CHAPTER 1
INTRODUCTION

1.1 Background

Holocene (10 ka to present) posed a major challenge for researchers from various disciplines (paleoclimatology, geology, archaeology, history and anthropology). None of the geological periods of the Earth's history has been as complex as the Holocene because it involves interplay of natural as well as anthropogenic factors. Holocene witnessed both climatic and sea level fluctuations. Unlike glacial and interglacial periods, Holocene did not experience major sea level changes. Thus, for Holocene period, instead of the global sea level curve, a regional or local sea level curve needs to be adopted.

The coastal regions are one of the most important zones capable of archiving the climate and sea level fluctuations. Sea-level variations, erosion, sedimentation and tectonic activities cause geomorphic alteration along the coastal regions. Such modification in the coastline has direct impact on the human habitation thriving these coasts.

Gujarat, the westernmost state of the Indian subcontinent is endowed with a longest coastline (1600 km) and has recorded past sea level changes. Gujarat is known for having varied climatic zones and is majorly influenced by summer monsoon. Therefore, numerous studies on Holocene climate as well as sea level fluctuations have been addressed by previous researchers.

Physiographically, Gujarat is divided into three regions, Kachchh mainland, mainland Gujarat and the Saurashtra peninsula. Amongst these the Saurashtra peninsula has the longest coastline along with various geomorphic features that indicate paleo sea level changes. Such geomorphic features have attracted attention of geomorphologists and thus studies were initiated to determine variations in the past sea levels (Gupta, 1972; Gupta and Amin, 1974; Pant and Juyal, 1993). There are no continuous records of sea level fluctuations and climatic variations during mid–late Holocene along the Saurashtra coast. On the other hand few studies from Kachhchh and mainland Gujarat suggested sea level and climatic variability during Holocene Period (Gupta, 1972; Gupta and Amin, 1974; Pant and Juyal, 1993; Juyal et al., 1995; Prasad et al., 1997; Chamyal et al., 2003; Prasad and Enzel, 2006; Gaur et al., 2007; Prasad et al., 2007; Prasad et al., 2014; Banerji et al., 2015).

Various coastal geomorphic features such as mudflats, tidal notch and intertidal platform are evident in Saurashtra peninsula. However, the locus of this study is to use mudflats in deciphering land sea interactions along the Saurashtra coast during Holocene. Efforts have also been made to investigate the climatic and sea level changes that occurred in Saurashtra during this period.

1.2 Holocene climate variability

Various chronostratigraphic methods have been applied to divide the Holocene period. However, there have been considerable inconsistencies in correlating climatic events globally (Wanner et al., 2008). Holocene has been broadly divided into three phases (Nesje and Dahl, 1993). The first phase that lasted from 11,600 to 9000 years BP coexisted with the ‘‘Preboreal’’ and ‘‘Boreal’’ chronozones. The second phase covered a period between 9000 to 5000 yr BP and is concurrent with the ‘‘Atlantic’’ chronozone while the third phase coincided with the ‘‘Subboreal’’ and ‘‘Subatlantic’’ chronozones and covers a period between 5000 yr BP to pre-industrial time (Wanner et al., 2008).

In the past few decades, the climatic variability during the mid–late Holocene period has become a prime focus among the research community due to its significance with respect to anthropogenic intervention and associated climate change. Unlike the glacial and interglacial cycles, where the boundary conditions changed dramatically, the mid-Holocene did not experience such extreme climatic perturbations. The factors responsible for the observed mid-Holocene climate variability are ascribed to the redistribution of solar energy caused due to the changes in orbital parameters. This influences both temporal and spatial shift of the Inter Tropical Convergence Zone (ITCZ) and in turn dictates the position of the monsoon front (Prasad and Enzel, 2006; Yancheva et al., 2007). As in the case of Africa and Asia, where pronounced weakening of the monsoon systems (increasing aridity and desertification) was caused due to the progressive southward shift in the ITCZ (Wanner et al., 2008). This shows that there exists a fairly good agreement in the causes of the temporal changes in moisture variability during the Holocene.

1.2.1 Major climatic episodes during last 2 millennia

In context of the present day global climate perturbation, an increased interest in documenting climate alteration during last millennium has been observed (Jansen et al., 2007) due to both natural and anthropogenically induced climatic variability. From the year 1860 to 1990, the global mean annual surface temperature increased by 0.55°C (Parker et al., 1994). This points that global climate has changed significantly since the post-industrial era (1750 AD), which resulted in the spatial and temporal changes in precipitation pattern (IPCC, 2007). This makes it important to generate long-term climate data so that a better understanding of natural verses anthropogenically induced changes in climate variability can be ascertained and if possible quantified. This comparison of reconstructed climatic record with the global climate data will help in ascertaining not only the major climate event in the past but also manifest the forcing factors of such climatic episodes. As instrumental meteorological records are short and limited, reconstruction of the long-term climate variability (beyond the instrumental record) and its forcing factors requires different climate proxies such as ice cores, marine records, relict and active mudflats, lake sediments etc. Such reconstructions (pertaining to past climate variability) are essential to predict the future climatic trends. Based on such climatic reconstruction using various archives, it has been observed that the northern hemisphere has witnessed alternate warming and cooling periods within a span of last 2 millennia viz. Roman Warm Period (RWP), Dark Ages Cold Period (DACP), Medieval Warm Period (MWP), Little Ice Age (LIA), and Modern warming (MW) (Lamb, 1965; Friis-Christensen and Lassen, 1991; Norgaard-Pedersen and Mikkelsen, 2009; Oppo et al., 2009).

One of the most intriguing questions within the climate debate is, whether the present temperature rise in the late Holocene is attributed to the anthropogenic activities, or is part of the natural climatic variability as observed during pre-industrial period! RWP (~200 BC–AD 400) is one such time interval where the historical records suggests that there existed climatic conditions similar to present (Frisia et al., 2005; Chen et al., 2011). Studies (Norgaard-Pedersen and Mikkelsen, 2009; Oppo et al., 2009) indicate the occurrence of DACP, MWP and LIA post the RWP. All these climatic episodes have been identified and studied worldover (Bianchi and McCave, 1999; McDermott et al., 1999; Castagnoli et al., 2002; Andersson et al., 2003; Shah and Chaudhary, 2007). But there have been limited information on the occurrence of these in the Indian subcontinent (Yadava et al., 2004; Rühland et al., 2006; Warrier and Shankar, 2009; Warrier et al., 2014).

Based on various evidences from Western Europe, Hubert Lamb inferred the persistence of a warm period between 1000–1200 AD and coined the period as MWP when the temperature was nearly 1–2°C higher than the average temperature between 1931–60 AD (Lamb, 1965). While revisiting the concept of MWP, (Hughes and Diaz, 1996) concluded that "*it is impossible at present to conclude from the evidence gathered here that there is anything more significant than the fact that in some areas of the globe, for some part of the year, relatively warm conditions may have prevailed*".

The period between 15th to 19th centuries famous as LIA has long been characterised as a period of glacial advancement (Le Roy Ladurie E, 1971), cold winters (Grove, 1988) and falling harvests (Lamb, 1995). As the LIA is followed by MW that has witnessed industrial revolution, this makes the study of the LIA a frontier in understanding the present climate and future trends in climatic variability. The LIA event has impacted both the hemispheres, however, not in a globally synchronous way (Grove, 1988) due to the fact that there exists uncertainty in the inception and duration of the LIA (Bradley and Jonest, 1993).

Various factors such as solar, volcanic activity (Crowley, 2000; Ammann et al., 2007), solar-oceanic feedbacks (Bond et al., 2001), ocean circulation (Broecker, 2001), Pacific ocean-atmospheric processes (Cook et al., 2007), and land-use changes (Goosse et al., 2006; Ruddiman, 2007) have been responsible for influencing MWP–LIA climate. Based on the paleoclimatic model, (Mann et al., 2009) concluded that solar forcing, volcanic and internal climate processes was responsible for the MWP–LIA temperature variability. Therefore, additional proxy records are required to constrain the regional model projections of future climate.

1.2.2 Mid–late Holocene Climatic reconstruction

A number of studies have addressed the mid–late Holocene climatic reconstruction using various proxies such as sediments, corals, speleothems, peat deposits, etc (Lee-Thorp et al., 2001; Peck et al., 2002; Yu et al., 2005; Mauquoy et al., 2008). Sediment cores raised from lakes and coastal environment have been used significantly for the Holocene climatic reconstruction. On the basis of multiproxy geochemical analysis of sediments from Lake Bliden, Denmark, 6700–5740 cal yr BP was inferred as wet period which corresponds to Holocene thermal maximum following which dry conditions from 5740–2800 cal year BP interrupted by wet conditions between 5300–5150 cal yr BP, 4300–4050 cal yr BP and 3700–3450 cal yr BP prevailed. Evidences suggest that the RWP (2200–1500 yr BP) and MWP were dry while the LIA was wet (Olsen et al., 2010). Similar study was carried out on two sediment cores raised from Alboran Sea and Zonar Lake, Spain, indicating a drier stage prior to 2.7 ka BP which correlated well with the global aridity. This period was followed by a wet period (2.7–1.4 cal ka BP) which continued even after MWP and during the onset of the LIA (Martin-Puertas et al., 2010).

Stable isotopic proxies have been significantly used to elucidate the past climatic conditions. Two sediment cores from the south eastern part of the mediterranean near the shore of Israel were studied for its isotopic and geochemical properties. Based on the data it was documented that humid period lasted between 3.5 ka–3.0 ka and 1.7 ka–1.0 ka BP and an arid conditions were prevalent between 3.0–1.0 ka BP. The signals of MWP and LIA at 0.8 ka B.P and 0.27 ka BP were seen in the form of warm and cold period respectively (Schilman et al., 2001; 2002).

Annually laminated or varved marine sediments allows to reconstruct the global climatic, oceanographic, meteorological and geological changes with high (yearly or seasonal) temporal resolution (Overpeck et al., 1996). Based on the multiproxy study of varved sediments from the Oxygen Minimum Zone off Pakistan, Northeastern Arabian Sea, reduced precipitation between 4000–3500 yr BP (Von Rad et al., 1999), coincided with the beginning of aridification documentated in the Nile River runoff data (Quinn, 1992) and lake records between Turkey, Ethiopia (Lemcke and Sturm, 1997) and northwestern India (Enzel et al., 1999). A fluctuating precipitation pattern continued till present, with a minimum precipitation during 200 BC–100 AD and 1000 AD. An intervening precipitation maxima was observed during cool period that corresponds to the LIA in Europe (Von Rad et al., 1999).

Pollens preserved in ice cores from the Dunde ice cap, northern Qinghai-Tibetan Plateau revealed relatively humid periods during 2700–2200, 1500–800, and 600–80 yr BP. A prominent change in the pollen was observed during the MWP (790–620 yr BP) and the LIA (330–80 yr BP) suggesting that the vegetation in this region is sensitive to abrupt climatic changes (Liu et al., 1998).

Based on the above studies it can be suggested that mid-late Holocene period witnessed varied climatic conditions worldover varying from warm and humid to cold and arid. The northern hemisphere mainly witnessed the climatic episodes such as RWP, MWP and LIA of last 2 millennia and its prominent persistence has been observed in Europe in the form of climate warming and cooling for LIA.

Studies in the Indian subcontinent for southwest monsoon during Holocene period were done using various paleoclimatic archives. Study based on pollens, C/N ratios and $\delta^{13}C$ from palaeolake deposit at Sangla, Kinnaur, Himachal Pradesh suggests warm and moist climatic conditions during 10,450 to 4310 yrs BP, implying enhanced monsoon. Reduction in the precipitation and dominance of drier climate is inferred between 4310 and 1800 yrs BP. Climate fluctuated between dry and wet conditions (1800–1000 yr BP) and the lake got desiccated around 1000 yrs BP (Chakraborty et al., 2006). The carbon and oxygen isotope study of spleothems from Madhya Pradesh and Orissa demonstrate that the rainfall patterns were similar to present day between 3400-3000 BP, followed by an onset of aridity around 2900 yr BP that continued till 1000 yr BP. After which a wet phase began which peaked between 750–500 BP. During 1900 AD significantly low rainfall event was evidenced from the spleothems (Yadava and Ramesh, 1999). Similar to oxygen, the stable isotope ratios of hydrogen in peats is considered to be an important proxy for past moisture variation (Brenninkmeijer et al., 1982; Dupont and Mook, 1987). Stable isotopic study on peat samples from the Nilgiri Hills, Southern India underscored a climate shift during the last glacial maximum (18 ky BP) and the subsequent deglaciation, followed by an arid phase from 6–3.5 kyr ago and a short wet phase 600 yr ago (Sukumar et al., 1993). The latter corresponds to MWP which was believed to be restricted in Europe and N. America (Gribben and Lamb, 1978).

Oxygen isotopic data from two species of foraminifera in a sediment core from eastern Arabian sea yielded the evidences for prominent arid events observed at 2000 yr BP followed by centennial dry events at 1500, 1100, 850 and 500 yrs BP (Tiwari et al., 2006). Similar arid episodes have been observed in other proxy records such as reduced thickness and low Ti/Al of varved sediments (Von Rad et al., 1999) and higher $\delta^{18}O$ of forams in sediment core from N. Arabian sea (Staubwasser et al., 2003).

Along with the lake sediment, the type of pollen that gets buried in the lake sediments is also an important archive for climatic fluctuations. As the type of pollen that gets buried in the sediment depends on the ambient vegetation, the variations in the intensity of the summer and winter monsoons in the region would be reflected in the pollens archived from the respective sediment section. Therefore, by identifying the plant species of the pollen grains in the sediment, it is possible to extract the information regarding the wet/arid conditions that prevailed in the past. Singh (1971) presented the first detailed paleoclimatic studies from NW India on pollens of lacustrine sediments from three playa basins, namely Sambhar, Didwana and Lunkaransar, in Rajasthan. Bryson and Swain (1981) provided the first quantitative palaeo-monsoon reconstruction for the Indian region based on pollen records (Singh et al., 1972; 1974) of sediment cores from the Didwana and Lunkaransar lakes of Rajasthan.

There are fairly good number of studies pertaining to Holocene climate variability from Gujarat. Based on the isotopic studies from Nal Sarovar lake sediment (Central Gujarat), a wet climatic condition was inferred during 4.8−3 ka, followed by an arid climate that persisted till ~2 ka (Prasad et al., 1997). In the Mahi Estuary (mainland Gujarat), pollen and phytolith based studies suggest a coupling between summer monsoon and enhanced winter precipitation between 3400−3000 cal yr BP followed by an arid climate from 2850 cal yr BP onwards has been observed (Prasad et al., 2007). Based on slack water deposits from Mahi River basin, four events of enhanced monsoon viz. >5 ka, 4.6 ka and during 4.6 to 1.7 ka has been identified (Sridhar, 2007). A recent study in the lower Narmada valley, mainland Gujarat indicated a sub-humid conditions during 3 ka followed by two drier events (2.1 ka and

1.3 ka) (Laskar et al., 2013). A multiproxy data obtained from a lake deposit from mainland Gujarat revealed a dry climate (5560−4250 cal yr BP) followed by a gradual strengthening of summer monsoon after 3500 cal yr BP. A dry climate (weak monsoon) persisted between 3238−2709 cal yr BP (Prasad et al., 2014). A recent multiproxy study on Narmada valley sediments suggests that prior to 2185 cal yr BP, a wet phase persisted which was followed by an arid phase till 1809 cal yr BP. After 1809 cal yr BP wet climatic condition existed in the region (Sridhar et al., 2014).

Mid–late Holocene climatic reconstruction from the Indian subcontinent suggest that moist climate persisted between 10–3 ka with a decreasing intensity which was followed by an arid climate during 2 ka. Nearly similar Holocene climatic conditions have been observed in various regions of Gujarat. Intensification of monsoons in Gujarat during 3500 cal yr BP might have resulted due to winter monsoons caused by western disturbances (Singh et al., 2007).

1.2.3 Signals of major climatic events during last 2 millennia: Indian Subcontinent

The climatic reconstruction of last two millennia has been significantly carried out globally. The studies have shown the persistence of global climatic events which has been discussed in the previous section. However, in the Indian subcontinent, there are sparse records pertaining to the signal of the global climatic events such as RWP, MWP, LIA and MW. High resolution pollen and diatoms evidence from a peat deposit in the Pinder valley, Higher Himalayas showed warm and moist climate during MWP while cool and moist during LIA. On the other hand abrupt climate shift towards warmer and wet during last 200 yr has been indicated by the compositional turnover of the diatom abundance (Rühland et al., 2006).

In order to reconstruct the paleorainfall intensities and paleoclimatic conditions, a study carried out at Thimmannanayakanakere Lake, southern India using various proxies suggests sub humid climate with moderate lake levels during 2–1 ka followed by humid phase with high lake levels persisted after 1 ka (Warrier et al., 2014). Rainfall reconstruction using carbon and oxygen isotopes during last 331 yr on the laminated stalagmite from Uttar Kannada district, Karnataka indicated that 1666 AD and 1900 AD has seen the highest and lowest rainfall respectively (Yadava et al., 2004). Another study based on stable isotope of old stalagmite record from Kumaun Lesser Himalaya, showed a persistence of wet phase during the LIA (1590–1850 AD) and comparatively dry phase during the post-LIA (after 1850 AD). Studies have also disclosed the presence of the minor dry events during the LIA and a wet episode after the LIA (Kotlia et al., 2012). A recent multiproxy study carried out at Pookode Lake, Kerala, Southern India indicated that overall warm and dry conditions prevailed during 6200–420 yr BP that were interrupted by short wet phases (during BC 4000 BC–300 AD, 800–1200 AD and 1570– 1860 AD) (Veena et al., 2014).

Studies pertaining to last 2 millennia in the Indian context suggest that the global MWP was warm and humid while LIA was cool and humid. humidity during LIA was probably due to the strengthening of westerlies (Kotlia et al., 2012).

1.3 Land-Sea level changes

The global coastline preserves feature as a function of sea level changes during the past and provides information related to sea level highs or low with respect to the land. The coastline emerged due to the higher sea level during the past which can be observed as occurrence of beach deposits or marine shell beds stranded above present high tide level, while the submerged coastlines are indicated by the drowned valley mouths excavated by rivers when the sea stood at a lower level (Bird, 2011). Usually, it is difficult to ascribe the changes in relative sea level (RSL) either to the tectonic movement (upward/downward movements of the land), eustatic movement (rise/ fall in the level sea level) or their combination to the resultant present day coastal morphology (Bird, 2011). Changes in the RSL occur when the sea invades the land (marine transgression) or due to sea level lowering (marine regression). Such variation in the RSL has routinely occurred throughout the geological time. Few coastlines display evidences of being tectonically stable for longer period, while some show obvious indications of continuous instability (probably due to earthquakes and volcanic activity). Nevertheless, there have been phases of still-stand, when the sea remained at or close to its level relative to the land for longer periods resulting in the development of recognisable coastline features. Some of these features developed could be located above the present sea level (emerged), while others might be submerged. Studies have shown that past 6000 yr have been a phase of still stand with a sea at its present day level globally (Bird, 2011).

1.4 Late Quaternary sea level changes

Evidences which indicate that global sea level was slightly higher than present during 80000 yr BP and later started lowering, and remained low during the Last Glacial phase (between 80000 and 6000 years ago) (Bird, 2011). The extent of sea level lowering during this Last Glacial Maxima (LGM) has been ascertained from the volume of water abstracted form the late Pleistocene glaciers and ice sheets, which leads to the fact that the sea level dropped by > 100 m below its present level. Due to the lowering of the sea level during the LGM, the continental shelves along the world's coastline got exposed as wide coastal plains, and coastlines advanced towards their outer edges. Even during 18000 yr BP, the climate of the earth remained cold, the glaciers and ice sheets were existing to their maximum extent resulting in lowering of the sea about 140 m below its present level. The beginning of Holocene period saw Earth's climate becoming warmer, the ice cover started melting and water returned to the oceans, resulting into the Holocene marine transgression (Bird, 2011).

1.5 Holocene Sea level changes

Unlike the Holocene climatic variability, the Holocene sea level records are fraught with lack of regional geological investigations and tectonic setting (tectonic upheaval or hydro-isostatic warping) of the coastal tract (Williams et al., 1998; Antonioli et al., 2002). This is considered to be one of the reasons for Holocene sea level discordance at regional scale (Li et al., 2012). Therefore, it has been suggested that instead of adopting regional Holocene sea level curve, site specific sea level curves should be generated (Hashimi et al., 1995). Although, studies have indicated the presence of high sea level during the Holocene, however, they lack adequate observations on the issues pertaining to climate-tectonic interactions during the Holocene sea level fluctuations.

1.5.1 Global sea level changes during Holocene Period

Various studies have attempted to ascertain the Holocene sea level changes. Holocene sea level changes in the central part of the Bangladesh suggested that the country experienced two mid-Holocene transgressions with intermediated regressions. The trangressive phase existed (7500–6000 cal yr BP) with sea level 4.5–5 m higher than mean sea level (msl) in the latter. The trangressive phases were punctuated with a regressive phase (6500–5500 cal yr BP), wherein the sea level was 1–2 m lower than the present msl. The present shoreline of Bangladesh was established at approximately 1500 cal BP (Rashid et al., 2013).

The geochemical evidences from the paleo-lagoon sediment core from south-eastern Brazil (Juréia) showed that the lagoon was established during 9400 yr BP. It was between 8385 and 8375 cal yr BP that the mean sea level reached or exceeded the current level. Stability in sea level was attained during 8375 cal yr BP accompanied by increase in the rainfall and sediment inflow (Sallun et al., 2012). Holocene sea level record from the study of lacustrine sediment core of Vestfold Hills, Antarctica, showed that the ice sheet retreated 30–40 km and thinned nearly 600–700 m since LGM (Zwartz et al., 1998).

The investigation of the Holocene sea level changes in Murrells inlet, northern coast of south Carolina indicated that highstands of relative sea level occurred during 4.2 ka, which was followed by lowering of the sea level by 2 m until 3.6 ka, and then a slow and steady rise in sea level took place with a rate of 10 cm/century till present (Gayes et al., 1992).

Based on sedimentological and ecological evidences, study carried out at the coast of Mauritania, West Africa showed a transgressive phase (relative sea level rise of +3 m) at about 5500 yr BP was followed by a regressive phase (relative sea level drop of -3.5 ± 0.5 m) at about 4100 yr BP (Einsele et al., 1974). Within the tropical belt, two phases of sea level rise i.e. during 3.6-2.8 ka (3–3.4 m) and 1.7-1.2 ka (1.4–1.6 m) had been reported by Van Andel and Laborel (1964) from Recife, Brazil.

The sea level fluctuations, recorded for the mid to late Holocene period along the stable coasts of South India (Banerjee, 2000), West Africa (Einsele et al., 1974) and

North East Brazil (Van Andel and Laborel, 1964) suggests that around 4 ka sea level fluctuations of a few meter has taken place (Banerjee, 2000).

Based on the above studies it has been observed that during last 5 ka the sea level has fluctuated within few meters however in some of the cases local tectonics have also played a significant role which makes it difficult to ascertain the fluctuation in sea level during mid-late Holocene period.

1.5.2 Mid-late Holocene Sea level variability along Indian coast

The Indian subcontinent being guarded by the Bay of Bengal in the east and Arabian Sea in the west endowed with the coastline of nearly 7500 km comprises of various evidences suggesting sea-level fluctuation during the past. A comprehensive review on Quaternary sea level changes along the Indian coast has been suggested by Merh (1987, 1992). Regional scale imprints of Late Quaternary sea level change along the East Indian coast were summarised by Banerjee (1993). Bhattacharya and Banerjee (1979) investigated the geology and geomorphology of Ajay-Bhagirathi valley in the Birbhum and Murshidabad districts of West Bengal and suggested glacial and interglacial oscillations in the sea level. Various studies (Rao and Vaidyanadhan, 1975; Raju and Vaidyanadhan, 1978; Meijerink, 1982) along the Vishakhapatnam coast of Andhra Pradesh have furnished data on high and low strandlines which in turn has negated the fact that early strandline was as high as +7 to +10 m, while during regressive phase it reduced to -25 m and later it rose to its present level (Raju and Vaidyanadhan, 1978).

A study from Godavari delta established the fact that the farthest strandline features recorded 35 km inland was +8 m high whereas the nearest is +2 m high nearly

2 km away from present coastline. Both the strandline features have been established during Holocene period (Rao and Vaidyanadhan, 1979).

Beach ridges are studied to understand the sea level fluctuation, sediment supply, climatic condition and coastal evolution. The study of beach ridges along the eastern coast of Indian sub-continent indicates that nearly 30-35 km of coastal stretch has been prograded since Holocene period (Kunte and Wagle, 2005).

Poompuhar, situated on the east coast, provides the evidence of a shoreline shift based on archaeological finds. Onshore and offshore explorations since 1989 have revealed a large number of terracotta ring wells, brick structures in inter tidal zone and submerged structures and early historic pottery in shallow waters (Vora et al., 2006).

Nair (1974) made pioneering attempt to study the Holocene sea level changes based on radiocarbon dates of the samples from the western continental shelf. Haneesh Kumar (2001) studied the sea level changes along the Kerala coast and concluded that from 14 to 6 kyr, the rise in sea level continuously dwindled with retreat of the coast and ultimately stabilising to its present position since last 1000 years. The study based on intertidal barnacle encrusted on foraminiferal tests indicated that the barnacle growth occurred during the regressive phase of 10,000 yrs BP, and therefore, it was proposed that the growth of intertidal barnacle on foraminifera can manifest to monitor paleo-sea level changes (Nigam et al., 1993).

The presence of prominent shelf edge reefs in the central and southern parts of the western continental margin of India revealed that the coral and algal growth commenced with the beginning of the Holocene transgression and continued till early Holocene. However, the rapid sea level rise submerged the reefs. Therefore, the late

Pleistocene/early Holocene shoreline is reflected by these relict submerged reefs (Vora et al., 1996).

The study of the submarine terraces along the continental shelf of western India indicated that the sea level fluctuated between late Pleistocene to mid-Holocene age (Wagle et al., 1994). After 7000 yrs BP it fluctuated more or less at the present level (Hashimi et al., 1995).

Saha et al. (2011) studied the tidal flat near Daman on the eastern flank of Gulf of Khambhat, wherein old beach signifies the sea level high stand in the west coast of India during 8 ka. Earlier studies based on onshore peat deposits indicate that the sea level was higher during mid-Holocene than the present-day level due to the submergence of coastal vegetation called mangrove which subsequently gave rise to onshore peat deposits (Agrawal et al., 1970; Powar et al., 1983; Rajendran et al., 1989).

1.5.3 Mid-late Holocene Sea level changes along Gujarat Coast

The Saurashtra coast of Gujarat is a prospecting regions for the study and reconstruction of past sea level changes. The coastal landscape of Saurashtra is an outcome of two major controlling factors viz. the eustatic sea level changes and neo-tectonism (Ganpathi et al., 1982; Pant and Juyal, 1993). Earlier studies along the Saurashtra coast were based on mapping of the raised terraces, wave cut notches and the distribution of the biogenic carbonates (miliolite) (Desai and Pandya, 1982; Baskaran et al., 1987; Pant and Juyal, 1993).

Attempts were also made to chronologically constrain various high strands. Gupta (1972) based on dated raised beaches and dead coral reefs from the coastal Saurashtra suggested that the Holocene sea level was ~ 2−3 m high. Based on the dated dead oyster and shell samples, a high sea level stand of ~2 m during 3 ka with an over printing of land component was suggested (Juyal et al., 1995).

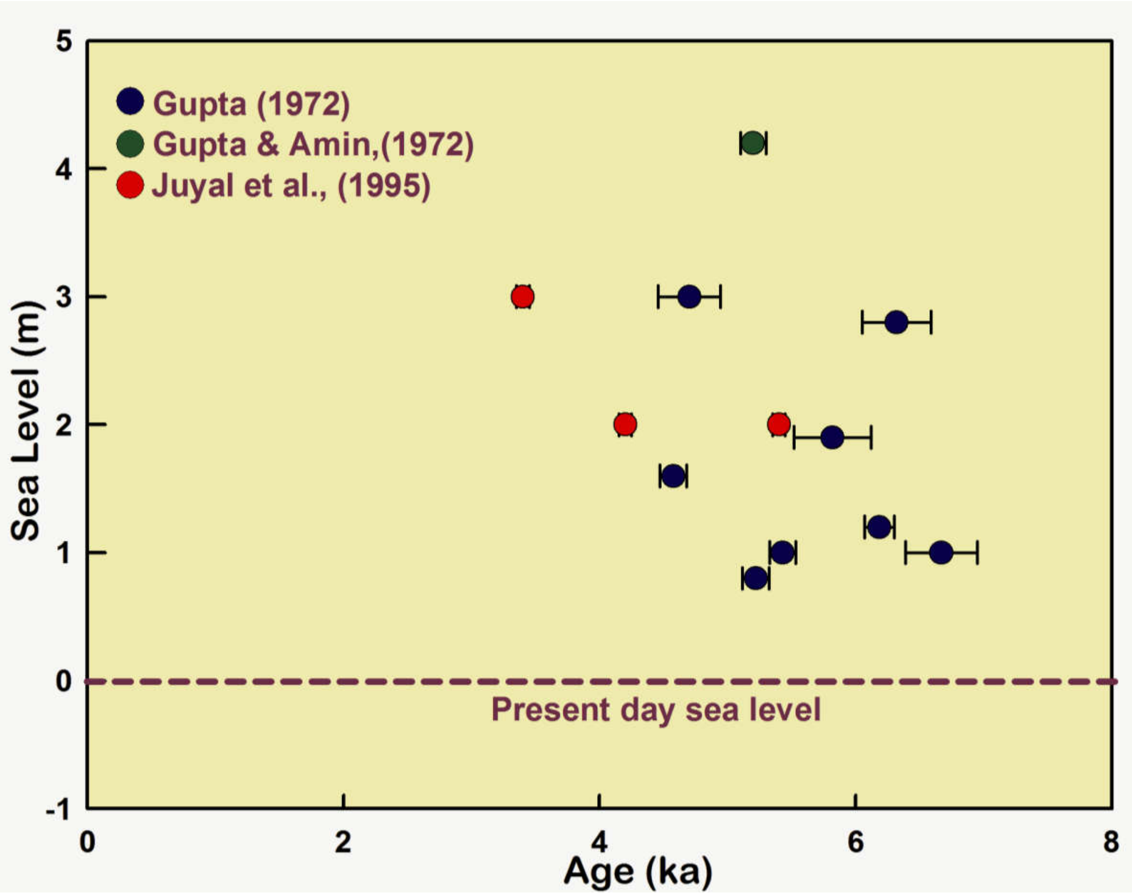

Figure 1-1. Sea level change along the Saurashtra coast during Holocene period. Data compiled from Gupta, (1972), Gupta and Amin (1972) and Juyal et al., (1995).

Additionally, the Kachchh mainland has also been studies for the past sea level changes. Tyagi et al., (2012) suggested a marginally high sea strand (compared to present) during 5.5 and 2 ka in the western Great Rann of Kachchh. Holocene sea level reconstructions based on archaeological sites around Gulf of Kachchh suggested that present day sea-level was attained at ~1000 yr BP, which resulted in the submergence of the historical sites (Gaur et al., 2007).

1.5.4 Past Sea level indicators along southern Saurashtra coast

The Saurashtra coast has been known for archiving past sea level changes in the form of various coastal geomorphic features such as tidal notches, intertidal platforms and relict mudflats.

Pirazzoli (1986) introduced the term 'tidal notch' referring to midlittoral erosion marks left by sea level on the limestone rock formation. The tidal notches generally appear as undercuts on rock cliffs, therefore, in the coastal zones, a marine notch is formed by sea erosion of the cliff which ranges from several centimetres to several meters deep. The marine notches are usually horizontal and developed with continuity which is easily recognised in the uplifted coastal areas. Emerged notches have often been used to infer former Quaternary and Holocene sea level positions. Their height generally corresponds to local midlittoral zone (Tidal range + average wave height) (Evelpidou et al., 2012).

A tidal notch has a recumbent v-shaped profile and its vertex represents the mean sea-level (Fairbridge, 1952; Hodgkin, 1964) and a roof near the highest tide level and a base near the lowest tide level (Evelpidou et al., 2012). Presence of tidal notch is a good indicator of coastal stability. However, any change in land or sea-level would modify the notch morphology (Pirazzoli, 1978) particularly the notch platform (intertidal platform).

A detailed investigation of tidal notches around Diu island suggested that region experienced land-sea level changes during the last 3 ka (Bhatt and Bhonde, 2006). Tidal flats are the region which gets exposed during the low tides and submerged during the high tides and hence result in continuous sediment deposition is the region.

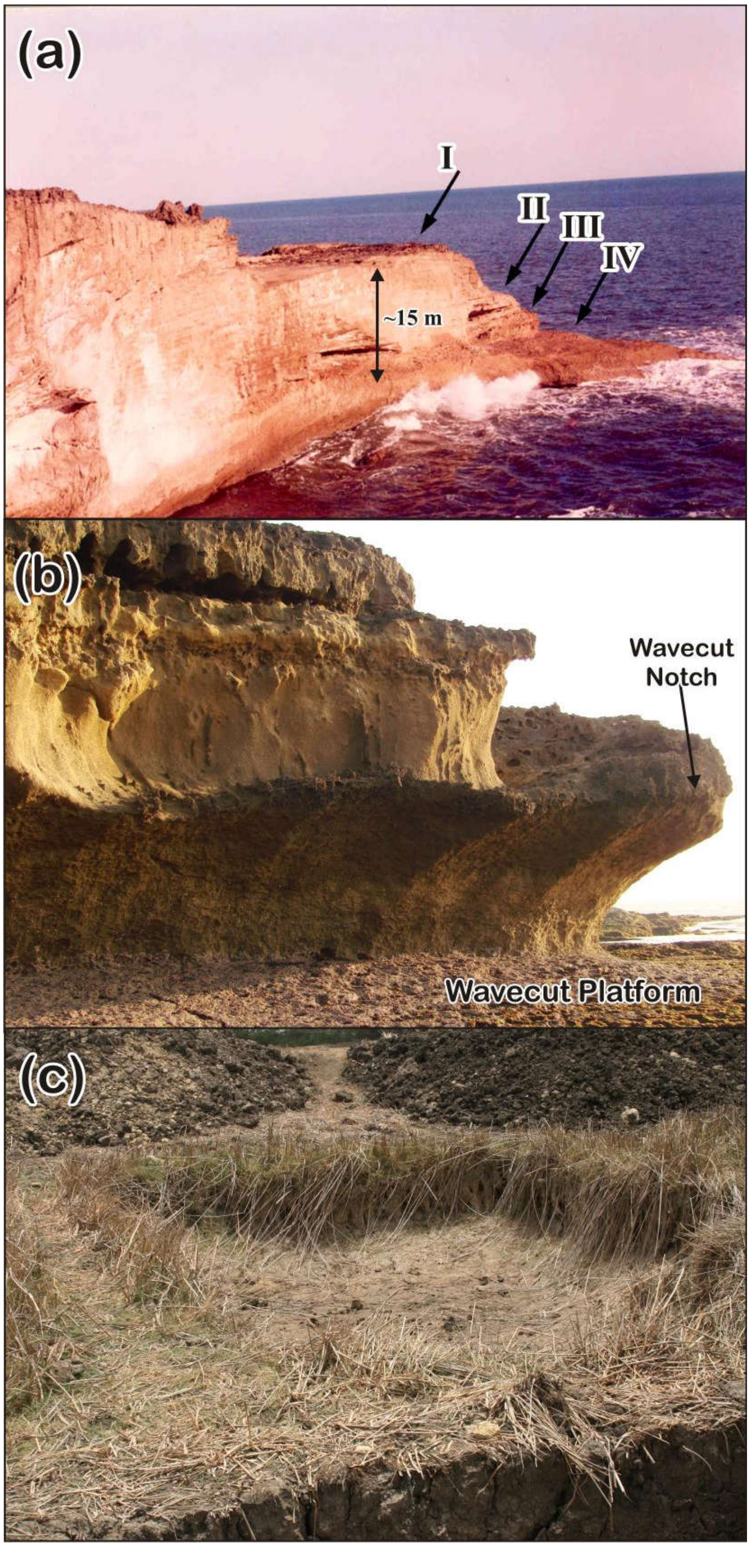

Figure 1-2. Sea level indicators along Saurashtra coast. (a) Intertidal platform where (I) represent terrace formed during stable sea while II, III and IV represent the induntations formed during land sea fluctuations(b) tidal notch formed by the present day sea level and (c) relict mudflat covered by terrestrial grasses.

However, due to eustatic/tectonic movement when the tidal flat stops getting submerged, it results into culmination of the sedimentation process. Hence, with ceased sedimentation, the tidal flat becomes a part of the land and terrestrial plants begins to dominate the region.

1.6 Mudflats: Black Box to Climate and Sea level change

The regions where the land and the sea processes interact is known as coastal zone, and the sections which remains under water during high tides and above water during low tides are known as intertidal zone. The intertidal zones can be rocky, gravelly, sandy or muddy and can include vegetated areas such as sea grass beds, salt marshes, mangrove swamp and reed swamps (wetlands) that are subjected to frequent submergence by the sea (Bird, 2011). The intertidal deposits may consist of mineral grains of varying sizes from clay to coarse sand, carbonate particle, shell fragments, coral debris and plant remains. The intertidal zone is characterised by the presence of tidal flats, mudflats and salt marshes.

The formation of the mudflat takes place where the stream of the seawater is gentle. Mudflats comprise of ridges and mounds and result due to the differences in sediment texture, deposition rates and tidal channel networks. Despite strong hydrodynamics, intertidal estuarine mudflats are preferential sites for the accumulation of fine grained sediments, organic matter and metals originated from numerous marine and terrestrial sources including those of anthropogenic origin. In the mudflats, the muddy sediment is widely dispersed by waves and currents wherein the silt, clay and organic matter remains suspended due to strong currents but as they slacken, the deposition begins, resulting into the formation of mudflats in the intertidal and near shore zones (Bird, 2011).

The average width of a mudflat could be over 5 km and is usually composed of particles with an average diameter of 0.031 mm. When the mudflat is unvegetated, its surface remains flat or gently sloping terraces are formed which are bordered by steeper slopes descending seaward or into tidal channels. Mudflats are generally diversified by channels or creek systems, often beginning in embayments or on the flanks of tidal divides and converging in dendritic patterns, but sometimes running almost parallel to each other down to the low tide shoreline. The intertidal mudflats are a prominent geomorphological component of estuaries whose development is both complex and difficult to predict due to the interplay of the physical, chemical and biological properties of the sediment (Paterson et al., 1990; Yallop et al., 1994). Intertidal mudflats represent large surface areas in macrotidal estuaries at low tide. Erosion, resuspension, advective transport and redeposition causes rapid and massive changes in the sediment level in some locations specially in macrotidal estuarine mudflats which are being controlled by waves and both tidal and river currents.

Intertidal mudflats can be separated into three distinct zones (Klein, 1985): the region that lies between low water neap and mean low water spring tide levels and are often subjected to strong tidal currents are known as the lower tidal flats; the region between mean low water neaps and mean high water neaps is known as the middle flats and the region between the mean high water neap and mean high water springs is known as upper flats. Salt marsh vegetation may colonize as far seaward as mean high water neaps. Mudflats will often continue below the level of low water spring tide, and form sub-tidal mudflats (McCann, 1980). The upper flats are generally characterised by fine grained sediments, the middle flats by fine silts and the lower flats by sandy mud (Shi and Chen, 1996). Mudflats and salt marshes are very sensitive to changes in sea level and the effects of reclamation and industry. They also record climatic changes that persisted during the deposition of the sediment in the region. Therefore, with the study of the mudflat the Holocene sea level and the climatic changes can be deciphered (Kshetrimayum, 2007).

The sheltered coastal environments such as mudflats, estuaries, lagoons, bays, inlets, rias, isolation basins are the potential regions for preserving thick sequences of Holocene sediments and hence provide opportunity to investigate past climate, sea level and land level changes along with more local environmental changes (Lamb et al., 2006). Studies have indicated the significance of intertidal regions in accessing the past climate and sea level changes. The potential application of $\delta^{13}C$ and C/N in the organic matter of the sediment collected from the intertidal region for the reconstruction of sea-level histories has been indicated by (Wilson et al., 2005). The changes in the sea level has been addressed using C/N and $\delta^{13}C$ as proxy for the sediment core raised from the Yangtze delta, China that suggested an abrupt sea level rise during 9.0 cal ka occurred (Zhan et al., 2011). A similar study of estimating past sea level changes based on C/N and $\delta^{13}C$ carried out on the sediment core retrieved from Humber Estuary, UK (Lamb et al., 2007). A sediment core collected from the NE part of Cauvery river delta was studied for palaeoclimate and palaeoecological reconstruction. The study suggested that the climate changed from warm and humid to cool and arid conditions, with an evolution of vegetation from moist to dry deciduous forest during last 3 millennia (Srivastava and Farooqui, 2013). To understand the past environmental changes, the sediment core raised from the mudflats of central west coast of India was analysed for its major and trace elemental concentration, mineralogy and grain size and the chronology was estimated by ^{210}Pb dating technique. A significant shift in sediment characteristics is observed after 1980, probably resulted due to changes in climatic conditions driven by the monsoon (Singh et al., 2013). A recent multi–proxy study carried out on mudflat sediment cores collected from the west coast of India showed depth profiles with two distinct sedimentation phases and suggested that the enhanced sedimentation rates of the recent time attributed to the anthropogenic influence (Singh et al., 2014). Palaeoclimate, palaeoecological and palaeoshoreline reconstruction since ~3700 yrs BP were carried out for the sediment core collected from the central part of Pichavaram mangrove wetland, Cauvery river delta. The study indicated that since 2100 yrs BP the climate amelioration took place from warm and humid with strengthened monsoon to a dry and arid climate coupled with weakened monsoon condition (Srivastava et al., 2012). A multiproxy study on the sediment cores raised from the Guadiana Estuary, SW Iberia suggested sea level rise at a rate of 7 mm/yr between early to mid-Holocene period and from mid Holocene to present the rate of sea level rise is 1.8 mm/yr (Delgado et al., 2012).

1.7 The Study Area

Gujarat is the western most state of the country has the longest coastline of 1600 kms. Geomorphologically, it is divided into three distinct divisions, viz. Gujarat mainland, *Saurashtra peninsula* and Kachchh peninsula. The geology of Gujarat is a result of complex interaction between tectonism and sea level changes during the Cenozoic Period. The initial framework was created during the fragmentation of the western margin of the Indian plate during the Late Mesozoic as it collided with the Eurasian plate in the North (Biswas, 1987). The Kachchh, Cambay and Narmada rift basins along the Delhi, Dharwar and Satpura trends were formed during the breakup of the margin (Biswas, 1987). Such processes resulted into deposition of tertiary and quaternary sediments with marine and fluvial origin respectively (Merh and Chamyal, 1993). However, during this period the Saurashtra peninsula remained as a foundered horst (Biswas, 1982) and hence the Saurashtra peninsula is devoid of Quaternary sedimentation except in its coastal areas where miliolites of quaternary period are fringed along the coastal tracks (Chamyal et al., 2003).

The Saurashtra coastline is one of its kind due to the fact that its various segments provide considerable diversity in respect of their geologic and geomorphic evolutions, each of them are characterised by varied assemblage of erosional and depositional landforms (Ganapathi et al., 1982). The peninsula essentially comprising of Quaternary deposits, Deccan Trap basalts and the coastal landscape provides an ideal example of differing responses in the various coastal segments to the eustatic sea level change and the neotectonism (Ganapathi et al., 1982).

Considerable studies have been carried out on tectonic movements, sea level changes in these basins during the Tertiary, but only a few studies are available on the Quaternary tectonics and sea level changes. However, negligible studies have been done on the Holocene sea level and climatic variations. Their remains a paucity in knowledge for the quantification of tectonic movement during the Holocene period that might have caused the formation of the present coastal morphology.

1.7.1 Tectonics, Geomorphology and Geology

Tectonics: The Saurashtra peninsula shows a unique structural set up which is essentially bounded by a number major faults on all sides viz. western cambay basin border fault, extension of Narmada fault, Gulf of Kachchh fault and west coast fault (Poddar, 1964). The Saurashtra peninsula as a whole doesn’t show any evidence of specular uplifts and subsidence as a single block however there exists ample of evidences to suggest that its various parts have experienced differential movement especially during Quaternary period (Ganapathi et al., 1982). Moreover, the drainage pattern has been controlled by various major lineaments of the trappean basement.

Geomorphology: The Saurashtra Peninsula is marked by flat-topped ridges typical of trappean areas and is bounded by the Gulf of Kachchh and little Rann of Kachchh in the North, by Gujarat plains in the East and NE, and on the SE by the Gulf of Cambay. The coastal Saurashtra is swashed by the Arabian Sea. The coastline of Saurashtra is extremely varied and comprises of narrow belt of low ridges, cliffs of miliolite limestone and other shore deposits. The northern coastal area of the Saurashtra peninsula comprises of a gentle seaward slope with tidal flats dominating the landscape. Dwarka–Okha coastline exhibits cliffs of Tertiary rocks upto 10–40 m high. While the coastline from Porbandar to Kodinar is straight and is considered to be among the best exposures of miliolite rocks (Chamyal et al., 2003).

The southern Saurashtra coast is marked by 40–50 m vertical cliffs of miliolite limestone. The coast is irregular and dissected further east up to Diu. Northeast of Diu Island consists of extensive tidal flats. The southern coast of this island is cliffy while beyond Diu, the coast is characterised by the presence of rocky foreshore with occasional beaches and miliolite cliffs. Along the coast of Saurashtra towards the east, locally extensive mudflats are observed near Jaffrabad. Further east along the coast, thirty to forty metres high miliolite cliffs and several sea stacks can be seen. However, the miliolites completely disappear near Bhavnagar and the Tertiary rocks extend right up to the coast (Merh, 1995).

Geology: Geologically, major part of Saurashtra peninsula comprises of a basalts and its derivatives belonging to the Deccan Trap Formation of upper Cretaceous period (Bhonde and Bhatt, 2009). The coastal plains are occupied by the Quaternary sediments of both marine and continental origin, which include miliolite limestone, oyster beds, alluvial valley fills and aeolianites. The miliolitic limestone are exposed in the southern, eastern and western coast of Saurashtra from Porbandar to Veraval and even southeast of Veraval (Marathe, 1981). The conspicuous outcrops of miliolite also occurs in localities along the gorges and slopes of hills of the Girnar ranges between Chotila and Rajkot, on the flanks of Chamardi hills of Sihor and of Osham hills. They rests unconformably on the Deccan Trap, Gaj beds, fluvial gravels and on clays. The age of the miliolites were estimated to be of three generations viz. 200–140, 115–75 and 70–50 ka BP (Baskaran et al., 1986). However, the origin and age of the miliolites is still controversial. Miliolites are underlain by a thick, channel gravel cemented with calcium carbonate. The fluvial deposits are mainly confined to the middle and lower reaches of the Heran and Saraswati Rivers (Marathe, 1981). The alluvial cover throughout the region does not exceed 10 m and is composed mainly of terrace deposits. The sedimentary succession reveals that the fluvial processes in the region were active during the pre-and-post miliolite phases. However, the Quaternary deposits of the Saurashtra need to be supported by absolute dates (Merh and Chamyal, 1993).

1.7.2 Southern Saurashtra coast-Lithostratigraphic units

I. Nageshri Group

The Nagshri Group was first studied by Verma (1982) and the group included two formations viz. Gaj and Dwarka Formations. These two litho units were considered under same group because these formations are naturally related and form successive geological units without any lithological or faunal break (Verma, 1982).

(a) Gaj Formation

The Gaj formation in general comprises of pale yellow to deep ocherous colour marly limestone. The thickness of the formation varies from 10 m near the Deccan traps to about 150 m near the coast. Best outcrops of Gaj formation are exposed near Balanivav, west of Timbi. The Formation is also well exposed near Una–Veraval road at its crossing with the road leading Diu. The abundant foraminifera along with Echinodermata, lamellibranch and gastropods makes them easily distinguishable in the field. The age of this formation was estimated to be of Lower Miocene as indicated by larger foraminifera (Verma and Mathur, 1979).

(b) Dwarka Formation

The Dwarka Formation was formerly known as Dwarka beds and can be identified lithologically for being highly arenaceous in nature. The Dwarka Formation comprises of broken shell fragments along with rounded to sub-rounded sand size grains of smoky quartz. This Formation is not well exposed in the study area however, it is noticeable near Jaffrabad area (Verma et al., 1974).

II. Porbandar Group

The name Probandar Group was proposed for the post-Tertiary carbonate sequence of Saurashtra which included Miliolite and Chaya Formation (Mathur and Mehra, 1975). The limestone of Miliolite and Chaya Formations were deposited near the strandline of shallow Quaternary Sea that oscillated in accordance with the sea level. Therefore, the two Formations are grouped under Porbandar Group that covers whole of the Quaternary sequence of Saurashtra except Holocene freshwater alluvium and coastal deposits (Verrna and Mathur, 1979).

(a) Miliolite Formation

The term “Miliolite Formation” was first used by Biswas (1971) that included all the consolidated and semi-consolidated carbonate deposits of post-Tertiary age in Saurashtra and Kachchh. Later, the term was redefined by Verma and Moitra, (1975) by including only pelletoid (and oolitic) calc-arenites and associated micrites but devoid of megafossils. The miliolites are considered to be of both marine as well as aeolian and are distinguished based on their sedimentary structures and quantitative faunal characteristics (Verma, 1982). The marine limestone are recognised on the basis of their horizontal bedding and low angle planar cross stratification while the aeolian types are recognised by high angles wedge planar cross stratification with long straight laminae and dune morphology (Verma, 1982). The exposures of miliolites are found near the Machundri river section, north of Una and also in the Rawal river section near the village Umes (Verrna and Mathur, 1979).

(b) Chaya Formation

The Chaya Formation includes white to dirty white, consolidated to semi-consolidated, porous, highly fossiliferous limestone. The name was coined after the village Chaya, near Porbandar in Junagarh district (Verma, 1982) and is mainly exposed along the coast. It forms cliff sections near Hematpur, Mandvi, Nawabandar and Khada. The exposed surfaces of this Formation are hard and compact but the weathered rock is rather friable and brittle. Coastal rocks such as the dead coral reefs, oyster beds and other highly fossiliferous limestone are included in Chaya Formation. The Chaya rocks with mega fossils are exposed near the band of creek near Hematpur wherein semi-fossilised remains of oysters and corals were found which are nearly 3–4 m above sea level. The age of Chaya Formation ranges between late Pleistocene to Holocene (Gupta, 1972; Gupta and Amin, 1974).

III. Alluvium and coastal deposits

The freshwater alluvium comprises of mostly sand and clay which are confined to banks of the present-day streams and old river channels. The coastal deposits include unconsolidated beach and dune sands, tidal clays and old tidal mudflats. The calcareous mud deposits occupy the old tidal flats of Delvada area. The carbonaceous clays along with carbonised woody matter and shells are seen at various places in the old tidal flats. The micrites exposed near Vansoj, Kadiali are dirty white in colour while those exposed near Jafarabad and Diu Island are much impure with a high ferruginous percentage that has imparted reddish-brown colour to the rock. The unconsolidated beach deposits consists of mechanically deposited carbonate sediments having sand size carbonate grains (Verma and Mathur, 1979).

The coastal deposits such as unconsolidated beaches, dune sands, tidal clay, old mudflats etc. have been studied extensively to get a clear understanding of the sediment deposited under known environments. This would help in deciphering the sedimentary environments of Holocene. In addition, the mudflats (active and relict) will help in ascertaining the climatic conditions under which the deposition of the sediment has taken place.

Table 1-1. Lithostratigraphic classification for the southern Saurashtra coast by Verma (1982)

GROUP	FORMATION	EPOCH	PERIOD
Beach and dune deposits; Rann clays; freshwater alluvial	–	Holocene (Recent)	Quaternary
Porbandar Group	Chaya Formation Miliolite Formation	Holocene to early Pleistocene	
Nageshri Group	Dwarka Formation Gaj Formation	Lower Miocene to Pliocene	Tertiary (Neogene)
Erosional Unconformity			
Volcanic rocks; Laterite, Bauxite	Deccan Trap	Upper Cretaceous (?)	Mesozoic to Lower Tertiary

2.1.1 Drainage system

The rivers of Saurashtra flows in all directions along the tectonic slopes from the central highland which resembles a radial pattern (Marathe, 1981). However, except Bhadar and Shetrunji none of the rivers are perennial. Machchhu, Bambhan and Chandrabhoga are the northward flowing rivers that flow into the Little Rann of Kachchh while Heran, Bhadar and Vartu are the southern and western flowing rivers that debouch into the Arabian Sea. The eastward flowing rivers are Bhogava, Kalubhar and Shetrunji that flows into the Gulf of Cambay. All the rivers of Saurashtra in general follow channels with steep banks in the hilly regions and show significant deflections as they meet the sea (Chamyal et al., 2003).

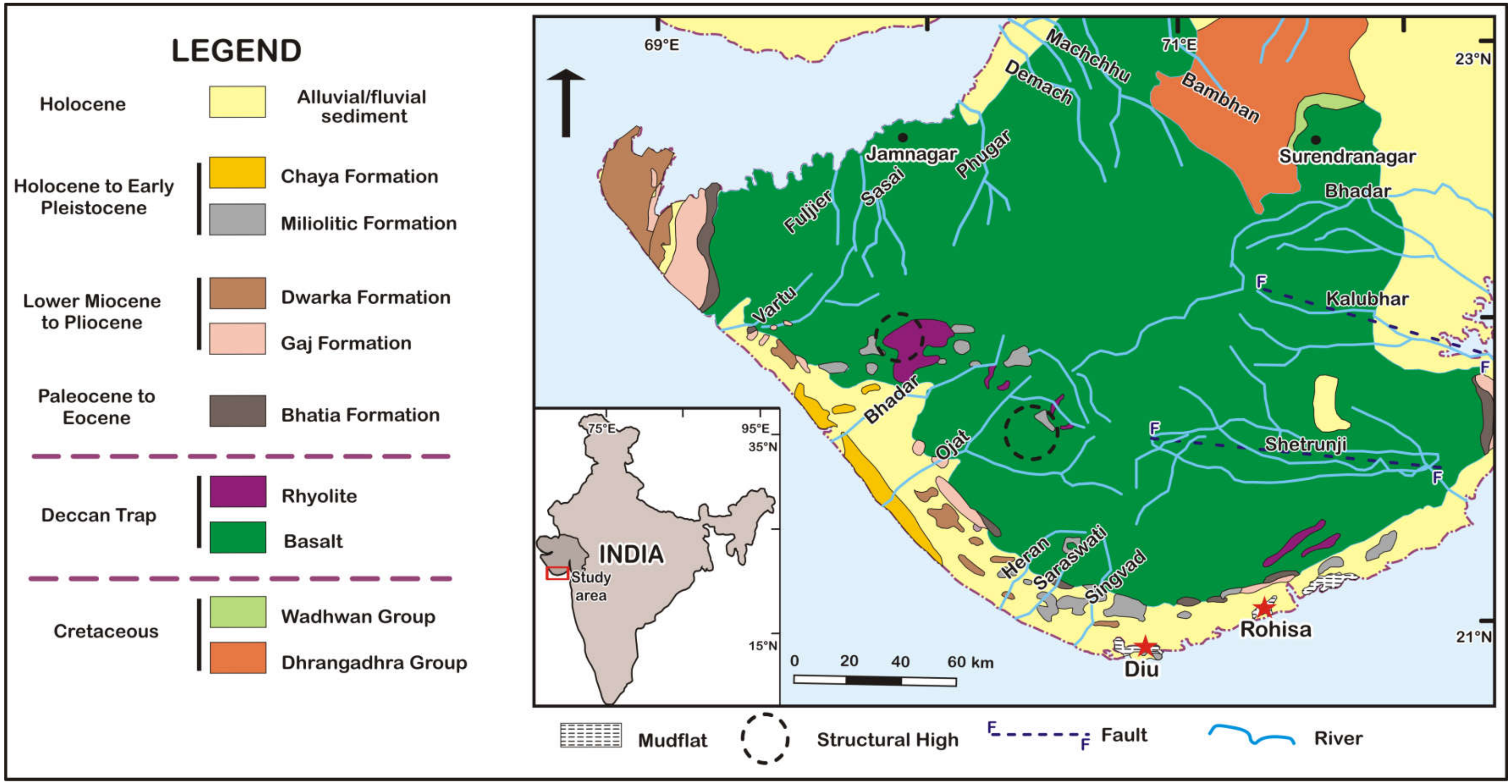

Figure 1-3. Geology and geomorphology of Saurashtra Peninsula wherein sampling location is marked by red star.

The southern Saurashtra coast is drained by various small streams flowing from north to south. They rise from the Girnar hills and debouch in the Arabian Sea. The region is deprived of any perennial streams but from east to west the main rivers in this area are Dhantravardi, Raidi, Rupen, Malan, Rawal and Machhundri. The rivers flowing in the southern Saurashtra do not form delta because of the sluggish nature of the rivers with little carrying capacity resulting from the paucity of rains in the catchment area. Additionally, the strong coastal current sweeping the coast also prevents the formation of delta. Rivers of the southern Saurashtra coast are almost lost in the tidal flats before reaching the sea. Relatively small quantity of water and sediments are delivered to the coast and tend to carry relatively high load of dissolved salts (Verrna and Mathur, 1979). Most of the rivers remain dry for the greater part of the year being active only during monsoon (Verma, 1982).

1.7.3 Climate and vegetation

The mean annual rainfall of the Saurashtra region is ~600 mm with majority of it received during the southwest summer monsoon (Farooqui et al., 2013). The mean maximum and minimum temperature varies between 34°C and 19°C respectively (Gundalia and Dholakia, 2013). Based on the forest type classification (Champion and Seth, 1968), the study area falls under 5A/C-1a (very dry teak forest) following Sub-type 5/DS1 (dry deciduous scrub forest) and 5/DS1 (dry savannah). The dry deciduous mixed forest comprises of *Acacia catechu, Terminalia crenulata, Ficus sps.* Open scrub forest constitutes of *Acacia leucophloea, Acacia nilotica, Zizyphus* spp. Riverine forest includes *T. crenulata, Emblica officinalis, Tamarindus indica, Vitexnigundu, Ficus racemosa, Syzigium* sp. The dry deciduous teak forest constitutes *Diospyros melanoxylon, Wrightia tinctoria, Tectona grandis, Terminalia.* Savannah includes

Acacia grasses such as *Sehima nervosum, Dicanthium annulatum, Cymbopogon, Chrysopogon, Apludamutica, Heteropogon, Aristida*. Thorn scrub forest consists of *A. nilotica, A. catechu, A. leucophloea, A. marmalos, B. aegyptica*, etc. (Farooqui et al., 2013).

The modern vsegetation growing in the southern Saurashtra coastal region is dominated by *Avicennia alba*, *Avicennia marina*, *A. officinalis* with fringes of *Aegiceras corniculatum, Acanthus ilicifolius, Suaeda nudiflora* and *S. maritime*, but other core mangrove species such as *Rhizophora mucronata, Bruguiera gymnorrhiza, Sonneratia* sp. and *Excoecaria agallocha* are not found in the Southern Saurashtra coast which are found in the Northern Saurashtra coast. Other significant mangrove associate species such as *Salvadora oleoides, Pongamia pinnata, Clerodendrum inerme*, *Terminalia* sp., *Sesuvium portulacastrum, Phoenix sylvestris*, *Derris scandens, Pandanus tectorius* and *Salichornia brachiata* are also present. In addition to the littoral scrub vegetation, deciduous and evergreen trees like *Lannea coromandelica, Schleichera oleosa, Holoptelea integrifolia, Casuarina equisetifolia, Acacia nilotica, A. catechu* and *Caesalpinia coriaria* are also found in the vicinity of the site. The other associated woody shrubs and herbs such as *Crotolaria bifaria, C. prostrate, Morinda citrifolia, Dermodium gangeticum, Artemisia parviflora, Tridax procumbens, Cressa cretica, Prosopis cineraria, P. juliflora, Mimosa hamata* etc. are sparsely distributed. *Typha angustata, Potamogeton indicus, P. pectinatus* and *Lemna* sp. are the common aquatic plants occurring along with sedges such as *Cyperus rotundus, Polygonum plebeium* etc. near the area (Santapau and Janardhanan, 1976).

1.8 Motivation

Climatically, Gujarat comprises various zones varying from arid to Humid (annual rainfall 250–2000 mm/yr) (Patel, 1997) and has been studied by various researcher for the paleoclimatic reconstruction (Prasad et al., 1997; Prasad et al., 2007; Singh et al., 2007; Prasad et al., 2014; Banerji et al., 2015; Sridhar et al., 2015; Sridhar et al., 2016). As the coastal Saurashtra achieved signatures of sea level changes, fairly good attempts were made to study the sea level fluctuations using geomorphic features and by chronologically constraining various high strands (Baskaran et al., 1987; Pant and Juyal, 1993; Juyal et al., 1995; Bhatt and Bhonde, 2006).

Summarising these studies, it can be underscored that though there exists reasonable database pertaining to the mid-Holocene monsoon variability, but majority of the studies are confined to the mainland Gujarat. Furthermore, there exists paucity in knowledge regarding the paleoclimatic reconstruction during last 2 millennia which is considered to be one of the important period which experienced both natural as well as human induced climate change. Quaternary sea level changes along the coastal Saurashtra has been addressed in previous studies, but none of those attempted to generate a continuous record of sea level and climate change during the Holocene keeping in account of the tectonic processes involved. The mudflat sediments are considered to have responded in accordance with the pace of sea-level and coastal changes during the Holocene, which can be used to reconstruct regional climate variability (Allen and Haslett, 2002, 2006; Bardhan et al., 2011). Present study thus attempts to reconstruct the multi millennial time scale climate variability as well as sea level changes from the active and relict mudflats of the southern Saurashtra coast, western India with multi-proxy approach.

The present study aims to reconstruct the Holocene climatic variability with the interplay of sea level changes along the Gujarat coast. The following objectives will be addressed:

- Reconstruction of mid–late Holocene climatic history of Gujarat using mudflat as climatic archive
- To ascertain the response of mudflats towards the recent global climatic events of last 2 millennia such as RWP, DACP, MWP, LIA and MW
- To study the response of mudflats towards the variation in Total Solar Irradiance (TSI) and to check the solar periodicities being engrossed in the mudflat sediments during its deposition using various climatic proxies.
- To estimate and reconstruct the eustatic and tectonic changes which occurred during mid-late Holocene period along the southern Saurashtra coast
- A novel technique of Sulphur isotopic systematics and total sulphur will be used for reconstructing the past sea level changes.

1.9 Outline of the thesis

The thesis contains seven other chapters.

- **Chapter 2** elaborates geology, geomorphology, climate and vegetation of the study area. Detailed protocol followed for analysis of various parameters have been discussed in this chapter.
- In **Chapter 3**, land–sea interaction during the last 4700 cal yr BP has been discussed using the relict mudflat of Vasoj Village. The chapter also describes climatic as well as the sea level change that took place during 4700–1500 cal yr BP. The role of tectonic processes that were operational in the study area have also been discussed in this chapter.

- **Chapter 4** reconstructs the mid–late Holocene monsoon from the partially active mudflat. This partially active mudflat can be considered as the contemporaneous record for the relict mudflat with improved resolution. The chapter further briefs the climatic conditions that persisted during last 2000 yr BP.
- **Chapter 5** contains the reconstructed climatic history for the last 2000 yr BP using sediment core raised from active mudflat of Rohisa. The chapter has provided an improved resolution for the climate of last 2000 yr BP for the Gujarat State and also point the response of mudflat towards global climatic events of last 2000 yr BP.
- In **Chapter 6**, the response of mudflat towards changing Total Solar Irradiance has been discussed using various climatic proxies such as detrital, productivity and weathering.
- **Chapter 7** details the application of sulphur isotope and total sulphur in ascertaining the sea level changes engrossed in the mudflat.
- In **Chapter 8**, discusses and concludes continuous reconstruction of climate and sea level change during a span of last 5 ka.