# CHAPTER - 1

# BASIC CONCEPTS

## 1.1 INTRODUCTION

The sedimentary basins preserved complete geological records from the beginning till they got filled up by the various types of sediments. To evaluate them, various types of events such as tectonics, sedimentological, paleontological, stratigraphical, etc. are to be observed, recorded and assessed in detail to understand the basin evolution. The peri-cratonic rift basin of Kachchh evolved during the Gondwanaland break-up and comprises of complete sedimentary records of part of the Jurassic and Cretaceous Period of the Tethyan Sea. The author has made an attempt to evaluate the Kachchh Basin, which consists of a number of sub-basins characterized by the different rock units of the Mesozoic era. In the present investigation, an attempt has been made to evaluate the eastern Kachchh sub-basins, where the sedimentary sequence of the Jurassic Period is exposed in three localities, namely Khadir, Bela and Chorar Islands. A number of studies including sedimentological, paleontological, lithostratigraphic, ichnological and sequence stratigraphic analyses were carried out in detail to understand the stratigraphic architecture of the eastern Kachchh sub-basins. Assessing the basin in fuller length is a prerequisite to understanding the basic fundamentals of the proxies that are going to be used in the evaluation. The author has considered the sedimentological, ichnological and sequence stratigraphical study of the basin in detail for evaluation and in turn, made a crucial attempt to understand the fundamentals which are briefly discussed in forthcoming paragraphs.

## 1.2 SEDIMENTOLOGY

The ultimate goal of a sedimentological study is to decipher the depositional process and process response of the sediments and unravel the complete depositional history of the basin (Sengupta, 2007). This involves the synthesis of the framework of the basin, its sediments and the biota associated with the sediments that form the stratigraphic sequences. Sedimentology and stratigraphy go hand in hand with each other as stratigraphy provides a framework for which sediments can be studied in detail systematically.

Sedimentology is the study of sediments (Wadell, 1932) as well as chemical precipitates such as carbonates, gypsum and salts. Thus, sedimentology dealt with the study of the processes and products of sedimentation where the sediments are produced either by chemical or mechanical weathering. Sediments are produced from preexisting rocks either by mechanical or chemical processes. These sediments are transported by wind, water or glacier etc., and are deposited and consolidated into sedimentary rocks. The bedforms, sedimentary structures, and the fossil content when preserved provide clues to the paleoenvironment as well as palaeocurrent. The texture of sedimentary rocks provides information on the changes it undergoes during the consolidation of sediments into sedimentary rocks.

Sedimentological analysis of a basin requires the application of the basic laws of Stratigraphy laid down by Nicolas Steno (1669). These laws are listed as follows.

*i.* *The principle of original horizontality* states that layers of sediment are originally deposited horizontally under the action of gravity. The principle is important to the analysis of folded and tilted strata.

*ii.* *The law of superposition* states that in any succession of strata, not disturbed or overturned since deposition, younger rocks lie above older rocks.

*iii.* *The principle of lateral continuity* states that layers of sediment initially extend laterally in all directions - they are laterally continuous.

Sedimentology deals with Siliciclastic, non-clastic and mixed siliciclastic rocks. Siliciclastic rock constitutes more than two-thirds of all sedimentary rocks which include sandstone, shale, and conglomerate (Nicols, 2009). The study of siliciclastic rocks includes grain size analysis, shape (sphericity, roundness, texture), fabric (grain orientation, grain packing, grain to grain relationship and porosity), sedimentary structures (stratification and bedforms, bedding plane marking and other structures), composition, classification and digenesis. This study plays an important role in deciphering the geological processes of the past.

Non-clastic rocks include carbonates, cherts, evaporites, phosphates and ironstone which are formed by precipitation from water or by biochemical processes (Sam Bog, 2006) and constitute about 10-15% of all sedimentary rocks (Nicols, 2009). Carbonate rocks include calcite, aragonite, dolomite and siderite. Carbonates are formed by carbonate-forming plants (algae, nanoplanktons etc.), animals (mollusks) and precipitation from water such as ooids (Kalkowsky,1908; Folk's, 1959; 1962). Folk’s classification is based on carbonate grains, microcrystalline carbonate mud and sparry calcite cement while Dunham’s classification (1962) is solely based on grain packing and the relative abundance of grains to micrite and depositional binding of grains and is widely used in petroleum industries. Cherts are microcrystalline quartz formed by precipitation from enriched silica pore waters. It can also form as nonspherulitic blades, rim cement, and overgrowths, and as massive cement (Maliva and Siever, 1988). Evaporite minerals are formed by precipitation out of a solution and include gypsum, anhydrite, halite, etc. Phosphates originate from the dissolution of granitic rock mineral apatite while ironstones are digenetic products or as an accessory igneous rock like magnetite (Nicols, 2009).

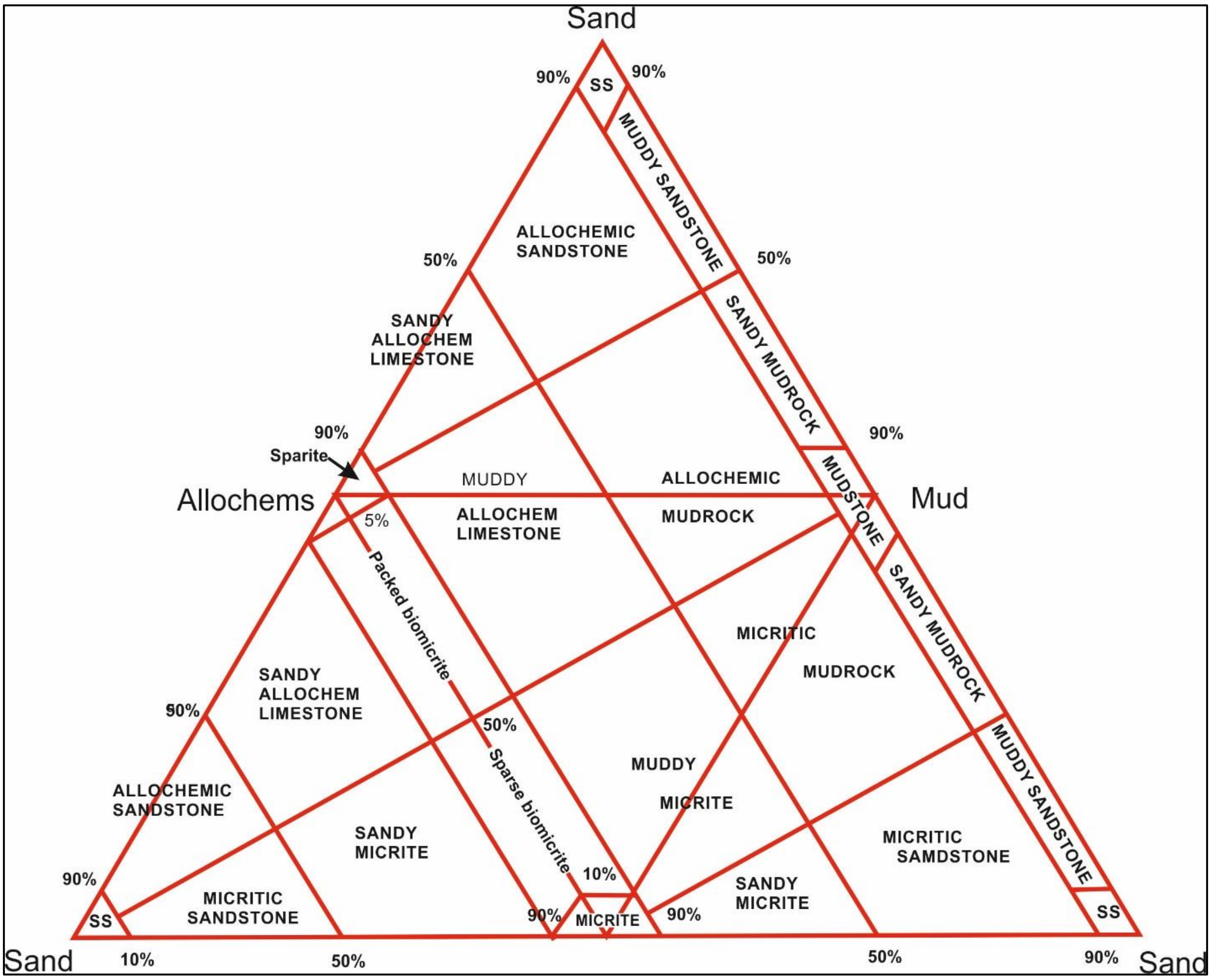


Fig. 1.1 Unfolded tetrahedra of Mount's classification (1985) of mixed siliciclastic-carbonate rocks with the classification of pure limestone by Folk, (1962) plotted.

Mixed siliciclastic-carbonate rocks are a mixture of siliciclastic and carbonate rocks both ancient and modern (Mount, 1985). Several authors have acknowledged the existence of mixed siliciclastic and carbonate rocks like Pettijohn (1975), Williams, Turner & Gilbert (1982) and Folk (1962, 1974) and consider them as hybrid sandstone (calcarenaceous/calcareous sandstones) or added pre-fix or suffix such as sandy biomicrite. Despite their differences in origin siliciclastic and carbonate sediment do mix, and they form rocks that are not readily accommodated in the most commonly used classification systems (Mount, 1985). Hence, Mount (1985) proposed a first-order classification to incorporate all mixed siliciclastic carbonate sediments and their corresponding lithified equivalents.

A sedimentary analysis is primarily based on the recognition of the main sedimentary components such as clastic, non-clastic and mixed siliciclastic-carbonate rocks, including the identification of heavy minerals and clay minerals for provenance studies (Weltje and Von Eynatten, 2004). Other studies may include colour reflectance using Spectro colorimeter to provide information on the mineralogy as well as early diagenesis, XRF spectrometry methods, to distinguish phases of increased terrigenous input to the ocean (St-Onge et al., 2007), magnetic susceptibility for current direction, grain size analysis for hydraulic energy condition of the depositional environment (McCave et al., 1995).

Different approaches have been applied by different workers to achieve different objectives. The present study focus on the reconstruction of the paleoenvironment and deduce the sequential filling up of the basin. As the paleoenvironment is the accumulation of chemical, biological, and physical properties and processes associated with the deposition of sediments that lead to a distinctive suite of sedimentary rocks, the present studies focused on proxies such as sedimentary rock types, sedimentary structures, texture and facies analysis, ichnological analysis as well as sequence stratigraphic analysis to achieve the objective.

## 1.3 STRATIGRAPHY

*Stratigraphy* is the study of rock succession that encompasses the physical properties, paleontological characteristics, geophysical properties, age relationships and geographic distribution of the layered rocks. The three fundamental stratigraphic units based on materials are lithostratigraphy, biostratigraphy and chronostratigraphy, where sequences are subdivided into smaller units. Stratigraphy may be described either independently or supplement information may be added to strengthen the logical description of the units. The studied Jurassic sequence of the eastern Kachchh is classified by Biswas (1971, 1977 and 2016) based on lithostratigraphy, considering them as the equivalent time of formation and identical units name were followed for the Khadir, Bela and Chorar Islands. The author has followed the lithostratigraphic classification of Biswas (2016) and described the units with utmost care and also facilitate the correlation for understanding the concepts and principles which is an indispensable part of the stratigraphic analysis.

## 1.4 ICHNOLOGY

Ichnology is a branch of paleontology that deals with the study of traces produced by organisms on or within a substrate. It comprises two divisions: i. Neoichnology; which deals with the study of modern traces and ii. Palaeoichnology; deals with the study of fossilized traces. Neoichnology serves as an important tool in decoding the behavior and anatomy of the trace maker which in turn helps in deciphering the fossilized traces. Paleoichnology or fossilized traces are produced in substrates ranging from unlithified sediment to sedimentary rock or organic matter by the activity of organisms. These traces may include burrows, bioerosion, biodeposition, trails, trackways and plant root traces. Ichnology thus encompasses the study of the process and the resulting product of biogenic sedimentary structures (trace fossils).

Trace fossils represent both sedimentologic and palaeontologic entities and also represent a unique blending of potential environmental indicators in the rock record (Savrda, 1991; Pemberton et al., 2004). Trace fossils approach can be used as a proxy for paleo-bathymetry, paleo-salinity, benthic oxygenation, hydrocarbon potential, biostratigraphy and genetic stratigraphy (Bromely 1996; Savrda, 2007).

### 1.4.1 Characteristics of Trace Fossils

Trace fossils are evidence of fossil behavior (Seilacher 1964). Analysis of the morphology and architecture of trace fossils reveals valuable information on the anatomy and ethology of their producers like mode of life, trophic type, and locomotion mechanisms (Buatois and Mángano, 2011). Trace fossils have their own peculiarities reflecting both their mode of formation and their taphonomic histories and allow the establishment of a rich conceptual framework for ichnology (Seilacher, 1964; Frey, 1975; Ekdale et al., 1984; Frey and Pemberton, 1985; Pemberton et al., 1990, 2001; Bromley, 1990, 1996; Buatois et al., 2002). The applications of ichnology in different fields such as paleoecology, sedimentology, stratigraphy, etc. rely on these unique peculiarities as trace fossils can provide an essence of the trace maker behaviour.

However, this peculiarity has its own limitation. The same organism may have produced more than one ichnotaxon as demonstrated by cleft foot deposit-feeding bivalve. *Protovirgularia* is the locomotion trace while *Lockeia* represents the resting or dwelling trace (Seilacher and Seilacher, 1994; Mángano et al., 1998) of the bivalves.  The different ichnotaxon may also be produced by same organisms like *Corophium volutator* producing simple vertical burrows, *Skolithos* in sandy substrates and a detritus feeder producing U-shaped burrows *Diplocraterion* in silty, nutrient-rich sediment (Seilacher, 1953a; Reise, 1985; Bromley, 1990, 1996). A complex trace fossil may also be produced by a single trace maker reflecting different behavioral patterns as demonstrated by *Hillichnus* where the trace fossils represent locomotion, feeding and dwelling behavior of the same trace maker tellinacean bivalves (Bromley et al., 2003; Ekdale and Ekdale, 2018). A complex structure may also be produced by more than one trace maker representing symbiotic relationships like that of the lobster *Nephrops norvegicus*, the crab *Goneplax rhomboids*, and the fish *Lesueurigobius friessi*, which usually produce independent structures in offshore muds but occasionally construct an interconnected burrow system (Atkinson, 1974). A complex burrow such as *Ophiomorpha* and *Thalassinoides* may show similar boxworks or mazes however morphological developments represents distinctive behavioural attributes within a complex burrow system, and must be named separately (Bromley 1996). Another such limitation of ichnology is that they display long stratigraphic ranges covering most, if not all, of the Phanerozoic Eon which does not reflect common producers through geological time, but rather the activity of different organisms producing the same Ichnotaxon.

### 1.4.2 Application of Ichnology

Trace fossils provide in situ information on the animal's behavior in response to its environmental changes based on factors that influence the individual and the community which is key to paleoenvironmental interpretation (Bromley, 1996). *Ophiomorpha nodosa* was a sure indicator of the littoral and shallow neritic environments (Weimer and Hoyt, 1964), while *Scoyenia* is a reliable indicator to discriminate between marine and non-marine environments. Trace fossils also serve as a reliable indicator of stress factors such as oxygen availability and salinity (Bromley, 1996). *Chondrites* (and *Planolites*) as an oxygenation indicator (Savrda and Bottjer, 1991). Ichnological data can also reflect the rate of sedimentation; where the rate of sedimentation far exceeds that of bioturbation, primary stratification features and physical sedimentary structures will predominate, the reverse is the case, primary stratification will be obliterated and biogenic sedimentary structures will predominate (Howard and Reineck, 1981).

A behavioural classification or ethology is defined as an internally coordinated control of movements or signals with which an intact organism interacts with conspecifics or other components of its animated or inanimated environment as well as activities that serve the individual’s homeostasis (Kappeler, 2012).  It distinguished groups of trace fossils based on the behaviour such as resting trace, feeding, locomotory, dwelling, and grazing traces

(Seilacher, 1964) and serves as the basic building block for trace fossils interpretation. It differs from ichnoassemblages as the later embraces all the trace fossils occurring within a single unit of rock. Thus, an ichnoassemblage may represent an ecologically related group, or they may represent several overprinted events of bioturbation (Bromley, 1996). Groups of trace fossils tend to recur in a particular association which was first recognized by Seilacher (1967) and proposed six recurrent sets of trace fossils (*Skolithos, Cruziana, Zoophycus, Nerites, Glossifung*ites and *Scoyenia*) which later came to be known as the archetypal Seilacherian Ichnofacies. The recognition of these basic ichnofacies groupings was of great utility to sedimentologists as an aid to paleoenvironment al interpretation (Mcllroy, 2004).

Sequence stratigraphy is based on the physical relationship of genetically related strata and their lateral continuity resulting from the interplay of sediment supply, accommodation space and eustatic sea-level changes (Catuneanu, 2011). Any change in the environment is reflected in both the facies association and biota of the strata. As trace fossils serve as a sensitive indicator to such environmental changes as depth, salinity, oxygen level, etc. Understanding the behavioral significance of individual trace fossils and the development of ichnofabrics allows key stratal surfaces to be identified, surfaces that may otherwise easily be overlooked (Bromley, 1996). *Diplocraterion parallelum* is a reliable indicator of marine flooding surfaces (Taylor and Gawthorpe, 1993) while *D. habichi* may indicate omission surface (Heinberg and Birkelund, 1984). The occurrence of plant rooting structures at bounding surfaces is a valuable indicator of subaerial exposure (Bockelie, 1994). Trace fossils as individuals or in a group may also serve as an important tool for sea-level changes indicator (Bromley, 1996). Ichnofabrics such as *Ophiomorpha nodosa* and *Macaronichnus segregatis* represent nearshore, shoreline and estuarine environments (Pollard et al., 1993). *Zoophycos* is an indicator of maximum flooding surfaces (Rioult et al., 1991; Savrda, 1991).

## 1.5 SEQUENCE STRATIGRAPHY

### 1.5.1 Definitions

*Sequence Stratigraphy can be defined as the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by the surface of erosion or non-deposition, or their correlative conformities* (Posamentier et al., 1988; Van Wagoner, 1995).

*The analysis of repetitive genetically related depositional units is bounded in part by surfaces of nondeposition or erosion* (Galloway, 1989).

*The analysis of cyclic sedimentation pattern that is present in stratigraphic succession as they develop in response to variations in sediment supply and space available for sediments to accumulate* (Posamentier and Allen, 1999).

*The recognition and correlation of stratigraphic surfaces represent changes in depositional trends in sedimentary rocks. Such changes were generated by the interplay of sedimentation, erosion and oscillating base level and are now determined by sedimentological analysis and geometric relationships* (Embry, 2001b).

*Sequence stratigraphy is a methodology that provides a framework for the elements of any depositional setting, facilitating paleogeographic reconstructions and the prediction of facies and lithologies away from control points* (Catuneanu, 2011).

### 1.5.2 Types of Sequence

The term ‘Sequence’ was first introduced by Sloss et al. (1949) for a stratigraphic unit bounded by a sub-aerial unconformity. Mitchum (1977) revised the concept to include a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities. The continuous development of the sequence stratigraphic paradigm led to the diversification of approaches, leading to different types of sequences including depositional, genetic, and T-R sequences. A sequence must correspond to a full stratigraphic cycle with trends that may or may not have unconformity or their correlative conformity; The fundamental difference is with respect to the “event” that is selected to mark the start and the end of the full cycle (Catuneanu et al., 2009).

Depositional sequences are genetically related strata bounded by subaerial unconformities and their marine correlative conformities. It requires negative accommodation space as a bounding surface that separates it from other sequences. The correlative conformity is marked at the seafloor at the onset of the seafloor (depositional sequence II), or as the seafloor at the end of forced regression (depositional sequences III and IV) (Catuneanu, 2002). The advantage of this concept is that correlative conformity is independent of sedimentation where the correlative conformity and subaerial unconformity are chronologically correlated. Depositional sequences are not bounded by maximum regressive or maximum flooding surfaces where the timings of which are offset relative to the timing of subaerial unconformities. However, the pitfall of this model is that correlative conformity is difficult to detect in a deep marine setting unless seismic data is available.

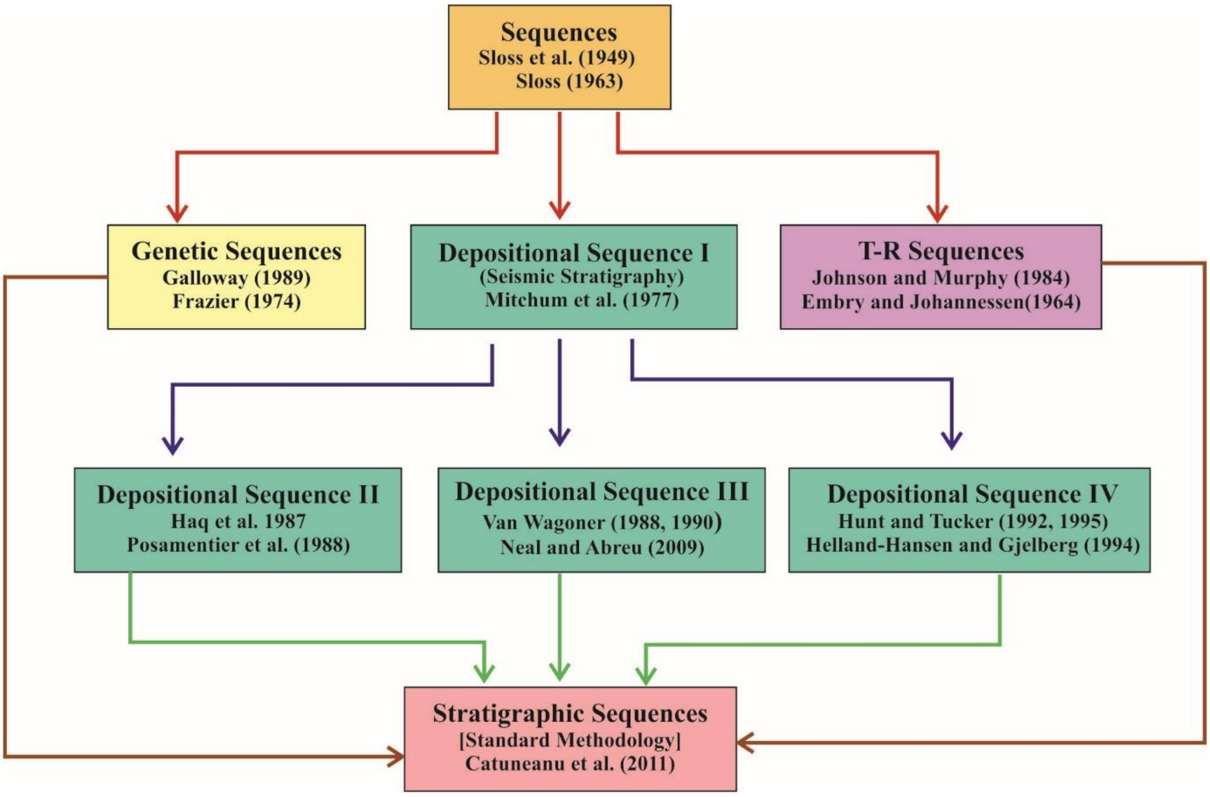


Fig. 1.2 Family tree of sequence stratigraphy (Catuneanu et al., 2017).

The "genetic stratigraphic" sequence model (Galloway, 1989) is formed during a full cycle of change in accommodation and uses maximum flooding surface (MFS) as sequence boundaries during positive accommodation. It includes highstand, lowstand (fall and early rise), and transgressive systems and may or may not include an internal subaerial unconformity, depending on whether or not the corresponding cycle includes a stage of negative accommodation (Catuneanu et al., 2011). This model overcomes the problem of the identification of correlative conformities in deep-sea settings and uses MFS as the bounding surface which is easily identified in outcrop, log data or seismic data. The pitfall of this model is that it includes subaerial unconformity within the sequence where which allows for the possibility that strata genetically unrelated are put together into the same ''genetic'' package (Catuneanu, 2002). Additionally, MFS depends on the interplay of base level and sedimentation where the surfaces may be diachronous (Posamentier and Allen, 1999).

Transgressive-Regressive (T-R) sequence has been defined originally as a sedimentary unit deposited during the time between the beginning of one transgressive event and the beginning of the next, providing that the two transgressive events are of similar scale (Johnson and Murphy, 1984; Johnson et al., 1985). This concept was later redefined by Embry and Johannessen, (1992) to include fluvial setting. In the latter definition, the T-R sequence is bounded by composite surfaces that include subaerial unconformities and/or ravinement surfaces and their correlative maximum regressive surfaces (Embry and Johanneseesn 1992). This model addresses the main pitfall of depositional sequence and genetic sequence. In this concept, correlative conformity is replaced by a maximum regressive surface which is easily recognizable in shallow marine settings (Catuneanu, 2002). The main pitfall of this model is that the marine portion (subaerial unconformity) and the marine portion sequence boundary are temporally offset and connected by cryptic wave ravinement surface during transgression (Catuneanu et al., 2009; Catuneanu, 2002). Additionally, both normal and forced regressions are included in the regressive system tract (Catuneanu et al., 2009).

### 1.5.3 Systems Tract

Systems tract is defined as the linkage of contemporaneous depositional systems (Brown and Fisher, 1977). A systems tract consists of a relatively conformable succession of genetically related strata bounded by conformable or unconformable sequence stratigraphic surfaces (Catuneanu et al., 2011). It is a subset of sequence based on stratal stacking patterns, position within the sequence, and types of bounding surfaces (Van Wagoner et al., 1987, 1988, 1990; Posamentier et al., 1988; Van Wagoner 1995; Posamentier and Allen 1999). Systems tract is broadly divided into shoreline related systems tract and shoreline independent systems tract. Shoreline-related systems tract is governed by the relative base-level changes and includes Falling Stage Systems Tract, Low Stand Systems Tract, Transgressive Systems Tract, Highstand Systems Tract and Regressive Systems Tract. Shoreline independent systems tracts are formed where sedimentation processes are unrelated to shoreline shifts. Shoreline independent systems tract by be observed in an upstream fluvial setting where sedimentation is independent of eustatic sea-level changes and shoreline shifting as well as deep-marine setting where sedimentation is controlled by sub-basin tectonism; however, no independent nomenclature is assigned (Catuneanu et al., 2011).

| Sequence model / Events | Depositional Sequence | | | Genetic Sequence | T-R Sequence |
|---|---|---|---|---|---|
| | *Haq et al. (1987) Posamentier et al. (1988)* | *Van Wagoner et al. (1988, 1990) Christie-blick (1991)* | *Hunt & Tucker (1992, 1995) Plint & Nummedal (2000)* | *Frazier (1974) Galloway (1989)* | *Curray (1964) Embry (1993, 1995)* |
| | HST | early HST | HST | HST | RST |
| end of transgression | TST | TST | TST | TST | TST |
| end of regression | late LST (wedge) | LST | LST | late LST (wedge) | RST |
| end of base level fall | early LST (fan) | late HST (fan) | FSST | early LST (fan) | |
| onset of base level fall | HST | early HST (wedge) | HST | HST | |

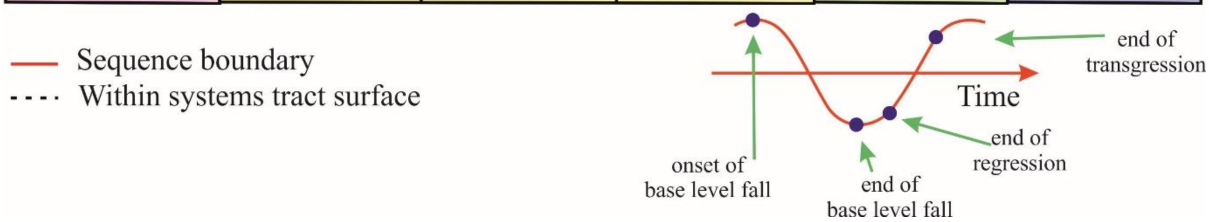


Fig. 1.3 Different types of sequence along with the associated systems tract and sequence boundaries (Catuneanu et al., 2011).

### 1.5.4 Methods of Sequence Stratigraphic Analysis

A sequence stratigraphic approach is a new approach to the analysis of sedimentary successions rather than a brand-new method on its own which requires the integration of various data sets and methods of data analysis into a unified, interdisciplinary approach (Catuneanu, 2006). This allows new insights into the genesis and architectural design of the sedimentary basin. The main analytical methods/data that need to be integrated for accurate sequence stratigraphic analysis and optimum resolution include seismic data; well log data and facies analysis of core data and outcrop data. Seismic data provides continuous subsurface imaging both vertically and laterally, structural styles, layout relationships, stratal stacking patterns, imaging of depositional elements, geomorphology and stratal geometries (Catuneanu, 2009). However, at higher resolution, the higher frequency stratigraphic units become amalgamated within a single reflection. Therefore, seismic data is applicable only for higher rank stratigraphic surfaces leading to a contributing factor to the dominance of the “third-order” frameworks in many seismic stratigraphic interpretations (Nummedal, 2004) and is widely used in petroleum exploration.

Well log data analysis is also an excellent approach for sequence stratigraphic analysis as it provides vertical stacking patterns, grading trends, depositional trends, depositional elements and systems, types of rocks and calibration of seismic data (Catuneanu, 2006, 2009). Well logs such as spontaneous log and gamma-ray log may be used to infer the lithology based on the porosity and naturally radioactive potash content to differentiate sandstone and shales respectively. Integration of these logs with resistivity log help to differentiate sandstone from coals. Gamma-ray log primarily detects potash in clay and are often interpreted in grading terms (fining/coarsening upwards). High gamma-ray responses to periods of restricted bottom-water circulation and/or with times of reduced sediment supply correlate with maximum flooding surfaces (Galloway, 1989). However, well log interpretation may be hindered by various factors such as a change in salinity may reverse the response in SP log, the occurrence of fine-grained sediment, presence of other radioactive minerals such as uranium or thorium may give a false reading. Similarly, the presence of siderite may show low resistivity.

Facies analysis is a fundamental sedimentological method of characterizing bodies of rocks with unique lithological, physical, and biological attributes relative to all adjacent deposits (Catuneanu, 2006). It is based on a detailed description of lithologic features including composition, grain size, bedding characteristics, and sedimentary structures which represent individual depositional events (Miall, 2000). It provides clues for paleogeographic and paleoenvironmental reconstructions, as well as for the definition of sequence stratigraphic surfaces. The sedimentological approach which includes facies analysis of outcrop data provides direct first-hand information on the cyclic paleodepositional environment while ichnological data provide indirect in situ information based on the biogenic response to the changes in depositional including sediment supply (less bioturbation when rate of sedimentation outpaces the rate bioturbation), salinity, oxygen level, substrate consistency etc. The integration of lithostratigraphic, sedimentological and ichnological data will be used for sequence stratigraphic analysis in the present work.

## 1.6 THE REGION OF KACHCHH

Kachchh formerly known as Kutch is an ancient region with great relics with unique geographical characteristics as well as topographic features. In the present work, the name Kachchh has been followed but in old geological literature, the word Kutch is used, do respect was given to the old literature, hence, both the words are used in the present work according to their priority. It is named because its shape resembles an inverted tortoise (Kachhua). Kachchh also means marshy region/wasteland. Kachchh lies in the western most district of Gujarat state, extending from 22°44'11"N to 24°41'25"N latitudes and 68°09'46"E to 71°54'4"E longitudes covering an area of approximately 44,200 sq. km. The crescent-shaped region is bounded by Banaskantha district to the east, Kathiawar Peninsula and Gulf of Kachchh to the south, the Arabian Sea to west and south-west, and Pakistan to northwest and north, and the Thar Desert to the north. It has a long coastline of about 352 km from Shikarpur in the east in the Gulf of Kachchh to Sir Creek in the west.

### 1.6.1 Climate and Biota

The Kachchh has a semi-arid climate where rainfall is erratic and highly variable (Mehta, 2001). The average annual rainfall of the district is 380 mm ranging from 440mm in southern Kachchh to 338 mm in western Kachchh (Raju, 1995). It rains only a few days per year in Kachchh (15 days on average) and is considered to be a drought-prone district as droughts are a recurring phenomenon (Mehta 2001, Lamba and Kapoor, 2006). The summer day temperatures are generally low in the coastal region than in the interior due to the coastal winds from the Arabian Sea. In summers the day temperatures go reach up to 47 °C and the minimum temperature in winter may fall to 7°-10°C (Thakkar, 2017). Humidity remains high throughout the year along the coast generally greater than 60% on average (Mehta, 2001). The occurrences of storms are quite often and depressions from the Arabian Sea in the latter half of summer and monsoon seasons are experienced.

### 1.6.2 Flora

Kachchh district is a semi-arid region surrounded by saline water on three sides. Kachchh is an ecologically sensitive area (Joshi, 2002) and is devoid of dense forest. Despite its extreme climate, a total of 988 angiosperm plant species (including one gymnosperm) belonging to 118 families; 503 genera, representing 805 species of dicots and 183 monocots are reported (Patel et al., 2011). They also recorded 21 threatened plant species which include *Helicrysum cutchicum, Commiphora wightii, Heliotropium bacciferum* var. *suberosum, Heliotropium* *rariflorum, Ipomoea kotschyana, Dactyliandra welwitschii, Indigofera caerulea* var. *monosperma, Limonium stocksii, Tribulusrajas thanensis, Campylanthus pungens, Hyphaene indica, Ammannia desertorum, Corallocarpus conocarpus, Dipcadiery thraeum, Pavonia ceratocarpa, Sidatiagii, Schweinfurthia papilionacea, Citrullus colocynthis, Convolvulus stockii, Talinumportula cifolium* and *Ephedra Foliat.* The Kachchh flora is mostly characterized by thorny and non-thorny shrubs and trees like Baval and Kher. The coastline has swamps vegetated with mangrove forests and grasses covering dunes and sand flats.

### 1.6.3 Fauna

The chief domestic animals found are horses, camels, oxen, cows, buffaloes, sheep, goats and asses. Wild animals are lacking due to the absence of forests. Great Rann is famous for its suitable nesting and breeding environment of Greater Flamingo in India. The center of Great Rann is known as Flamingo city- Hunj Bet (Hunj stands for Flamingo in local language), breeding grounds for Greater Flamingo (*Phoenicopterus rubber*) discovered in 1886 by Maharao Khengarji (Patel, 1971). Lesser Flamingo (*P. minor*) and Avocet are also reported from Great Rann (Singh, 2001). The migratory birds are attracted due to the availability of food in the region of the marshy ecosystem. Reptiles of the region are lizards like spiny-tailed lizard (*Uroma stixhardwickii*), desert monitor (*Varanus griseus*), common India krait (*Bungarus caeruleus*), black cobra (*Najaoxina*), and saw-scaled viper (*Echiscarnatus*). *Cyrinodondispar*- A small wild species found in Rann. Mammalian species are India porcupine (*Hystrix indica*), Indian rattle (*Mellivora capensis)*), caracal (*Felis caracal*) and striped hyena (*Hyena hyena*), the *Panthera pardus* (Panther), *Canis lupus* (Indian wolf), *Canis aureus* (Jackal), *Vulpes bengalensis* (Fox), *Sus scrofa* (wild boar), *Antelope cervicapra* (Blackbuck), *Equus hemionus pallas* (wild ass), and *Lepus nigricollis* (Indian hare). Total of 93 invertebrate species is reported which includes, 27 spiders have been recorded from Nanda and Shedwa Bet, 25 species of zooplanktons, 24 insects, 12 molluscans, 4 crustaceans and one species of Annelid in Little Rann. It supports brackish water fisheries mainly prawn fisheries due to the mixing of tidal waters of the gulf and rivers draining in Little Rann, it is favorable for prawns; eleven species have been found *Metapena cuskutchensis* (endemic to Kachchh) and *M. affinis* mainly. A variety of resident and migratory birds belonging to at least 178 species occur in the Wild Ass Sanctuary of Little Rann of Kutch (Singh, 2001) and is well known for last only left species wild ass (*Equus hemionus khur*) (Meena et al., 2008), the only gene pool in the world and one of the six geographical categories/sub-species on earth.

### 1.6.4 Communication and Transport

The capital of Kachchh, Bhuj is well connected with the entire country by rail, road and air. It is connected with Ahmedabad, Vadodara, Rajkot and Mumbai by rail, road and air. Ahmedabad-Kandla national highway is the only national highway passing through the district. The interior of towns and villages are well connected by state highways like Bhuj-Khavda road, Bhuj-Anjar-Gandhidham road, Bhuj-Laakhpat roads, Bhuj-Mandvi, Bhuj-Jakhau port road, Chitrod-Gadhada road, and Samakhyali-Adesar-Piparala road (Gazetteers of Gujarat, Kachchh District). There are also five ports in the Kachchh district, namely, Kandla, Mandvi, Mundra, Jakhau and Koteshwar where imports and exports of commodities are made.

### 1.6.5 Geomorphology

The physical features of Kachchh are characterized by the contrasting occurrence of extensive plains and highlands with lofty hills (Biswas, 1977). It is surrounded by low-lying plains in the north, the Arabian Sea in the west, and coastal plains in the south where the shallow Gulf of Kachchh separates it from Saurashtra (Kathiawar peninsula). The highlands and the hilly regions occur as isolated upliftment in the form of Kachchh Mainland, Island Belt Zone and Wagad Highland each separated by low-lying plains. The landscape of Kachchh is tectonically-controlled 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). Thakkar (2017) divided the Kachchh region into 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 considering the factors of altitude, slope and ruggedness of relief.

#### 1.6.5.1 *The Ranns*

The Ranns of Kachchh are the most remarkable salt-encrusted low-lying pains with an elevation of 3-4 m above MSL comprising of the Great Rann of Kachchh in the north and Little Rann in the east. The Great Rann of Kachchh is a vast partially dry mudflat extending from the North of Mainland Kachchh to Thar Parker of Pakistan in the North (Biswas 1997). The Rann remains mostly dry during summer and winter when it is covered by salt encrustation. During the monsoon, it is inundated by water thereby surrounding the isolated upliftment appears as a chain of Islands and Islets. A chain of Islands includes the Patcham, Khadir, Bela and the Chorar Islands and the Islets include Chhad Bet, Bear Bet, Kuar Bet, Kakindia Bet, Cheriya Bet, Tangari Bet, Gangta Bet, Vongara Bet, Kara Bir, Gora Bir and Chirak Dhoi imparting undulating topography. Little Rann forms the head of the Gulf of Kachchh and is formed by the regressive sea. It is connected with the Great Rann by a narrow strip of mudflat between eastern Wagad and Gujarat Plains in the East.

Merh and Patel (1988) identified the following five geomorphic units in the Ranns. These are: (i) Northern Bet Zone (NBZ), (ii) Linear Trench Zone (LTZ), (iii) Banni Grassland Plains (BGL), (iv) Great Barren Zone (GBZ), (v) Little Rann of Kachchh (LRK).

#### 1.6.5.2 *The Low-Lying Banni Plain*

The Low-Lying Banni Plain represents the low-lying plains that run between the highlands of Patcham Island in the North, Kachchh Mainland in the south and Wagad Highland in the east. Banni Plains are the higher portion of the Rann of Kachchh made up of aeolian along with alluvial sediments brought from rivers of north and east. The plains are mostly dry and covered with sparse grass and shrubs, inundated during monsoon seasons only.

#### 1.6.5.3 *The Hilly Region*

The hilly region comprises three major uplifts including the Island Belt Uplift, the Wagad Highland and the Kachchh Mainland. The Island Belt Uplift consists of four islands: Patcham, Khadir, Bela and Chorar Islands. They form a chain of islands within the Greater Rann in the east-west direction in the south of the Island Belt Fault, each separated by the Greater Rann. These uplifts are called islands because the sea inundated the low-lying areas during Neogene-Quaternary (Thakkar, 2017), making them appear as isolated islands.

The Patcham Uplift is a southward tilted block surrounded by mudflats in the north and west, and the Greater Rann in the east and south. It is faulted in the middle resulting in a central valley called the Dhorawar-Tuganipur syncline separating the two hill ranges called the Kaladongar and the Goradongar hills (Biswas, 1983). The Khadir Uplift lies east of Patcham Island and is uplifted as a triangular southward tilting block with a straight northern escarpment. The Bela Uplift lies in the east of the Khadir Uplift and north of the Wagad Uplift. These uplifts are a horst block between the Great Rann Graben in the north and the Rapar Half-Graben in the south, bound by Island Belt Fault and Gedi Fault (Thakkar, 2017). The faulted edges are tilted opposite to each other forming a central syncline, the Balasar Low. The Muwana Dome occurs at the eastern end of the Bela Uplift characterized by basic igneous intrusion at the core. The Chorar Uplift is the smallest uplift and lies east of the Bela Uplift.

The Chorar Uplift is mainly characterized by Quaternary deposits with Mesozoic deposits exposed in an elliptical dome near Aaval village. The Mainland Kachchh uplift is an elongated E-W oriented, the southward tilted block bounded by the Banni plains in the north and extended up to the Gulf of Kachchh in the south. The back slope of the Kachchh Mainland is faulted by the east-west trending Katrol Hill Fault which divides the uplift into two south-tilted blocks repeating the stratigraphic sequence (Thakkar, 2017). The Wagad Uplift is bounded by Banni and Samakhiyali depressions in the west and south and a Desalpar depression separating it from the rest of the island belt on the north side. The Wagad Hills in the eastern part of Kachchh, mainly comprise rocks ranging in age from the Upper Middle Jurassic (Biswas, 2016) encircled by a thin and narrow fringe of Tertiary sediments (Deshpande and Merh, 1980).

#### 1.6.5.4. *The Coastal Plain*

The southern coastal plains that border the Kachchh Mainland and the Gulf of Kachchh in the south and the Arabian Sea in the west consist of Paleogene-Neogene and Quaternary sediments and form a 25-30 km wide belt showing a very low gradient. The entire coastline has been divided into five morphologically distinct segments by Maurya et al., (2008) from west to east. These are, Narayan Sarovar–Jakhau, Jakhau–Khuada, Khuada–Bhada, Bhada–Mundra, and Mundra–Surajbari segments. The major geomorphic features of the division include variable width of the intertidal zone; beaches, bars, spits, coastal dunes, raised mudflats, raised beaches, uplifted estuarine tidal terraces, and the coastal alluvial plain.

#### 1.6.5.5 *Drainage*

The drainage pattern of the Kachchh district is a combination of lithological and structural (tectonic) controls along with the influence of sea-level fluctuations of the Quaternary period (Karanth, 2010). There are no perennial rivers and water flow only during the monsoon season. The major streams originate from the Central highland with north-flowing rivers debouching into the Rann while the south-flowing rivers debouching into the Arabian sea. The north-flowing rivers include Chhari, Bhukhi, Trambo, Kaila, Pur and Kaswali streams while the south-flowing rivers include Naira, Kankawati, Chok, Sai, Vengdi, Kharod, Rukmawati, Khari, Nagavanti, Phot, Bhuki, Mitti, Sakra and Larekh streams. The drainage pattern of the Kachchh district is largely dendritic and becomes radial around the domes. 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 (Thakkar, 2017).

## 1.7 GENERAL GEOLOGY

The Kachchh basin is an E-W oriented pericratonic rift basin situated in the western part of the Indian continental margin (Biswas, 1982). The basin owes its origin to the break-up of Gondwanaland during Late Triassic – Early Jurassic. The Neo-Tethys Sea transgression into the Indo-African rift through the Somalian Gulf during the Early Jurassic (Rai and Jain, 2013) marks the beginning of sedimentation in the basin. The transgression during Middle Jurassic formed a marine embayment till the Early Cretaceous. The Late Cretaceous was a period of uplift and erosion during rift inversion ending with the eruption of the Deccan volcanoes forming the Deccan trap. Kachchh preserved the most complete record from Late Triassic to Lower Cretaceous in the form of ~3000m thick lithified rocks (Biswas, 1987). These sediments were deposited during two episodes of transgression during the Middle Jurassic and Late Jurassic-Early Cretaceous in an environment ranging from sub-littoral to deltaic environments (Biswas, 1981). The Mesozoic successions of Kachchh are exposed in isolated patches in the Mainland Kachchh, the Patcham, the Island Belt Zone (Khadir, Bela and Chorar) and the Wagad Highland. A separate lithostratigraphic classification was assigned due to a lack of lateral continuity and facies variation (Biswas, 1977, 2016). The Mesozoic succession of Mainland Kachchh is represented by the Jhurio, Jumara, Jhuran and Bhuj formations; the Patcham Island by the Kaladongar, Goradongar and Modar Hill formations; the island belt by Khadir and Gadhada formations while the Wagad Highland by the Washtawa and Wagad formations. The Mesozoic sedimentation was terminated by a period of non-deposition and Deccan volcanism. The igneous rock was both intrusive – sills, dykes, laccoliths and extrusive in the form of lava flows at the end of the Cretaceous. The Mesozoic rocks are overlain by Cenozoic rocks and are exposed along with the southern parts of Kachchh Mainland bordering the coastal plain. The Cenozoic rocks of Kachchh are represented by deposits ranging in age from Paleocene to Pliocene and Quaternary sediments (Biswas, 1993). The Quaternary sediments are overlying the eroded surface of the Paleogene-Neogene, Deccan trap and the Mesozoic rocks as well as cover the low-lying area of the basin.

## 1.8 STRUCTURE AND TECTONICS

Kachchh is a peri-cratonic rift basin formed by the reactivation of a primordial fault in the Precambrian Delhi fault belt during the Late Triassic Gondwanaland breakup (Biswas, 1987, Norton and Sclater, 1979). The basin is bounded by Nagar Parker uplift in the north, Radhanpur-Barmer arch on the east and Kathiawar uplift in the south (Biswas, 1993). The basin is structurally characterized by three major uplifts, the Kachchh Mainland, The Island belt

(Patcham, Khadir, Bela and Chorar) and the Wagad uplifts, bounded by five parallel faults, Nagar Parkar Fault (NPF), Island Belt Fault (IBF), South Wagad Fault (SWF), Kachchh Mainland Fault (KMF), and North Kathiawar Fault (NKF). The uplifts are due to the upthrust basement blocks tilted along sub-vertical faults with initial normal separation (Biswas, 2016b) prior to Cenozoic thereby exposing Mesozoic succession. The uplifts are surrounded by structural lows – the Great Rann and the Little Rann of Kachchh representing the original grabens during the uplifts (Biswas, 1993). The Banni Half Graben and the Gulf of Kachchh Half Graben are formed due to the southward tilting of the Island Belt Block and the Kachchh Mainland Block respectively. The compressive regime of post-collision of the Indo-Eurasian plate resulted in strike lateral slip movement. This movement shifted the uplifts progressively eastward relative to each other from south to north resulting in the present-day structural style of *en echelon* positioning of the uplifts with respect to the Kachchh Mainland uplift (Biswas, 2003).

## 1.9 MINERAL WEALTH

Kachchh district is rich in mineral wealth. About 75% of the total minerals of Gujarat State are produced in the Kachchh district with major minerals such as bauxite, lignite, gypsum, lime stone, and limestone. the minor minerals include silica sand, laterite, ball clay, gypsum, fire clay, pozzolanic clay, red ochre, china clay, white clay, black trap and hard murrum, soft murrum, building lime stone, ordinary sand, ordinary clay. Kachchh's lignite is suitable for power generation purposes and is currently mined by Gujarat Mineral Development Corporation (GMDC) around Panandhro and Matanomadh. Kachchh is also a home of several cement industries M/s UltraTech Cement Limited, Vadraj Cement and Sanghi Industries ltd promoted by Sanghi Group because of its rich limestone reserve is the main raw material for such industries.

## 1.10 STUDY AREA

The proposed study was carried out in the Khadir, Bela and Chorar Islands located in the Island Belt Zone, Kachchh, Western India. These islands are located in the northern part of Kachchh basin along the Island Belt Fault bearing latitude N 23°46'50 to N 23°56'37″ and longitude E70°10′12" to E70°29′15", latitude N 23°45'54"to N23°57'22", and longitudes of E70°32'10" to E70°55'37" and latitude N 23°41'06" to N 23°57'00" and longitude E71°00'55" to E71°18'36" respectively. The islands are separated by graben where recent evaporites of the Great Rann of Kachchh were deposited. The Jurassic rocks of Khadir, Bela and the Chorar Islands were deposited in an isolated sub-basin ranging in age from Aalenian? to Oxfordian and comprise two formations namely, Khadir and Gadhada formations (Biswas 2016), characterized by clastic, non-clastic and mixed siliciclastic-carbonate rocks. The succession shows wide vertical and lateral variation in sedimentary facies, structures and is often highly bioturbated. The Jurassic succession of Khadir Island is exposed in most of the back slope and north-facing scarp of the island as well as in two small islets (locally called 'bets') called Cheriya Bet in the north and the Kakinda Bet in the south. In Bela Island, the Jurassic succession is exposed along the north-facing cliff of the island as well as in the Muwana Dome. Muwana Dome is a half domal structure with an abundant igneous intrusion at the core. Similarly, on Chorar Island, the Jurassic succession is exposed in and around an elliptical dome near Aaval village.

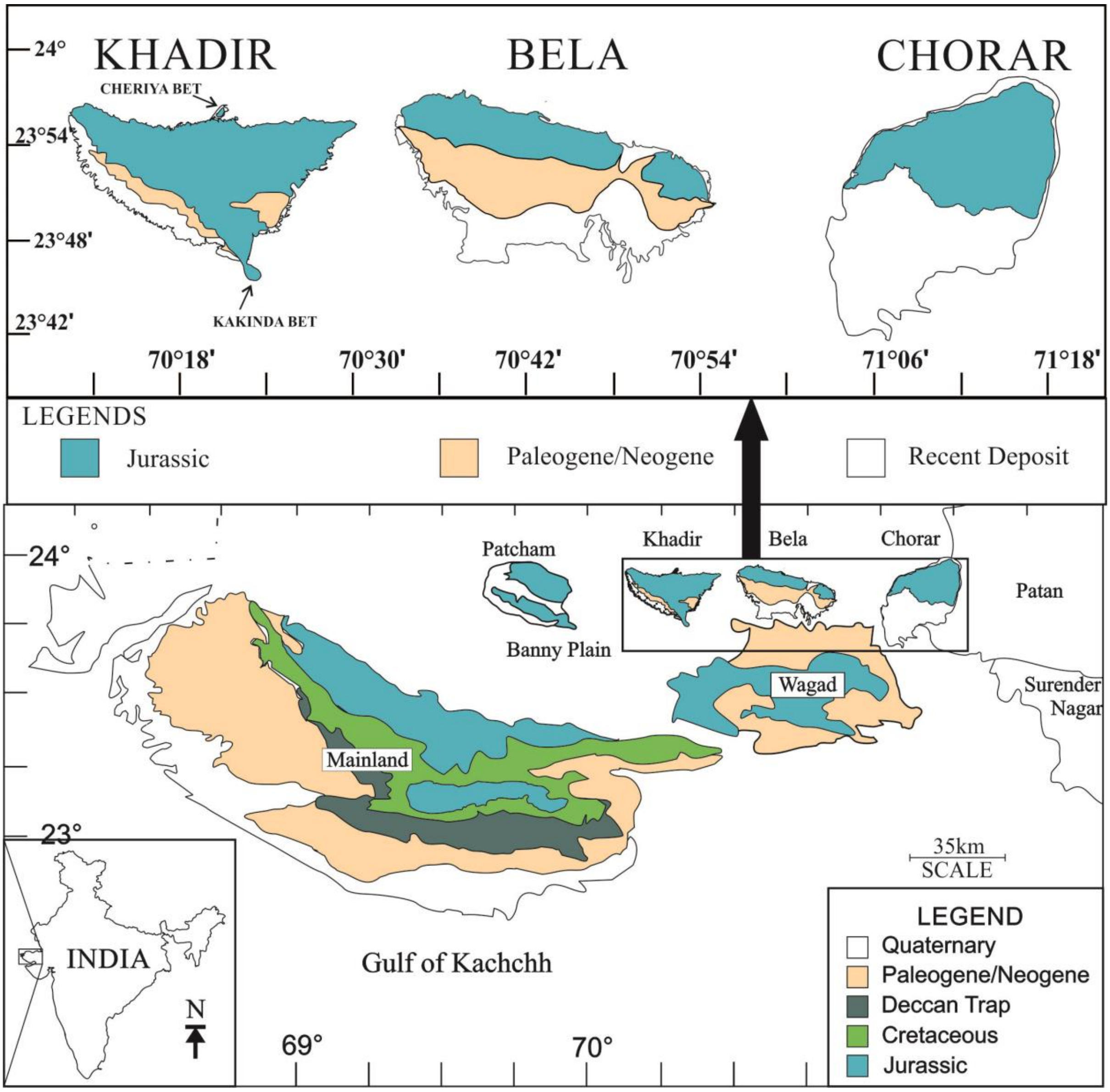


Fig. 1.4 Location and general geological map of the Kachchh.

## 1.11 AIMS AND OBJECTIVES

The aim of the study is to describe and interpret the sedimentary facies, ichnofacies, various sequence stratigraphic boundaries and surfaces of exposed Mesozoic sequence in the proposed study area and reconstruct the 3D-depositional model. The main objectives of the investigations are as follows:

i. Delineation with sedimentary facies; mark their lateral and vertical continuity; interpret them into the framework of environmental facies and correlate them between the Khadir, Bela and Chorar Islands.

ii. Identify the trace fossils and analyzed them for ethology, ichnoassemblages and ichnofacies to interpret the various paleoecological parameters.

iii. Integration of the sedimentological and ichnological data for genetic interpretation of sequence stratigraphic surfaces/boundaries and their associated system tracts.

iv. To determine the depositional environment and basinal history of the Jurassic rocks of Khadir, Bela and Chorar Islands.

## 1.12 METHODOLOGY

The following methodologies have been adopted to achieve the above-mentioned objectives:

i. Stratigraphic sections were measured at different places and generalized lithologs were prepared.

ii. Systematic samplings was done for laboratory analysis. Trace fossils were photographed, collected and identified at the species level.

iii. Lateral and vertical continuity of facies were mapped and correlations was done.

iv. Ichnoassemblage and ichnofacies analysis were made to infer the paleoecological parameters.

v. Sedimentological and ichnological data were integrated for genetic interpretation of sequence stratigraphic surfaces/boundaries and their associated system tracts.

The basinal history is evaluated and 3-D depositional model was reconstructed for the Mesozoic sediments of Khadir, Bela and Chorar Islands.