Chapter 5

PHYSICAL STRATIGRAPHY AND SEDIMENTOLOGICAL CHARACTERISTICS

The study of sedimentary structures leads to the interpretation of the processes acting on/in the particular environment at the time of deposition. These may be processes of abrasion, deposition, or post-depositional alteration of the sediments. Although mechanisms of abrasion remove sediment and thus remove components of this record, it still results in the preservation of unique structures that could be used as a tool for an interpretation of the depositional environment. The identification of those processes can, in turn, give the accurate reconstruction of the palaeoenvironments. Sedimentary structures are commonly formed as a result of erosion, deposition, or due to post-depositional deformation of sediments. Understanding the mechanisms by which sedimentary structures form is a vital tool for geologists to delineate the evolution of depositional records over a period. The formational mechanism for these structures is well established and is widely accepted. The mechanisms resulting in sedimentary structure formation, study of which can be used as a significant tool for reconstructing past environments which often enhance more information about the conditions of deposition (Reading, 1996). This variability is often related to fluvial systems which play a vital role in defining their depositional conditions, with rivers differing widely in discharge, sediment load, seasonality, and grain size (Bhattacharya and Giosan, 2003). The associated sediment transport regimes are typically related to high energy; however, they vary considerably due to the size of tidal cycles and the discharge of the seasonal rivers. Most sedimentary structures formed because of deposition provides a clear indication of the depositional process, for instance, asymmetrical ripples suggest a unidirectional flow (Shukla et al., 1999; Dalrymple, 2012). Some depositional structures are even indicative of very specific processes, for instance, herringbone cross-stratification indicates a tidally-dominated environment. Secondly, the structures formed at the time of interaction with the opposite medium of depositional agencies are important and allow to know the depositional conditions as well as features of that area.

An understanding of the mixture of processes that result in erosional, depositional, and post-depositional structures related to the soft sediment can result in paleoenvironment reconstructions (Wright, 1977). The shallow-marine depositional system is established upon the long-term movement of the shoreline and in association with insitu depositional processes. This shoreline movement is controlled by the transportation of sediment supply and accommodation space created over a period of time (William, 2008). The depositional environment, as well as the associated facies succession of shallow-marine sediments, may preserve some sedimentary indicators of change in sea level during transgression and regression which could be often easily identified, due to the unique conditions required to deposit the various facies successions.

RECOGNISING SEDIMENTARY STRUCTURE IN SOFT SEDIMENT CORES.

Reconstruction of palaeo-depositional environments is commonly based on the interpretation and recognition of internal sedimentary structures, bedding types, and stratification sequences observed in rock outcrops or cores (Saito et al., 2000; Hori et al., 2001; Tanabe et al., 2013). In some modern environments, visualization of internal structures is done by trenching and preparation of peels or, by coring and preparation (where conditions are harsh and hostile) of relief casts using suitable resins (e.g., Bouma 1969). Due to the water-saturated nature of the sediments, coring is the only feasible procedure in tidal influenced areas. While sedimentary structures are well preserved in cores, they have the disadvantage of only revealing narrow sections of laterally more extensive structures (Flemming, 2012). Recognising sedimentary structures in the drilled cores holds importance for the delineation of past interaction of different transporting agents and the depositional condition of the past. It enables researchers to deal with soft sediment deposition conditions related to paleoenvironments. The technique has the leverage to deal with the subsurface features and marine settings to know the past conditions of deposition.

SEDIMENTARY CHARACTERISTICS OF THE CORES

The GRK is believed to be a paleo-gulf which received sediments during the transgression phase under rising sea level after the Last Glacial Maximum (Glennie and Evans, 1976; Maurya et al., 2009). Major known and currently noticeable rivers debouching into the GRK from the northern margin is River Nara in the west and the eastern part is River Luni (northeast), however, in past, there is evidence that there existed one or more river/s draining the Himalayas and emptied sediments in GRK basin till recent past (Malik et al. 1999; Khonde et al., 2017a, 2017b). The fluvial inputs are very limited at the southern margin and do not receive significant sediment supply owing to the hyper-arid climate, seasonal nature of the rivers and their generally small catchments. A detailed description of the geomorphic setup of the GRK is described in chapter 2. The Great Rann of Kachchh

(GRK) features shallow-marine depositional conditions and mainly possesses the depositional system that exists between the landward influence of the marine processes and the seaward influence of continental as well as fluvial (river) processes. Waves action and storms, tidal currents and river-derived flows are the main physical processes which operate in shallow-marine settings. Secondly, the organisms, either as body fossils, specifically benthic organisms that are abundant in shelf environments or as trace fossils (distinct shallow-marine trace fossil assemblage like burrows, track and trails.). The macro fossils of the shallow depositional conditions are found well distributed in the GRK (Desai and Patel, 2008; Tyagi et al., 2012).

DHORDO CORE

The Dhordo core is raised from the central part of the basin (23°49′37.9″N; 69°39′09″E) providing a continuous sedimentation record of ~60 m section (Maurya et al., 2013). Based on field observations, Dhordo core site is ~3 m above the present mean sea level (AMSL) where it is not covered by the inundation with the tidal ingression or during the strong SW monsoon winds, however, the marine water ingression is of only a few inches during extreme wind events that qualify it into supra tidal salt flat environment (Maurya et al., 2013; Padmalal et al., 2019; Kumar et al., 2021). Therefore, this central core from the GRK basin may be sensitive to the basin wide-scale changes and potentially has preserved the most significant records of paleoenvironmental depositional conditions.

The core was raised through the rotary drilling method from the central basin which is ~60 m long and has 90 % recovery rate. The compression effect during the rotary drilling resulted in 10% compaction of the cores (Khonde, 2014). To recognise the sedimentary features of the core the recovered pipes were subjected to produce X’ ray photographs through radiography before splitting the core pipes (Figure 5.1a and Figure 5.1b). The photographs were taken of each core pipe after splitting it into two halves. With the combination of both taken manually and through x ray the sedimentary features were recognised (Figure 5.1a and Figure 5.1b).

The Dhordo core sediments can be divided into sedimentary units, 1, 2 and 3, in ascending order, consisting of two sedimentary facies. Each sedimentary unit and each facies are characterized by lithology, colour, sedimentary structures, textures, contact character, succession character, fossil components, mud content, and radiocarbon dates.

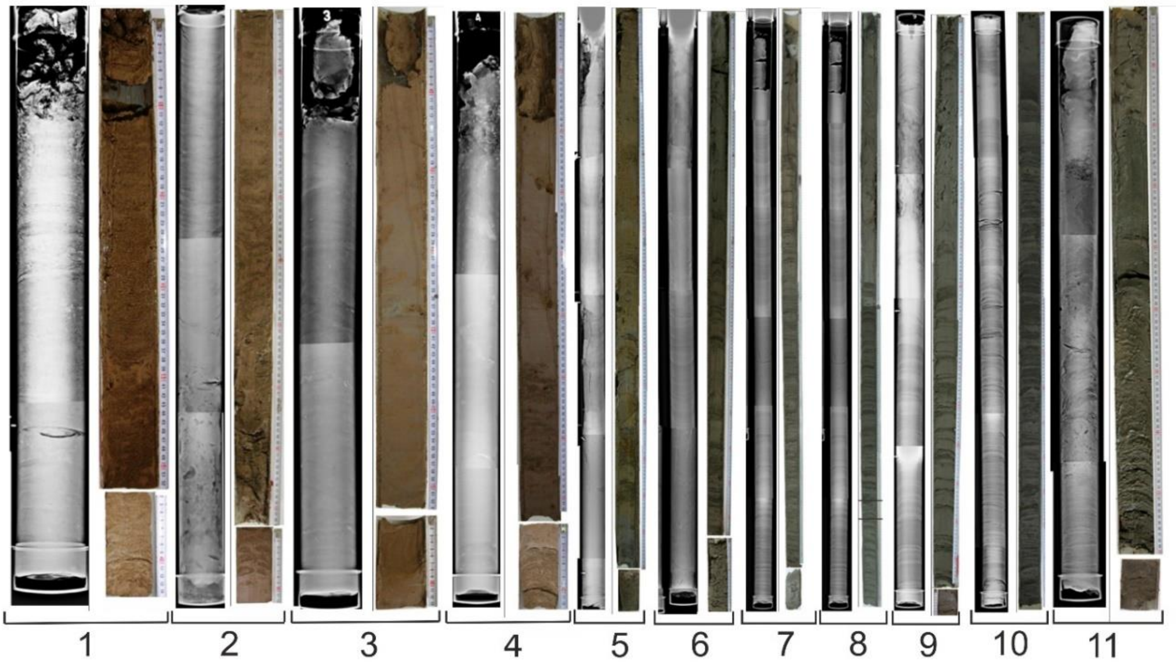

Figure 5.1a Photographs of 11 core pipes out of 24 pipes are shown, each pipe is shown in the combination of the split pipe photograph acquired manually (right) along with their respective x ray photographs (left). Scale is attached along with photograph of each core pipe.

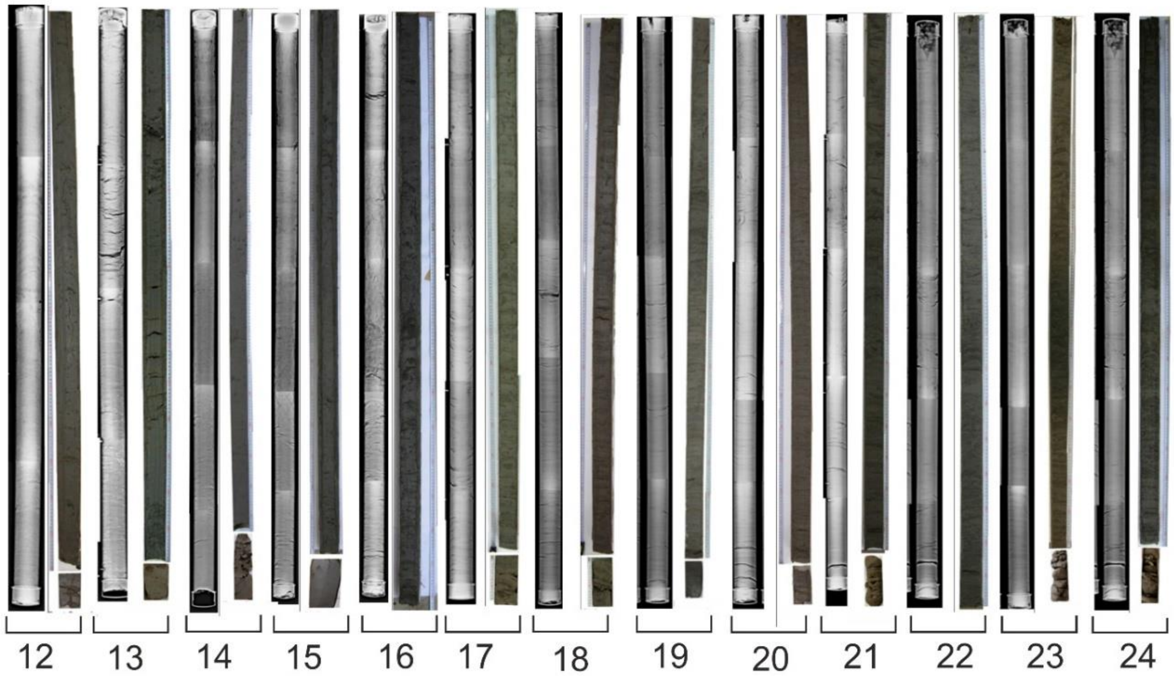

Figure 5.1b Photographs of 13 core pipes out of 24 pipes are shown, each pipe is shown in the combination of the split pipe photograph acquired manually (right) along with their respective x ray photographs (left). Scale is attached along with photograph of each core pipe.

We discuss the sediment character and sedimentary structures preserved in the core of ~60 m raised from the present day supra tidal flat to the north of Dhordo village. The core lacks a prominent mark of wave dominated setting maybe because of the sheltering effect around the core site and the possibly fine grain sedimentation dominated under low tidal energy. The fine-grained sedimentation from the GRK is recorded in almost all the studies carried so from the GRK basin (Patel and Desai, 2008; Tyagi et al., 2012; Khonde, 2014; Sharma et al., 2020; Kumar et al., 2021).

Based on physical observations of all the split core pipes (sediment colour, sedimentary structures, nature of contact, organic matter distribution), particle size data (texture, mean, mode, median, skewness, kurtosis), fossil shell contents, bioturbation activity. The Dhordo core shows three broad depositional environments (facies) which are named Unit 1 to Unit 3 in the Dhordo core. The description is given below: -

Unit 1

Lower intertidal to subtidal flat deposits (60 – 19 m)

This unit is mainly characterised by two cyclic finning upward succession where the sand contributes more than ~15 % at 56 m and 43 m depths (Kumar et al., 2021). The unit is marked by the overall increase in the grain size (coarsening upward) up to 53 m depth followed by finning of sediments where the sand reaches ~1% at the depth of 43 m (Kumar et al., 2021). The second cycle of coarsening marks it ends at 39 m which thereby leads to finning up of sediments up to 30 m depth. Sand noted from this unit ranges between 1 % to 15 %, whereas silt and clay percentage remain constant throughout this unit (Kumar et al., 2021). The mean grain size average is 6.3 phi with positively skewed sediment that shows finer to coarser sediment input to the Dhordo core site. The unimodal mode of deposition participates 40 %, bimodal participates 35% and trimodal participates 20 % of the total sediments in this unit (Kumar et al., 2021), indicating tidally influenced settings during the deposition of these sediments. The laminae (millimetre to centimetre thick) are commonly undulatory laminated and parallel-laminated. The unit is mainly composed of blackish grey clayey silt to silty sand with occasional thickly interlaminated to thinly interbedded sand and mud. Presence of sand – mud couplets is encountered from 57.4 – 58.1 m depth. The burrowing activity is found from 39.1 - 40 m (Figure 5.4a (t) along with tract and trail activity located between 41.6 – 43.2 m depth. The organic matter is found scattered throughout the core pipe between 31.1 – 33.2 m (Figure 5.4a (r). This unit is differentiated from the above unit with the presence of alternate greyish to brownish coloured sediment gradual contact with the upper unit sediments. This shift from one unit to other is gradual and lacks any sharp contact between the units. This unit is considered to be deposited under submersed water coulomb and is represented as deposition under low tide mark (45 m).

The presence of three coarsening upward cycle at ~55 m, ~40 m and 20 m depths represent the accumulation of sand at low tide level. The subtidal environment is dominated by coarser sediment having lag-scour structures produced by lateral migration of bedforms under subtidal high energy currents (Dalrymple et al., 2012; Daidu et al., 2013). It is evident that accumulation of high organic matter represents the high-water coulomb where the organic matter gets settled and well distributed (Omand et al., 2020) this accumulation and distribution of organic matter can be encountered at 33 m depth in the core. Moreover, in the Dhordo core the presence of gravel is encountered between deformed structure at 25 – 25.3 m depth which suggests inputs of coarser sediments during deposition at this depth (Figure 5.4b (o) which is suggestive of high energy condition during its deposition as is the case found in sub tidal condition or along low water line (Dalrymple et al., 2012; Daidu et al., 2013).

The borrowing activity found at 52 m depth points toward the deposition under lower inter tidal/sub tidal conditions as for the survival of suspension-feeding organisms, water is required to be under agitated conditions to keep the mud and organic matter in suspension mode—a condition usually found in the lower intertidal/subtidal zone (more frequently toward the low water line) (Desai and Patel, 2008; Dalrymple et al., 2012). Similar to this occurrence the presence of burrowing activity is also encountered from the sediments of Pleistocene age of Dwarka Formation exposed along the southern shores of the Gulf of Kachchh (Desai, 2016). The presence of tidal bundles at 20.2 – 20.4 m depth confirms it to be deposited under tidal influence and are more commonly present in the lower tidal flats/ sub tidal flats (Figure 5.4b (n) (Middleton and Southard 1984). This unit is distinguished from the overline unit by the increase in sand percentage which reaches more than ~35% at around ~19 m (highest sand percentage from entire core) depth. This phenomenon suggests shallowing of the basin and lowering of water depth during sediment deposition. Increased sand percentage is coupled with broken shell lump deposit (Figure 5.3 and Figure 5.4b (n) suggestive of translation in mode of depositional condition. The agitated depositional environment is more frequent in the upper tidal flat environment (Reineck, 1975). This unit is marked by the overall increase in the grain size (coarsening to finning upward cycle) as compared with the other units. Sand proportion increase to 35% from 1% of the preceding unit and drastically reduces at the upper part of the unit (Kumar et al., 2021).

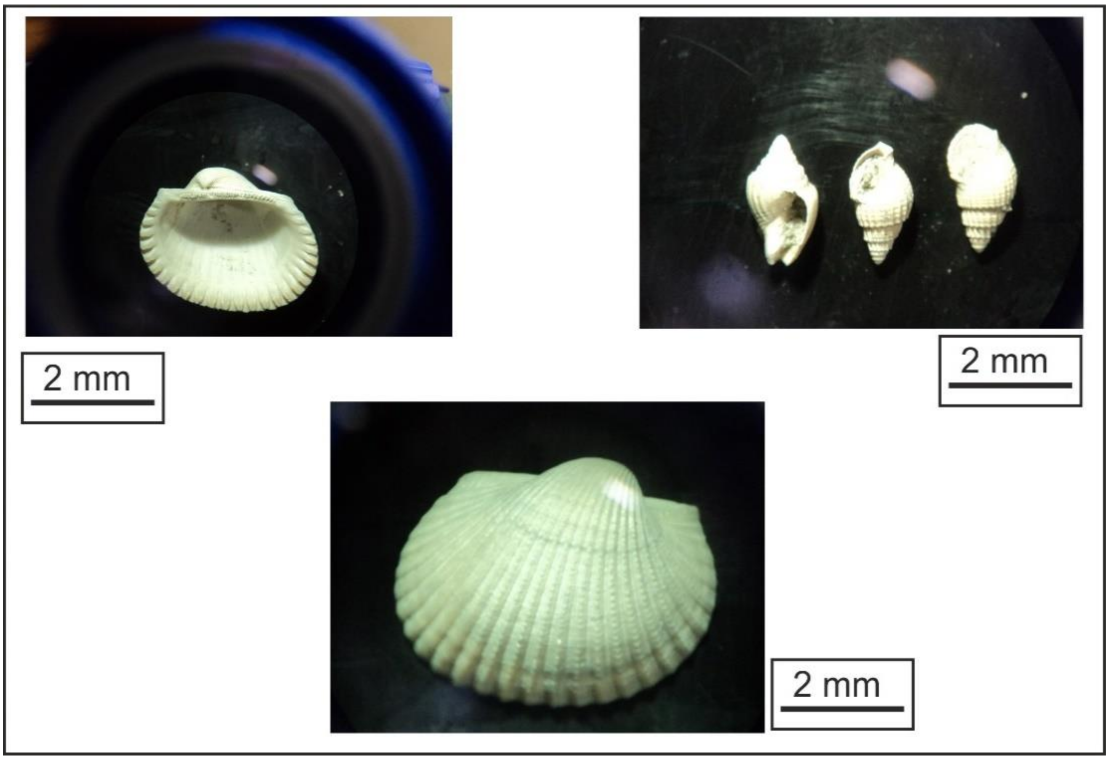

Figure 5.2 Complete shells of Bivalves and Gastropods recovered from the Dhordo core.

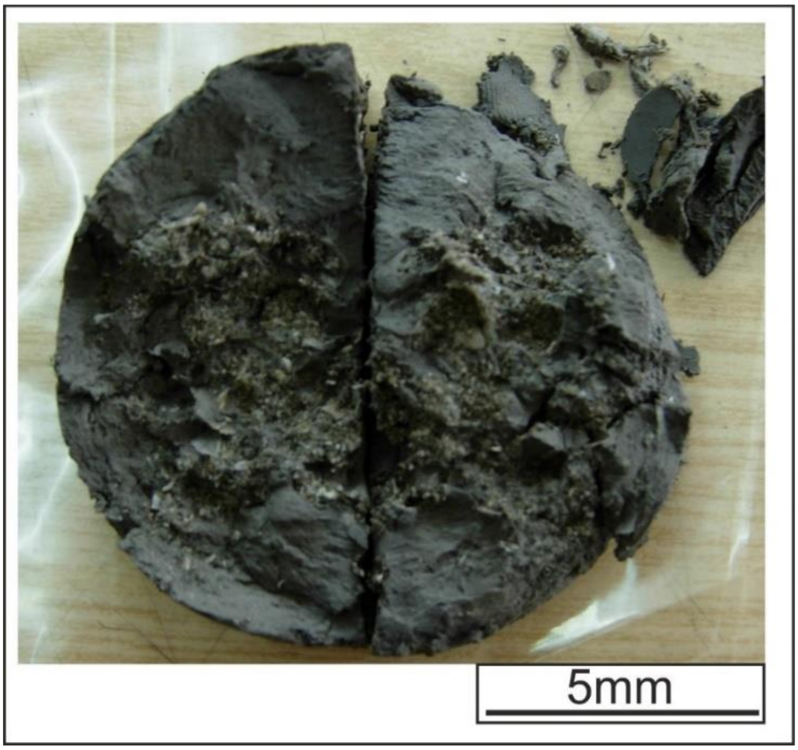

Figure 5.3 Broken shell present in the muddy sediment recovered from the Dhordo core.

Unit 2

Upper tidal flat deposit (Intertidal) (muddy) (19 – 4.9 m)

This unit overlies the unit 1 sediments and is characterised by a uniform deposit of muddy sediment where mud reaches <95%. Muddy intertidal flat facies are characterized by thin mud dominant couplets with the presence of bi-directional cross-bedding (Figure 5.4b (l) (Hori et al., 2002). The upward thickening of mud sand intercalation is encountered at 19.1 m where the mud layer shows >1 mm bi-directional sand mud intercalation is recognised as the translation to upper tidal flat environment deposition (Figure 5.4b (m), (n). The change from the tidal bedding to falser bedding observed at the same depth is also suggestive of an upper tidal flat environment (Flemming et al., 1995; Black et al., 1998). Moreover, 18.3 to 14 m depth high abundance of tidal bundles is noted (Figure 5.4b (j) these bundles are prominently formed at high tide limits towards the landward side (Dalrymple et al. 1990). Major sedimentary structures observed in tidal flats is well known that are controlled by water depth, bed shear and grain size (Middleton and Southard 1984).

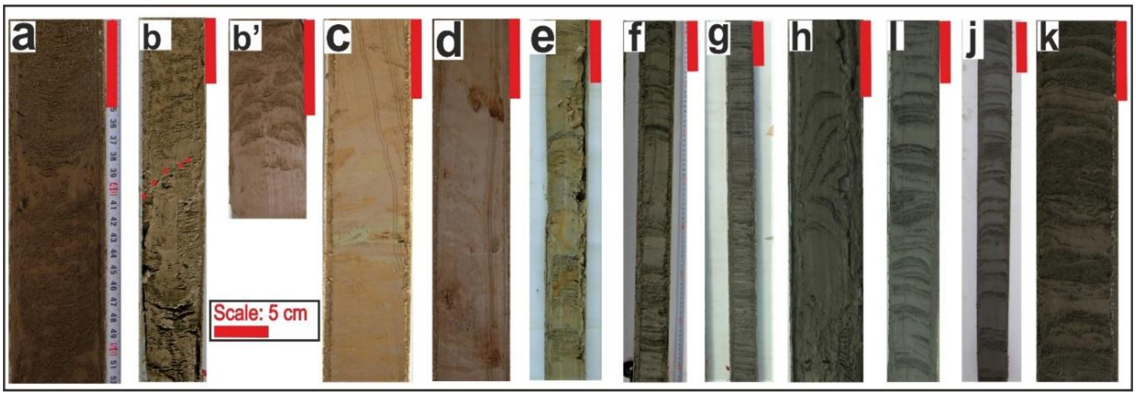

Figure 5.4a. Selected photograph of sedimentary structure a) 0.3 – 1 m, recent soil sediments deposits b) 1.5 – 2 m gradual contact or erosional contact separating undisturbed sediments from well preserved sediment b') 2.1 – 2.2 m, flaser structure (bit core) c) 2.4 – 3.1 m, greyish yellow and greyish dark very fine sand to silt, containing sand–mud couplets, thin rhythmic laminations d) 3.6 – 3.9 m, organic matter dissolution mark e) 4.9 – 6.2 m, colour alteration of grey and yellowish grey sand-clay f) 7 – 7.9 m, laminated sand mud caplets g) 10.4 – 12.3 m highly compacted lenticular bedding h) 13.5 – 13.8 m, cross bedding i-j) 14.2 – 15.1 m; 16.7 - 17.2 m, parallel lamination.

The input of muddy sediments like clay and silt sediments is suggestive of transition from high to low energy conditions during deposition, where the upper tidal flats deposits are known to process low energy conditions of deposition (Alexander et al., 1998; Black et al., 1998). The mean grain size average is 6.1 phi sediments pointing fine sediment input to the core site. Furthermore, the grain size parameter points towards increase in participation of clay particle confirming the sediments grades into more finer sediment at the upper part of this unit (14 m- 10 m) (Kumar et el., 2021). The sediments from this unit represents unimodal to trimodal mode of deposition but is largely characterized by unimodal and bimodal sediments, suggestive of upper tidal flat deposition (Alcantara-Carrio et al. 2017). Biogenic activity plays an important role in the distribution of sediments on the upper tidal flat surface (Chakrabarti 1980). Presence of complete shell of gastropod at the depth of 18 m suggest the deposition in upper flat environment (Flemming et al., 1995; Black et al., 1998) (Figure 5.2). Faint lamination is found at 7 m depth (Figure 5.4a (f) and discontinuous parallel lamination in the upper part of this unit points towards the transition in the depositional conditions towards supra tidal conditions.

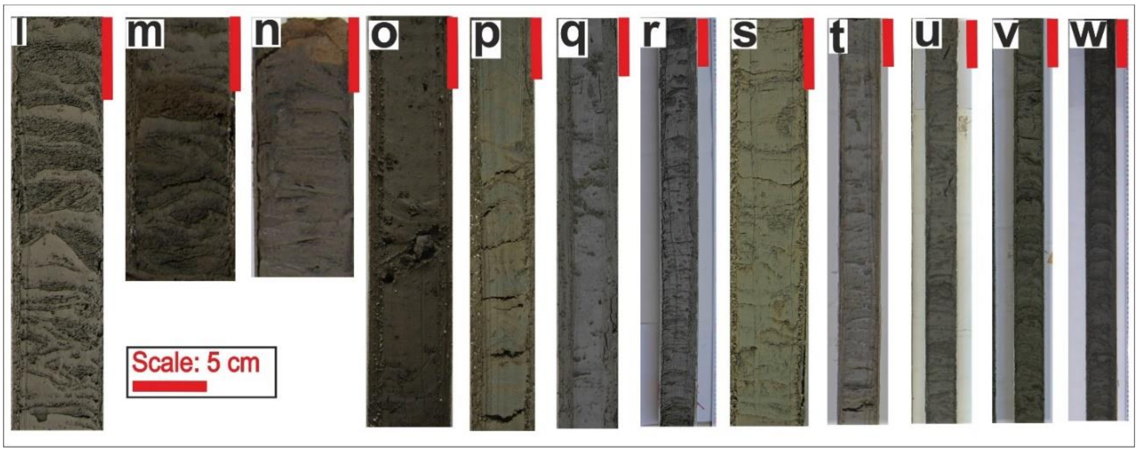

Figure 5.4b Selected photograph of sedimentary structure k) 18.3 – 18.7 m, clayey silt with very fine sand couplets, cross laminations and bi-directional current structures l) 19.1 – 19.7 m, transition from bi-directional cross-bedding to high energy cross laminations m) 19.7 – 20.2 m, thickly interlaminated to thinly interbedded sand and mud couplets are common n) 20.2 – 20.4 m, massive brownish lump deposit with broken shells & (Figure 5.3) o) 25 – 25.3 m, presence of gravel within deformed structure p) 25.5 – 25.9 m, massive deposit with alternate grey and brown colour sediment, presence of complete gastropod shell q-r) 29.7 – 30.1 m; 31.1 – 33.2 m, broken shell layer, scattered organic matter throughout core pipe s) 35.8 – 37.5 m, structureless greenish to brown clay deposit t-u-v) 39.1 - 40 m; 41.6 – 43.2 m; 47.9 – 48.9 m, burrow activity along with track and trail present w) 57.4 – 58.1 m highly compact silt layers and laminations.

Unit 3

Supra tidal deposits [4.9 – 0 m (+3 m above sea level)]

This unit is separated from the underlying unit 2 at 4.9 m depth where alternation of brown to light brown coloured sediment band is observed (Figure 5.4b (e). The transition is evident from the colour contrast of the sediment noted at ~4.9 m. This unit is predominantly marked by unimodal mode of deposition whereas the bimodal mode of deposition marks the second highest with 25% of the total sediment from this unit. Structureless to massive deposition is commonly present with the occurrence of the anhydrite minerals like gypsum which is more evident in semi-arid and harsh conditions. The presence of colure alteration in the muddy sediments is more commonly formed in a supratidal flat condition and experienced intermittent inundation and exposure (Dalrymple et al. 1990; Alexander et al. 1991).

The clay and sand intercalation are observed with faint ripple marks which is clearly distinguished at 2.1 m depth (Figure 5.4b (b') suggestive of exposed conditions prevailed during the deposition of sediments in this unit. The transformation from intertidal condition to supratidal conditions was enhanced due to the falling sea level as well as changing climatic conditions (Kumar et al., 2021). Gradual contact is present at 1.5 m depth which separates the lower supratidal deposits from the modern soil formation.

BERADA CORE

The Berada core is recovered from the Banni plain represent the changes of the GRK basin from the hinterlands where the ephemeral rivers might have contributed sediments seasonally. The core was raised through rotary drilling method from the sothern margin of the basin which is ~50 m long and has 90 % recovery rate. The compression effect during the rotary drilling resulted in 10% compaction of the cores (Khonde, 2014). To recognise the sedimentary features of the core the recovered pipes were subjected to produce X' ray photograph through radiography before splitting the core pipes. The photographs were taken of each core pipes after splitting it in to two halves. With the combination of both taken manually and through x ray the sedimentary features were recognised (Figure 5.5a and Figure 5.5b).

The Berada core sediments can be divided into 5 sedimentary units, 1, 2, 3, 4 and 5 in ascending order, consisting of 3 sedimentary facies, respectively. Each sedimentary unit and each facies are characterized by lithology, colour, sedimentary structures, textures, contact character, succession character, fossil components, mud content, and radiocarbon dates. The sediment character and sedimentary structure preserved in the core of ~50 m (Figure 5.5 a and Figure 5.5 b). The core lacks a prominent mark of the wave-dominated area maybe because of the sheltering effect around the core site and the possibly fine-grain sedimentation dominated under low tidal energy. The fine grain sedimentation from the GRK is recorded in almost all the studies carried so from the GRK basin. Based on physical observations of all the core cut sections (sediment colour, sedimentary structures, nature of contact, organic matter distribution), particle size data (texture, mean, mode, median, skewness, kurtosis), fossil shell contents, bioturbation activity; we have identified five different depositional units (facies) which are named as Unit 1 to Unit 5 in the Berada core. The description is given below: -

Unit 1

Fluvial sediments deposits (50- 39.6 m)

Unit 1 consists of pebbly sand and coarse to medium sand. Sedimentary structures identified in this unit are planar crossbedding, with earth brown to grey/ ash colour sediment. Ferruginous sediments are devoid of any organic content and ripple cross laminations (current-ripple laminations). Hard compact clay along with reddish mottled sediments is present at ~43 m. It may be chronologically late Pleistocene sediments. The channel fills deposits in the Berada core locations. The sediments show fining sequence with gravels at the bottom of the core pipes at 50m to coarse sand to silt at the top of the core pipes at 39.6 m. The presence of bimodal is mainly confined to this unit.

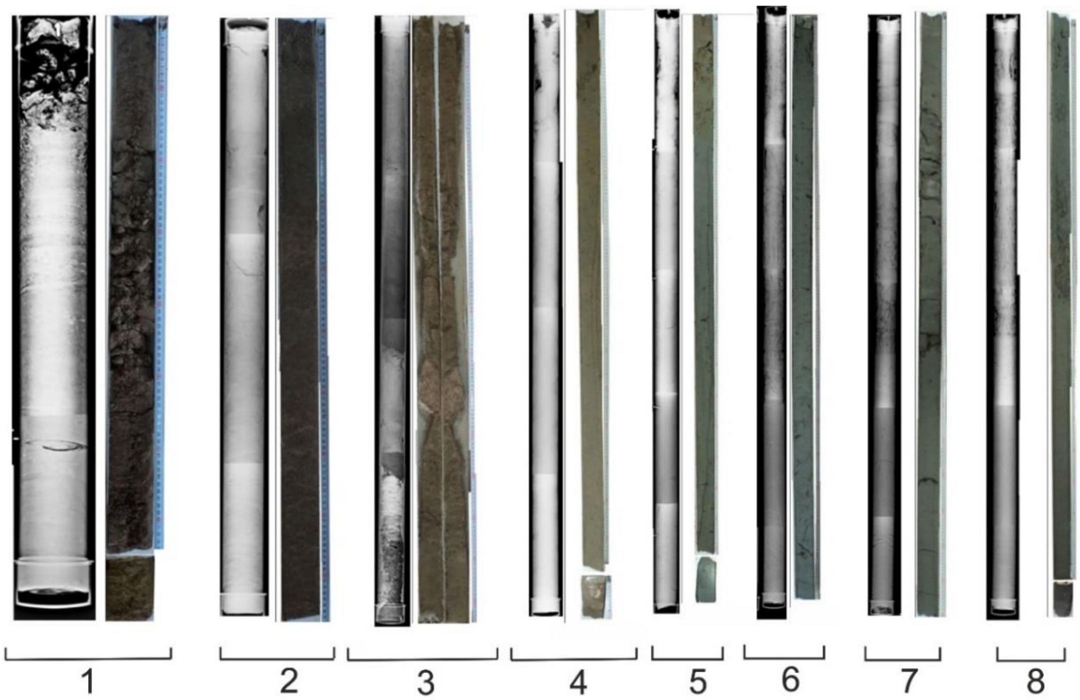

Figure 5.5a Photographs of 8 core pipes out of 15 pipes are shown, each pipe is shown in the combination of the split pipe photograph acquired manually (right) along with their respective x-ray photographs (left). Scale is attached along with a photograph of each core pipe.

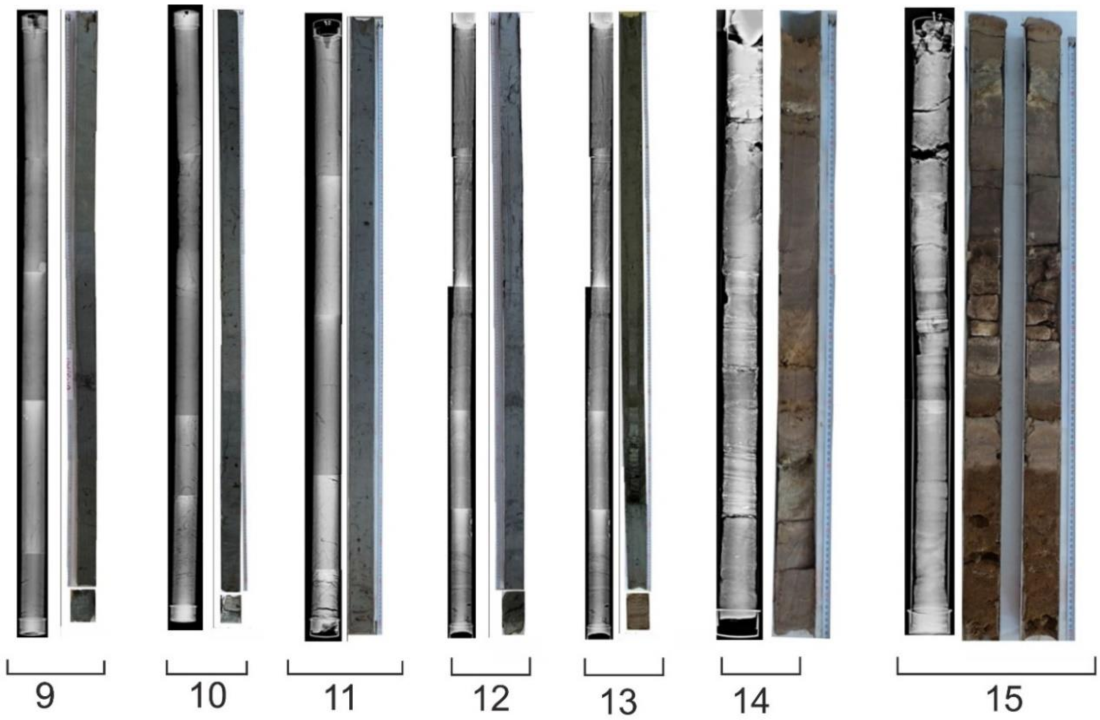

Figure 5.5b Photographs of 8 core pipes out of 15 pipes are shown, each pipe is shown in the combination of the split pipe photograph acquired manually (right) along with their respective x ray photographs (left). Scale is attached along with a photograph of each core pipe.

This unit forms the bottom-most part of the Berada core that is characterized by the presence of coarse, pebbly poorly sorted, massive sands that occur between ~51 m to 39.6 m in depth (Figure 8a). The colour of the coarse sandy part of this unit shows variation from yellow to orange indicating the deposition in oxidising, shallow water conditions during deposition (Reineck and Singh, 1980; de Boer, 1998) (Figure 5.6 (j). Quartz, feldspars and dark minerals are the primary constituents of these sediments which marks the fluvial regime near the core site. The source for these sediments appears to be from local/proximal sources i.e., from the Mesozoic sandy formations that are exposed in Kachchh Mainland Hill range (Maurya et al. 2013). Earlier studies have documented dominantly coarse-grained, colluvio-fluvial Quaternary sediments in front of KMF scarps marking the northern margin of the mainland (Kar et al., 1993; Chowksey et al., 2011; Maurya et al., 2013; Biswas 2016; Khonde 2017a). There are no direct chronological measurements for this unit, however, most likely this unit marks the late Pleistocene period during the low sea-level stands (river aggradation phase). These coarse, massive sandy sediments are overlayed by hard, semi-compacted, grey to earthy brown coloured muddy sediments which show mottling at ~ 47.5 to 42.5 m depth (Figure 5.6 (j). The presence of foraminiferal tests in these muddy sediments suggests a brief interval of marine encroachment at the core site

(Khonde., 2014; Maurya et al., 2013). Therefore, this zone marks fining upward sequence from pebbly/coarse fluvial sands to marine-influenced mud deposition. Such finding upward sequences along the marginal marine basins are often found to be overlayed by marine successions under advancing sea levels (Dalrymple et al., 1992; Allen & Posamentier, 1993).

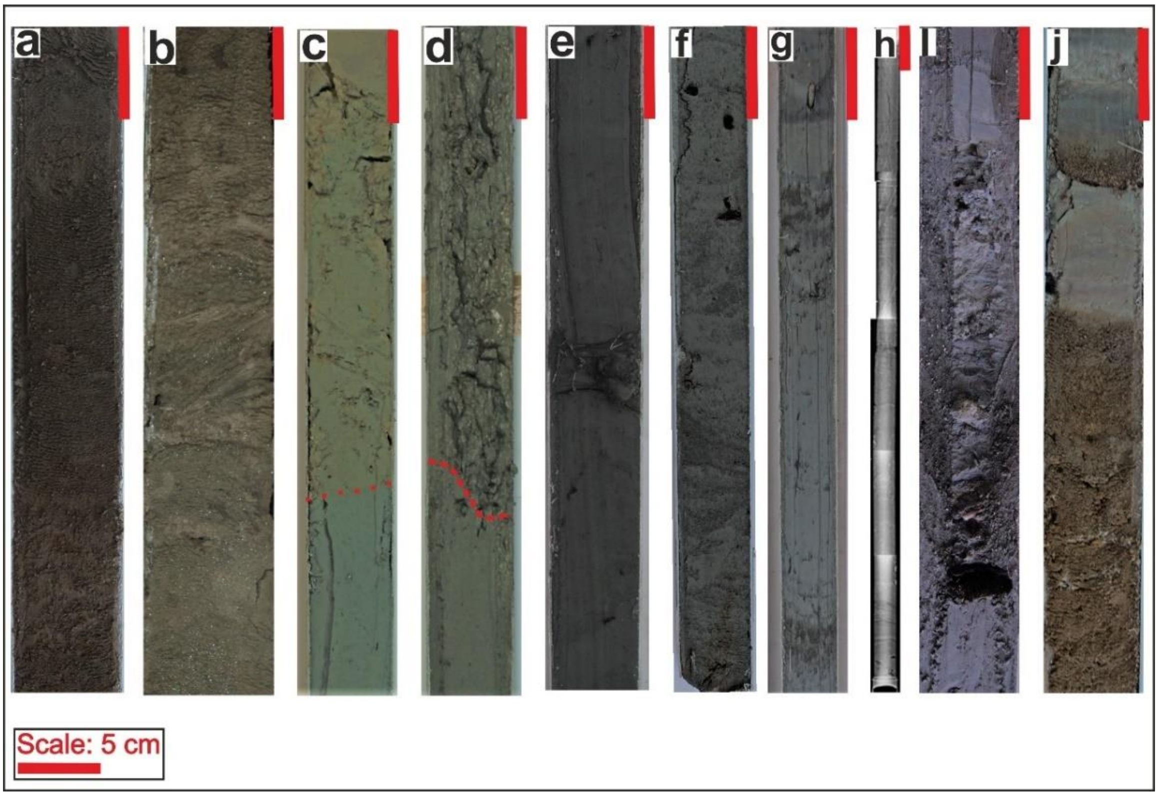

Figure 5.6 Selected photographs and X-ray radiographs of the slab samples obtained from Berada cores. a) 1.35 – 0.3 m, uniform deposit of sand b) 1.75–2.30 m, sand clay brownish colour sediments with poorly laminated sediments c) 4.75–6.50 m, colour alternation of greenish grey to brown clayey sand, dotted line is drawn to represent the lithological colour variation. d) 17.6 – 15.8 m, high mud content, dotted line representing the highly bio turbidite sediment unit overlying homogenous deposition, high mud content. e) 24-22.1 presence of gravel within deformed structure f) 27.25–25.60 m, represents rootlets, note the upward increasing sand mud couplets: lenticular to wavy structure with increase in sand content. g) 35.8 –35.6 m, increasing upwards mud and sand intercalation. h**)** 39.1–38.1 m, extensive burrowing activity with scattered organic matter i) 39.6 –39.1 m, peat layer within clayey sediments having gradual contact with the underling homogenous undisturbed sediment deposit. j) 44.3 – 43.2 m, hard compact brownish oxidised clay with laminations.

Unit 2

Estuarine deposits (marshy deposition) (39.6 – 30 m)

Colour contrast from pale yellow ferruginous sandy silt to more clayey sediment. Sand mud ratio decreases indication finning upwards sediment deposit. Gradual contact between the peat layer present at 38 m and the bio turbid massive clay where the mud content is more than 98% sediment above it, which shows coarsening fining coarsening grain size indication estuarine condition. Burrowing is present at 35 m depths along with an abundance of organic material which is scattered throughout the core pipe (Figure 5.6 (g) and (h).

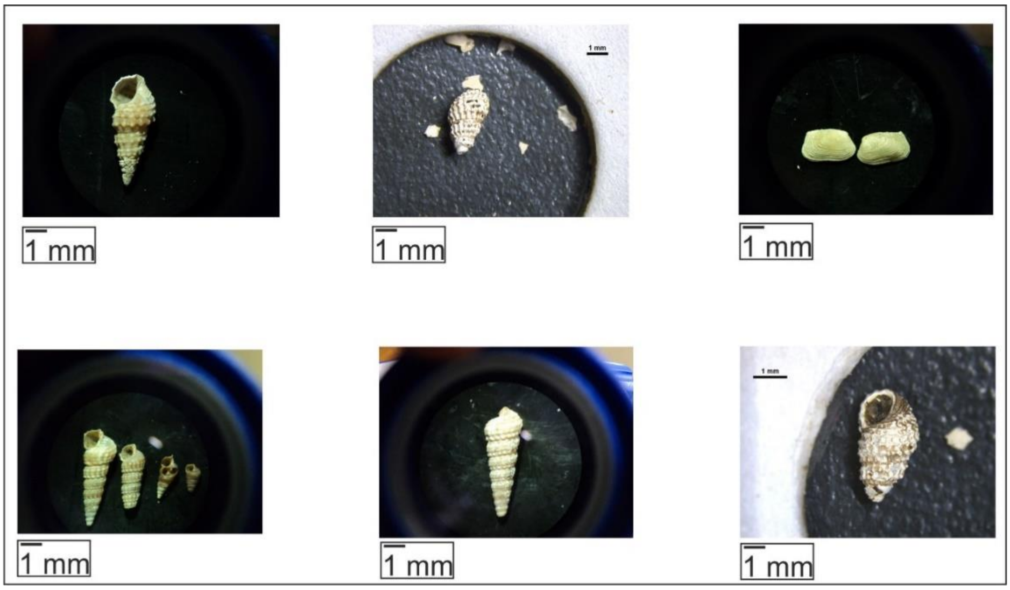

Figure 5.7 Complete shells of Gastropods and Bivalves recovered from the Berada core.

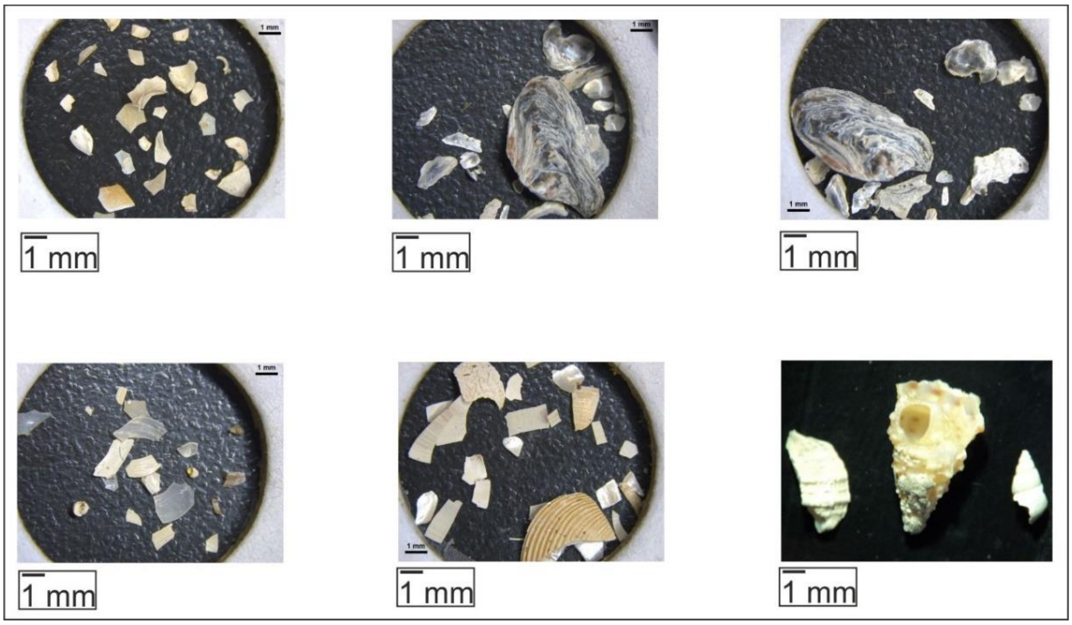

Figure 5.8 Broken shells recovered from the Berada core.

Sediments in this unit show sharp erosional contact between the semi-compacted muddy sands and a 1.5 cm thick peat layer at around 38 m that is overlaid by bioturbated mud (sand >5%) suggests the decrease in energy of depositional conditions (Figure 5.6 (g). The peat/organic matter layer encountered at 38 m along with the presence of cross lamination or inclined lamination between 38-39 m shows the sharp change in the depositional conditions which further indicates the changing energy condition along with the steady changing environment of deposition. The peat/organic matter layer may have been deposited during the transgressive sea during the early Holocene (Maurya et al2, 2013; Khonde, 2014).

The abundance of organic material is common in estuarine conditions which may be transported to the location by the approaching freshwater or deposited during the stagnant water column (Song et al., 2013; Khonde, 2014). This unit shows the unimodal mode of deposition at 56 %, whereas the bimodal contributes 46% suggesting a tidally influenced estuarine environment (Li et al. 2001). Particle size data for this unit shows <95% mud with low sand content which is typical in estuarine/marshy settings under moderate to low energy conditions (Dalrymple et al. 1990). This deepening upwards sequence that records landward stepping facies pattern is recorded in micro-tidal to meso-tidal transgressive estuarine (e.g. Allen, 1991; Dalrymple et al., 1992; Allen & Posamentier, 1993).

The scatterplot between skewness vs sorting clearly shows the deposition under a sheltered/closed environment that is consistent with the geomorphic set-up of the basin/core site (Chapter 6). The occurrence of distributed organic matter in the upper part of the unit, formation and preservation of peat layer in this unit suggests the initiation of calm and low energy of deposition with a relatively increased water column at the core site during early Holocene ~9.5 ka BP. Furthermore, upward decrease in sand content and change in colour from yellowish-brown in the preceding section to greyish to blackish colour sediments with bioturbation activity, which is indicative of increased water column, reduced energy condition supports the interpretation of advancement of marine condition at the core site under estuarine to marshy settings (Reineck and Singh, 1980; Boer, 1998). The presence of bioturbated clay along with extensive burrowing activity and broken shells in this unit above the peat/organic matter layer shows the prevalence of marshy estuarine environment during the deposition in the study location.

Unit 3

Subtidal flat deposits (28- 24 m)

Sand mud ratio increases drastically (coarsening upwards) where sand reaches up to 20% from 2 per cent bounded by finning upwards sequence where the sand percentage reaches to ~10%. Lenticular to wavy structure encountered at 28 m which is the sand mud couplets with presence of laminations.

This unit is marked by the overall increase in the grain size (coarsening upward cycle) as compared with the underlying unit. Sand proportion increase to 15% from 2% of the preceding unit and drastically reduces in its upper part (Figure 5.6 (f). The mean grain size average is 6.4 phi with positively skewed with average value of 0.5 phi that shows coarser sediment input to the core site. The mode of deposition is dominantly by unimodal and bimodal settings whereas one sample (out of thirteen) yield trimodal mode of deposition (Figure 5.6 (f). indicating tidally influenced estuarine to sub-tidal settings during the deposition of these sediments (Avramidis et al., 2013). Based on lithological characteristics, structure/textures and grain size coarsening upward trend with lenticular to wavy structures, presence of sand mud couplets with lamination the deposition appears to be under sub-tidal zone. The couplet between the sand and mud at 28 m along with lenticular to wavy structure is marked by increment of sand mud ratio where the sand percentage reaches upto 15 % at depth of 25 m along with cross bedding structure mimics the varied energy condition which indicates the depositional condition in the sub tidal setting (Figure 5e) (Tanabe et al., 2003). Falser, lenticular bedding and mud drapes suggest that these facies were deposited under a tide dominated environment (Dalrymple and Makino, 1989; Reineck and Singh, 1980). The energy condition is higher at the sub tidal zone which may be deposit relative coarser sediment during the ebb tides of the MLT (mean low tide) (Dalrymple et al., 2012; Daidu et al., 2013). The typical subtidal zone accommodates sand which is due to ebb tide which may be the case during the deposition of this unit (Allen and Posamentier, 1993).

Unit 4

Intertidal flat deposits (mix tidal zone to mud tidal zone)

Finning up sequence at 24 m up to 20 m. Homogamous sedimentation and sedimentary structure less deposition. Broken shell encountered at 19 m depth. Bioturbated massive clay with a gradual contact to the upper present sediment unit (Figure 5.6 (d). The Unit-4 is characterised by finning up sequence observed between 24 m to 20 m deposition that distinguishes it from the underlying unit. The average mean value is 6.7 phi from this unit where the contribution is ~85% unimodal and ~15% bimodal. Lowering in the sand mud ratio at around ~24 m a fining upwards sequence is observed that is accompanied with presence of strong laminated layer between clay and sand which is more visible in the x ray image. This unit also marks the change in light greenish to dark green colour of the sediments as observed in the core cut sections. Broken shell (Figure 5.8) is encountered at 19 m depth along with the presence of bioturbated massive clay which makes a gradual contact to the upper present sediment unit (Figure 5.6 (d). The layer of broken shell is encountered at 19 m depth which interpreted as shell which thrives on the tidal flats which gets exposure during the low tides (Figure 5.8). The homogenous sedimentation with structureless deposition can be seen with no or very less cross lamination mimics the constant with little change in the energy of the deposition through these depths (Semeniuk, 2005; Wang et al., 2015).

The bioturbated sediment encountered at 16 m which lies gradually over the undisturbed homogenous deposit of mud. The presence of laminated mud at 13 m, is interpreted as the change from the mixed flat to mud flats. The mud flats have a typical characteristic of strongly bio-turbidied mud along with mud lamination (Dalrymple and Makino, 1989). The sand mud ratio from this depth also remains more than 90%. The scattered organic particle and the characteristics of these sediments indicate that they were more influenced by riverine silts and clay and deposition in mixed to muddy tidal flat (Duanne, 1964).

Unit 5

Supratidal flat deposits [7 – 0 m (+5 m above sea level)]

A gradual change in the colour contrast encountered at 7 m which changes from light greyish to earthy brown colour. The typical dark brown colour of the sediments moves more towards more sand ratio. The cross lamination at 3 m. The highest sand percentage 40% from this unit is noted. The rootlets and organic debris found scattered which can be seen from x ray (Figure 5.5 a and b) image from the entire core image from 2.25 – 3.6 m. Sand shows finning towards the surface at ~0.5 m. A gradual change in the colour contrast encountered at 7 m which changes from light greyish to earthy to light brown colour (Khonde, 2014).

The typical dark brown colour sediments is encountered in this unit moreover the marked changes noted in the unit is reflected by change in sand percentage (40%). The transition is evident from the colour contrast of the sediment noted at ~5 m (Figure 5.6 (c) The unit shows coarsening upward deposition along with cross lamination present at 3 m (Figure 5.6 (b). The rootlets and organic debris found scattered identified from x ray image of the core from 2.25 – 3.6 m (Figure 5.6 (b). Fine, organic rich sediment is common in a vegetated floodplain or salt-marsh environment (Hori et al., 2002).

Moreover, there is highest record in the sand percentage from this unit with cross laminations mimics for the change in the depositional environment towards more marshy but relatively more terrestrial condition which supports more shrubs growth. The present grass land conditions are evident for the change in the depositional environment, whereas the transformation towards the grassland is mostly enhanced during this stage. The occurrence of the anhydrite minerals like gypsum is evident of semi-arid and harsh conditions. The sand could also be transported to the area by the hydrological activity of the nearby flowing rivers.

STRATIGRAPHY AND DEPOSITIONAL CONDITION IN GRK

The stratigraphy of both cores was established based on the sedimentary facies described in the sedimentary section. A lithographic comparison between both the cores was established to delineate the depositional changes in and around the cores site during Holocene period. The accumulation rate and the sedimentary facies of both the cores are closely related. The stratigraphic relationship between them is shown in Figure 5.9. Both curves indicate a high accumulation rate during Greenlandian Stage where the average sedimentation rate of Dhordo is 1.8 cm/y and 1.1 cm/y is shown by Berada core (Figure 5.9). Low accumulation rate was reflected during Meghalayan Stage from both the cores.

The fluvial facies encountered in Berada core is marked as fluvial deposits characteristic of channel fill sediments. This fluvial channel can be considered as small channel within a channel complex flowing from the southern part of the area (Maurya et al., 2013; Khonde 2014). These sediments are deposited to the Berada core site by the northerly flowing river channels from Kachchh Mainland Fault which was inundated during the transgressive phase under sea level rise after LGM (last glacial maximum) (Figure 5.9). The fluvial facies are overlined by the marine influenced estuarine facies. Moreover, the presence of peat layer at 39 m suggest presence of stagnant condition of sediment deposition and increased water column in the Banni plain (Maurya et al., 2013; Khonde 2014). These sediments are deposited to the Berada core site by the northerly flowing river channels. The Dhordo core in the central basin shows sub tidal sediment facies at the bottom most part of the core. The sub tidal condition in the central basin was established much prior to the Berada core in the Banni plain.

High sedimentation rate was noted from both the cores during Greenlandian Stage where Dhordo continues to relect sub tidal condition of deposition whereas Berada core continues receiving sediment under estuarine/marshy condition. The depositional condition in GRK during Greenlandian Stage demonstrates the presence of shallow marine condition in the central part of the basin which approached the banni plain during high tidal conditions. The Northgippian Stage in the Berada marked the change in the depositional condition where it accumulated sediments under sub tidal condition which is in conformity with the similar depositional condition established at Dhordo core (Figure 5.9). The extension of the similar depositional condition points toward the transgressive phase of sea level in GRK where the shoreline remained stagnant and continues to approach towards the south of GRK during high tide conditions. At the end of Northgrippian Stage the transformation of facies from sub tidal to intertidal marked from both cores is evident for the change depositional condition under regressive sea level. The Meghalayan Stage is noted as regressive sea level phase in the GRK basin where the sediment accumulation curve shows a dip in sedimentation rate of both cores which marks the lowest from the entire Dhordo and Berada core. The sea level withdrawal from the GRK is noted at around ~2 kyr which quantifies the cores to be deposited under supra tidal conditions (Figure 5.9).

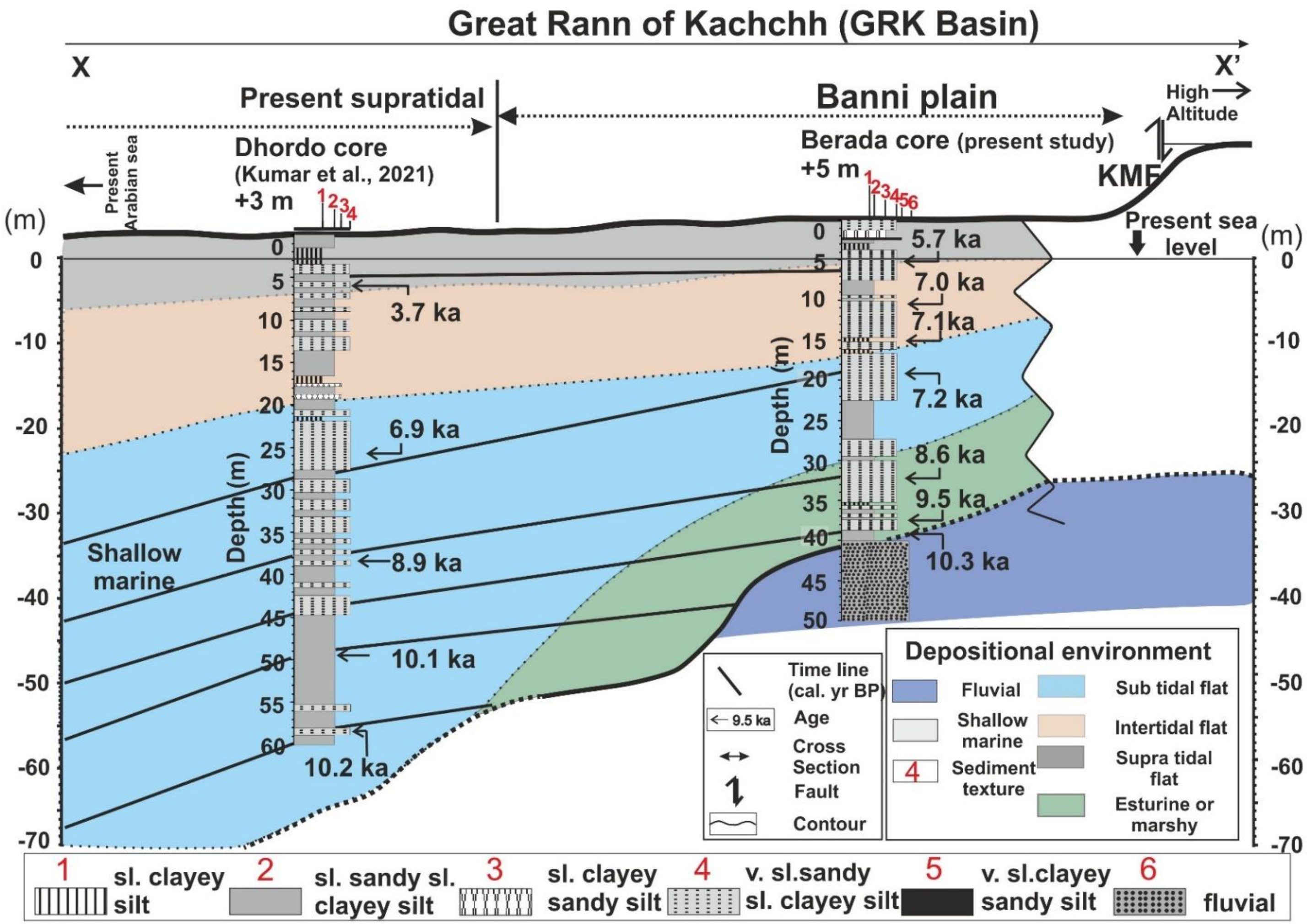

Figure 5.9 Stratigraphic cross-sections with isochrons of the Great Rann of Kachchh basin (X – X'), including detailed information about the lithology, dating, sedimentary facies and depositional conditions. Isochrons are drawn based on radiocarbon ages. Note the termination of fluvial and estuarine depositional condition before Dhordo core.