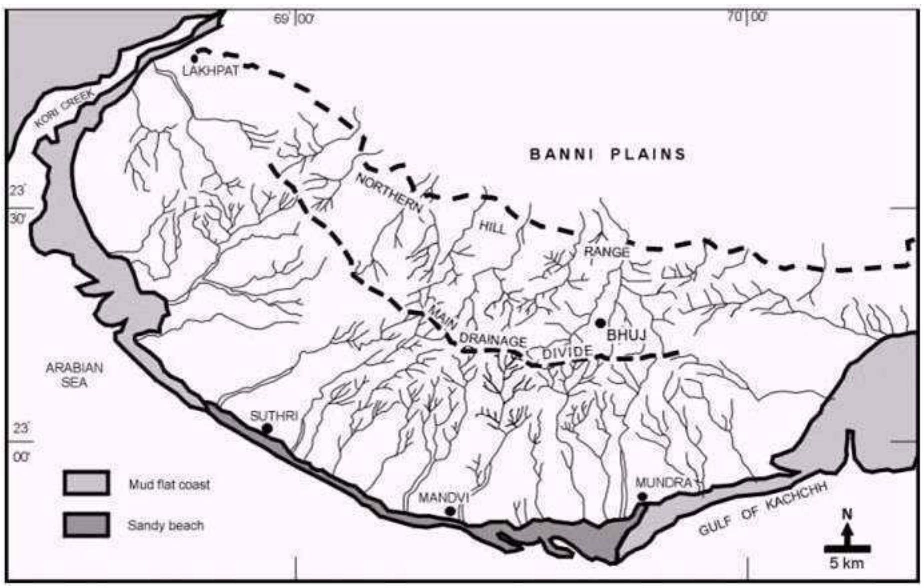


Fig. 10. Drainage map of Kachchh Mainland.

Socio-economic Aspects

Because of the vast desolate Ranns, the large salt-affected plains, the mangrove swamps, the hilly terrain and an arid climate, Kachchh district has a very low density of population. The 2011 density was 46 persons per sq. km (as compared to 308 persons per sq. km in the state of Gujarat as a whole), while the 2001 density was 35 persons per sq. km. With a total of 2.09 million persons, the district's contribution to the total population of the state is only 3.47%. Kachchh has many religious and ethnic groups. The majority of the inhabitants are Hindus, but the Jains and the Muslims are also numerous. The major occupation for centuries is agriculture and cattle breeding. Despite the low population density, the district is known for engaging a large section of its population in international trade and commerce, especially in the Middle East and East Africa. This generates huge financial resources, which has helped much in stabilizing the economy of the district and improving the life style of the inhabitants. For millennia most households of the Kachchhis are known to have engaged partly in international trade through sea routes across the Arabian Sea, especially following the Trade Winds. Even today, a visit to many farmlands in Kachchh will surprise a visitor to find womenfolk and elderly people managing the agricultural production system, the younger men mostly managing the trade abroad, or in large metropolis, with periodic visits to home. The enterprising nature of the people and a large outside contact has helped the inhabitants to experiment with innovative ideas in their land management practices, wherever a scope was noticed. Although summer cropping of pearl millet is universal, with low yield, groundnut, cotton and some pulses are also grown extensively during summer monsoon. Wheat and mustard are grown during winter in some pockets with groundwater-irrigation potentials. The most spectacular recent development in agriculture has, however, taken place in diversification to orchard development, especially for national and international markets. Date palm, mango, banana and papaya are now the high-value crops in parts of the Coastal Plain, especially between Anjar and Mandvi. Diversification is also taking place towards growing spices and medicinal plants like cumin, coriander, fenugreek and Isabgol, as also vegetables.

Kachchh is also known for its sturdy cattle population that has thrived on the vast Banni grassland and on the crops and plant resources of the rugged hilly terrain. It has about 0.6 million cattle and buffaloes, and 1 million sheep and goats. Encouragement given to dairy farming and associated value chain development has vastly improved the scope of livestock raising as a means of livelihoods in the district. Although for centuries Kachchh district remained engaged in agricultural and in trade and commerce, the large-scale devastation of life and property during the 2001 earthquake made the state to think about a policy shift from a totally agriculture-based economy to encouraging industrialization, especially utilizing the large barren and otherwise wastelands. Consequently, by 2011 the district became a major hub of small and medium industries. Two large modern sea ports at Kandla and Mundra help in boosting the economy. The downside is that industrialization has affected the coastal ecosystem of the district, especially as the mangroves have almost vanished from near Mundra Port, making the coastal segment more vulnerable to storm surges, tsunamis, etc. Industrial pollution through effluent discharges and atmospheric loads is another major issue to be tackled now.

Bhuj, Mandvi, Mundra, Gandhidham and Anjar are the major towns in the district. Bhuj is the district headquarters, and is well connected with other major cities of Gujarat through road. Bhuj and Kandla are also connected with other parts of India through air. Bhuj has direct air accessibility with Mumbai, the business capital of India with two flights operating every day, while Kandla – the business capital of Kachchh has daily flight connecting Mumbai and Ahmedabad. Kandla is a major port and a 'Free Trade Zone' in India. Mundra sea port has the largest container cargo facilities in Asia and is nurturing the best goods transport business of India. Almost all the villages in the district are well-connected with Bhuj through all-weather metal roads (Fig. 11).

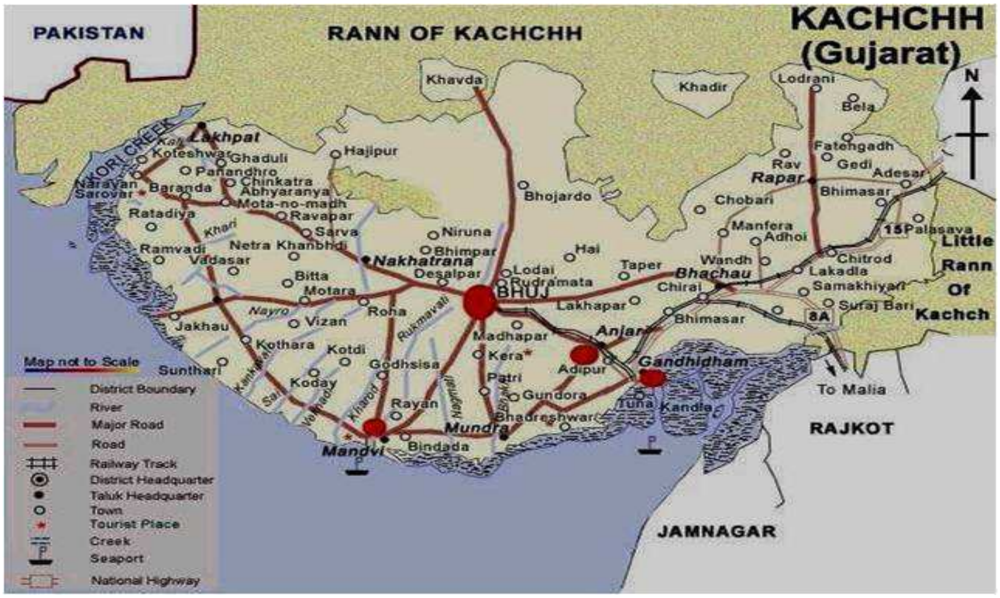


Fig. 11. Towns of Kachchh district and the major surface transport network.

As the connectivity with the rest of the country has improved, Kachchh is gradually becoming a major tourist destination, especially because of the vast salt expanse of the Great Rann, at the southern fringe of which the state now sponsors a “Rann Festival” that attracts tourists from India and abroad. The discovery of a 4000-year old Harappan township at Dholaveera along the north-western fringe of the desolate Khavda Bet, facing the Great Rann draws many tourists, especially as it showcases the advanced water conservation system of those early inhabitants, and the navigability of the Rann during the period. The marshes fringing the Great Rann and the Little Rann attract many different kinds of birds, including the majestic cranes from as far as Siberia, who flock in large numbers during the mild winter, especially in search of good marine food. This has also become an interesting tourist destination. Apart from the above, Kachchh is known for ages for its religious tourism. Two temples at the western end of the mainland at Koteswar and Narayan Sarovar along the Kori Creek, which are dedicated to Lord Shiva and Lord Vishnu, respectively, are mentioned in the ancient Indian scripture, the Mahabharata, as the must-visit places for purification of mind and soul. Another very old temple dedicated to Goddess Durga at Mata-no-Madh (to the west of Bhuj) is among the 16 most-sacred temples of the Goddess Durga in the Indian Subcontinent, and attracts huge congregations from across the country during special religious festivals. The Tertiary clay beds in the surroundings of the temple exude a soothing fragrance. For millennia, therefore, the clay has been used as a natural incense material for temples in

India and abroad, this being a major export item to the Greek and Roman empires during their heydays. Sadly, over-exploitation of the clay has now almost exhausted the reserve. Lakhpat at the north-western end of the mainland was a known seat of higher learning during the time of invasion by Alexander the Great and up to the Early Century Ads, which was described in some details in the writings of the celebrated Chinese visitors of the time. It was also a port en-route to Sind. Repeated earthquakes and wars destroyed the site, but it now attracts some informed tourists. Apart from the above, edifices in Bhuj and Mandvi also attract many tourists.

Bhuj town, with a population about 225000, is centered around the large Hamirsar Tank, which serves as a water storage during the dry months. In the middle of the lake lies a small island (Rajendra Park). The city's most visited sight, the palace of the king of Kachchh, lies adjacent to the water tank (Fig. 12). It consists of several buildings constructed in different centuries, each with its own style and character. The Aina Mahal (the mirror palace) was built in AD 1752 and includes a small museum displaying some of the king's possessions. The younger Prag Mahal, with its massive tower reminiscent of the architecture of a European church, dominates the landscape of Bhuj. A visit to its halls shows the taste of the then king, but the damages done by the massive earthquake of 2001 and the neglect over time, have left the building in a dilapidated condition. The oldest part of the palace is the Durbar Garh. Although it has been in ruins for a long time, some of its walls still stand with beautifully ornamented and latticed windows.

Fig. 12. Aerial view of Hamirsar Lake and surrounding areas of Bhuj town.

Kachchh district has now a university, the Krantiguru Shyamji Krishna Verma Kachchh University, which is located at Bhuj (Fig. 13). It offers education in different branches of Science, Arts, Commerce and Engineering. The University was established in March 2003 with 6 affiliated colleges, but now has 39 affiliated colleges and 14 on-campus academic departments, including the Department of Earth and Environmental Science. The post-graduate (PG) courses run on the campus are for the degree of MBA, MSW, M.Sc. in Chemistry, Geology, Environmental Science, Computer Applications and

Information Technology; M.A. in Gujarati, Sanskrit, Economics, English, Archeology; M.Com; and M. Phil in Gujarati, Economics, Sanskrit and Education. The PG student strength in the campus is about 1000. The university also runs Ph.D programmes in all the departments. About 125 students are currently pursuing Ph.D. Apart from the above courses almost 6,000 students are studying B.A./B.Com and M.A./M.Com courses in distance education mode.

Some other research facilities are also located in the district, especially in and around Bhuj. These include the Gujarat Institute of Desert Ecology (GUIDE), a Regional Research Station of Central Arid Zone Research Institute (CAZRI), and a sub-station of Gujarat Agricultural University.

The main building of the KSKV Kachchh University.

B. DESCRIPTION OF THE FIELD SITES

Day 1
Arrival at Bhuj
Stay at Bhuj.

The first day of the field trip will be spent on a pre-field discussion at KSKV Kachchh University on the areas to be visited, and on the logistics, etc., followed by a visit to the Geological Museum in the University, and then a field visit to some interesting sites around Bhuj. The places to be visited during the field trip are shown in Fig. 14.

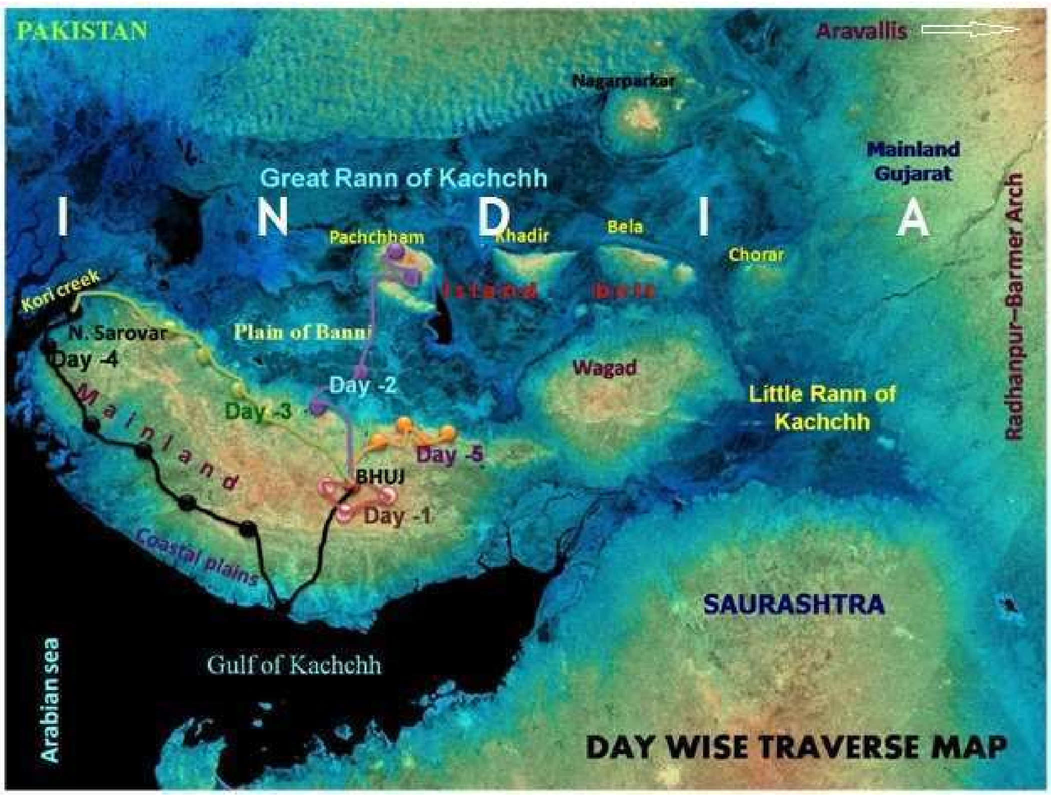


Fig. 14. Image-map of Kachchh district, showing the routes of field traverses in Kachchh Mainland.

Geological Museum, Department of Earth and Environmental Science, KSKV Kachchh University

The Department of Earth and Environmental was established in the year of 2008. The major physical resources of the Department include a Remote Sensing and GIS Laboratory, a Petrography Laboratory, an Environmental Chemistry Laboratory, some geological and geographical field surveying instruments, a library with spacious reading rooms for students and staff members, and a state-of-the art museum of geological specimens, including rocks, minerals, fossils and 3-D models of interesting geological features. Some of the displayed fossils of marine and land reptiles and mammals of Tertiary and Jurassic periods, collected from different parts of Kachchh district, are rare.

Field Trip

Stop 1: Khari Gorge on Kodki Road

A significant young landform on the rocky platform around Bhuj town is a gorge along the River Khari, found 4 km to the west of Bhuj town on Bhuj-Kodki road (Fig. 15). The NE-SW flowing Khari River cuts the sandstone bedrock into a deep gorge for a kilometer in length. This section of the river reveals a deep and narrow gorge with four different tectono-erosional terraces in sandstone, depicting slow tectonic uplift and lateral erosion. The uplifted bedrock terraces have many pot-holes and flutings, indicating high energy conditions during the past climate. The feature is useful in understanding the tectonic and climatic evolution of Kachchh Mainland.

Fig. 15. The Khari River gorge, 4 km to the west of Bhuj town.

Stop 2: Kodki Road Fault and Dyke

The road from Bhuj to Kodki village is full of interesting geological structures. The road-cutting at ~10km from Bhuj exhibits many transverse faults (Fig. 16). Many text-book-type faults with dip-slip movements and down-throw of few cm to a metre can be noticed at the site. A typical dolerite dyke of 5-6 m thickness is also seen to be intruded along the N-S trending transverse fault (Fig. 17). The rocks exposed at the site are sandstones and shales of Cretaceous age. These normal and reverse faults with insignificant down-throws are associated with a NNE-SSW trending 'Median High', a structural high across the Kachchh basin. Such faults are known as hinge faults.

Stop 3: River Section near Rata Talab on Bhuj-Tapkeswari Temple Road

The road from Bhuj to Tapkeswari Temple to the south of Bhuj town runs along the dip slope of the Jurassic, Cretaceous and Tertiary formations. The E-W trending Katrol Hill Fault (KHF) appears as a simple south-dipping fault plane, and also as an intensely-flexured zone at places. The KHF plane is so conspicuous that its hanging wall shows the older Jurassic sandstone, and the footwall block shows the Cretaceous sandstone, indicating a reverse fault (Fig. 18). The common fault plane features like striations and slickenslides are well preserved on the fault plane. The flexure zone at the site is highly complex and structurally complicated as ductile to brittle deformation is very common at the site.

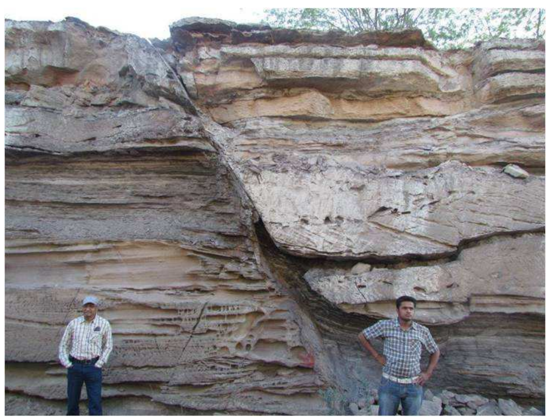


Fig. 16. A N-S trending transverse fault on Bhuj-Kodki roadwith showing more than 1 m down-throw.

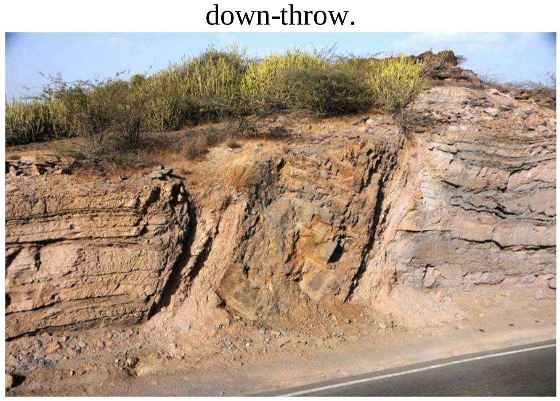


Fig. 17. A dolerite dyke intruding the Cretaceous Sandstone beds on Bhuj-Kodki road.

Fig. 18. Katrol Hill Fault separating the Jurassic Shale from Cretaceous Sandstone on either side near Rato Talab.

Stop 4: Tapkeswari Temple

The receding scarps of the hill on which the old Tapkeswari Temple has been built belong to the 65 km long Katrol Hill Range (Fig. 19). Geologically the area is highly faulted with some transverse faults that have shifted the KHF further north. The scarps are almost 2 km to the south of the Katrol Hill Fault (KHF), which was observed at Stop 3. Some textbook-type faults with horst and graben structures can be noticed at the site. Prolonged uplift along the KHF and erosion has resulted in such topographic peculiarities (Fig. 20). The streams from the scarp slopes show several knick points as evidence of neotectonic movements (Fig. 21). The formation of a cave in the sandstone beds at the top of the hill could be due to weathering and erosion along the bedding planes (Fig. 22). The name Tapkeswari came from the trickling of water along rivulets from the scarp base.

Fig. 19. A panoramic view of the Katrol Hill Range.

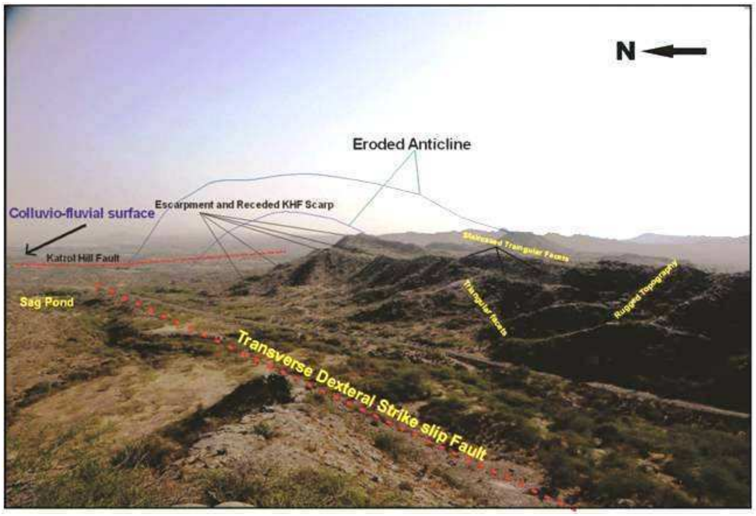


Fig. 20. Eroded domes and transverse strike slip faults guiding the topography near Tapkeswari Temple.

Stop 5: Khatrod Hill on Bhuj-Kukma Road

The most elevated part of Katrol Hill Range occurs to the south of Kukma village, where the hill is called Khatrod Hill. The site provides some good examples of fault scarp morphology and tectonic landforms. The ideal features associated with a fault scarp, like the crest, the scarp face, the colluvial fan slope, wash slope, triangular facets and the alluvial plain surface can be identified at the site (Fig. 23). The scarp face exposes the Jurassic rocks (Jhuran Formation) with alternate sandstones and shale beds. The Quaternary deposits in the area also show various aeolian to fluvial episodes. A structural dome along the KHF, the Khatrod dome, can also be seen here. The older beds are exposed in the core of the eroded dome and the anticlines here. The temple at the top of the hill is called the Ashapura Temple.

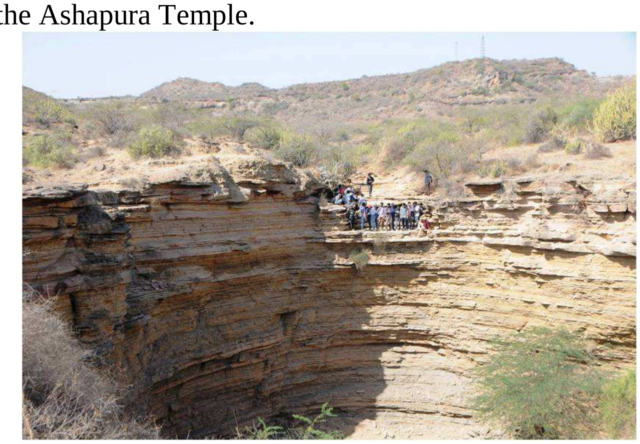


Fig. 21. Knick point along a stream cutting across the Katrol Hill Fault near Tapkeswari Temple.

Fig. 22. Caves in Bhuj Sandstone exposed in the KHF zone near Tapkeswari Temple.

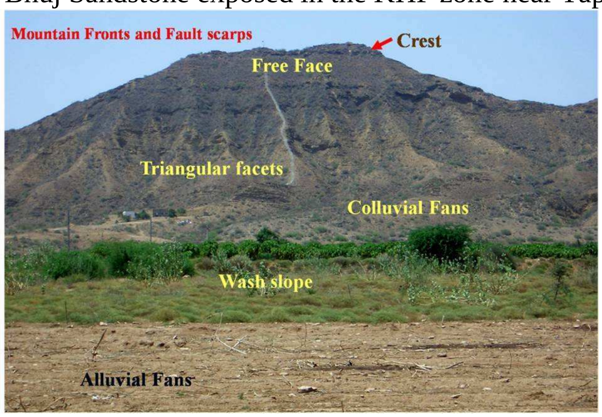


Fig. 23. Khatrod Hill near Kukma village, an ideal site for studying fault scarp morphology.

Day 2

Bhuj to Nirona, Banni, Simri Vandh, Kaladungar Range and back

Stay at Bhuj.

The day will be spent in exploring the geological and geomorphological features to the north of Bhuj town up to Pachchham Island.

Stop 1: Nirona Canyon

Nirona River is essentially a bedrock river that passes through the Jhura Hills (a part of the Northern Hill Range in Kachchh Mainland). A large geological structure, known as the Jhura Dome, has formed the hill. As the river has cut its course through the hill, it has incised its bed into the Jurassic sandstones and shales of Kimmeridigian and Tithonian age in the core of the dome. The rocks vary in colour from black to brown, red and yellow, providing a picturesque view of the valley (Fig. 24). A number of faults and intra-formational unconformities, primary and sedimentary structures and trace fossils could be noticed at the site. This is an ideal location for studies on sedimentology and structural geology. Several streams here follow the structural lineaments and lithology.

Fig. 24. Jurassic sandstone and shale beds of different colours exposed along the Nirona River valley.

Stop 2: Banni Plain

The Banni Plain is a unique geomorphic surface having a maximum elevation of 10-15 m from msl and 8- 10 m from the Great Rann of Kachchh. The dominantly silt and clay layers of the plain are very saline and allow only halophytic grasses and shrubs to grow on the surface. Groundwater is also very saline. However, during the monsoon rains the silt and clay layers, topped by a thinner fine sand deposit, restrict the percolation of water underground, and help to form small pools of fresh water, thus making available some potable water for the sparsely settled people and their livestock in this vast saline plain. Two such types of water body, known locally as the ‘Dhandh’ (for a large water body) and the ‘Thath’ (for a small water body), can be found in the area. The larger ‘Jhils’ (large pools of water) within the plain are typically the salt marshes along the lowermost parts of the Banni, which also receives rainwater during the monsoon months, and become less saline. After the rainy season and till the end of winter these Jhils abound with aquatic life and so attract many different kinds of birds from as far as Siberia in search of good food. During good monsoon years the Jhils get flooded and inter-linked, which cuts off the plain from the mainland in the south and the Pachham Island in the north. The Jhils gradually dry up as the summer sets in.

The natural grassland of the Banni also depends on the meagre monsoon rains, and provides good fodder for the livestock. The higher part of the Banni, with a less saline soil, hosts some of the best grass species (Kar, 2011), which is a boon for the local livestock raisers, called the ‘Maldharis’. These people have settled here several centuries ago, and have preferred to live in this largely inhospitable and secluded plain with their cattle and buffalos, sheep and goats, despite all the hardship for a livelihood based mostly on milk and milk products that they sell in the mainland. Through their toil and constant care they have developed one of the best cattle breeds in the region that is not only drought-hardy but also high milk yielder. Unfortunately, the Banni grasslands are now getting largely invaded by thorny bushes of mesquite (*Prosopis juliflora*), an aggressive coloniser that has no fodder value, and that does not allow grasses to grow in its shade. Consumption of its leaves and pods by the livestock leads to mortality. The plant is not native to Indian sub-continent, but was introduced in the 1940s from Latin America, mainly for the purpose of greenery of the Thar Desert and for fuelwood. Unfortunately, the plant proved to be a menace. Because of its very fast growth, strong and proliferating roots and excellent adaptability to saline and drought conditions, mesquite has replaced the best quality grasses over much of the area (Kar, 2011). Although its dry branches have fuel value, these hardly had any special attraction for the Banni inhabitants. The state is now trying to uproot the mesquite clumps from the Banni plains by using machines, but the battle is proving difficult and long.

Stop 3: Paiya Dome

After crossing the Banni Plain one enters the rugged hilly terrain of Pachham Island (Bet) in the Great Rann of Kachchh. A small structural dome situated between Kaladungar and Goradungar hill ranges in the island, and called the Paiya Dome, is of some interest (Fig. 25).

Fig. 25. A distant view of Paiya Dome between Kaladungar and Goradungar hills. It provides a good example of doubly plunging anticline and syncline structures.

Geologically this structure consists of a series of small double-plunging anticlines and synclines. Here the younger Goradungar Formation, containing fossiliferous limestone and sandstone are exposed abutting the secondary 'Goradungar Fault' that passes between the two ranges. The isolated domal uplift is a result of transverse faults that dissects the Kaladungar Fault, a part of the Island Belt Fault. The Quaternary deposits along the northern face of the dome show signs of continuous upward movement as rising anticlines, above which the deposition of some aeolian dunes has formed miliolitic limestones (sandy biomicrites). Quaternary fluvial deposits in the large valley between the two ranges have reworked miliolites. During the late Pleistocene to Holocene period some alluviation have taken place in the island, making the land suitable for early civilization, as discovered at a site known as 'Kuran archeological site'.

Stop 4: Bandi River Section

The river section here provides evidence for past wet climate during the late Quaternary period. The high river banks exhibit Tertiary rocks (mostly Miocene) overlain by un-assorted Quaternary debris, with sediments ranging from boulders to sand and silt (Fig. 26). This suggests a fast depositional phase, possibly involving some unusually large floods and debris flows. The site is along a valley at the back-slope end of a gently-sloping cuesta of the Kaladungar Range. The mixed debris flow deposits, with intercalation of coarse to fine sand of channel bar deposits that are seen as lenses along the vertical banks suggest deposition by high-intensity flash floods during a wetter climate in the past, as well as debris flow. The exposed Tertiary bedrocks indicate the base level of erosion, following a slow uplift in the area. The meandering course of the river downstream of the site is controlled by activities along the transverse faults in later periods, which have shifted the river courses at places.

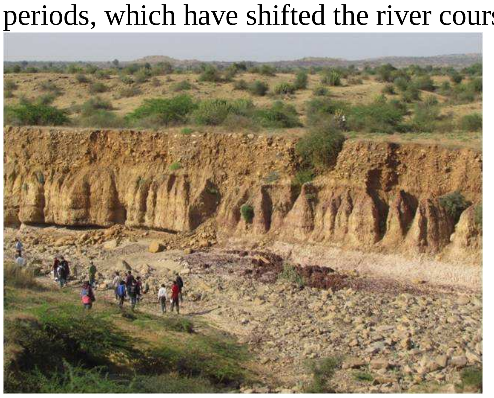


Fig. 26. The Bandi River section in Pachham Island, exposing Quaternary deposits over the Tertiary rocks.

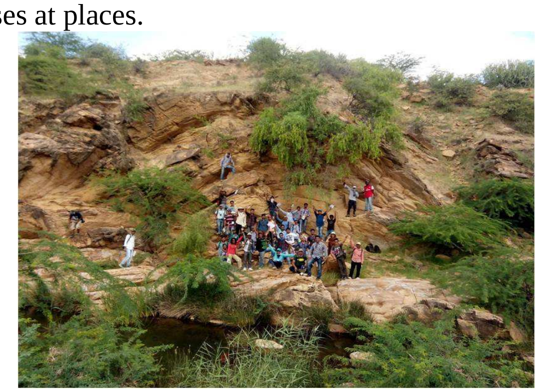


Fig. 27. A symmetrical plunging fold in sandstone, exposed along the northern bank of a stream near Simri Vandh.

Stop 5: River Section near Simri Vandh

Further to the north, and near the Kaladungar Hill range, the stream sections expose the flexures in Jurassic rocks of the Goradungar Formation. Near Simri Vandh village the northern bank of a stream has exposed a symmetrical plunging anticlinal fold in the Jurassic sandstone beds (Fig. 27). Such flexures in the Jurassic rocks are common in the Kachchh Mainland and in Pachham Island, especially due to early Tertiary reversal movements of the horst blocks in the Kachchh basin. It is because of this that the rocks have duel behaviour of ductile and brittle deformations at places. The limbs of the fold and the river beds expose the Raimalro Sandstone member, which is very rich in different trace fossils. Rizocorralum and diplocraterian are very common, indicating their deposition in a shallow shelf to sub-littoral condition during the Callovian to Oxfordian time.

Stop 6: Babia Peak of Kaladungar Hill range

Babia peak of Kaladongar hills (meaning Black Hill in local language) is the highest peak in Kachchh with a height of 462 meters (Fig. 28). Located at the northern end of Pachham Island it occurs along the northern faulted border of the island, conspicuously marking the boundary between the rugged hilly terrain and the vast Great Rann of Kachchh (Fig. 29). The oldest rocks in Kachchh are exposed along the Kaladungar Hill range as the Kaladungar Formation. It is composed of very hard, yellow to gray, nodular limestone. Excellent three sets of joints, and gravity collapse linear valleys can be noticed here. The older rocks of this formation include alternate bands of sandstone, siltstone and conglomerate while the younger ones in the upper part consist of massive sandstone and bands of calcareous sandstone. The younger Goradongar Formation overlies the Kaladongar Formation, showing the change in rock assemblage from sandstones to flaggy limestones and shales. The rock characteristics suggest that depositions took place in a near-shore environment. The southern part of the hill contains hard limestone of Upper Kaladungar Formation. The top of the Babia Hill shows vertical scarps that suggest reactivation of the Island Belt Fault during the later phases of emergence of the Kachchh landscape. There is a laccolithic intrusive body in the core of the dome-shaped hill. Basic (doleritic, andesitic and lamprophyric) dykes are common in the area.

Fig. 28. A view of the N-facing IBF scarp on the Babia Peak of Kaladungar Hill range.

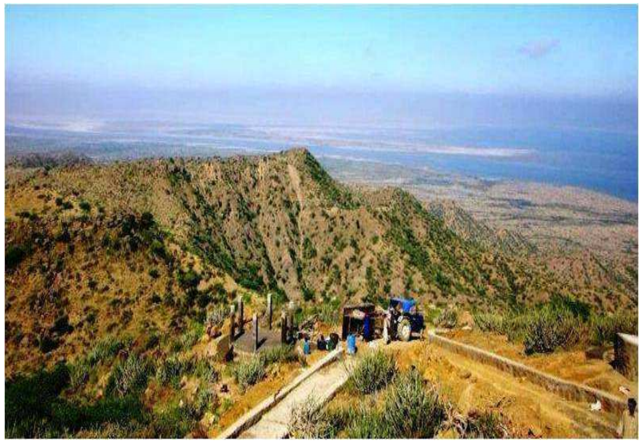


Fig. 29. A panoramic view of the N-facing scarp of Kaladungar Hill range and the Great Rann of Kachchh beyond.

Stop 7: The Great Rann of Kachchh

Descending from the hill, one approaches the vast expanse of the Great Rann of Kachchh (Fig. 30). The apparently stable-looking surface of the salt-encrusted Rann surface is highly tricky for venturing into it, as water occurs just below the surface, and often bogs down an un-suspecting intruder (Fig. 31). Only at some locations the water level goes down during some dry months of the year, and makes the surface trafficable. Such locations are known mainly to the local inhabitants who, in earlier time, used to move across the Rann with their livestock and other supplies for trading purpose. As has been described earlier, the northern end of the Great Rann is slightly elevated due to the Allah Bund Uplift (Fig. 32). Once on that surface, one is able travel more freely on the muddy surface.

Constructing road across the Great Rann is, therefore, difficult. Maintaining a road in its saline marshy environment is still more difficult. However, overcoming all the difficulties, India has constructed a few defence roads across the Great Rann for defending its border.

Fig. 30. The vastness of the salt-encrusted Great Rann of Kachchh.

Fig. 31. Dried up, but deceptive mud polygons along the fringe of the Great Rann of Kachchh near Kala dungar Hill.

Fig. 32. The youthful topography of Allah Bund uplift.

Day 3
Bhuj to Dhinodhar, Lakhpat and Narayan Sarovar
Stay at Narayan Sarovar.

The day three of the field trip will be spent in exploring the fascinating landscape to the west of Bhuj and up to the western tip of Kachchh Mainland along the bank of Kori Creek that once used to carry the waters of the Indus River. The night stay will be at Narayan Sarovar, which is described in the early Indian literature, the Mahabharata, as one of the holiest places in India.

Stop 1: Dhinodhar Plug

Dhinodhar Hill, with a height of 386 m (the second highest peak in Kachchh district) is located about 17 km to the NE of Nakhatrana town, and is an old volcanic plug (Fig. 33). The drainage lines from the hill have developed a radial pattern, and the steep hill slope is covered with scree of cuboidal blocks of basalt. The plug was formed inside an abandoned and eroded volcano, and came into existence during Late Cretaceous period as an eruptive centre of the Deccan Trap lavas. The plug is composed of a closely-spaced cluster of basaltic hills, among which the Dhinodhar peak is the highest. The trekking route for Dhinodhar peak starts at Thän, the ancient ‘Jägir’ of the Princely state. Excellent columnar joints in basalt can be seen in the valley that leads to the hill top (Fig. 34). Mostly the fine-grained thoeiitic basalt was erupted, but occasionally the early-crystallized olivine xenoliths could also be noticed. The lava cuts across the Jurassic rocks and finds its way close to the major Kachchh Mainland Fault.

Fig. 33. A Google Earth view of the Dhinodhar Plug with radial drainage.

Fig. 34. Columnar joints formed due to the cooling of basalt at Dhinodhar.

Stop 2: A Hillock near Dhori Village on way from Dhinodhar to Guneri

Near Dhora village, on way to Guneri and Lakhpat, one can stop at a small hillock formed of the highly-eroded shales of Jurassic Formation. Climbing on to the hillock one can have a panoramic view of the N-S transect across the Northern Hill range of Kachchh Mainland Uplift. This gives a good idea of the regional topography that runs with the structure. To the west one can see a gentle anticlinal flexure of the Keera Dome at the northern edge of the tilted uplift as well as the conical hill of Keera Dungar, which is a plug that had intruded through the master fault, KMF. To the south extends the gently dipping back-limb of the anticline, followed further south by a high escarpment called the Jaramara Cliff that exposes the rocks of Callovian to Oxfordian and Kimmridgian ages, with a protective cap of sandstones of the Uppermost Jumara Formation.

Stop 3: Jumara Dome

The Jumara domal structure is another important structure in the chain of folds in the KMF deformation zone, and is magnificently exposed like a chopped onion, which marks the climax of a syn-rift stage. The formation is predominantly greenish gray shale with thin fossiliferous limestone/marl bands and occasional fine-grained sandstone beds of mid-Callovian to early Oxfordian (Mesozoic) age, constituting the Jumara Formation, which were deposited during the highest sea-level stand in Mesozoic. The top 30 m is glauconitic with oolitic limestone bands, distinguished as Dhosa Oolite Mbr. This member is a treasure house of ammonite fossils, which attracted the attention of British geologists to this area during the early 19th Century. A thin sill of basalt is seen below the Dhosa Oolite Mbr, going round the dome. Towards the centre of the dome the road crosses the shale - limestone boundary between the Jumara and the Jhurio (Bathonian-Early Callovian) formations (Fig. 35). The entire sequence is very rich in fossils from ammonite to coral. At the core of the dome several coral biostromes are present. The northern limb of the dome dips steeply to the N with a hard dirty brown limestone bed. This limb, draping the Kachchh Mainland Fault (KMF), forms a near-vertical E-W ridge, beyond which stretches the Banni plains.

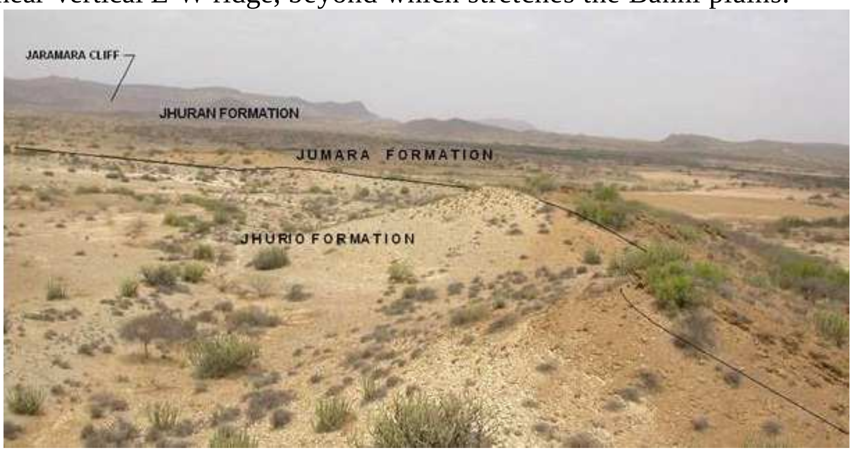


Fig. 35. The contact between the Jhurio and the Jumara formations, exposed in the core of the Jumara Dome.

Stop 4: Ghuneri Structural Dome

Ghuneri structural dome is in the northwestern corner of Kachchh Mainland Fault near Ghuneri village, and is distinguished by escarpments facing the Rann surface to the north. A zone of second order faults is exposed along the foot of the marginal escarpment which is considered as the KMF zone (Fig. 36). This marginal fault is exposed in segments. Where exposed, steeply upturned (ankle fold) Tertiary strata are juxtaposed with steeply down-folded (knee fold) Mesozoic strata. Such fault ridges are offset at places by tear faults. This is a distinct geological and geomorphic structure where the streams follow circular paths along the lithology, and form a circular drainage patterns.

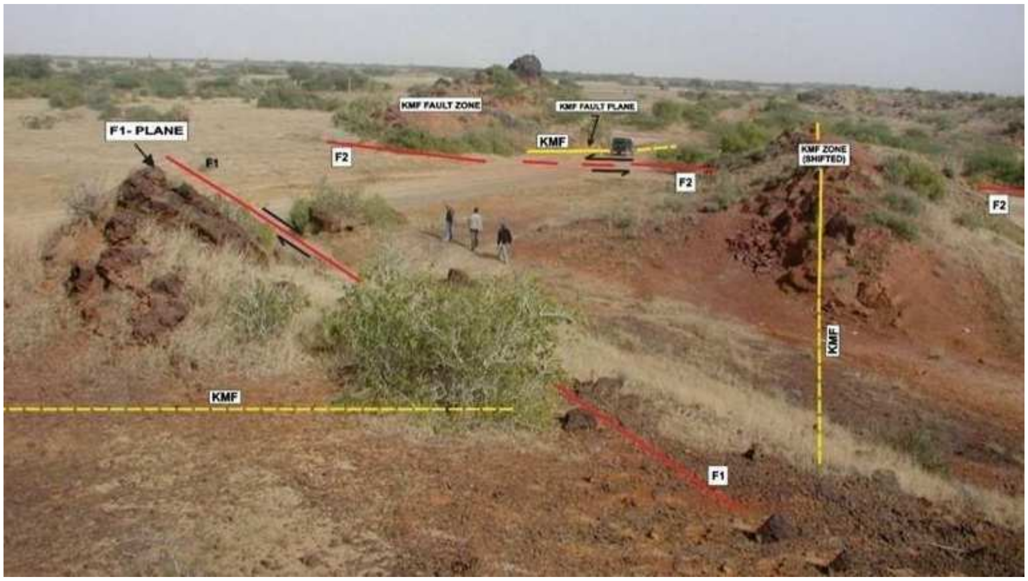


Fig. 36. The western termination of the KMF at Guneri, dissected at places by transverse faults.

Day 4
Narayansarovar to Koteswar, Naliya, Mandvi and Bhuj
Stay at Bhuj.

On the fourth day of the field trip the terrain along the Coastal Plain bordering the Arabian Sea will be explored.

Stop 1: Narayan Sarovar

Narayan Sarovar near the eastern bank of the Kori Creek is an ancient holy place for pilgrimage for the Hindus, and is described in the Mahabharata as having a pond fed by natural spring, where bathing ensures purity of body and mind. Unfortunately, the natural spring has now ceased to exist, possibly due to very high exploitation of groundwater in the surroundings. The bathing facilities have been spruced up to cater to the needs of large number of devotees that gather here annually. The Sarovar (a Sanskrit word for lake) and the temple complex associated with it is situated on a low limestone terrain detached from the mainland, and surrounded by tidal mud flats associated with the Kori Creek. The lake water is always sweet and rarely gets dry, probably due to the aquifer in the synclinal structure in Tertiary rocks here.

Stop 2: Koteswar

The temple at Koteswar is located on a rocky promontory on the bank of the Kori Creek, 1 km to the southwest of Narayan Sarovar. This is also a very old pilgrimage site, and is described in the Mahabharata as having very high spiritual significance. The

Creek is about 12 km wide here, and the coastal tract from Lakhpat to Koteswar and further south and east up to Jakhau is muddy with an inter-tidal area that is rich in marine life and mangroves.

Several other creeks between Kori Creek and India's border with Pakistan along the Sir Creek are extremely rich with fish and other marine life. In ancient times, the maritime route for trade and commerce from Sindh (now in Pakistan) to the cities along the west coast of India, and to the African shores used to follow the Kori Creek via Sindri, Lakhpat and Narayan Sarovar-Koteswar. The devastating earthquake of 1819 in the Great Rann of Kachchh created a huge mud wall across the creek between Sindri and Lakhpat, and disorganised the steam, the Puran, through it. The high mud wall was named by the inhabitants as "Allah Bund" (i.e., a dam created by the Almighty). Sindri town and the Puran's course from there to the Allah Bund got submerged, while the stream segment south of the Allah Bund to Lakhpat and beyond got tilted, but survived. In between, the river lost its navigability in the up-thrown segment. According to the descriptions of Greek historians, Alexander the Great might have sailed through either Kori Creek or any of the many other creeks in the Indus Delta during his campaign in the Indus plains around 325 BC. One of the detachments of his army, while returning to Greece, might also have experienced tsunami due to a major earthquake along the coast to the west of present-day Karachi, and might have suffered some losses. While coastal segment to the west of Kori Creek and up to Sir Creek is an unfinished delta, the segment from Koteswar to Jakhau in the east is characterised by several features of drowning, including a ria coast (Kar, 1993; 2011).

Stop 3: Coastal Dunes at Pinjor Pir

About 5 km to the north of Narayan Sarovar a number of 10-12 m high coastal sand dunes can be observed along the eastern bank of the Kori Creek. The dunes are fine-to-medium-grained, partly vegetated, and are oriented SW-NE, in the direction of the dominant summer monsoon wind. They rest partly over the narrow mud flat along the Creek, and partly over the Tertiary limestone terrain inland.

Stop 4: Kakdi River

Continuing the journey south-eastward towards Mandvi, the road crosses a small stream with a rocky bed, the Kakdi River (Fig. 37). It exposes the Deccan Trap basalt and the lower part of the Paleocene Formation, while to the north of the road bridge, shales rest over the eroded, partially lateritised surface of the Deccan Trap, which is the basement of Tertiary Formations in western India. This formation overlaps the Late Paleocene Mata-no-Nadh Formation at this site.

Fig. 37. The Kakdi River bed, exposing the Deccan Trap basalt, with a sharp contact with Palaeocene formations.

Stop 5: Rakhadi River

The deeply incised ephemeral valley of the Rakhadi River in the near-horizontal Eocene Limestone beds provides a spectacular site of a canyon-like feature with vertical rocky banks (Fig. 38). Walking away from the road and by the right-hand side of the river one finds a palaeo-channel filled with Quaternary conglomerate and sand on the cliff. Walking 500 m upstream, large caves are seen in the massive foraminifera-infested nummulitic limestone (Fig. 39). Several such caves of different sizes can be noticed upstream of this site, which occur at the base of the cliffy bank of limestone. Such mid-Eocene cavernous limestone beds proved to have excellent reserves of oil & gas in the western offshore fields.

Fig. 38. The Rakhdi River exposing the mid-Eocene nummulitic limestone beds with caves.

Fig. 39. A close view of a solution cave in nummulitic limestone along the Rakhdi River.

Stop 6: Wayor on Naliya Road

At Waior village, one can walk up the river valley for 1 km to a 12 m high cliff section. This section is known as the Chattian type section, and is internationally recognized as an important reference section for the yellow, bedded, and bio-turbated limestone, inter-bedded with thin calcareous shale, rich in forams like Miogypsina and Spyroclypeus. It also exposes other mega-fossils, including ichno-fossils.

Stop 7: Khari River

Turning E from the main road on the Khari River, the type section of Early Miocene (Aquitanian) Khari Nadi Formation (yellow and variegated fine sandstones) can be observed resting over the highly fossiliferous blue clay with molluscs.

Stop 8: Mandvi Beach

Mandvi, the second largest town in Kachchh district, has a wide beach, which is composed of a foreshore and a backshore, followed landward by a raised beach of 2-3 m height, the foredune and then a tidal mud flat at its back and a saline sand flat (Fig. 40). The coastal alluvial plain occurs beyond it. Longshore drift is present along the coast, which carries the sand eastward to form a spit between Mandvi and Mundra. The raised beach appears to be related more to neotectonic activities associated with the Median High than to eustatic change of base level (Kar, 1993).

The return journey from Mandvi to Bhuj will be through the hilly terrain across the Katrol Hill range.

Fig. 40. The foreshore, the backshore, the raised beach and the foredune at Mandvi.

Day 5
Bhuj to Habo Dome, Kas Range, Lothia Nala and back
Stay at Bhuj.

On the 5th day of the field trip we propose to explore the terrain to the north-east of Bhuj, which is nearer to the epicentre of the devastating earthquake of 26 January 2001. The traverse route provides some excellent examples of the geomorphic expressions of a tectonically active large dome and anticline, especially along the escarpments, stream valleys, etc.

Stop 1: Zikdi Road Cutting

The first stop at Zikdi road cutting is on the south-western fringe of Habo Dome, which is roughly of the size of 16 km (Fig. 41). This domal structure, upwarping the Mesozoic rocks in the form of a cluster of hills, occurs roughly between the Khari River in the west and the Kaswali River in the east, both exploiting transverse faults bordering the Habo Dome, and across the Kachchh Maniland Fault, and both debouching into the Great Rann of Kachchh in the north. The dome's fringing curvilinear escarpment in the east, roughly along the Kaswali River, leads to the Kas Hill Range. The rocks exposed at the site are sandstones of upper Jhuran formation formed in a deltaic to fluvial depositional environment. The site is at the junction of two faults. One to the north of the scarp runs E-W, while the other, a transverse strike-slip fault, dissects the E-W trending fault. It displaces the escarpment by several metres along the N-S trend. To the north, a large cluster of hills in dome shape characterises the Habo Dome.

Fig. 41. The southern flank of the Habo Dome, where the Kas Hill provides a cuesta landscape.

Stop 2: Dhrang, at the core of Habo Dome

The path along a small stream to the south of Dhrang village leads to a huge exposure of laccolith intrusion in the core of the Habo Dome. The rock type is gabbro, which has a sharp contact with the Mesozoic limestone bed (Bathonian) above (Fig. 42). The Mesozoic rocks at the site seem to be dipping due north. The sedimentary sequence at the site consists of bands of Dosa oolite (Jumara Formation), golden oolite and thickly bedded limestone (Jhurio Formation). The bedding of the limestone appears up-wrapped due to the igneous intrusion. Small micro-faults are seen to displace the limestone beds at several places. Towards the northern and southern margins of the intrusion the limestone beds dip by 3°/290°. Towards the centre, the beds are almost horizontal. The laccolith-like intrusion is approximately 20 m thick in the centre and gets reduced considerably towards the north and the south. The contact between the intrusion and the overlying limestone is sharp but protrusion in the form of small sills, appophysis, etc., along and across the bedding planes are noticed. At places the contact zone is marked by the presence of suspected serpentine (green). The intrusion is fine-grained along the contacts, but becomes coarse-grained towards the centre, where pyroxene crystals of 1-2 cm size can be noticed. The igneous intrusion is highly jointed; the joints are vertically disposed, suggesting that the cooling front was horizontal. The joints become more regular and closely-spaced in the coarse grained rock near the centre of the plug. Towards the northern end, there are a couple of large (> 50 cm) angular xenoliths of limestone in the intrusion. The eastern and western limits of the domes are marked by N-S transverse faults. Such distribution indicates a close genetic relationship of magmatism and tectonism in this part. The second mode of uplift is caused by the sub-crustal intrusions. The existence of laccolith at Dhrung is suggestive of shallow level of uplift of the sedimentary strata.

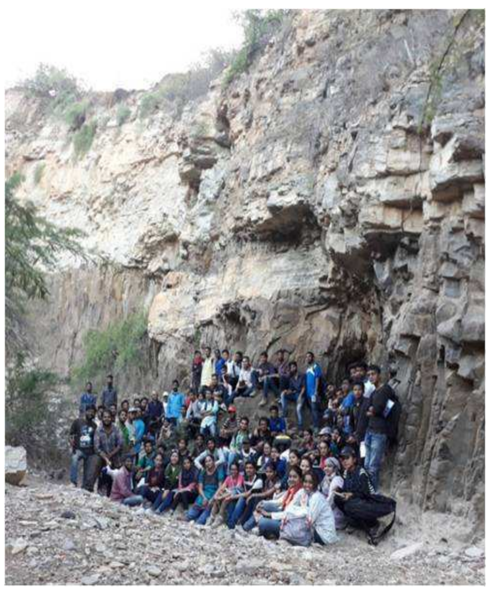


Fig. 42. A gabbro laccolith in contact with Mesozoic limestone bed in the core area of Habo Dome.

Stop 3: Foothills of the Kas Hill Range

The Kas Hill Range to the east of Habo Dome is an anticlinal ridge with a prominent N-facing escarpment in the Mesozoic rocks (Jumara Formation), roughly from near Lodai in the west to the vicinity of Jawaharnagar in the east (Fig. 43). The escarpment is followed southward by the dip slope of a cuesta that forms the southern limb of the large Kas anticline, the northern limb of which was eroded out.

The narrow Kas Hill anticline occupies the entire length of the eastern half of the main flexure, and retains mostly the original form of the flexure. It has a chain of domes along its axis, the most important among which is the Kas Hill Dome and the associated Kas Hill Fault, which branches off from the Kachchh Mainland Fault (KMF) as a feather fault, with a tilted block between them. It is believed that movements along the KMF resulted in the major earthquakes of 1819 and 1956. Faults are much less in number further to the east. Only a few NE-SW or NNE-SSW oblique faults are seen across the Kas Hill anticline.

Fig. 43. The Kas Hill range with its escarpment marking the Kas Hill Fault near it. This is one of the most active seismic areas in Kachchh.

Stop 4: Lotia River Gorge

Lothia River, originating from the Kas Hill, traverses through the hill's piedmont zone in the middle reaches, and then ends up along the margin of the Banni Plain. Like the other north-flowing streams, Lothia River also forms an alluvial fan before it meets the Banni Plain. The river flows through Bhuj Sandstone in its middle and lower reaches. At the mouth of the river, thin Quaternary cover is present in the form of valley fill sequences. As the river crosses the north dipping scarp of the KMF, it abruptly incises Bhuj sandstone beds by about 11 m and forms a gorge (Fig. 44). Here the river behaves like a fault-controlled channel.

Fig. 44. Bedrock terraces in Bhuj Sandstone along the Lotia River to the east of Kas Hill.

Day 6: Depart from Bhuj.

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