CHAPTER 1
INTRODUCTION

Background

The present day climatic patterns, landscape changes and sea levels could be predictably studied under the umbrella of the study of Quaternary geology, and hence it is of vital importance in developing sustainability for the mankind (Dawson, 1992; Shajan 1998). Quaternary geologist can address disseminating information from the past studies and effect on climate change and its effect on life. Climate science being highly interdisciplinary, recognised and developed as a trans-disciplinary science such as climatology, atmospheric chemistry, computational mathematics, palaeobotany, archeology, glaciology, isotope chemistry, geoarcheology, soil-agriculture sciences and history that lead to the better understanding on geosphere-biosphere interactions during the Quaternary time (< 2.6 Ma).

In the history of geology, the Quaternary branch has been neglected mainly because of the little economic wealth it offers. In the beginning it was considered only as a branch of prehistoric archaeology. The scenario has now considerably improved. The recent concerns about the present and future climatic changes dramatically transformed this discipline to one of the most important branches within the earth science discipline. Now geomorphologists, geologists, archaeologists, oceanographers, climatologists and a host of other scientists from many other disciplines show their interests in this new upcoming branch of geology. Now several institutions and organizations all over the world are engaged in the research related to Quaternary geology, climatic and sea level changes. The present study is aiming to understand the geological evolution of the southern Kachchh during late Quaternary time, primarily based on the unique kind of bioclastic sedimentary record (Miliolite Formation) that occurs on inland hilly landscape of the Katrol Hill Range (KHR).

Quaternary Period

The Quaternary Period is the current and most recent of the three periods (Paleogene, Neogene and Quaternary) of the Cenozoic Era in the geologic time scale of the International Commission on Stratigraphy (ICS). Quaternary covers 2.5 million years (Ma) and is divided into two epochs: the Pleistocene(2.588Ma to 11.7 ka) and the Holocene (11.7ka to present). Geologists have now defined the last 4,200 years as a new chapter in Earth's history, the 'Meghalayan Age' (IUGS, 2018). This age began at the time when an agricultural society around the world "experienced an abrupt and critical mega-drought and cooling".

The International Chronostratigraphic Chart (v 2018/07), which contains significant updates to the Quaternary and Cambrian System, is now formally released. The Executive Committee of the IUGS has now ratified the proposal submitted by ICS that subdivides the Holocene Series into the Greenlandian (11,700 yr before AD 2000), Northgrippian (8326 yr before AD 2000), and Meghalayan (4200 yr before AD 1950) stages, and that these stages correspond to the Lower, Middle and Upper Holocene subseries, while completely ignoring the Anthropocene.

Quaternary follows the Neogene Period and spans from 2.588 ± 0.005 Ma to the present. The informal term "Late Quaternary" refers to the past 0.5-1.0 Ma. As per IUGS (v2018/07) chronostratigraphic chart, the boundary of Quaternary has been fixed at 2.588 million years based on the key changes in Earth's climate, oceans, and biota that occurred 2.588 million years ago at the beginning of the Gelasian stage in Europe that is marked by the Gauss-Matuyama Magnetic Reversal. Quaternary involved considerable expansion of the cryosphere which characterized as ice age. The Quaternary Period is typically defined by the cyclic growth and decay of continental ice sheets driven by Milankovitch cycles and the associated climate and environmental changes that occurred. Milutin Milankovitch proposed that these regular cycles of the Earth, as they changed the Earth's relationship to the Sun, had an effect on the Earth's climate, driving hot and cold cycles, to include the ice ages throughout ancient era. Many mammals die off due to glaciations and man appeared and domain. Some of the land was not covered under ice but were subjected to freezing of permanent or seasonal permafrost in Quaternary.

Hays, Shackleton and Imbrie (1976) demonstrated that oscillations in climate over the past few million years could be corrected with variation in the orbital and positional relationship between the Earth and Sun. Shackleton (1967) was key figure in paleoceanography, studied oxygen isotope composition of calcareous microfossils. He also found evidence of magnetic field reversal was 780,000 years ago.

Last Quaternary ice age having lasted nearly 2.5 Ma ago is now over. The period of the ice growth ended by 10ka BP (before present) marked onset of the interglacial condition. In the Holocene period glaciations retreat began and still is going Holocene marine transgression (Wisconsin). Glacio-Eustacy has fundamental control over-sedimentation and mechanism of the Quaternary sediments over sub-continent in relation to its climate and/or tectonic controls.

The Earth is presently entering into a regime of warm climate. Substantial climatic and rapid environmental changes have potential to interfere with dynamic processes on Earth’s surface, affect eco-systems and social systems including human habitability.

Quaternary sediments in Gujarat

The Quaternary sediments in Gujarat represent three depositional environments viz., marine, fluvial and aeolian. The interplay of paleoclimate and glacio-eustasy factors controlled the shaping of the landscape of Gujarat during Quaternary period (Merh, 1995). On the basis of landscape characteristics, sediments types and geological history, the Quaternary sedimentation has given rise to three distinct geomorphologic units which are still active sites of the sedimentation. These are;

1. The Ranns of Kachchh,
2. Coastlines of Kachchh, Saurashtra and South Gujarat, and
3. Alluvial plains of Central and North Gujarat.

Quaternary sediments in Kachchh

Late Quaternary geological history of the Gujarat state has been studied in detail with special emphasis on Mainland Gujarat (Merh and Chamyal, 1993; Chamyal and Juyal, 2005 and references therein). There are two principal areas in Kachchh, which have witnessed significant Quaternary sedimentation. One is the flat saline wasteland of the Ranns, which includes the Great Rann of Kachchh and the Little Rann of Kachchh which is obviously the product of marine deposition. Khonde et al. (2017) studied a sedimentary core raised from the southern fringe of the Great Rann of Kachchh and using clay mineralogy therein suggested that the area remained a shallow marine depositional site since 17.7 ka BP receiving predominant sediment load from the Indus (i.e. Himalayan) in comparison with that from the Kachchh hinterland and Aravallis.

The other area is the narrow E-W trending plains of southern Mainland Kachchh which are mainly formed by fluvial processes; however, some fluvial-marine interaction is indicated in the near-coastal areas (Maurya et al., 2008). As the overall landscape of the Kachchh region is constituted by the rocks of Jurassic to Miocene age, the Quaternary record could be seen only in specific areas. A significant member of the Quaternary sedimentary record of Kachchh is the Miliolite Formation or miliolitic limestone which is the prime aspect of the present study. The counterpart of this in Saurashtra has been well investigated and all possible details about its sedimentology and geochronology are also now available (Bhatt, 2003; Sharma et al., 2017; Acharya and Bhatt, 2018 and references therein). In the geological literature this sequence is also referred to as the biogenic carbonate deposits and due to its nature it has enjoyed a century long debate regarding its origin, whether marine or aeolian.

After a long gap since the miliolite limestone was described by Carter (1849) and following studies by Evans (1900) and Chapman (1900), Fairbridge visited India in 1958 and revived the interest in this Quaternary carbonate deposits which have potentiality to check the sea level during the Pleistocene and Holocene period (Fairbridge 1960;1961). Prof. S S. Merh triggered the enthusiasm and interest of the scientific community in the study of the different aspects of miliolite problem during his addresses at the Section of Geology and Geography at the 67th Session of the Indian Science Congress, Jadavpur in 1980. In conclusion remarks Prof. Merh wrote “These fascinating carbonate rocks are yet to be investigated in detail and my purpose will be served if I am able to generate adequate enthusiasm and interest of the scientific community in study of the different aspects of miliolite problem”. Although the details about available understanding on milolites of Kachchh has been discussed under ‘Literature Review’ in the next chapter, the importance of these deposits in understanding the evolution of the southern Kachchh has been realized by the present author and therefore the study has remained focused on the miliolites of the Katrol Hill Range with an attempt to achieve the following objectives.

Objectives

1. To evaluate the Miliolite Formation of Kachchh for its significance in late Quaternary history of the region.
2. To reconstruct the late Quaternary paleoenvironment and geological history of southern Kachchh.

Methodology

To achieve the above objectives following methodology was adopted.

1. Literature review.
2. Geomorphological mapping using remote sensing data and SOI topographic maps.
3. Reconstruction of lithostratigraphy through regional correlation and lateral mapping of late Quaternary sequences exposed in natural and artificial cuttings.
4. Collection field data and sampling.
5. Textural and compositional studies using standard sedimentological procedures and also using advances techniques like SEM-EDS, XRF, Kappa-bridge, etc.
6. OSL Geochronology
7. Synthesis of the data to reconstruct geological evolution model of the study area.

Study Area

The old spelling ’Kutch’ has been modified as ‘Kachchh’ by the Survey of India in the recent addition of the maps. Kachchh is a mystery land, not easy to comprehend. Kachchh is a Sanskrit word meaning land, which gets intermittently wet and dry. Most of the human population lie in central part of district consisting of rugged hill terrain and flank by shallow coastal plain at south called “Kachchh mainland” and its resemble that of tortoise shell, which also is possibly why the name of Kachchh (Sanskrit word of tortoise-which gets intermittently wet and dry). Its vast length and breadth cannot easily be covered, and it is greater in area than some states of India. It’s the second largest district of the country (next only to Ladakh). Kachchh general appearance of isolated from the rest of Gujarat is now changed due to NGO and Government effort to rebuild its infrastructure and shifting its total agriculture based economy to encouraging the industrialization after 26 January 2001 earthquake.

Kachchh district spread over an area of 45612 km^2, occupies almost one-fourth (24%) of the geographical area of Gujarat State located at the extreme west of India, lies between 22ºand 24ºN latitudes and between 68ºand 71ºE longitudes (Fig. 1.1). It has length and width extensions of 320 and 170 km, respectively. Besides, it accounts for nearly 60 percent of the drought-prone area of the State. More than half (51%) of its area consists of saline marsh, in the north and the east it is flanked by two vast saline marshes, the Great Rann of Kachchh (~15127 km^2), and the Little Rann (~4000 km^2), with few small rocky islands in between (~83 km^2). The district is flanked on the southwest by the Arabian Sea has a vast coastline of 352 km long southern margin forms the coast of the Gulf of Kachchh. Its northern margin makes the International border with Pakistan and the eastern abuts Gujarat Mainland. In the west lies a vast

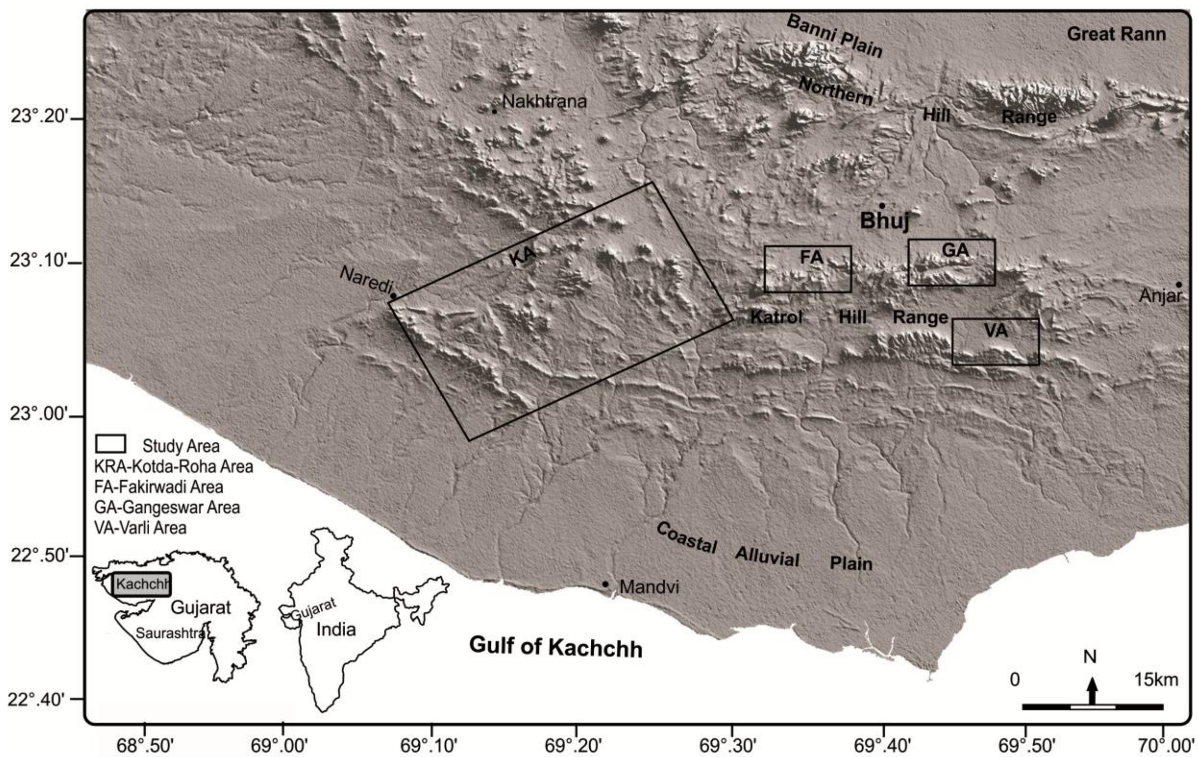

Fig. 1.1 Location Map (DEM) of the study area in southern Kachchh. (Source ISRO & GSI) KA-Kotda-Roha Area; FA-Fakirwadi Area; GA-Gangeswar Area; VA-Varli Area.

unfinished delta with tidal creeks and thickets of mangrove (1285 km^2). 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 km^2).The Great and Little Rann of Kachchh are the breeding ground of Flamingo, Pelican & Avocet. The flamingo's most characteristic habitats are large vast stagnant saline wet land that usually lack vegetation. Kachchh is also the home of the rare Indian wild Ass which is now a protected species. The major religious attraction are Shiva temple at Koteswar, Western end of mainland, Vishnu temple at Narayabn Sarowar along Kori Greek and Goddess Durga at Mata no Madh to west of Bhuj.

All weather road connectivity to all around the small villages and travellers easily get their refreshment shop near by interior road and villages. Bhuj is the district headquarters and Mandvi, Mudra, Gandhidham and Anjar are major towns, while Kandla is the business capital of India due to 'Free Trade Zone' of India and its major sea port facilities having largest cargo containers in Asia. All are well connected with rail and road to other major cities of Gujarat. Bhuj and Kandla both have air connectivity with other parts of India. I have observed during my field work, the scientific way of farming and diversification to orchard development, and earning good income through exporting their farm products. Also dairy farming is also great potential in barren land of Kachchh by improving live stock on Banni and hilly grass terrain.

Kachchh having low density population because of above desolate Ranns, Banni plain, mangrove swamps, hilly terrain and arid climate contribute only 3.47% population, having 35 person density per sq km compared to 308 person per sq km in state of Gujarat as whole as per 2001 census. The majority of the inhabitants are Hindus, but the Jain and Muslims are also numerous among the many religious and ethnic groups (Thakkar, 2017).

The Kachchh region experiences a semi-arid to arid climate with low average annual rainfall of 348 mm during the south-west monsoon moths of June to September, Indian summer monsoon (ISM) with an average of 15 rainy days in a year. But with high spatio-temporal variability that commonly occurs either drought or sometimes localized it gets intense rainfall within 24 hours which is more than the annual average. Droughts are frequent almost 6 in a cycle of 10 years. The mean temperature reaches up to 42 º to 43 ºC and often touches 47º C in May, during the summer (April to June), while dropping to as low as below 1 ºC degree in (January) in the interior parts of the district during winter (Nov to Feb). Mean day temperature in January being 28º to 30 ºC and night 7 ºto10 ºC.

The landscape of Kachchh have received a special attention with reference to its seismicity, neotectonic and coastal geomorphorphic evolution, as specially shaping the present land form unraveling the contemporary geological processes, largely controlled by the climate change and tectonism. The following is summary of geological architecture of the Kachchh basin mainly based on Biswas (2016a & b).

Geomorphology of Kachchh

The Kachchh landmass is a central high plateau, which stands dissected in the north, west and east. Its physiographic features, comprising hill ranges, gently sloping peripheral coastal plain and the intervening low are extensively mud and salt flats (Playas and saline marshes), dissected coastal erosional plain fringed successively by younger deltaic plains, tidal flats, spits and marginal accretionary zones, can broadly be divided into four characteristic units, viz, Rann, Banni plains, hilly tracts and coastal plains. There are two major low separated by mainland, southern most is Gulf of Kachchh and in the Northern side Banni grassland up to island belt and then continue as Great Rann of Kachchh up to NagarParkar Ridge. Eastern flank of the Gulf of Kachchh ending up a mudflat between Wagad and Saurashtra highland to east mainland is Little Rann of Kachchh. Great Rann occupying E-W trend chain of island in north while little Rann in East side (Fig. 1.2).

Form South Kathiawar peninsula to the North occupying, the Gulf of Kachchh, and Coastal plain, Mainland, Banni grassland and E-W chain of small chain of four islands, the Great Rann of Kachchh and Nagar Parkar Ridge. The Gulf of Kachchh, Banni grassland and The Great Rann of Kachchh are the major structural lows.

The Ranns

A fascinating barren untouched since its existence, with no surface exposures, hardly beyond 3-4 m amsl, are obviously the product of marine deposition, even you can drive four wheels on flat saline white terrain in dry season.

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

These are: Bet Zone (BTZ); Linear Trench Zone (LTZ); Great Barren Zone (GBZ) and Little Rann of Kachchh (LRK) As early stated Great Rann of Kachchh is salt marsh located Northern district of Kachchh occupying chain of island while little Rann in East side (Fig.1.2).

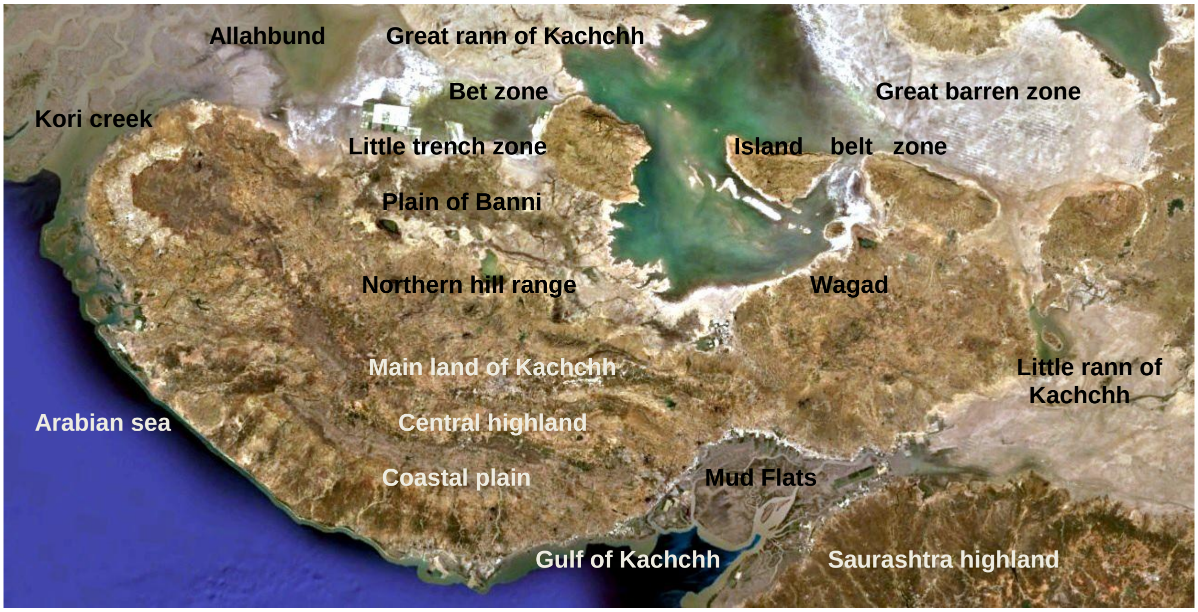

Fig.1.2 Image-map showing geomorphology of the Great Ranns of Kachchh.(After Merh and Patel, 1988)

The Banni Plain

Banni terrain is plain without any outcrop covers 6000sq km little riser than northern ward Great Rann of Kachchh covered with grass and shrubs. Banni form low recession in between mainland in south and uplift of Pachham in north. Many North flowing rivers and waters from eastern and Northern island debouch and dying out in the Banni-Rann plains (Fig. 1.2).

Hilly Tracts

All highlands are characterized by frontal escarpment and hill range along master faults and a gentle back slope. Hilly area within the Kachchh can be broadly divided in to main four group (1) Island Belt (ISB) Fault Range (2) Main Land uplift consisting of rocky Plain of Northern Hill Range (NHR) of mainland comprising chain of domes (250-400m) in the west along KMF and (3) Central highland Range (CHR) of mainland is Katrol Hill Range (150-445 m) along KHF forming drainage divider and (4) Wagad in East along SWF (Fig. 1.3).

The island belt comprising a linearly arranged in the north forming E-W chain of small chain of islands consisting of four highlands: the Pachham, the Khadir, the Bela and the Chorar highland. These four islands amidst the surroundings plain of Banni and Rann, resembles ‘island‘ (Fig.1.2) In fact these island were Real Island during Late Tertiary-Quaternary, surroundings low land were indurate by sea in these highland (Biswas 1971, 2016b).

Coastal plains

Southern most to mainland consisting of lower denudation origin piedmont plain (debris slope) and pediplain complex is overlooking in the Gulf of Kachchh in south and the Arabian Sea in the West. Gently sloping peripheral coastal tract, dissected coastal erosional plain fringed successively by younger deltaic plains, tidal flats, spits and marginal accretionary zones. Coastal plain which are mainly formed by fluvial processes; however, some fluvial-marine interaction is indicated in the near-coastal areas. On the basis of geomorphologic variations broadly five segment of coast line can be classified (Kar, 1993). The deltaic coast to the west of Kori Creek; the irregular drowned prograded coast between Kori Creek and Jakhau; the straightened coast between Jakhau and Bhada; the spits and cuspate foreland complex between Bhada-Mandvi and Mundra, and the wide mudflat coast to the east of Mundra up to the Little Rann.

Geology of the Kachchh Basin

The Kachchh sedimentary basin of India is located in the state of Gujarat, Northern end of Western continental margin of India, spreading over entire coastal district of Kachchh and part of the adjacent Banas Kantha district close to Rajasthan dessert. Kachchh sedimentary basin of India is a unique geological 3D model. Kachchh basin is well studied and well known for the Mesozoic, since its fossils rich as especially Cretaceous stratigraphy particularly rich in ammonites, fascinated paleontologists who made enormous work since mid 19th century.

Kachchh stratigraphy occupying three packages of Mesozoic, Tertiary and Quaternary sediments The Mesozoic package comprise of Late Triassic pre-rift continental sediments, Middle to Late Jurassic syn-rift marine sediments and Late Jurassic to Early Cretaceous post-rift fluvio-deltaic sediments (Table-1.1).

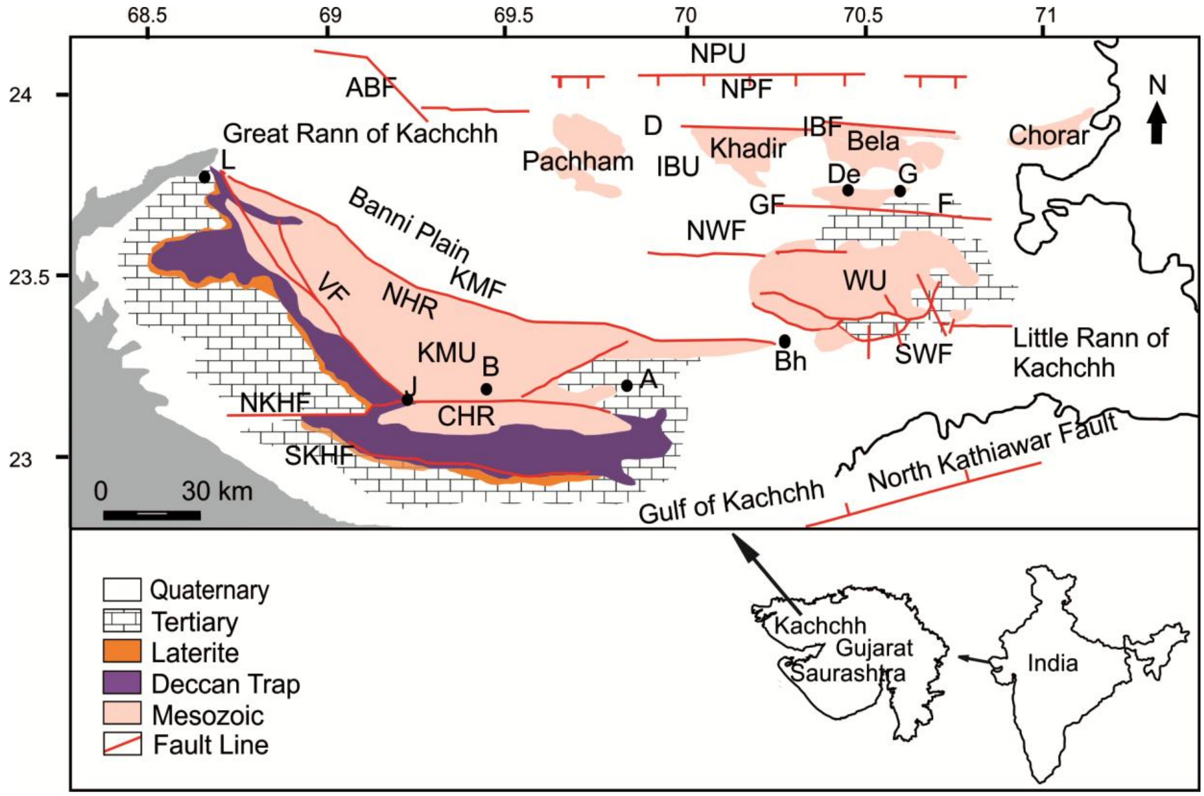

Fig.1.3 Geology and Tectonic Set up and Location Map of Study Area (After Kothyari et.al. 2016c). A-Anjar, B-Bhuj, Bh-Bhachau, D-Dholavira, De-Desaplar, F-Fatehgadh, G-Gedi, L-Lakhpat.
Faults: ABF-Allahbund Fault, GF-Gedi Fault, KHR-Katrol Hill Range, KMF-Kachchh Mainland Fault, IBF-Island Belt Fault, NKHF-North Katrol Hill Fault, NPF-Nagar Parkar Fault, SKHF-South Katrol Hill Fault, SWF-South Wagad Fault, VF-Vigodi Fault.
Uplifts:CHR-Central Hill Range, KMU-Kachchh Mainland Uplift, IBI-Island Belt Upland, NHR-Norhten Hill Range, NPU-Nagar Parkar Uplift and WU-Wagad Uplift.

Kachchh sedimentary basin have three main sub basins Rann Half Graben (RHG), Banni Half Graben (BHG) and Gulf of Kachchh half Graben (GOKHG) on the basis of different domain of Syn rift sediments accommodated in the half-grabens due to combine effect of subsidence-tilting of the basement blocks, sea level changes and regional subsidence of basin.

GOKHG among three main sub division of basin preserved 3000(+) m of which only 2200m are exposed on back slope of main of the main land uplift. In BGH 2208m thick sediments are underlain by Precambrian basement in the North of the KMF footwall of which the lower 620(+) m exposed in back slope of Pachchham uplift and upper one 1070(+) m in Wagad uplift. RG sediments is not exposed as outcrops suggest sediment fill in earliest phase of rift in form of piedmont fan conglomerate with thin marine sediments (Fig.1.4).

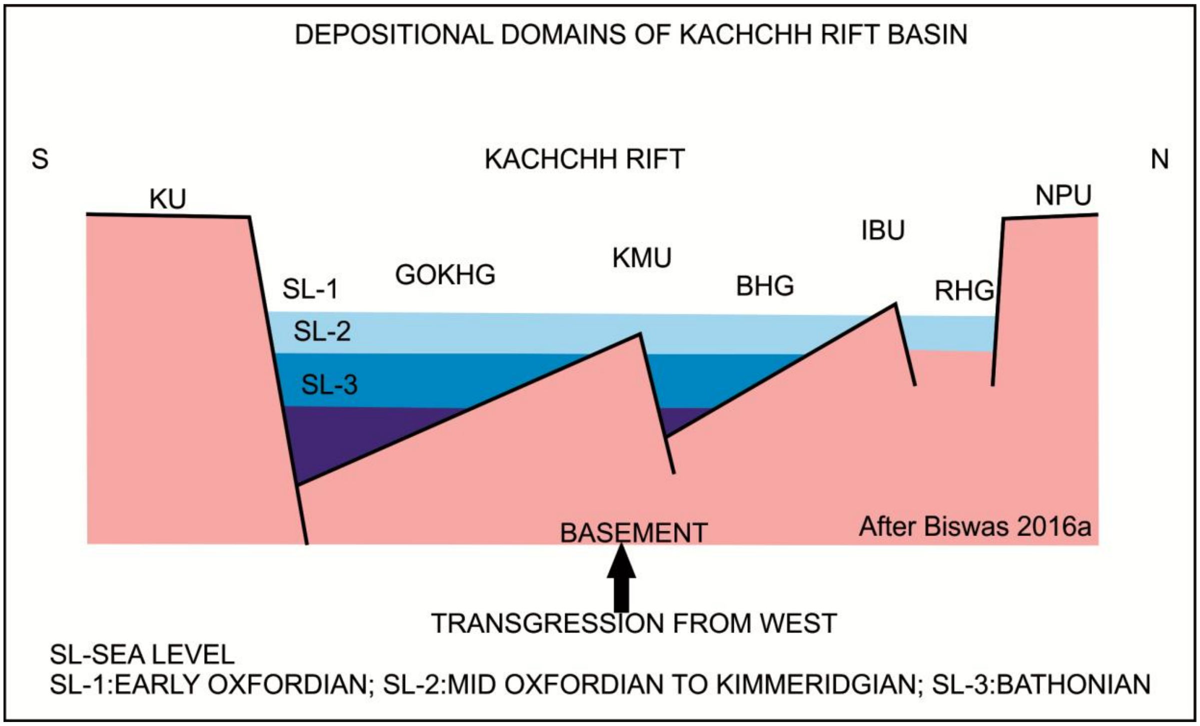

Fig.1.4 Depositional Domain of Kachchh Rift Basin. BHG-Banni Half Graben, GOKHG- Gulf of Kachchh Half Graben, IBU-Island Belt Uplift, KU-Kathiyawar Uplift, NPU-Nagar Parkar Uplift, KMU-Kachchh Mainland Uplift, PU-Pancham Uplift, RHG-Rann Half Graben (After Biswas 2016a)

The Kachchh asymmetrical rift basin tilted southwest thickening toward its SW paleoslope, maximum thickening took place along NKF against southern rift shoulder preserve about 2500(+) m thick sediments ranging in between Middle Jurassic to Early Cretaceous and About 1000 m thickness of Cenozoic sediments (Biswas, 1977; 1982). The Exposed tertiary appearance as littoral to shallow marine shelf sediments deposited in the peripheral and intervening structures lows rocks bordering the Mesozoic uplift area rocks along the coastal belt of southern and western Kachchh. Coastal plain which are mainly formed by fluvial processes; however, some fluvial-marine interaction is indicated in the near-coastal areas. The Quaternary sediments consist of inter-fingering of marine, fluvial and terrestrial sediments ranging from marine to fluvial, lacustrine and aeolian deposits (Thakkar, 2017).

Mainland Mesozoic Stratigraphy

In the Mainland includes full sequence Middle Jurassic (Bathonian) to Early Cretaceous (Albian), Deccan Trap flows (Late Cretaceous) and well complete sequence of well developed Tertiary formation from Paleocene to Pliocene are exposed.

Kachchh Main Land uplift group, the hilly tract geomorphology of Kachchh as early mention, is dominated by rugged hills of CHR and NHR terrain with sparse vegetation, exposing Mesozoic rocks highland surrounded by low lands, consists of the records of Juro-Cretaceous sediments in the form of the Jhurio, Jumara, Jhuran and Bhuj Formations non-conformably overlain by the magmatic rocks of the Deccan Trap Formation in ascending order, surrounded by gently dipping thins strip of low land are extensively alluvial plain, mud, Ranns of salt flats and Banni of grassy flats host the Cenozoic record (Paleocene to Pleistocene and recent) is also equally fascinating that occupies north-western and southern parts of the Kachchh and is represented by the Madh, Berwali, Ber moti, Khari and Kankawati Series and Recent deposit of Pleistocene. The Quaternary history is recorded in the Miliolite Formation and other Late Pleistocene-Holocene records of the coastal areas.

Kachchh basin was studied and mapped by Wyne first in 1872 and classified upper and lower Jurassic groups. Subsequently in1875, Waagen gave Chronolithostratigraphy of Mainland, popular in Paleontologist known as older Stratigraphy. This Chronolithostratigraphy by Waagen (1875) was further updated by Fursich et al. (2014) who subdivided it as the Patcham, the Chari, the Katrol and the Umia Series.

Biswas (1977) recognized three main lithological provinces within the basin accordingly their strato-types and classified the rocks of each province separately and named the units accordingly. This new Biswas's lithostratigraphy is popular amongst the sedimentologists. 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; 1993a & b). The major lithological characteristics of these formations as worked out by Biswas are briefly described below (Biswas, 1974; 1977; 1981; 1982; 1987; 1993a & b. Table-1.1).

The Mesozoic of Kachchh also studied on special facets are correlation, sedimentological, sequence-stratigraphy, tectono-sedimentological, fossils and environmental significance and biostratigraphy. Enormous work on paleontology and biostratigraphy was done but compilation, systematic documentation of the biostratigraphic classification and its formal presentation still remains to be done (Biswas, 2016a).

Based on the detail mapping entire basin and intra-basin correlation studies carried out by Biswas (1977, 1991, 1993a & b) and Fursich et al. (2001, 2014). Further sedimentological studies were carried out by Bose et al. (1986), Osman and Mahender (1997), Bandyopadhyay (2004), Misra & Tiwari (2005, 2006), Mahender et al. (2008), Misra (2008, 2009), Misra and Biswas (2009), Mahender and Sharma (2010) and Desai (2013). Sequence-stratigraphy was attempted by Fursich and Pandey, (2003), Krishna et al. (2000). Tectono-sedimentological analysis was carried out by Biswas (2005b). During last two decades much work focused on the trace fossils and environmental significance that was done by Kulkarni and Ghare (1989), Kulkarni and Borkar (2000, 2016), Desai et al. (2008), Patel et al. (2008, 2009), Desai and Patel (2009), Desai and Saklani (2012), Desai (2012, 2013). Foraminiferal biostratigraphy presented formally by Pandey and Dave (1993). Ammonite matched with global transgressive-regressive cycle and listed the zones formally by Krishna et al (2009).

Jhurio Formation

Exposed in Habo, Jhurio and Jumara dome hills, consisting of 290m thick marine sediments succession, characterized by rusty brown ferruginous limestone with golden pdeudo-oolitic and oolites, composed of concentric layer of chamosite, characterized by Golden Oolite beds. Golden color is due to oxidation of chamosite. Thick shale bed alternative Golden Oolite beds in lower part of formation indicating cyclic marine transgression during early stage of Jurassic sedimentation. The thin bedded white limestone is upper part formation marking maximum flooding surface (Biswas, 1991). The physical and biological characteristics of formation specify littoral to infra-littoral environment. The formation ranges from Bajocian-Jocian to Aalenian-Bathonian (Table-1.1).

Stage	Kachchh Mainland Group					
	(After Fursich et al. 2014)			(After Biswas 1977,1993; Furisch et al. 2001; Krishna et al.2009; Deshpande and Merh 1980)		
Tertiary	Formation			Member		
Maastrichtian-Danian	Paleocene to Late Cretaceous		Deccan Traps 500m	Basalt flows		
Albian (Early Cretaceous)			Bhuj Formation 850m	fluvio-deltaic sediments	POST RIFT	Upper Member:massive sandstones
Aptian						Ukra Member:Green glauconitic shale / ferruginous bands with fossil
Hauterivian to Barriasian						Ghuneri Member / Lower Member: Sandstones / shales / ferruginous bands / Shales with plant fossils
			Jhuran Formation 760m	marine sediments	LATE SYN RIFT	Katesar Member: Massive sandstone
Tithonian		Umia Formation				Upper Member: fossiliferous sandstones, shales, hard calcaereous sandstones
Kimmeridgian		Umia Formation / Katrol Formation				Middle Member: mainly shales, fossiliferous with sandstone interbeds.
						Lower Member: sandstones / shales / arenaceous limestones with fossils
	HIATUS					
Oxfordian	Chari Formation	Dhosa Conglomerate Bed / Dhosa Oolite mb	Jumara Formation 275m	Marine sediments	CLIMAX SYN RIFT	Dhosa Oolite Member
		Dhosa Sandstone mb				
Callovian		Gypsiferous Shale mb				Gypseous Shale Member
		Ridge Sandstone mb.				Ridge Sandstone Member
		Shelly Shale mb / Keera Golden Oolite mb				Shelly Shale Member
Bathonian (Middle Jurassic)	Patcham Fm	Sponge Limestone mbm	Jhurio Formation 290m			Member G: Thin bedded White Lst. & Nod. Lst
	Jhurio Formation	Purple Sandstone / Echinoderm Packstone JCL mb				Member F: Purple sandstones / Packstones
						Member E: Bedded rusty grainstone with golden oolite
		GYF Mb				
Bajocian ???		JGO mb / - CL/BLGO				Member D: Gray Shales
		Badi White Limestone mb				Member C: Brick red weathering rusty grain stone with golden oolites
						Member B: Gray Shales
						Member A: Thin bedded yellow white limestones, shales, rusty brown limestones with golden oolites ? ? ?
Early Jurassic to Late Triassic				Continenta sediments	PRE RIFT	
	Precambrian Basement					

Table 1.1 Updated and modified lithostratigraphic classification of the Mesozoic rocks of Kachchh Mainland (After Deshpande and Merh 1980; Biswas 1977,1993a & b ; Krishna et al.2009; Furisch et al. 2001, 2014).

Jumara Formation

The overlying Jumara Formation is best exposed in Jumara dome comprise of 275m thick succession marine sediments mainly shale with interbeds of thin marlite (marl), sand stone and siltstone. Upper top formation west to east throughout mainland marked by Dhosa Oolite member comprising of greenish glauconite, oolitic limestone and glauconite shale inter-beds indicating maximum transgression during Jurassic surface.The lower part of if dominantly shale faces to golden Oolite limestone-shale interbedded facies in Keera dome (Biswas, 1977; 1993a & b). The formation ranges from Callovian to Oxfordian (Table-1.1).

Jhuran Formation

Shale/sandstone alternation within thin bedded hard calcarious sandstone constitutes the 760m thick marine sediments succession of Jhuran formation overlain by Bhuj formation. The formation ranges from Kimmeridgian to Barriasian. The Middle shale member of the Jhuran Formation is a prominent marker member across the entire length of the Mainland. It is the prodelta shale deposit below the deltaic sandstone of the overlying formations (Biswas, 1981; 1991). The Bhuj and Jhuran formation are extensively exposed over the Mainland on the slope of the NHR between two fault KMF and KHF while Jhurio and Jumara Formations are exposed only in the cores of the anticlines and domes which occur in the narrow deformation zones along the tilted up Northern edge. The formation ranges from Kimmeridgian to Tithonian (Table-1.1).

Bhuj Formation

Jhuran Formation overlain by brown and pink sandstone with bioturbated ferruginous beds which dominated the deltaic Bhuj Formation, having huge successive thickness of 850m non marine, fluvio-deltaic sediments. Upper member sandstone/shale alternation represents transition to deltaic facies in paralic environment.

The boundary between the Jhuran and Bhuj formations is gradational. Local disconformity is seen at a few places. Above the Upper Member of Jhuran Formation The Katesar Member represents a deltaic lobe developed towards the sea existing only in Western Mainland. A local unconformity marked by gypseous ferruginous bed defines the Katesar-Bhuj boundary. The Bhuj formation is disconformably overlain by the basic lava flow of Deccan Trap in Southern

Mainland while the base of the Jhurio formation is unexposed (Biswas, 2016a). The formation ranges from Barriasian to Albian (Table-1.1).

Tectonic Evolution of the Kachchh Basin

Kachchh is first the fractured oldest rift in western volcanic passive margin of the Indian craton during the Late Triassic break up of Gondwanaland (Kachchh-Jurassic; Cambay-Cretaceous and Narmada-Late Cretaceous). The rifting occurred within the weak zone of the Mid-Proterozoic mobile belt by reactivation of pre-existing faults. During northward drifting through Jurassic to Early Cretaceous as Indian plate separated from Africa, Kachchh basin evolved and accommodated with syn rift oldest Mesozoic sedimentation overlain by post rift Deccan lavas and marginal Tertiary sediments. Cambay rift is filled by Lower Cretaceous-Tertiary rift fill sediments. The youngest Narmada basin-fill is Late Cretaceous syn-rift sediments capped by Deccan volcanic flows. The Kachchh Mesozoic package comprise of Late Triassic pre-rift continental sediments, Middle to Late Jurassic syn-rift marine sediments and Late Jurassic to Early Cretaceous post-rift fluvio-deltaic sediments.

The palaeo rift of Thar and Southern Indus basin of Pakistan border in the North the Kachchh basin (Zaigham and Mallick, 2000) to the south Saurashtra the tailing edge of the India continental plate horst three intersecting rift system. The N-S trending Cambay rift basin to the west end which crosses the E-W trending two parallel rifts, Kachchh rift and the western offshore extension of Narmada rift. South to the Narmada rift, Mumbai offshore shelf rifted trending by N-S grabens / half graben and horst.

The basin is active tectonic zone and originated as E-W orientation at the periphery of the Indian craton and evolved through three tectonic phases: (1) Rift phase, (2) Late rift divergent wrench phase, and (3) post rift convergent wrench phase (Biswas, 2016a&b; 2005a&b; 1993a &b; 1999; 1987; 1982). These three phases correspond respectively to break up, drifting and collision of Indian plate (Table 1.2)

Kachchh Rift developed due to extensional forces generated by conventional current of Asthenosphere engendered plate movement. It originated as a peri-cratonic rift basin in the volcanic passive margin of Western India during pre-break up crustal distension prior to India-Africa separation in Early Jurassic.

Tectonics	Structures	Major Activity	Plate movements	Stages	Sedimentation
Compression Till continue inversion	Transtensional movement (Physiographic height)	Compression stretching, spilting and linking of fold (Basin closed)	Post collision compression	Quaternary Pliocene	**POST RIFT** convergent (aeolinite-fluvio-conti. sediments)
Inversion Rift evolved within the Mid-proterzoic Arvalli-Delhi fold belt	Transtensional movement off folds to higher order and associated conjugated faulting	Hot spot Reunion igneous intrusions, volacanic activities	Drifting stage, prior to collision. tilting of plate and uplift of trailing edge	Early Cretaceous to Late Jurassic	**SYN RIFT PHASE** **late rift** divergent wrench phase (fluvio-deltaic-Mesozoic sediments)
	Up thrust of blocks, drap folding of ductile carapace. present evolved structures	Ductile sedimentation carapace	Rifting and drifting of Indian plate. End of rifting. Aborting rift		**post-rift** subsidence (marine Mesozoic sediments)
Extensional Precambrian mobile belt	Tilted half graben - graben	Pre-break crustal distension sedimentation accommodation	Breaking of Eastern Godnwana land- India / Africa separation	Early Jurassic to Late Triassic	**syn-rift** (Climax- Mesozoic sediments)
			Break up of Eastern Gondwanaland		**PRE-RIFT** (Mesozoic continental sediments)

Table1.2. Kachchh Basin tectono-sedimentary history of the Kachchh basin (After Biswas 2016a and b).

In this set up, the basin evolved through intense tectono-magmatic episodes particularly during post rift stage ending with Deccan volcanism in Late Cretaceous as the Indian plate passed over the Reunion hot spot. Rifts opened successfully due to anticlockwise drifting of Indian plate, after its detachment from Gondwana land. The rift expanded from north to south by tensional activation of E-W striking primodial fault and post-rift constructional inversion stage which witnessed of present evolved structure. The drift motion and the counter-clockwise rotation induced strike-slip movements. Structural evolved through an extensional Rift phase of Mesozoic sedimentation.

Rift phase

Rift developed during the break up of Gondwanaland in Late Triassic within Precambrian mobile belt. It originated as a peri-cratonic rift basin in the volcanic passive margin of Western India during pre-break up crustal distension prior to India-Africa separation in Early Jurassic. In Late Cretaceous, during pre-collision stage of the Indian plate with Eurasian plate the rifting was aborted as a result the trailing edge uplifted as the leading edge was dragged down towards the Tethyan trench (Biswas, 1982).The uplifts came into existence by upthrust of the footwall blocks. The intra-rift KHF and GDF were activated during this time (Biswas, 2016b).

Late rift divergent wrench phase

As the plate tilted towards the Tethyan trench in response to pre collision slab-pull and later became a shear zone during inversion stage following collision (Biswas, 1982). The uplift caused structural inversion during rift-drift transition when most of the uplifts with drape folding over the edges came into existence by upthrusting along the master faults. The motion during the drift stage of the plate induced horizontal stress and the near vertical normal faults, which were reactivated as reverse faults during initiation of inversion cycle, became strike-slip faults involving divergent oblique-slip movements. Drifting of the plate, induced horizontal stress and wrench-related structures developed. At this stage divergent wrench movements set up the framework of the present structural style.

Post rift convergent phase

This was followed by rift inversion during post collision compressive cycle that is continuing till date. Post-collision compressive regime is responsible for present active neotectonic movements continue till date. Due to the onset of inversion tectonic the Kachchh basin was closed by the end of the Pliocene time and major structural elements such as NPF, KMF and KHF started manifesting the uplift of the area that gave rise to prominent physigraphic highs mostly oriented along east-west (Maurya et al., 2017). These faults were dissected by the transverse fault system to accommodate the stresses built up along the major faults.

During wrench tectonics, the KMF became the principal right lateral strike-slip fault and active since then. Eastward KMF side steps sinistrally and continues as SWF. The two faults overstep each other, creating a convergent overlapping transfer zone between them. Epicenters of two big earthquakes including the major Bhuj earthquake are situated in this zone. All the aftershock hypocenters are located within this zone. The eastern part of the basin is highly strained between Radhanpur arch and Median High under the present NNE–SSW-directed compressive stress. The KMF-SWF overstep zone is the most strained part. This part is thus seismically active. Study of intrusive igneous rocks and seismic tomography data indicate the presence of a deep-seated magmatic body close to the mantle.

Sedimentation in rift basin is evolved through rift phase in three stage, Pre-rift (within Precambrian mobile belt), syn-rift-(climax maximum sedimentation) and post rift (Subsidence).

The rift is developed by extensional faulting giving rise to a series of half-grabens and footwall uplifts. Hanging wall subsidence in half-graben are the main depositional domains structures. The fault s bordering them open sea wards i.e. expanded from north to southward by successive reactivation of primordial fault of Mid-Proterozoic Delhi fold belt. Matching Precambrian structural trend and rift fault of the craton evident of Kachchh rift evolved within the Mid-proterzoic Arvalli-Delhi fold belt. NE-SW trending Delhi fold swings to E-W towards Kachchh across Cambay Basin. The Kachchh faults strike E-W but eastward the strike swings to NE-SW merging with the Delhi- Aravalli strike (Biswas, 1987).

The Kachchh uplift characterized by positive Bouguer anomalies reveal relatively high basement (Chandrashekar and Mishra, 2002; Mishra et al, 2005). This endorsed by well drilled in Banni and KMU back slope, basement encountered 2.2km to 3.5km depth (Pandey and Dave, 1993) and outcrops of granite boulders conglomerate and basement at Meruda Takkar, north of KU (Biswas and Deshpande, 1968). The most striking features in basin is NNE-SSW oriented meridional high referred as Median high (MH) a basement ridge across the middle of the E-W rift system along the hinge zone of the basin which was activated in Upper Jurassic (Biswas, 1987) .

The Kachchh basin was originated as a western marginal pericratonic rift during the break up of Eastern Gondwanaland in Late Triassic within Precambrian mobile belt. Kachchh Rift (KR) includes six major E-W striking intra-rift faults; KMF, KHF, SWF, GF and IBF and two rift bounding fault; North Kathiawar fault (NPF) in the north and North Kathiawar fault (NKF) in south.KMF is the longest fault, extends 120km approx among KR. The basement fault and bounding fault are not exposed. Kachchh Rift basin bounded by Nagar Parkar uplift on the north and Saurashtra uplift on the south on along respectively fault plain Nagar Parkar fault and North Kathiawar fault (NPF & NKF). Table 1.2 summarizes the tectono-sedimentary evolution of the Kachchh basin after Biswas (2016 a & b).

Structures of Main land and Major Fault (KMF & KHF)

E-W trending wide quadrilateral topped upward is south tilted biggest uplift along KMF on the north. Bhachau-Anjar in east and Lakhpat and Narayan Sarovar are in west end of uplift where plunges occur. This uplift (KMU) can be divided in to four structural zone.

1. North Range Deformation zone; forming Northern Hill Range along marginal fault KMF, mainly faulted domes and anticlines of varying size, shape and geometry.

2. Katrol Range of Deformation Zone; along KHF, mainly fold,faulted domes and anticlines of varying size, shape and geometry.

3. Vigodi-Gugriana-Khirsara Deformation Zone (VGKDZ); Splaying trend of KHF at western end forms the Vigodi-Gugriana-Khirsara fault branch in continuation of Chaduva Hill Range in continuation of the Katrol Range with NW-SE trend in the west central part of main land.

4. Peripheral Platform; consisting of tertiary strata wrapping around uplift and coastal plains.

Kachchh Rift (KR) includes six major E-W striking intra-rift faults; KMF, KHF, SWF, GF and IBF and two rift bounding fault; Nagar Parkar Fault (NPF) in the north and North Kathiawar fault (NKF) in south. Both KMF and KHF strike parallel E-W.

KHF is striking fault in middle of south tilting block of the KMU, separating in to two south tilted block KMF and KHF within NHR and KHR, providing and exposing repeating the stratigraphic sequence. Although (KHF) is not rift fault unlike KMF/IBF and have no control over syn-rift sedimentation accommodation. KHF is of inversion tectonics product forming reverse fault after post rift activated along primordial fault. KMF is the longest fault; along northern hill range extends 120km approx and 75 km long on surface it is expressed as steep north facing scarp in the KHR. KHF is of inversion tectonics product forming reverse fault after post rift activated along primordial fault.

Down thrown on the north forms the Cretaceous Bhuj low (BL) on northern side dip uniformly 3^o to 5^o towards south, not effected by fault and up thrown side, while Mid-jurassic strata highly folded along very sharp, well exposed fault line. This provides evident for strike slip types of fault and fraying nature of fault towards west proves Sinistral strike slip type fault.

The main E-W fault splay west to Jarjok continue westward after dislocation of Jarok fault and extend across offshore shelf. The western half of the KHF shows different dips with reverse separation and eastern half to Ler, the fault dips 70^o to 80^o with normal separation. The fault plane is well exposed all along its length. It is a single sub vertical plane, very sharp, marked by thin plastered and ferruginised surface between undisturbed homocline of Cretaceous rocks and sharply folded Mid-Jurassic rocks (Biswas, 2016b).

Kachchh rift is one of the best examples of tectono-magmatic activity. Igneous intrusion is a common phenomenon particularly in the marginal rifts associated with plate breakup, witnessed. in all the uplift areas of Kachchh. The Mesozoic rocks of Kachchh had been intensively intruded by basic/ultra-basic igneous rocks. Almost all forms of intrusive bodies are present: plugs, dykes, ring-dykes, sills, complexes of dykes and sills, and laccoliths (Biswas, 1980; 1993a&b).

Dikes are most common in all uplifts and intruded mostly through the faults. Basalt and dolerite dikes occur along predominating fault lineaments. Plugs and big intrusive bodies are seen at the crossing of faults. Such association with extensional faults suggests post-rift plutonism. A series of igneous plugs occur in the central region of KMU close to KHF. The biggest Nana Dungar plug occurs at the western end of KHR where KHF is dislocated by a tear fault. Some of these plugs are related to Deccan Trap flows as seen in the outcrops where plugs are capped by Trap flows. Besides plugs, shield volcanoes are also the source of Deccan lavas (Biswas and Deshpande, 1973).

Neotectonism along KMF and KHF

The drift motion and the counter-clockwise rotation induced strike-slip movements. In Late Cretaceous, the trailing edge of the Indian plate was uplifted as the leading edge was dragged down towards the Tethyan trench (Biswas, 1982). The rift basins at the trailing edge of the plate were aborted. The uplifts came into existence by upthrust of the footwall blocks. The intra-rift KHF and GDF were activated during this time. Drifting of the plate, induced horizontal stress and wrench-related structures developed. At this stage divergent wrench movements set up the framework of the present structural style (Biswas, 2016b). Post-collision compressive regime is responsible for present active neotectonic movements continue till date. Post-collision stage was the period of compression and wrench movement was mainly transpression which continued episodically since Early Tertiary. Same stress regime continues, causing neotectonic movements.

Neotectonic activities along the KHF then must have intensified the incision (Patidar et al. 2007; Das et al., 2016a) however, their estimates of rate of uplift cannot be precise due to the fact that the erodibility of miliolitic units is much higher and flash flood like events in seasonal rivers can incise such a sequence regardless any change in the base level (Talati and Bhatt, 2018).

The KHR constitutes a conspicuous physiographic high which is formed due to the tectonic uplift along KHF situated south of the Bhuj. Major rock mass of this is composed of the shale and sandstones of Jhuran and Bhuj Formations of Jurro-Cretaceous age with patchy occurrences of the Miliolite Formation of Middle to Late Pleistocene age. These were largely ignored by the previous workers who mostly focused on the seismicity and tectonic activities during the late Quaternary. The present study has mainly dealt with this fascinating sedimentary record as it bears the clues for better understanding of the evolution of the southern Kachchh in general and the Katrol Hill Range (KHR) in particular.