CHAPTER – 2

REGIONAL STRUCTURE AND GEOLOGY

The western rift basin of India (Figure 2.1) such as the Kachchh, Saurashtra, Cambay and Narmada comprising of the rift-fill sediments are contemporaneous with the Upper Gondwana formations, of which, the most complete record of the Mid-Jurassic to Early Cretaceous sediments is found only in the Kachchh basin (Biswas, 1999). After the Late Cretaceous Deccan Trap volcanism, the Kachchh basin experienced rift inversion due to initial collision and anti-clockwise rotation of Indian plate which also caused the uplifting of the present highland areas comprising of complex anticlines and domes near the marginal faults of the uplifts (Biswas, 1987). These uplifts are observed along five east-west trending principal faults such as – (**i**) the Nagar Parkar fault, (**ii**) the Island Belt fault, (**iii**) the South Wagad fault, (**iv**) the Kachchh Mainland fault and (**v**) the North Kathiawar fault. The Kachchh basin is conspicuously characterized by these highlands surrounded by extensive low-lying mudflats and saltflats. The highlands are formed of the uplifted tilted horsts between the half-grabens which are delineated as the lowlands. The highlands consisting of the uplifted areas along marginal faults show rugged hilly topography and expose the Mesozoic rocks, while, the low-lying areas enclose the Tertiary to Recent marine and fluvio-deltaic sediments (Biswas, 2016a). The slopes and coastal plains bordering the highlands expose the Tertiary rocks. The low-lying areas or half grabens are composed of the Tertiary-Quaternary and Recent sediments resting above the Jurassic- Cretaceous sediments (Biswas, 2016a).

STRUCTURAL FRAMEWORK OF KACHCHH RIFT BASIN

The Narmada, Kachchh, and Cambay are the three marginal rifts (Figure 2.1) which form an integral part of western continental region of India with the presence of many active faults (Biswas, 1987; 2005; Talwani and Gangopadhyay, 2001). The faults in these rifts follow important tectonic trends, viz. Kachchh basin in Delhi trend, the Narmada in Satpura trend, and Cambay basin in Dharwar trend (Biswas, 1982). The structural style of the Kachchh basin on the western continental margin of India is exceptional. The Kachchh basin is a pericratonic rift basin, located southeast of the Makran triple junction between the Arabian–Eurasian–Indian plates (Biswas, 1987). The northern and the southern part of the Kachchh basin is bounded by Nagar-parkar uplift and Saurashtra horst respectively, which in turn forms the shoulder highs for the basin. The open continental shelf and the Randhanpur- Barmer arc limit the basin extension towards its west and east (Biswas, 1987).

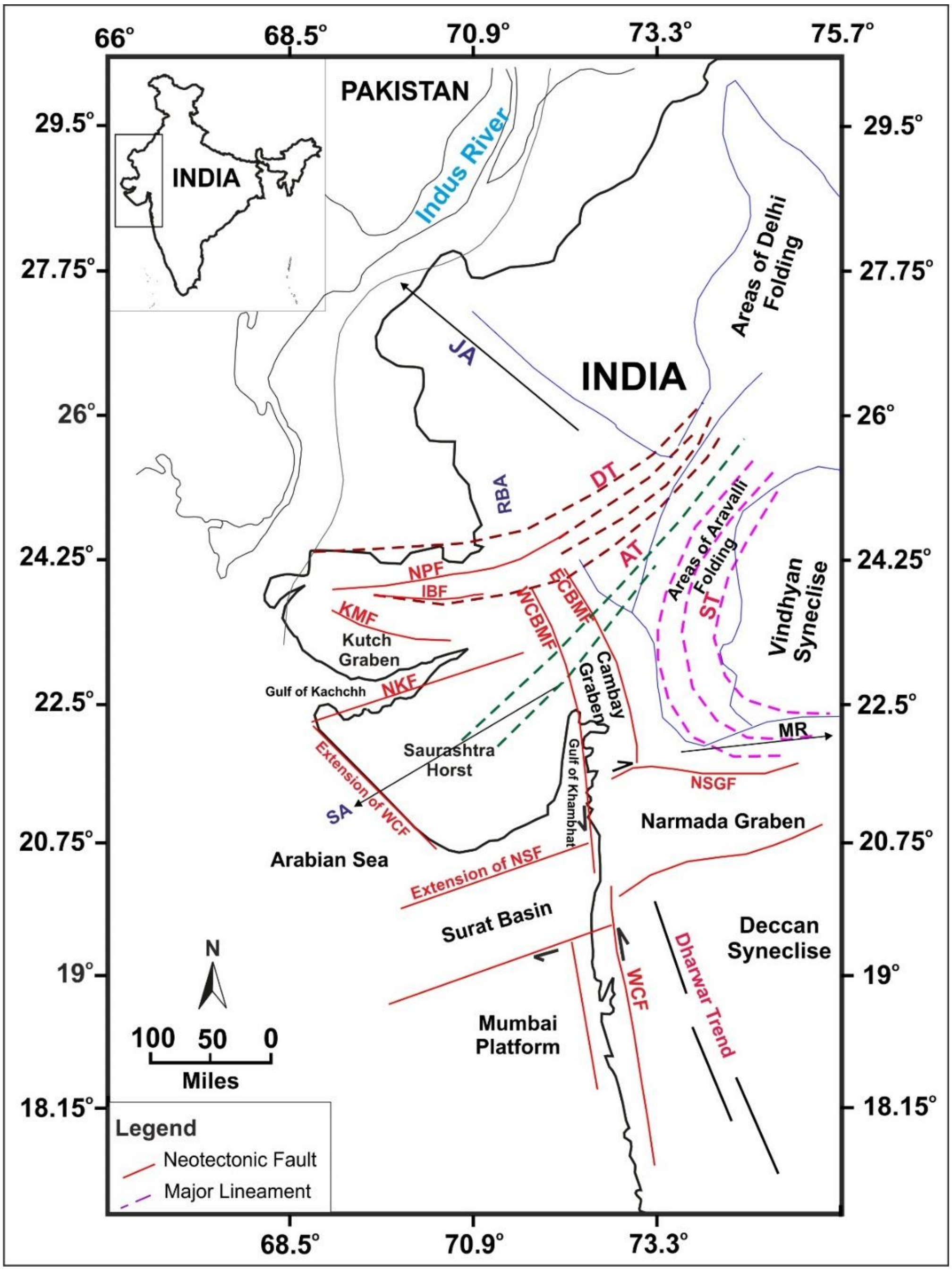

Figure 2.1 Tectonic map of the western part of India showing pericratonic rift basins with major structural lineaments and faults. Modified from Biswas (1987). Inset – location map of India. (JA-Jaisalmer Arch; RBA-Radhanpur Barmer Arch; SA-Saurashtra Arch; MR-Malwa Ridge; DT-Delhi Trend (maroon dashed lines); AT-Aravalli Trend (green dashed lines); ST-Satpura Trend (pink dashed lines); WCBMF-West Cambay Basin Margin Fault; ECBMF-East Cambay Basin Margin Fault; NPF-Nagar Parkar Fault; IBF-Island Belt Fault; KMF-Kachchh Mainland Fault; NKF-North Kathiawar Fault; WCF-West Coast Fault; NSF-Narmada Son Fault; NSGF-Narmada Son Geofracture). Compiled from Biswas (1987); Merh (1995); Dasgupta et al., (2000) and Rastogi et al., (2012).

The basin was subjected to several episodes of uplift exposing Mesozoic rocks and is bounded by roughly east–west trending major intra-basinal faults (Biswas, 1987). The tilted block uplifts in the region are caused by sub-parallel faults (from north to south) such as Nagar Parkar Fault (NPF), Allah Bund Fault (ABF), Island Belt Fault (IBF), South Wagad Fault (SWF), Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF) (Biswas, 1987). These uplifted highlands are surrounded by plains of the Great Rann, Banni and Little Rann. The northern hill range is bounded by major faults, namely the Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF). The marginal hill ranges of the highlands with escarpments facing the plains of the basins, are marginal flexures or monoclines along the master faults of the uplifts (Biswas, 1987).

The most striking feature of the Kachchh basin is the occurrence of NNE-SSW trending Median High (subsurface basement ridge) in the middle of the basin. This feature controlled the facies and thickness of the sediments in the basin (Biswas, 1987). The western side of the median high is comparatively deeper and is characterized by thicker accumulation of sediments showing change of facies from shallow to deeper shelf; while towards its eastern side, the basement is shallow with thinner sediment layers and the facies varies from shallow marine to littoral and fluvial (Biswas, 1987). Most of the uplifts occur on the higher eastern part of the basin. Thus, this Median High appears as the hinge line of the basin and forms a tectonized zone characterized by intense faulting, folding and intrusions.

The Kachchh basin evolved in two major stages (Biswas, 2016b) – the first, the extensional rift stage which was initiated during the Late Triassic breakup of the Gondwanaland in the context of India/Africa separation. The extension phase, during the pre-break crustal expansion in Late Triassic- Early Jurassic time, induced the tensional activation of the primeval faults, triggered the formation of tilted horst and half-graben structures and initiated the Mesozoic sedimentation (Biswas, 2016b). The rifting was aborted in Late Cretaceous pre-collision stage of the Indian plate which was marked by end of sediment accumulation and uplift due to post-break up crustal rebound. Biswas (2016b) called this as a “Rift-Drift” transition movement of Indian plate. After this, Deccan volcanism occurred during the Late Cretaceous-Early Paleocene period (Shukla et al. 2001; Pande, 2002) which got deposited adjacent to fault lines and domed the overlying Mesozoic sequences. During the drift phase, the slab-pull from Tethyan trench caused tilting of plate, resulting in to trailing edge uplift of the plate preceding to its collision with Asian Plate. This phase was accompanied by the trans-tensional movement due to the drift motion of the plate, splitting of marginal first order drape folds into second and higher order folds and associated conjugate faulting (Biswas, 2016b).

After the volcanism, occurred the second stage of inversion of the basin, which resulted due to the onset of the compressive stress regime in response to collision of the Indian plate with the Eurasian plate during Early Eocene (Biswas and Khattri, 2002). During this phase, the basin was periodically uplifted along major E-W trending intrabasinal master faults- Katrol Hill Fault (KHF), Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and Island Belt Fault (IBF) which resulted in the asymmetry of domes. Some of the stress was accommodated by the transverse faults formed along the master faults (Maurya et al., 2003b). Vertical stress regime dominated in between the two phases. The Tertiary sedimentation mainly took place in Paleogene and Neogene times. These deposits crop out along narrow coastal plains of Kachchh Mainland and peripheral plains of uplifted Mesozoic structures (Biswas, 1992). The Quaternary sediments occur as colluvio-fluvial deposits, aeolian and valley-fill miliolites and coarse to fine-grained alluvial deposits. These deposits are further covered unconformably by the Recent alluvium (Biswas, 1971).

STRATIGRAPHY OF KACHCHH BASIN

The Kachchh paleo-rift basin bears a complete record of syn-rift sediments belonging to Middle Jurassic to Early Cretaceous and post-rift sediments belonging to Late Paleocene to Pliocene and the most recent Quaternary sediments (Biswas, 2016a). The post-rift inversion related uplift and Deccan Trap volcanism mark the Late Cretaceous-Early Paleocene break in sedimentation. The Deccan Trap flows separate the two rock groups – Mesozoic and Tertiary. The stratigraphy of Kachchh comprises of the rocks belonging to Mesozoic, Tertiary and Quaternary (Figure 2.2). The recent sediments which mostly cover the older deposits occur mainly as alluvium and calcreted or ferricreted loose sediments (Biswas, 2016a). The Quaternary deposits comprise of a range of sediments from marine to fluvial, lacustrine and aeolian deposits. The Tertiary sediments were mainly deposited in littoral to shallow marine shelf environment, while the uplifted areas exposing the Mesozoic sequences were deposited in sub-littoral to deltaic environment (Biswas, 1987).

Mesozoic stratigraphy

Biswas (1977) recognized three main lithologic provinces and correlated the three sets of rock-unit sequences in the Kachchh basin. The three Mesozoic provinces ranging in age from Middle Jurassic to Lower Cretaceous are Kachchh Mainland, Pachham Island and Eastern Kachchh as shown in Figure 2.1.

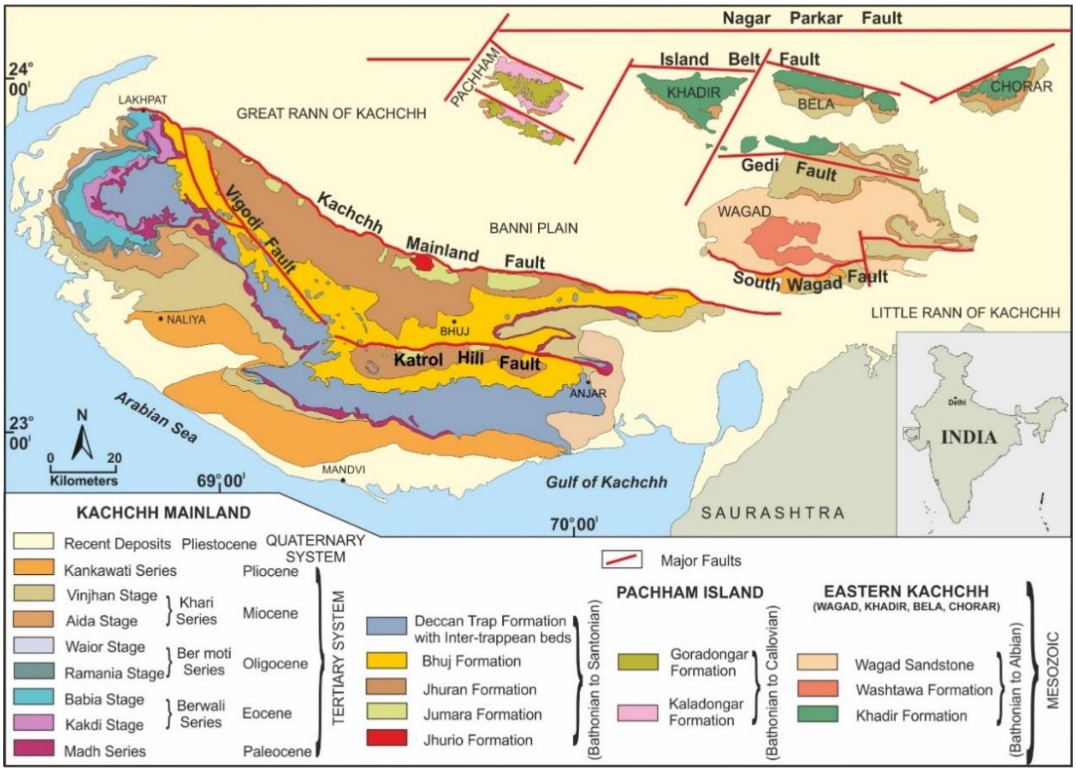

Figure 2.2 Geological map of Kachchh Basin showing major formations and faults. Map redrawn by Patidar (2010) based on Biswas (1993).

The Late Triassic pre-rift sediments, Jurassic syn-rift sediments and Early Cretaceous post-rift sediments form the Mesozoic sequence of rocks (Biswas, 2016a). Fossiliferous shales with thin limestone beds (Jumara and Washtawa formations) were deposited during the rift climax during the Callovian-Oxfordian time. The maximum flooding surface is marked by thin glauconitic, oolitic limestone bands in greenish glauconitic shales (Dhosa Oolite Member) in the upper part of the formation (Biswas, 2016a). The regressing sea left behind Late Jurassic sediments, winding up with the post-rift Early Cretaceous deltaic sediments of the Bhuj Formation. The three lithostratigraphic provinces identified by typical lithologic association are Mainland Group, Pachham Group and Eastern Kachchh Group; wherein, the Mainland Group characterizes sediments deposited in the Gulf of Kachchh half-graben, while the Pachham and Eastern Kachchh groups designate the lower and upper part of the Banni half-graben deposit respectively (Biswas, 2016a).

<u>Kachchh Mainland Group</u>

The Mesozoic rocks of the Kachchh Mainland are divided in to four mappable rock stratigraphic units - Jhurio, Jumara, Jhuran and Bhuj formations in the ascending order of their ages (Biswas, 1977). The Bhuj Formation is unconformably overlain by the Deccan Trap flows. Base of the Jhurio formation is not exposed in the Mainland.

Table 2.1 Stratigraphic set-up of Kachchh basin (after Biswas, 2016a).

AGE		MAINLAND GROUP		PACHHAM GROUP		EASTERN KUTCH: (KHADIR-BELA-WAGAD) GROUP	
		FORMATION	LITHOLOGY	FORMATION	LITHOLOGY	FORMATION	LITHOLOGY
LATE CRETACEOUS to PALEOCENE		DECCANTRAP 500 m	Basalt flows				
ALBIAN to NEOCOMIAN	POST-RIFT	Unconformity BHUJ 850 m	Mainly sandstones with ferruginous bands and shale interbeds with plant fossils. (Fluvio-deltaic)	Quaternary &Recent cover	Quaternary &Recent cover	Quaternary & Recent cover Teritary rocks 150 m+	
TITHONIAN to MID-OXFORDIAN	LATE-SYNRIFT	JHURAN 760 m Unconformity	Sandstones with calcareous bands and shale, (delta front) middle part mainly shale (Pro-delta)	Tertiary rocks300 m+ Unconformity	Laterite & shale	Unconformity WAGAD SANDSTONE 365 m (not exposed in KHADIR)	Laterite & shale Mainly sandstone withferruginous bands and shale interbeds with occasional plant fossils(Delta front).
EARLY OXFORDIAN	CLIMAX	JUMARA 275 m	Mainly shale with thin limestone beds, oolite bands on top (Shallow marine)	GORADONGAR 154 m	Upper: shales/sandstone, Middle: cherty limetstone, Lower: flaggy limestone with golden oolite bands (Shallow marine)	GADHADA (Exposed in KHADIR)	(WASHTAWA Fm. inWAGAD) Upper: maily shale/sadstone - shallow marine. Middle: shale and sandstone - deltaic. Lower: cherty limestone, shale and siltsontes - shallow marine/tidal flat. Basalpart. granite cobble conglomerate & arkosepiedmont fan.
CALLOVIAN	>>>>>>						
BATHONIAN to BAJOCIAN	SYNRIFT	JHURIO 290 m+ Unconformity Basement	Interbedded shale and limestone with golden oolites. Upper part: bedded limestone. (Shallow marine) Not exposed	KALADONGAR 470 m+ Unconformity Basement	Mainly sandstones withshale interbeds (Marine Fore-shore) Not exposed	KHADIR 650 m (Exposed in KHADIR) Basement	
PRECAMBRIAN							Basement: Precambrian granies/syenite

Jhurio Formation

The Jhurio formation has been named after its type-section in the Jhurio hill located in north-central mainland and comprises of a thick sequence of limestone and shales with bands of ‘golden oolites’ (Biswas, 1977). The formation is exposed as small inliers along the northern margins of Habo, Jhurio and Jumara domes. The upper part of the formation is made up of thinly bedded white to cream colored limestones (pelmicrite and biomicrite) with thin bands of golden oolite. The middle part is composed of thick beds of grey yellow weathered shales alternated with thick beds of golden oolitic limestones and the lower part comprises thin beds of yellow and grey limestones (Agarwal, 1957). The base of this formation is not seen anywhere while, it conformably underlies the green shales of Jumara formation. The age of the formation ranges from Bathonian to lower Callovian.

Jumara Formation

The Jumara Formation has been named after its type section in Jumara dome hill near the Rann, north of Jumara village and comprises of monotonous olive-grey gypseous laminated shales with thin red ferrugenous bands (Biswas, 1977). Thin, fossiliferous oolitic limestone bands called ‘Dhosa Oolite beds’ occur in shales which serve as the main key-bed in the mainland stratigraphy. Maximum transgression during Jurassic is also marked by the Dhosa Oolite member, found on the top of Jumara Formation from west to east across the Mainland. It also characterizes the Early Oxfordian maximum flooding surface followed by Middle Oxfordian-Early Kimmeridgian hiatus (Krishna et al., 2009), which indicates absolute erosion of the whole highstand sequence above the maximum flooding surface due to tilting of the Mainland block above the relative sea level (Biswas, 2016a). Local disconformity is observed at places where the Jhuran shales are seen resting over the eroded Dhosa oolite member. The age of the formation ranges between Callovian to Oxfordian.

Jhuran Formation

This formation is divided into four members - lower, middle (Rudramata shale), upper and Katesar member (Biswas, 1977) and has been named after its type section for its lower and middle member exposed along the stream by the ruined Jhuran village. The type section of the upper member is the southern flank of Mundhan Anticline located ~3 km SW of Mundhan. The Jhuran Formation comprises of thick sequence of alternating beds of sandstones and shales. The boundaries of the formation are defined by the Dhosa Oolite member below and non-marine sandstones of Bhuj Formation above. The lower, middle and the lower part of the upper members are exposed in the central and western parts of the Mainland (Biswas, 1977). The lower member consists of alternating red and yellow sandstone and shale; while, the middle member is mostly shaly comprising dark grey to black laminated gypseous shales. The upper member is largely arenaceous and composed of red and yellow massive current bedded sandstones with intercalations of shale, siltstone and calcareous sandstone. A deltaic lobe formed towards the sea in the west is represented by the Katesar Member above the Upper Member of Jhuran Formation and is found only in the western Mainland (Biswas, 2016a). The Katesar-Bhuj boundary is demarcated by a local unconformity marked by gypseous ferruginous bed. The age of the formation ranges from Kimmeridgian to Valanginian.

Bhuj Formation

The Bhuj Formation has been named after its type locality near Bhuj and is the youngest formation of the Mesozoic stratigraphy of Kachchh (Biswas, 1977). The formation comprises of a huge thickness of non-marine sandstones of uniform character that overlie the marine beds of Jhuran Formation and overlain by Deccan Trap flows. The sandstones are pale brown to buff, soft, friable, usually current bedded, fine to coarse grained, well sorted and loosely cemented quartz arenites which are usually micaceous, ferruginous and/or calcareous. The rocks belonging to Bhuj Formation are exposed extensively in the Mainland occupying about three-fourth of the total area of Mesozoic outcrop. The age of the formation ranges from Lower Cretaceous (Valenginian) to Santonian (Biswas, 1977). There occurs a gradational boundary between the Jhuran and Bhuj formations, while local disconformity can be noticed at some places (Biswas, 2016a).

Pachham Group

The Pachham Group of rocks are exposed in the Pachham Island, which is the westernmost island in the chain of four rocky islands, named Khadir, Bela and Chorar within the Great Rann of Kachchh, that are bounded in the north by the Island Belt Fault (IBF). The Pachham Group of rocks can be classified into two parallel and structurally controlled formations – the lower Kaladongar formation and the upper Goradongar formation named after the two hill ranges of Pachham Island (Biswas, 1993). The lower part of the Kaladongar Formation consists of granite-cobble-conglomerate beds, which points towards the proximity of the basement near the northern basin margin. The Kaladongar Formation is largely composed of sandstone. This formation along with its Eastern Kachchh Group equivalent – Lower Khadir Formation, form the oldest formation of the Kachchh basin, which apparently overlie the Precambrian basement, as suggested by the Cheriyabet Conglomerate member at the base of the Khadir formation (Table 2.1) (Biswas, 2016a).

The Goradongar Formation comprises of interbedded shale and flaggy limestone (Goradongar Flagstone Member) in the lower part, thick sandstone member (Gadaputa

Member) in the middle and a cherty limestone member on the top (Railmalro Member). The best exposure is found in the Raimalro Hill, north of Khavda (Biswas, 2016a). The Raimalro Limestone is distinguished by thickly bedded yellow limestone beds with chert nodules and laminae. The overlying Modar Hill Formation, mainly comprising of sandstone, is well exposed in the hill section located at the southeast corner of the Goradongar Hill. The Khavda Shale, which occupies the lower portion of this member, consists of ammonite rich, highly fossiliferous shales, with thin limestone bands (Biswas, 2016a). The Goradongar Formation is found bordering the Pachham Island towards the south and slopes into Banni mudflat.

<u>Eastern Kachchh Group</u>

The stratigraphy of Eastern Kachchh Group is represented by interrelated rocks exposed in Khadir, Bela, Chorar islands and Wagad Highland (Biswas, 1977); and is divided into four formations – Khadir Formation, Gadhada Formation, Washtawa Formation and Wagad sandstone (Biswas, 2016a). These four formations are interrelated by correlating the outcrops and marker defined beds. The Khadir Formation, the oldest formation of the succession, contains Raimalro Limstone of the Goradongar Formation as a marker bed and thus, behaves as a facies variant of the Goradongar and the upper part of the Kaladongar formations of the Pachham Group (Biswas, 2016a). In the Khadir Formation, the equivalent of the Raimalro limestone member of the Goradongar Formation is called the Hadibhdang Sandstone Member. The Hadibhadang Sandstone Member is characterized by thinly bedded limestone with chert nodules interbedded with calcareous sandstones. The northern cliffs of all the islands are observed to be capped by the cherty limestone bed, which forms an important lithologic marker-defined unit and is used for the correlation of the stratigraphy of all the four islands (Biswas, 2016a). The Hadibhadang Shale and Cheriyabet Conglomerate, which are the lower members of the group are correlatable to Goradongar Flagstone and Babia cliff sandstone members respectively belonging to the Pachham Group. The shallowing of the basement east of the Median High hinge zone has resulted into the absence of the sediments equivalent to Kaladongar formation in the eastern part of the basin towards the east of Pachham uplift. In the Gadhada Formation, The Bambhanka Shale Member is equivalent to the Nara Shale Member of the Washtawa Formation consisting of the marker beds – Kakindia Limestone and Kanthkot ammonite Beds which is exposed only in Wagad (Biswas, 2016a).

The deltaic Wagad Sandstones overlie the marine Washtawa Formation, the lower part of the former grades westward forming the Kanthkote Member belonging to marine facies; whereas, the overlying Gamdau Member belongs to deltaic facies (Biswas, 1977, 1991; Bandyopadhyay, 2004). The upper Jumara and lower Jhuran formations are found correlatable with the formations of Eastern Kachchh Group (Biswas, 2016a). Although the base of the Khadir Formation and the top of the Wagad Sandstone are not exposed, the presence of Cheriyabet conglomerate member containing pebbles, cobbles and boulders of Precambrian rocks at the lowest end, points towards this formation being the oldest in the succession which probably rests over the Precambrian granitic basement (Table 2.1). The outcrop found in the Meruda Hill, ~27 km N of Khadir Island exposes the basement (Biswas and Deshpande, 1968).

Tertiary stratigraphy

The first detailed classification of the Tertiary sediments of Kachchh was given by Wynne (1872). Later Biswas (1974) established a formal chronostratigraphic classification by applying modern concepts. The Late Paleocene marine transgression occurred cyclically till Mid Eocene with brief pauses (Biswas, 2016a) during which, Tertiary sediments were deposited in a post-rift marginal sag basin (Kingston et al., 1983). The sea transgressed again in Oligocene following a hiatus in Late Eocene and the transgression continued till Mid Miocene (peak transgression period) which was followed by regression in Late Eocene. Mostly claystone, shale and limestone were deposited as Eocene – Miocene sediments; whereas, the sandstones were mostly deposited during post-Miocene regression (Biswas, 2016a).

The Tertiary sequence of Kachchh consisting of limestones, shales and sandstones are grouped into discrete mappable formations based on vertical differentiation of gross lithology and unconformities (disconformities) are generally marked by lateritised undulating surfaces or by bioturbated cut and fill structures and regional overlaps recognized in the field (Biswas, 1992).

The Tertiary rocks occur as narrow strip in Kachchh fringing the Mesozoic outcrops of the highlands. They are best developed in the coastal strips off the southern and western parts of Kachchh Mainland. The maximum development is noticed in the south-western part of the Mainland. The Tertiary rocks range in age from Paleocene to Pliocene. The Lower Tertiary rocks overlie the Deccan Trap flows in Southern and Western Kachchh Mainland; while, in other areas they are directly over the Mesozoic rocks (Biswas, 1992).

Table 2.2 Tertiary stratigraphy of Kachchh basin (after Biswas, 2016a).

AGE	STAGE	FORMATION	LITHOLOGY	ZONE (FORAMINIFERA)	SEQ. STRAT.

?Late Miocene to Pliocene	Kankawatian Super-stage	SANDHAN 249 m+ --- Disconformity ---	Sandstones, minor limestone and shale Upper part calc. concretionary	*Poorly fossiliferous*	SEQ 6
Burdigalian	VINJHANIAN	CHHASRA 16 m	Upper: silty shale Lower: shale/ limestone highly fossiliferous	*Ammonia papillosus* *Miogypsina* (*Lepidosemicyclina exentrica*) *M.* (*L.*) *Droogeri* *M. globulina*	SEQ 5
Aquitanian	AIDAIAN	KHARI NADI 65 m --Unconformity---	Variegated siltstones and sandstones	*M.* (*Miogypsinoides*) *tani* *Poorly fossiliferous*	
Chattian	WAIORIAN	MANYARA FORT 35 m	Upper: Foram. limestone/oolite sandstone, Middle: limestone with coral biotherms, Lower: lumpy claystone, glauc. gypseous shale	*M. complanata-formosensis* *M* (*M.*) *bermudezi* *Planolinderina freudenthali*	SEQ 4
Rupelian	RAMANIAN			*Nummulites fichteli* - *Lepidocyclina dialata* *Nummulites fichteli*	
Priabonian	HIATUS	--- Paraconformity ---		Stratigraphic Break	Hiatus
Bartonian	RAKHADIAN	FULRA LIMESTONE 60 m	Dense foraminiferal limestone	*Truncorotaloides rohri* *Orbulinoides beckmanni*	SEQ 3
Lutetian	BABIAN	HARUDI 14 m	Claystone/limestone, coquina highly fossiliferous	*T. topilensis* *Nummulites obtsus*	
	Hiatus	--Paraconformity---		Stratigraphic Break	Hiatus
Ypresian	KAKDIAN	NAREDI 40 m --- Disconformity ---	Upper: ferruginous claystone. Middle: Assilina limestone. Lower: glaucontic gypseous shale	*Poorly fossiliferous* *N. obtusus* *Assilina granulosa* *A. spinosa* *Schizocythere spinosa* Stratigraphic Break	SEQ 2
Thanetian	MADHIAN	MATANOMADH 49 m --- Disconformity ---	Laterites & volcanoclastics; tuffaceous shales & sandstones bentonitic clay	No micro-fauna / Rich in micro-flora	SEQ 1
Maastrichtian to Danian		DECCAN TRAP	Basalt	Terrestrial lava flows	

The *Matanomadh Formation*, named after its type section located at Matanomadh village in western Kachchh consists of brightly coloured rock types with different admixtures of clastics and volcanic materials. The common rock types in this formation include red laterite, bauxite, lateritic trap-pebble-conglomerate, trap-wash, variegated plastic bentonitic clays, red and yellow ferruginous clays, grey and white tuffaceous shales and red, current bedded, tuffaceous sandstones and occasional layers of lignite. The age of this formation is established as Late Cretaceous to Early Palaeocene (Mehrotra and Biswas, 1989).

The *Naredi Formation* overlies the lateritic volcaniclastic rocks of the Matanomadh Formation and its type section is located south of Naredi village in the cliffs of Kakdi Nadi. The three members that constitute the Naredi Formation are Gypseous shale member (Late Paleocene), Assilina limestone member (Early Eocene) and Ferruginous claystone member (Biswas and Raju, 1971). A plane of disconformity separates this formation and the underlying Matanomadh formation. The disconformable contact exists between Naredi Formation and overlying Harudi Formation.

The *Harudi Formation*, named after its type section exposed in an escarpment west of Harudi village consists of green and greyish, splintery shale with yellow limonitic partings in the lower part and calcareous claystone and siltstone with occasional layers of gypsum and carbonaceous shale in the upper part (Biswas and Raju, 1971). The age of Harudi Formation is found to be Middle Eocene (Biswas, 1992). Exposed on the southern flank of Babia hill near Fulra village is the type section of *Fulra limestone*, which comprises entirely of massive to thickly bedded, white and buff coloured foraminiferal limestone. The limestone shows the presence of many megafossils besides the microfossils. The age of the Fulra limestone Formation is Late Middle Eocene (Biswas, 1992).

The *Maniyara fort Formation* paraconformably overlies the white Fulra limestone Formation, whose type section is exposed along the Bermoti Nadi flowing from near Maniyara fort. This formation consists of four members – the basal member, the lumpy clay member, the Coral limestone member and the Bermoti member. The age of this formation is Oligocene (Biswas, 1992).

The *Khari Nadi Formation*, named after its type section exposed along the cliffs of Khari Nadi, lies conformably over the limestone bed of Maniyara fort Formation (Biswas, 1992). The lithology consists of laminated to thin bedded and yellowish siltstone and yellowish sandstone with occasional grey and brown gypseous claystone. The middle part of the type section consists of cross bedded, fine grained, micaceous sandstone, while the middle and upper part consist of few thin fossiliferous marl and limestone beds. The age of Khari Nadi Formation is Late Aquitanian (Biswas and Raju, 1971). Overlying conformably with the Khari Nadi Formation is the *Chhasra Formation*, named after its type section in Chhasra village. This formation was originally named as Vinjhan Shale by Biswas and Raju (1971; 1973). The Chhasra Formation consists of a lower claystone member and an upper siltstone member. The age of the formation is Burdigalian.

The *Sandhan Formation*, named after its type section exposed in Sandhan village, lies disconformably over the Chhasra Formation (Biswas, 1992). The lower part of Chhasra

Formation consists of micaceous, quartzose sandstones, overlain by clayey, laminated siltstones and topped by thin yellow fossiliferous limestone beds; while the middle and upper part is composed of conglomerate and sandstones and silty sandstone with calcareous nodules. The upper part of the formation gardes into Quaternary/Recent beds with increasing calcareous content forming ‘Kankars’. The tentative age of Pliocene has been assigned to this formation due to absence of any diagnostic fauna (Biswas and Raju, 1973).

QUATERNARY SEDIMENTS

Large-scale deposition of Quaternary sediments is found in the *Great and Little Rann of Kachchh* and along the *Gulf of Kachchh coastline* in narrow alluvial plain found in the southern Mainland Kachchh (Figure 2.1). Both the Great and Little Rann mainly exhibit distinct Holocene sedimentation (Maurya et al., 2003a). A fluctuating strandline since the onset of Holocene has accumulated these sediments in a shallow gulf located in both the Ranns, the origin of which is considered to be the Indus drainage basin (Merh and Patel, 1988). Salt encrusted surfaces called *sabkhas* are found in desert areas in the lower portion of the Great Rann. This surficial salt layer is underlain by light grey to bluish micaceous non-calcareous clay, which becomes yellowish to brownish on exposure (Srivastava, 1971). The oldest Holocene sediments coalesce into the Late Pleistocene fluviomarine to fluvial sediments (Merh, 1995). The Little Rann of Kachchh comprises of four layered sediment succession, out of which, the upper three layers of >5m thickness belong to early Holocene (~9000 – 4200 years BP), while, the bottom layer belongs to Pliestocene age (4200 – 1500 years BP) (Gupta, 1975). The saline grassland of the Banni plain exists as a raised mudflat (Kar, 1995), occupying the area between the Mainland Kachchh and Great Rann of Kachchh. The Banni grassland is nearly flat and gradientless saline terrain which is elevated by almost 3m – 10m from the Great Rann. The three sub-units of the Banni plains are – (i) raised mudflat, (ii) undifferentiated sloping and low-level mudflat, and (iii) a residual saline depression (Kar, 1995). Alluvial fan sediments are reported to be present in the eastern elevated portion of the plains.

The pre-Quaternary rocks found along the coast south of Kachchh Mainland, are fringed by a narrow belt of fluvial deposits, and cover the area up to the coast. The outcrops of Late Quaternary fluvial deposits (Maurya et al., 2003a) can be found along the incised cliffs of rivers such as Nagwanti, Rukmavati (Mandvi), Phot, Khari, Naira and Rukmavati (west) are found to be correlatable.

The inland areas for e.g., the rugged terrain is characterized by patchy occurrences of Quaternary deposits, found associated with pre-Quaternary rocks in the form of alluvial and colluvial fans, fluvial sandbars, valley-fill miliolites and fluvio-aeolian miliolite patches (Maurya et al., 2003a). The alluvial fans are observed at places where the rivers and their tributaries cross the Katrol Hill Fault and Kachchh Mainland Fault. These fans comprise of sub-angular to rounded fragments with medium to fine grained sand (Maurya et al., 2003a). The majority of colluvial fan deposits are mostly found at the base of the E-W trending scarps, while, the NNW-SSE trending fault scarps display meagre traces of colluvial sediments due to less degradation and subdued tectonic activity along these faults (Thakkar et al., 1999).

Biswas (1971) for the first time described the Late Quaternary miliolite rocks and discussed about their origin and environment. The term '*miliolite*' is attributed to Late Quaternary, carbonate-rich sediments with foraminifera belonging to Genus *Miliolina* and deposited by wind blown off from the coastlines to far inland areas where they got accumulated in depressions and against obstacles (Biswas, 1971). Stratigraphically and compositionally, these deposits are broadly comparable to the well-known Late Quaternary aeolianite deposits documented from various parts of the world including Australia, Bermuda, South Africa and the Mediterranean region (Marker, 1976; White, 1995; Brooke, 2001; Engelmann et al., 2001; Price et al., 2001). The miliolite deposits of the study area form a part of the regionally extreme phase of aggradation in the entire Kachchh basin and Saurashtra in the south (Maurya et al. 2003a).

Miliolite deposits of Kachchh

The outcrops of miliolite deposits in Kachchh are encountered in the highland areas which are clearly observed protruding on the vast plains of the Great and Little Ranns of Kachchh, while the low-lying areas show conspicuous absence of these deposits (Biswas, 1971). The Miliolite Formation found in the Kachchh region is rather discontinuous in comparison to the miliolites found in the coastal belt of Saurashtra region and the outcrops appear scattered throughout the region.

The mode of occurrence of miliolite deposits in the Kachchh region corresponds to those found in the inland areas of the Kathiawar region (Biswas, 1971). Evidently, the miliolite rocks are found far away from the coast as the coastal tract of Kachchh lacks the deposition of miliolite rocks. In the low-lying areas fringing the Rann, these rocks are seen at the base of the hills and high up in the valleys and gaps. The topographic depressions of the Rann encountered in the hilly areas such as the valleys, ravines, wind gaps, plains surrounded by the ridges and the hill slopes are the most favourable places for the deposition of miliolites.

Frequent occurrences of miliolite rocks are also found in the hilly terrain scattered over the highland areas of Kachchh Mainland, Pachham and Wagad uplifts; while, the deposits become sparsely distributed in the Khadir and Bela islands. The miliolite rocks are absent in the Chorar Hill located towards the east of the Little Rann of Kachchh (Biswas, 1971). The miliolite rocks occur along the E-W trending longitudinal hill ranges such as the Northern Hill Range, the Charwar (also called Chaduva) Range and the Dhola Range. The miliolite rocks are most frequently encountered in the Dhola Range, followed by the Charwar Range where the rocks are found on the cuesta slopes lying next to the wide lowlands as well as along the foothill zones of the scarps. The miliolite rocks in the Northern Hill Range occupy the marginal areas surrounding the high hills, foothill regions of the steep hogbacks on the northern side of the hills and in the valleys found in between the hills (Biswas, 1971). These deposits are also commonly found along the slopes of the isolated hills such as Dhinodhar, Dhrubiya and Roha created by intrusive bodies.

Patchy occurrences of miliolite deposits are found adjacent to the vertical ridges and in the lowland flanked by the hogback ridges and the southern slopes of the central hills (Biswas, 1971). The miliolite deposits found near Washtava is a typical example of the presence of miliolite deposits in the valleys of the central hills region. In the Pachham island, the miliolite rocks are observed occupying the deep valleys of the Goradongar Range and in the central valley formed between the Kaladongar and Goradongar ranges. However, these deposits are not reported from the region fringing the northern escarpment of Kaladongar Range near the border of the Rann (Biswas, 1971). The central depression which covers Hadibhadang Pir area in Khadir and its northern escarpment shows the presence of miliolite rocks. The wind gap between the Bela and Mouana hills which is characterized as a saddle structure in Bela also displays the presence of miliolite deposits. The miliolite outcrops display variable thickness throughout the Kachchh region, for e.g., the miliolite outcrop thickness is found to be ~100ft along the Charwar Range; ~50ft on the Bhuj-Mandvi road; ~100ft on the southern side of Dhinodhar Hill and north of Dhrubiya Hill (Biswas, 1971).

HISTORICAL AND RECENT SEISMICITY

After undergoing several major tectonic deformational phases such as – rifting apart from Africa at 184 Ma, breakup from Madagascar at 88 Ma and Deccan flood volcanism at 65 Ma, the Indian plate collided with the Eurasian plate and resulted in the subduction of the

Indian plate beneath the Eurasian plate. This collisional process led to very high seismic activity all along the Himalayan Frontal arc in northern India and significant intra-plate seismicity in the south of India (Bilham et al., 2003). The intraplate region of peninsular India shows historical records of significant earthquakes such as the 1819 Kachchh, the 1900 Coimbatore, the 1938 Paliyad, the 1938 Satpura, the 1956 Anjar, the 1967 Ongole, 1969 Bhadrachalam, the 1969 Mount Abu, the 1970 Broach, the 1975 Shimoga, the 1993 Latur, the 1997 Jabalpur and the 2001 Bhuj earthquakes (Chandra, 1977; Chung and Gao, 1995).

Kachchh is a pericratonic rift basin situated in western part of Indian sub-continent which opened during early Jurassic and as a result thick Mesozoic and Cenozoic succession got deposited (Biswas, 1977). The Kachchh basin is broadly divided into five geomorphic divisions - the Island belt, low lying Rann of Kachchh, Banni plain, Mainland Kachchh with chain of dome shape Jurassic structures and the coastal belt. The flat saline wasteland of the Ranns include the Great Rann of Kachchh and the Little Rann of Kachchh. The E-W trending master faults such as Nagar Parkar Fault (NPF), Allah Bund Fault (ABF), Island Belt Fault (IBF), South Wagad Fault (SWF), Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF) controls the geomorphic set up of the Kachchh region. A characteristic feature of all these faults is the presence of a narrow flexure zone consisting of domes and anticlines on their upthrown side (Biswas, 1987). The periodic reactivation of faults during the post-Cretaceous inversion phase is indicated by the deposition of thick Cenozoic sediments in structural lows, the fault-controlled present-day landscape and the ongoing seismic activity (Biswas, 1987; 1993). The Deccan Trap lava flows exposed in the western and southern parts of the mainland Kachchh Basin mark the northern limit of the Deccan magmatic activity that took place during the Late Cretaceous–Early Paleocene period (Shukla et al., 2001; Pande, 2002).

Since the past 20Ma, the Kachchh region is under to NE-SW compression due to inversion tectonics (Talwani and Gangopadhyay, 2001). The Kachchh region falls under seismic zone 5 and has experienced several large to moderate scale earthquakes in past 300 years (Malik et al, 1999). The low-to-moderate level of seismicity (Figure 1.1) since the 2001 Bhuj earthquake indicates that the earthquakes have been migrating spatially in an unpredictable pattern (Mandal and Chadha, 2008; Mandal, 2009). Paleoseismic and paleoliquefaction events suggest that the Kachchh region has undergone active tectonic movements in recent past (Biswas, 1971; Maurya et al., 2006; Mandal, 2016).

Since the historical times, earthquakes have been occurring in the Kachchh region (Rajendran and Rajendran, 2001). The Allah Bund earthquake in 1819 (M 8) occurred only about 100 km northwest of the 2001 Bhuj earthquake epicentre. Another event of moderate magnitude (M_w 6.0), known as the Anjar earthquake, occurred south of the epicentre of Bhuj Earthquake (Chung and Gao, 1995). Thus, the region has experienced two large magnitude earthquakes within a span of 182 years (Rajendran et al., 2008). In addition, 15 historic and recent earthquakes of M 5–6 have also been reported from the region (Rajendran and Rajendran, 2001). The devastating Bhuj earthquake (23.412° N, 70.232° E, M_w 7.7) estimated to have an intensity of XI close to the epicentre (Hough et al., 2002), occurred on 26th January 2001, along a south-dipping thrust fault at 23 km depth and killed approximately 20,000 people. Rastogi et al. (2013) reported that due to the stress transfer after the 2001 Bhuj earthquake by viscoelastic processes, the seismic activities have increased in Kachchh and its adjoining regions as shown in Figure 1.1. Some larger aftershocks occurred along the Gedi fault in 2006–2007 and there was a spatial increase in the aftershock zone (Mandal, 2009). Since the last high magnitude Bhuj earthquake (M_w 7.7) and the prolonged aftershock sequence, the eastern part of the Kachchh basin is identified as the Kachchh Seismic Zone (boxed area in Figure 1.1) (Mandal and Chadha, 2008; Mandal and Pandey, 2010) that encloses the Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and the Island Belt Fault (IBF). All these E-W trending faults exhibit a neotectonic setting where the fault planes demarcate the mechanically rigid block composed of Mesozoic rocks on the upthrown side and the evidently softer block composed of Tertiary rocks on the downthrown side (Maurya et al., 2017a). This kind of the geometrically opposite arrangement of the blocks with significantly different mechanical strengths proves to be a crucial factor in the accumulation and release of tectonic stresses and the consequent seismic activity (Maurya et al., 2017a). In the last two decades, most of the studies have been confined to these faults (Mathew et al., 2006; Chowksey et al., 2011; Maurya et al., 2013; 2017b; Malik et al., 2017), while very few studies exist for other faults lying outside the confines of Kachchh Seismic Zone, viz. the Katrol Hill Fault (KHF) (Patidar et al., 2006; 2007; 2008; Patidar, 2010).

The Kachchh rift basin is also included among the stable continental regions (SCR) of the world (Schulte and Mooney, 2005) with the 1819 Allah Bund earthquake (M_w 7.8) as the fourth largest SCR earthquake. In spite of the fact that the SCR earthquakes release only 1% to 10% of the energy released in the plate boundary settings (Johnston, 1989) and show comparatively low average level of seismicity, they pose a significant threat to lives and property worldwide (Johnston and Kanter, 1990).