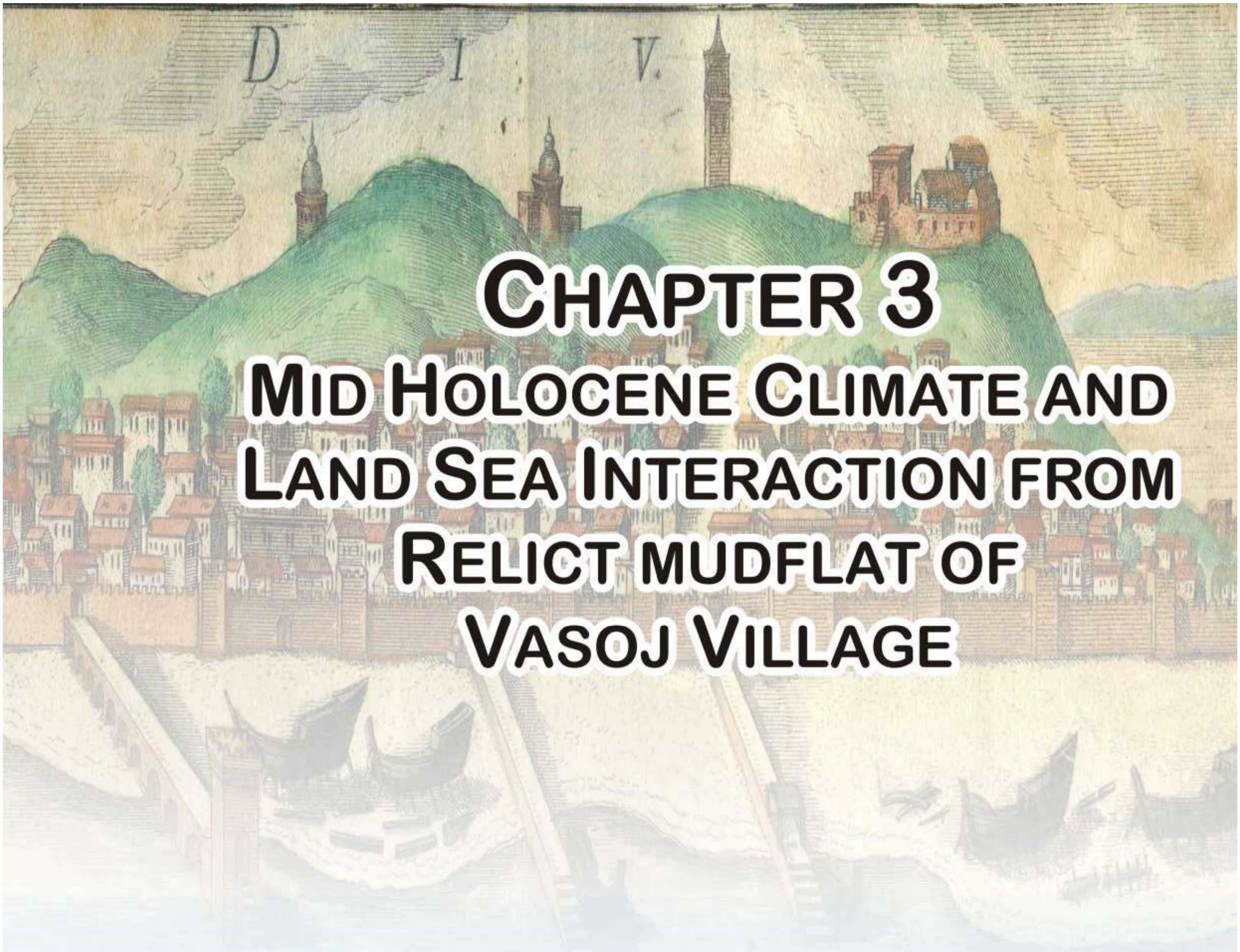
# CHAPTER 3

## MID HOLOCENE CLIMATE AND LAND SEA INTERACTION FROM RELICT MUDFLAT OF VASOJ VILLAGE



### 3.1 Relict Mudflat: Vasoj Village

The mudflat formation takes place in the region where the stream of seawater is gentle hence depositing sediments slowly thereby archiving the climatic perturbation. The relict mudflat is the region where, the sea used to deposit sediment, which later ceased. Therefore, the study of the relict mudflat will invoke both the climatic as well as the sea level changes in the region. In view of this a relict mudflat near the Vasoj village (VV) (20°45'1.7''N; 71°0'14.3"E) ~10 km northeast of the Diu Island was selected and dug till the bed rock (Miliolite) was struck.

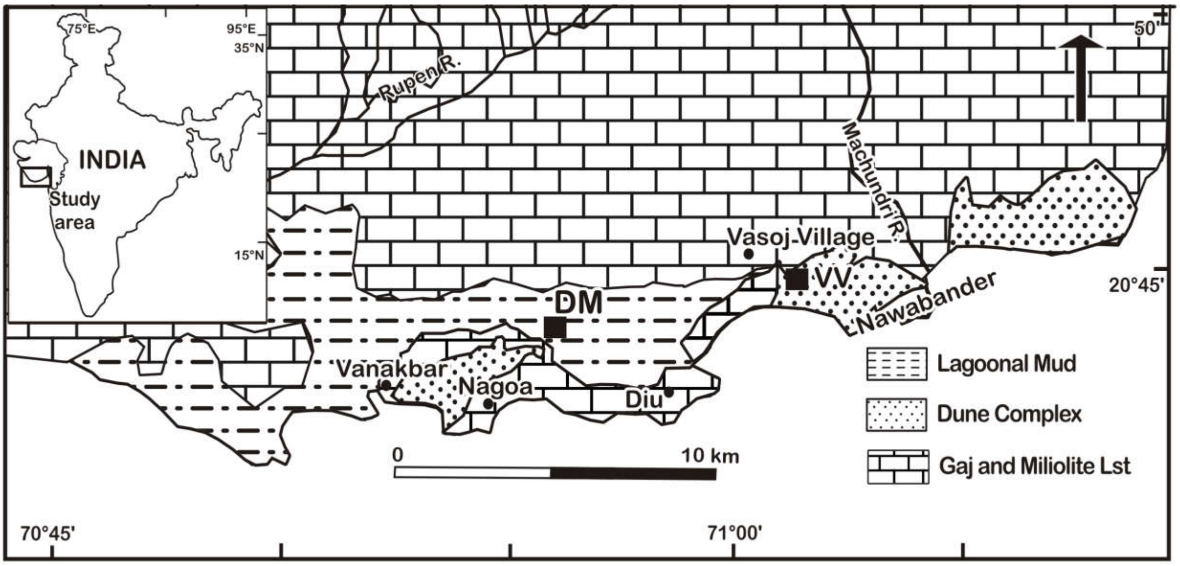



*Figure 3-1. Location of the pit dug at the relict mudflat of Vasoj Village (VV) and surface sample collected from the active mudflat of Diu (DM) (Modified after Pant and Juyal, 1993).*

### 3.2 Litho–section of the relict mudflat

A 100 cm thick sediment profile was dug from the surface of the relict mudflat overlying a weathered miliolite bed rocks. Based on the textural variations, the entire profile was divided into three major units, which are numbered from bottom upwards as Unit-I to Unit-III (Fig.3–2).

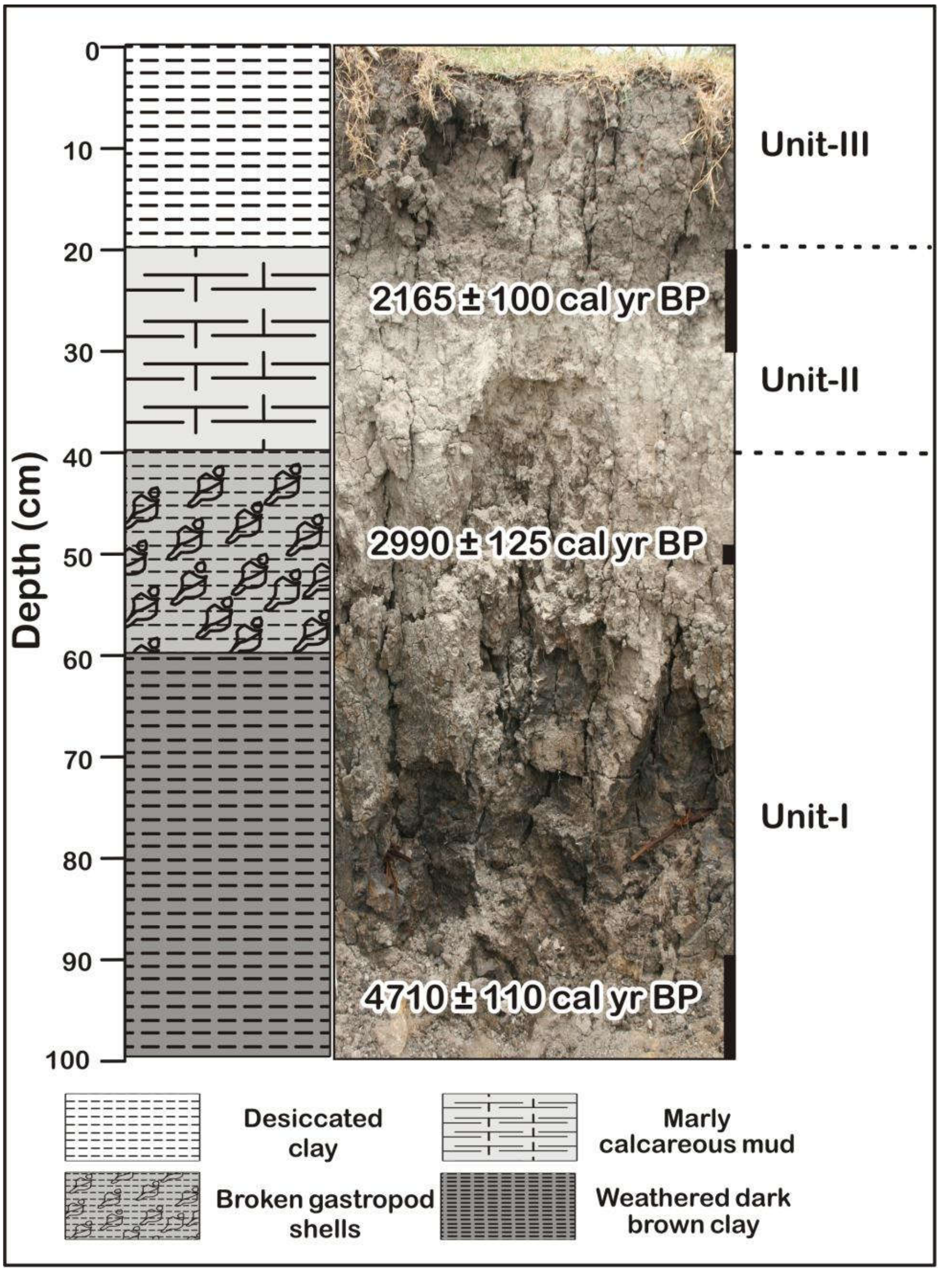



*Figure 3-2. Lithosection of the relict mudflat (VV) overlying the weathered miliolitic limestone near Vasoj Village. Based on the textural attributes, the section is divided into three units. Black bars indicate the layer sampled for radiocarbon dating.*

Unit-I is 60 cm thick (100–40 cm), weathered mottled clay overlying the weathered miliolite bedrock. Miliolite is the foraminiferal lime stone which has derived its name from foraminifer genus 'Miliolina' (Baskaran, 1996) and the upper 20 cm of the Unit-I, contains broken gastropod shells (*Turritella* sp). The gastropod shell

Turritella sp. belonging to family Turritellidae are among the most abundant and diverse macrofossils of Mesozoic and Cenozoic marine deposits (Allmon, 1988). They usually occur in most type of substrates but also commonly found in mud and fine sand (Allmon, 1988). Unit-II is 20 cm thick (40–20 cm) section comprises marly, light grey, calcareous mud showing evidence of mottling and moderate weathering. Unit-III is 20 cm thick (20 cm–surface) section dominated by moderately weathered desiccated clay.

From a 100 cm thick sediment profile, 10 sediment samples were collected for geochemistry and pollen study and three samples for radiocarbon dating. Further, surface sediment from the active mudflat (Fig. 3–1, DM) was collected from ~3.5 km southwest of the relict mudflat (Fig.3–1, VV). In order to study the modern pollen deposition pattern, six surface sediment samples were collected in transect at 50 m interval from the study site.

### 3.3 Chronology

The lower most organic rich clay (at depth of 95 cm) and the *Turritella* (at the depth of 50 cm) of the relict mudflat have yielded a conventional $^{14}C$ age of 4680 ± 60 yr BP (4710 ± 109 cal yr BP) and 3190 ± 96 yr BP (2990 ± 125 cal yr BP) respectively. The AMS date for the organic carbon fraction (at the depth of 25 cm) is 2652 ± 48 yr BP (2165 ± 102 cal yr BP) (Fig. 3–2). The age-depth model reconstructed based on calibrated ages (Fig. 3–3) suggests that the Unit–I and II were deposited during 4710 to 2825 cal yr BP and 2825 to 1835 cal yr BP respectively. The Unit–III was deposited after 1835 cal yr BP and the extrapolated age to the surface indicate that deposition ceased after ~1500 cal yr BP (Fig. 3–3).

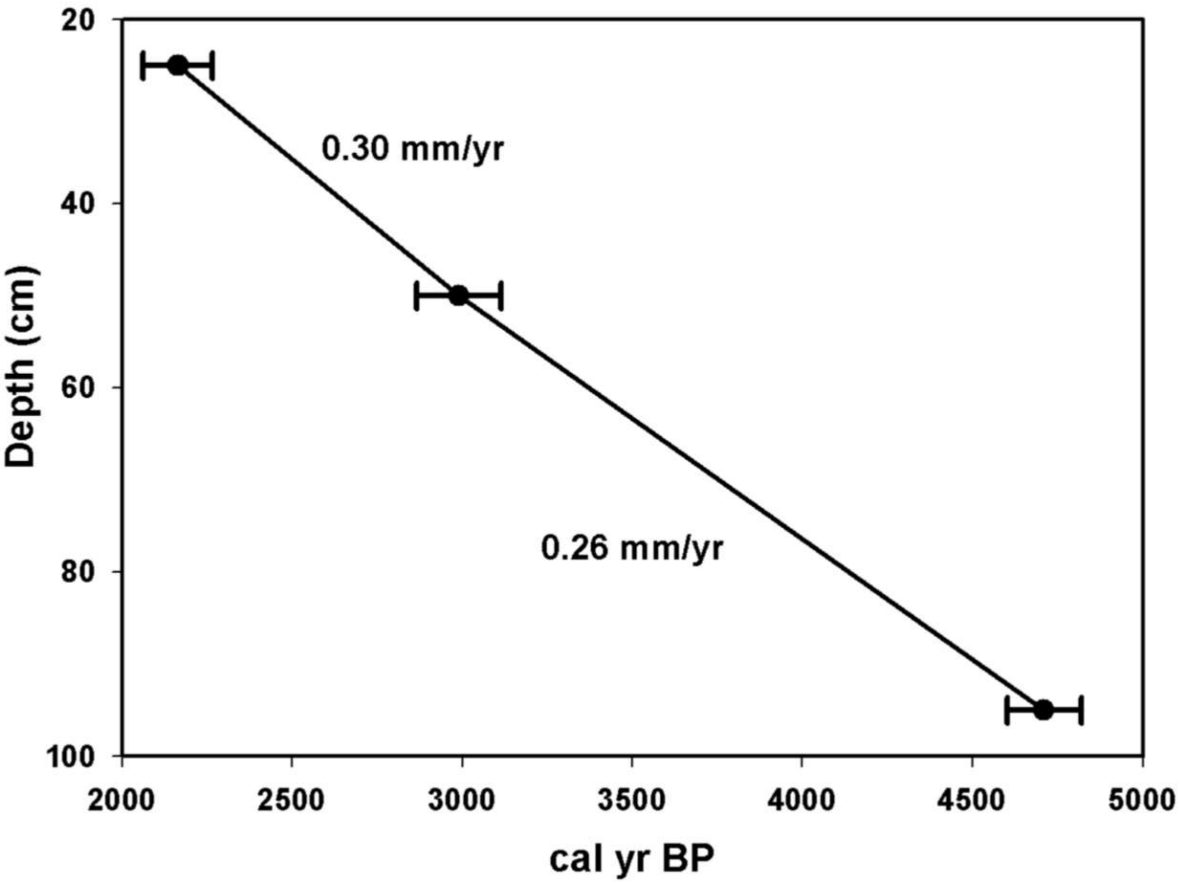



*Figure 3-3. Age-Depth Model of the relict mudflat section. A sedimentation rate of 0.26 mm/yr persisted during 4710 to 2990 cal yr BP and after 2990 cal yr BP the sedimentation rate increased to 0.3 mm/yr*

### 3.4 Results

#### *3.4.1 Geochemical Analysis*

Generally, $Al_2O_3$, $TiO_2$ and FeO are considered to be of detrital tagged components, however, the FeO concentration may get effected under reducing conditions. The evaporation/ precipitation during past can be inferred with the help of Ca/Σ [Al,Fe,Ti] wherein the higher ratios reflects the dry climate and the lower ratios reflect humid climatic conditions (Mueller et al., 2009).

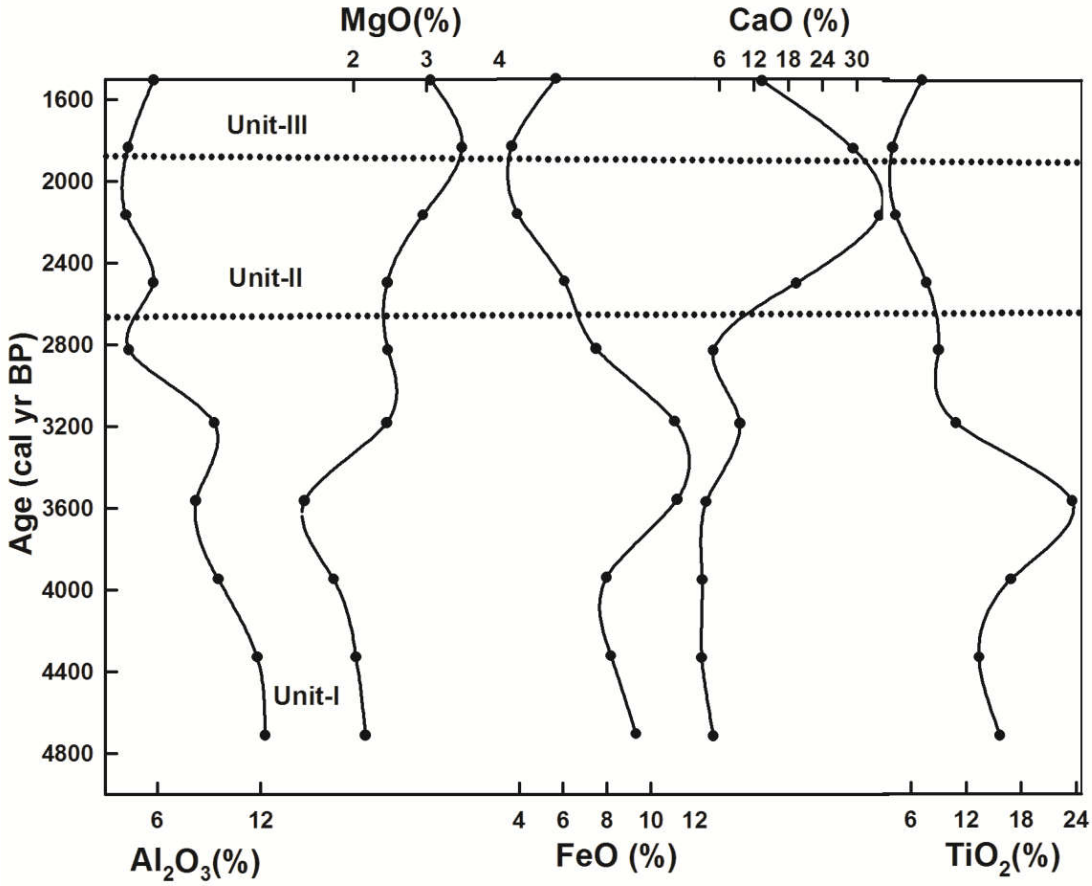



*Figure 3-4. Major element variation during last 4710 cal yr BP for the relict mudflat section VV from the Vasoj Village.*

(a) Unit-I (100–40 cm; 4710 to 2825 cal yr BP)

The TOC, TOC/TN ratio and $CaCO_3$ content of Unit-I range from ~0.6–1.8 %, 14–21.7 and 1.5–25.2 % respectively (Fig. 3–6). The $Al_2O_3$, FeO, MgO, CaO and $TiO_2$ concentrations vary from 4.3–12.3 %, 7.5–11.1 %, 1.33–2.47 %, 2.9–9.6 % and 15.7–23.6 % respectively (Fig. 3–4). An overall decrease in organic carbon and TOC/TN ratio is observed between 4710 and 2825 cal yr BP (Fig. 3–6). The $Al_2O_3$ and FeO shows a decreasing trend which increases marginally at the top of the Unit-I whereas the $CaO/Al_2O_3$ and $MgO/Al_2O_3$ show a near constant value (Fig. 3–5).

Compared to this, the calcium carbonate shows an increasing trend in the upper part of this unit (Fig. 3–6).

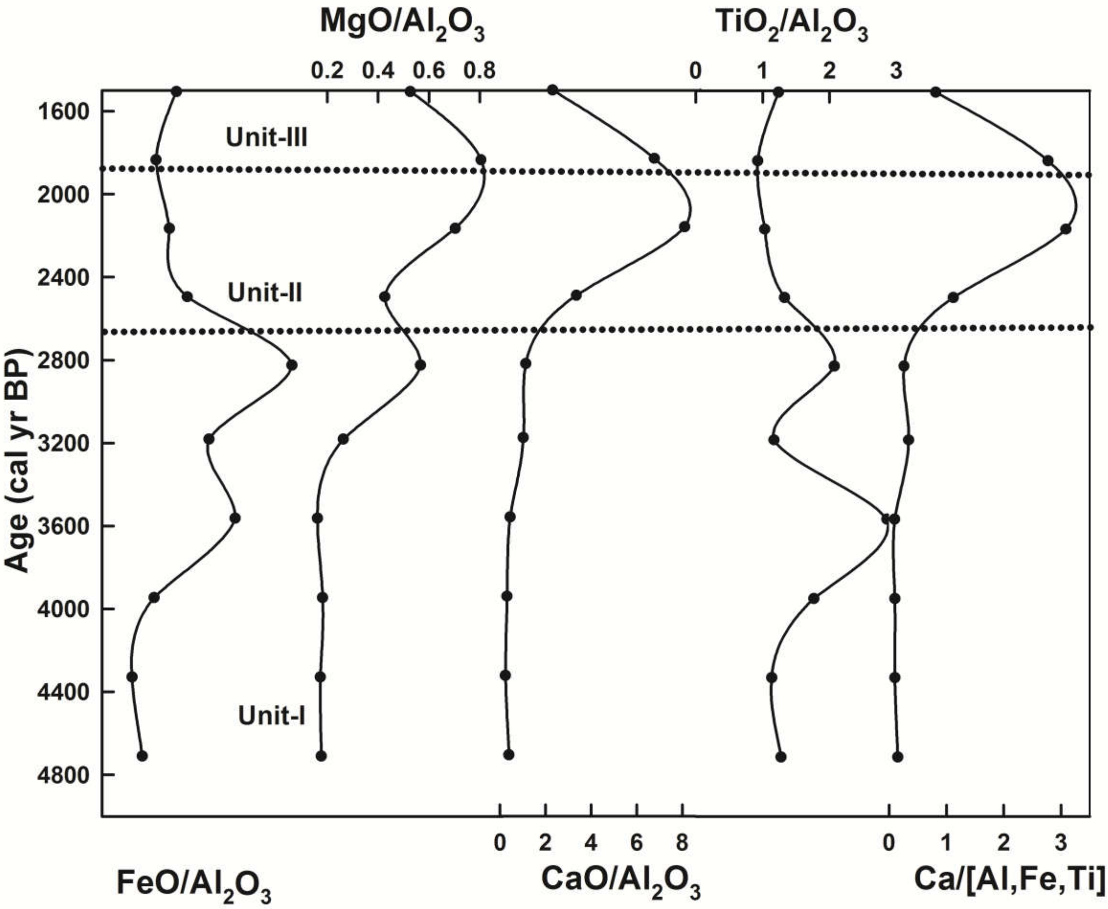



*Figure 3-5. $Al_2O_3$ Normalised major elements and Ca/∑ [Al,Fe,Ti] variation indicating persistence of arid climate after 2825 cal yr BP which continued till 1835 cal yr BP. After 1835 cal yr BP, a decline in the arid conditions is observed in the relict mudflat section VV from the Vasoj Village.*

(b) Unit-II (40−20 cm; 2825 to 1835 cal yr BP)

Unit-II comprises calcareous marl. The TOC content is ~0.6 % with TOC/TN ratio and $CaCO_3$ ranging from 11−16 and 34−50 % respectively (Fig. 3–6). The $Al_2O_3$, FeO, MgO, CaO and $TiO_2$ content vary from 4.1−6 %, 4−6 %, 2.4−3 %, 19.4−34 % and 7.7–4.3 % respectively (Fig. 3–4).

Unit-II shows a decrease in the $Al_2O_3$, FeO and TOC/TN, whereas CaO and MgO show an increasing trend. The increased CaO and MgO are due to the presence of calcareous marl which overlies the *Turritella* shell horizon. Further the $CaO/Al_2O_3$ and Ca/∑ [Al,Fe,Ti] ratios of Unit-II also show an increasing trend (Fig. 3–5).

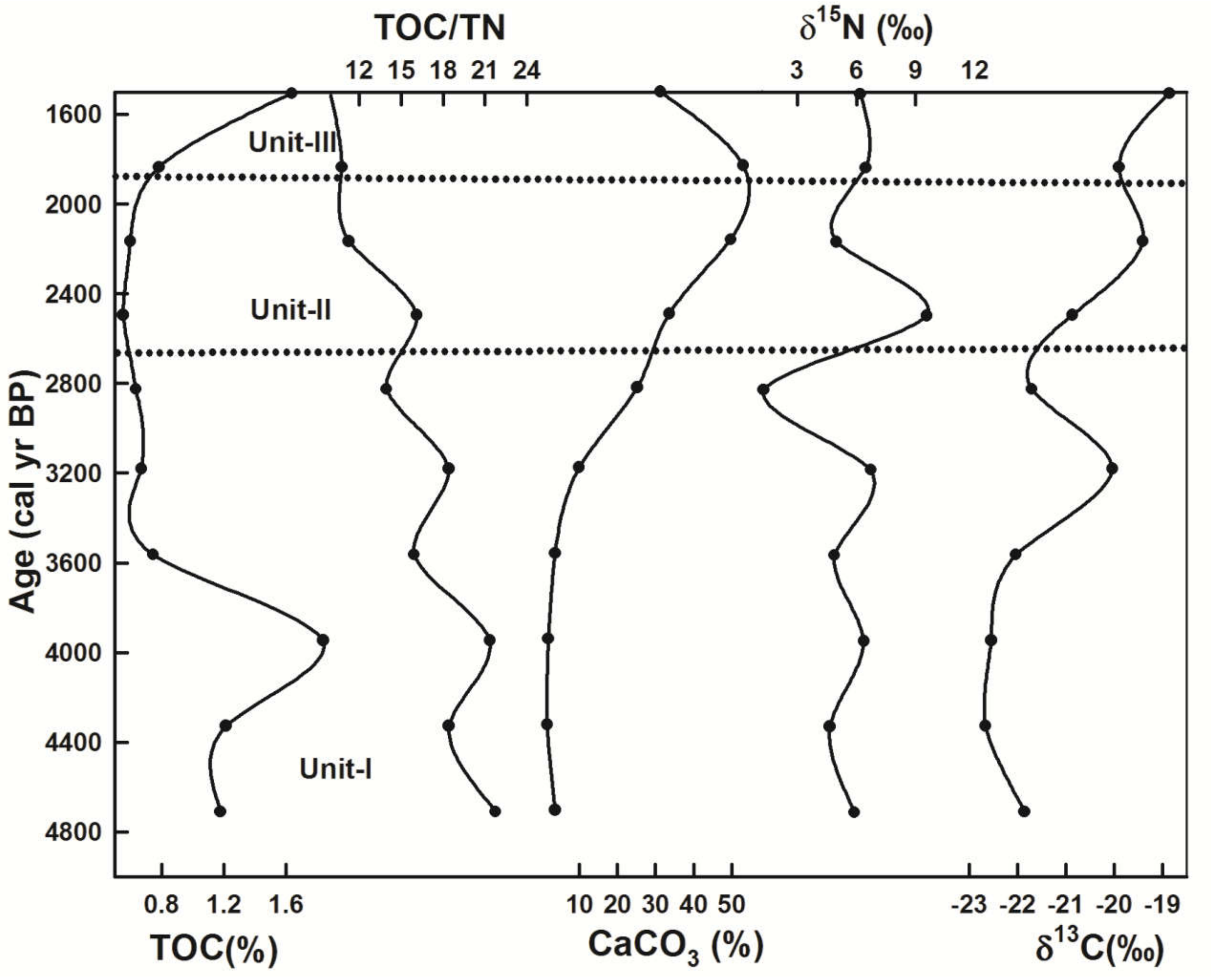



*Figure 3-6. TOC, TOC/TN, $CaCO_3$ and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) variation seen in the relict mudflat section (VV) of Vasoj Village.*

(c) Unit-III (20–0 cm; 1835 to 1500 cal yr BP)

The Unit-III shows an increase in organic carbon (0.8–1.6 %), $Al_2O_3$ (4.3–5.8 %), FeO (3.7–5.7 %) and $TiO_2$ (4.0–7.1 %). The major elements are anticorrelated with the CaO, MgO, $CaO/Al_2O_3$, $MgO/Al_2O$ and Ca/∑ [Al,Fe,Ti] (Figs. 3−4 and 3−5). There is also an appreciable decrease in mangrove pollen (Fig. 3−7).

### *3.4.2 Palynological Analysis*

Mangrove vegetation is considered to be one of the crucial coastal ecosystem associated with the intertidal habitat in the tropical and subtropical regions. The development of mangrove is generally related to the sea level changes and the fresh water flux caused by the monsoon systems (Limaye and Kumaran, 2012).

#### **I. Active mudflat Pollen Distribution**

The study of modern pollen deposition is prerequisite prior to the investigation of sub-surface pollen. This provides the modern analogue for the appropriate assessment of the changing vegetation scenarios and contemporaneous climatic changes during the past. To achieve this comparative database, six surface sediment samples were analysed from the vicinity of the study site which provide data regarding the representation of modern pollen in relation to the extant vegetation (Fig. 3−7). The pollen assemblages of these samples show that the pollen recovered from surface sediments are compatible with the actual floristic pattern of the area. The pollen spectra reflect the dominance of *Avicennia marina* (8.4−22.9 %), whereas, other mangrove associates such as *Salvadora* sp. (4.3−15.3 %), *Pongamia pinnata* and *Terminalia* sp. (5.3−9.1 %) are also recorded in moderate frequencies. Amongst the midland taxa, *Acacia* sp., *Prosopis* sp. and *Holoptelea integrifolia* are recorded constantly in moderate values, whereas, other tree taxa viz. Anacardiaceae, *Casuarina equisetifolia, Caesalpinia* sp. and *Lannea* sp. are recorded sporadically. Amongst ubiquitous taxa, Chenopodiaceae (16.8–21.7 %) are the most representative followed by Poaceae, Caryophyllaceae, and Cyperaceae. Pollen grains of *Artemisia* sp., Asteraceae and Malvaceae along with fresh water taxa viz. *Potamogeton* sp. and *Typha aungustifolia* are scantily represented. Similarly, the surface sediment sample collected from the active mudflat (Fig. 3–1, Site DM) was analysed in order to ascertain the major element concentration in modern day tidal mudflat.

### II. Relict Mudflat Pollen distribution

(a) Unit-I (100–40 cm; 4710 to 2825 cal yr BP)

The pollen analysis shows that Unit-I is characterized by the predominance of mangrove pollen taxa (48.2 %). *Rhizophora* sp. pollen (6.1–22 %) is the dominant taxa followed by *Sonneratia* sp. (8.1–13.5 %) and *Bruguiera* sp. (4.5–16.8 %) (Fig. 3–9). Other mangrove pollen taxa are recorded in relatively low values and range between 1.6–9.6 %. Midland taxa are also recovered with the most abundant pollen among them are Malvaceae (3.2–11.2 %), *Azadirachta indica* (1.3–9.6 %) and Asteraceae (4.6 %). Pollen of *Acacia* sp., Myrtaceae, *Holoptelea* sp. and *Prosopis juliflora* show moderately low percentages. The ubiquitous taxa are strongly represented by Poaceae (7.2–18 %) followed by Cyperaceae (7.2–14.7 %) and Chenopodiaceae (6–14.6 %), whereas, Caryophyllaceae show relatively low values. Pollen taxa of aquatic groups such as *Typha* sp. (2–7.2 %) and *Potamogeton* sp. (3.6–7.4 %) are recorded. Fungal and pteridophytic spores (monolete and trilete) are found in moderate frequencies throughout this zone. Increased values of marine elements such as dinoflagellate cysts and foraminiferal linings are also noticed.

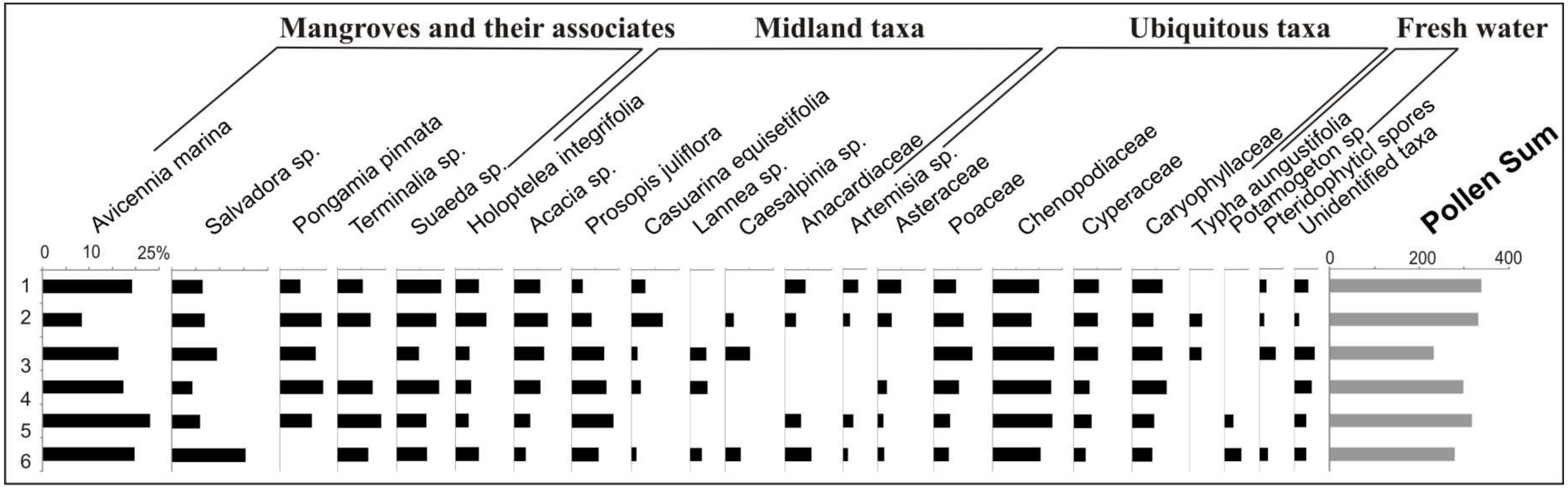



*Figure 3-7. Pollen spectra obtained from surface samples showing modern pollen distribution.*

(b) Unit-II (40–20 cm; 2825 to 1835 cal yr BP)

Palynological data is represented by slight decrease in pollen frequencies of mangroves such as *Rhizophora* sp., *Bruguiera* sp., *Sonneratia* sp., *Aegiceras corniculatum* and *Acanthus ilicifolius.* However, pollen grains of *Avicennia marina* (9.7–18.2 %) and *Suaeda* sp. (7.9–12.7 %) show higher percentages as compared with preceding zone (Unit-I). There is an appreciable presence of midland taxa such as Malvaceae (8.4–11.5 %), Asteraceae (11.8 %), *Prosopis juliflora* (5–8.4 %), *Azadirachta indica* (5–7.9 %) and *Holoptelea* sp. (4.2 %) occur. Other pollens of this group is represented by their low concentrations. Ubiquitous taxa like Chenopodiaceae (15.7–18.6 %) followed by Poaceae (6.4–8.8 %) are also recorded. However, the pollen of Caryophyllaceae and Cyperaceae are present in low frequencies.

(c) Unit-III (20–0 cm; 1835 to 1500 cal yr BP)

An appreciable decrease in the mangrove pollens has been opbserved. Amongst mangroves, salt tolerant species such as *Avicennia marina* (25.6 %) and *Suaeda* sp. (14.8 %) are dominant throughout the zone. A similar decreasing trend is observed in midland taxa excepting *Acacia* sp. (10.5 %) and *Prosopis juliflora* (10.1 %), which show higher concentrations than in Unit-II (Fig. 3–9). Amongst the ubiquitous taxa, Chenopodiaceae (15.5 %) is recorded in high values whereas pollen grains of Poaceae, Cyperaceae and Asteraceae are represented by low values.

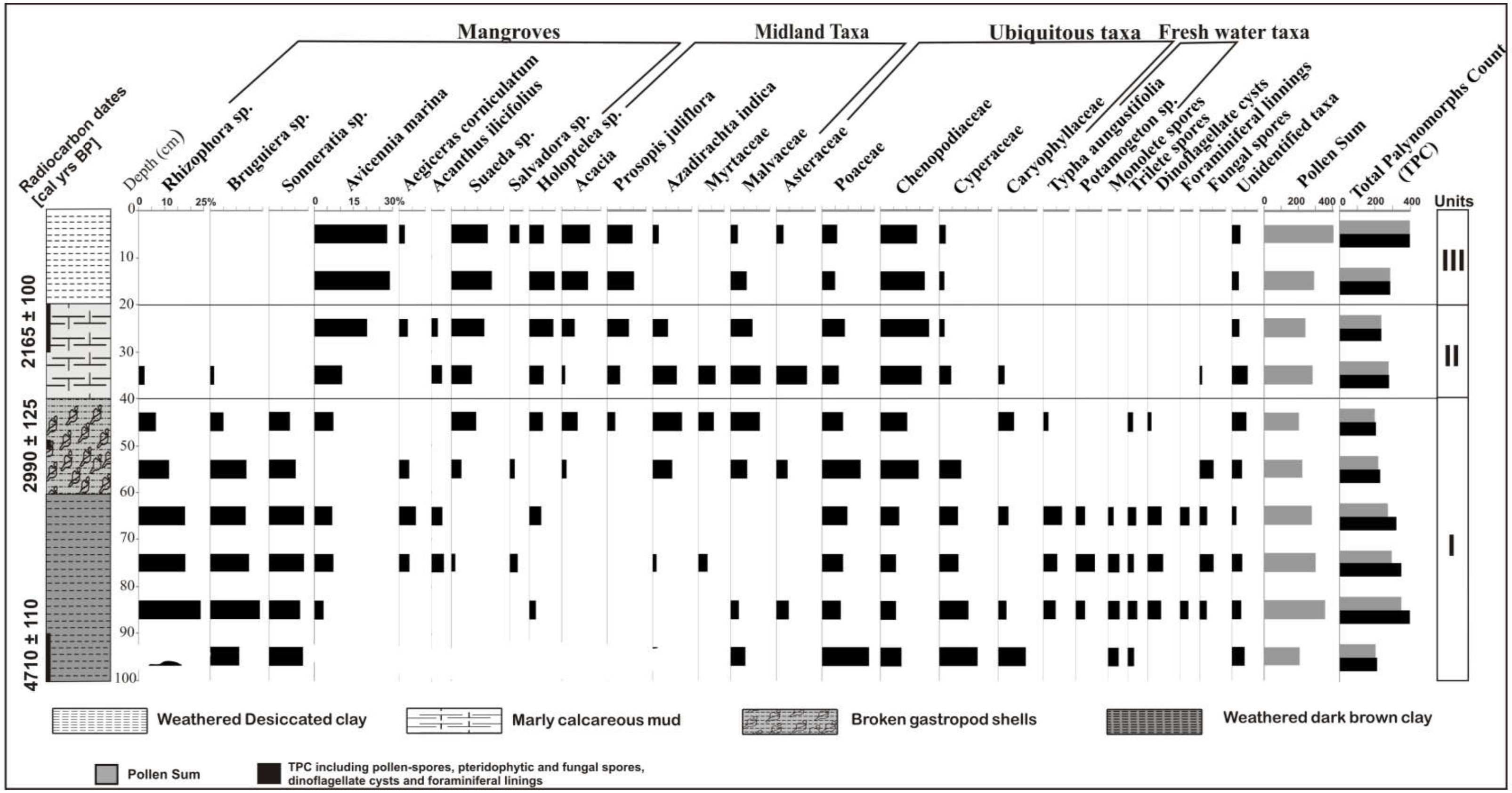



*Figure 3-8. Pollen diagram of the lithosection from southern coast of Saurashtra.*

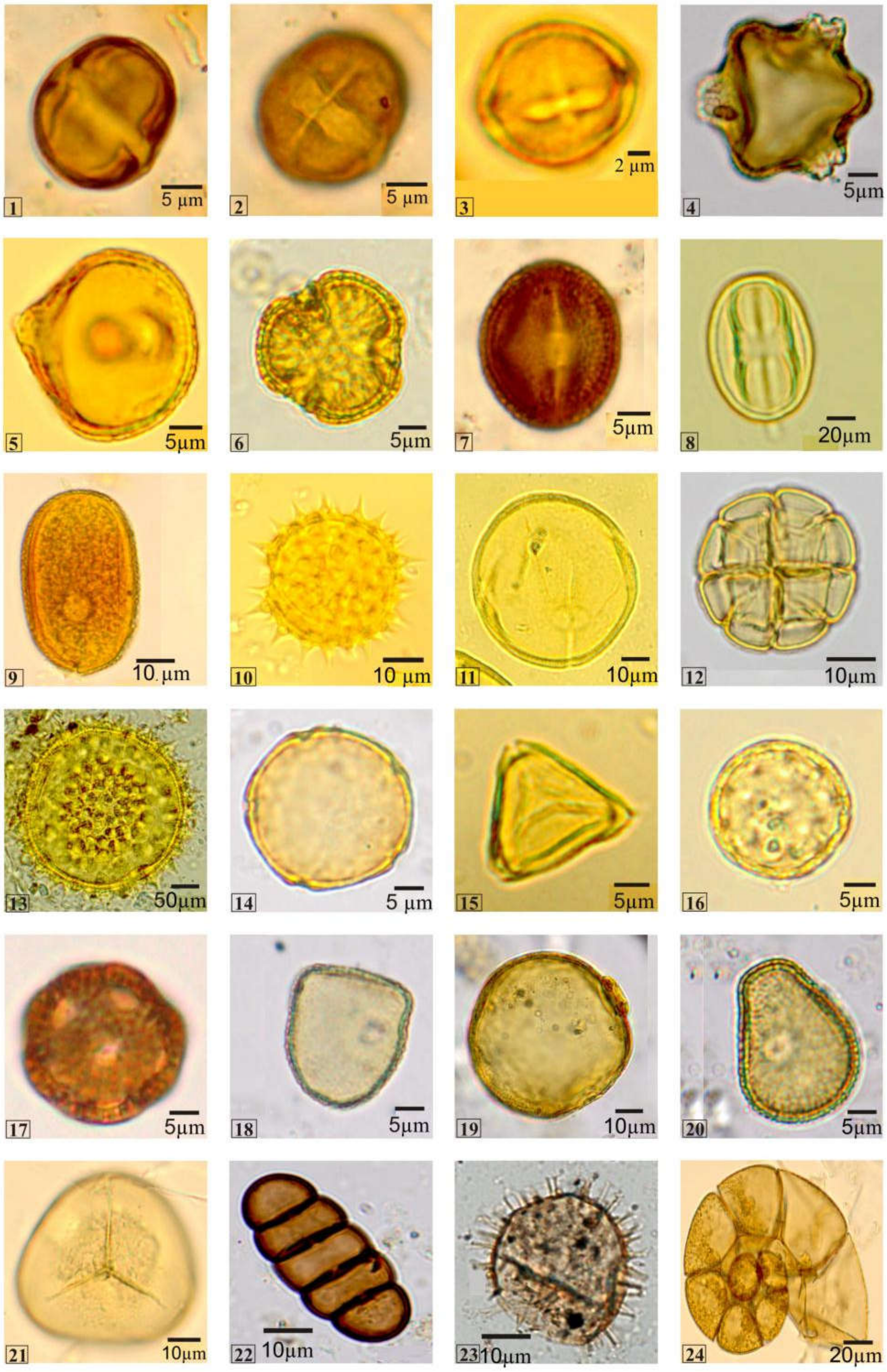



*Figure 3-9. Palynoassemblage recovered from the Vasoj core, southern coast of Saurashtra. 1-2, Rhizophora sp.; 3, Bruguiera sp.; 4-5, Sonneratia sp.; 6-7, Avicennia marina; 8, Aegiceras corniculatum; 9, Acanthus ilicifolius; 10, Asteraceae; 11, Azadirachta indica; Azadirachta indica; 12, Acacia sp.; 13, Malvaceae; 14, Holoptelea; 15, Myrtaceae; 16, Chenopodiaceae; 17, Caryophyllaceae; 18, Cyperaceae; 19, Poaceae; 20, Typha angustifolia; 21, Trilete spore; 22, Fungal spore; 23, Dinoflagellate cysts; 24, Foraminiferal lining.*

### 3.5 Discussion

Based on the multiproxy data (geochemical and pollen) supported by radiocarbon ages, three major phases of climate variability and associated sea-level changes have been discerned during the last 4710 cal yr BP (discussed below).

(a) Phase-I (100−40 cm; 4710 to 2825 cal yr BP)

The relatively high TOC/TN and TOC (with gradual decreasing trend towards the upper part of Unit-I) imply high biomass productivity. This is further indicated by the dominance of mangrove pollen taxa, which implies that the site was under the tidal influence. Beginning of the phase-I is marked by higher concentration of $Al_2O_3$, FeO, TOC and high TOC/TN ratio. This is followed by a gradual decrease (with temporary increase) before the onset of phase-II sedimentation (Fig. 3–4 and 3–6).

Since there is no major stream draining into the tidal flat, we can discount any terrestrial contribution of clay into the tidal flat sedimentation. In view of this, changes in the concentration of detrital proxies e.g. $Al_2O_3$ and FeO can be ascribed to the deposition of clay as suspended fall out transported to the site by the tidal current. This is evidenced by the comparable values of $Al_2O_3$ (12.3 %) with that of the active tidal flat clay sample (11.16 %) collected southwest of the study area which accords well with the estimate obtained on the near coastal sediments in the Arabain Sea (Luckge et al., 2001). The comparatively low FeO concentration at the bottom of this unit is ascribed to the prevalent reducing environment with consequent increase in the TOC caused due to the proliferation of mangrove forests (Fig. 3–9).

The $CaCO_3$ content with near constant values show a distinct increase at the boundary between the Unit-I and II. This increase is attributed to the presence of *Turritella* shells in the upper part of Unit-I and the marl (see below) in Unit-II (Fig. 3–2). Similarly, the nearly constant values of Ca/∑ [Al,Fe,Ti] in the Unit-I suggests overall improved moisture condition. This is further supported by the pollen data with high percentages of *Rhizophora* sp. (wind pollinated and high pollen producing species), *Bruguiera* sp., *Sonneratia* sp. and other recovered taxa of the mangrove community suggesting prevalence of an intertidal environment with mangrove forests.

The rich and diverse mangroves with noticeable percentages of midland and fresh water taxa indicate warm and humid climate. Occurrence of dinoflagellate cysts and foraminiferal linings along with the fresh water forms portray an estuarine condition, tidal influx and freshwater run-off from hinterland as have been observed in the Chilka Lagoon located in the east coast of India (Pandey et al., 2014). Contrary to the geochemical proxies, the pollen data suggest that there was reasonable freshwater surface runoff contribution from the continental margin to the mudflat during the deposition of Unit-I (4710 to 2825 cal yr BP). Combining the geochemical and pollen data, it may be suggested that the deposition of Unit-I sediments began during the enhanced moisture conditions (monsoon). However, a progressive decline in monsoon can be suggested towards the termination of Unit-I with an exception of a minor increase (reversal in declining trend) between 3560−3180 cal yr BP.

A recent pollen based study from mainland Gujarat although suggested the onset of dry climate during 5565–4255 cal yr BP, however, there was enough moisture to sustain the lake hydrology (Prasad et al., 2014). Likewise, the climatic reconstruction based on lake sediments from Nal Sarovar, central Gujarat (Prasad et al., 1997) and Lunkaransar and Didwana Lakes of Rajasthan, Western India (Wasson et al., 1984; Enzel et al., 1999) witnessed a declining trend after 6 ka and before 4.2 ka (Enzel et al., 1999). It has been observed that during 4.6 ka and 1.7 ka, Mahi river basin experienced high magnitude floods which is ascribed to the periods of strengthened monsoon condition (Sridhar, 2007). A minor reversal in declining trend between 3560–3180 cal yr BP implies temporary improvement in the moisture condition. Evidences similar to this were also observed in the mainland Gujarat e.g. at Itola (Singh et al., 2007), Kothiyakad (Prasad et al., 2007) and Wadhawana (Prasad et al., 2014). Outside the mainland Gujarat, in Pokharan (Rajasthan), stable fresh water regime was observed during the above period (Roy et al., 2009).

The study site is located at an elevation of 5 m whereas the tidal water inundates areas that lie ~3 m above the present day sea level (Fig. 3–1) (http://www.altitude.nu/). This implies that compared to present, the tidal ingression was ~2 m higher during 4710 to 2825 cal yr BP (Phase-I). However, considering the tectonic instability of the Saurashtra coast in general and Diu coast in particular (Pant and Juyal, 1993), the above estimate appears to be on the higher side (discussed later). Nevertheless, existence of higher sea-level during mid-Holocene has been invoked from various sites along the Gujarat coast (Gupta, 1972; Gupta and Amin, 1974; Juyal, et al., 1995) and western India (Nambiar et al., 1991; Nigam et al., 1993; Vora et al., 1996) which accords well with the present study.

(b) Phase-II (40−20 cm; 2825-1835 cal yr BP)

During phase-II, marginally high sedimentation rate of ~0.3 mm/yr is observed which is attributed to the contribution of the suspended sediment from the open sea through tidal current as also reworking of the older mudflats corresponding to phase-I. The decrease in the continental flux (as indicated by the geochemical proxies) and the occurrence of intertidal *Turritella* shell rich horizon (Desai and Patel, 2008), suggest slight reduction in water depth caused due to marginal sea-level regression which probably stabilized (temporarily) around Vasoj village.

The above inference is supported by the presence of calcerous marl and increased Ca/∑[Al,Fe,Ti] (Mueller et al., 2009) indicating high evaporation (weak monsoon) and pervalence of arid condition. The lowered sea-level during this period is also supported by the palynological data which indicate general reduction in the mangrove pollen content, especially *Rhizophora* sp. and *Bruguiera* sp., constituting the most important components of mangrove community. Thus, retreat of mangrove forests suggests a slightly comparatively lower sea-level during this period. Increased aridity is supported by enhanced pollen of *Avicennia marina* and *Suaeda* sp. (high salt tolerant species), which depict vegetation change probably due to the reduction in tidal magnitude along with occasional fresh water influx, thereby resulting in an unfavourable environment for the growth of mangroves. This inference is supported by a rapid increase in pollen of midland taxa and also reduced values of aquatic forms. This is in accordance with the observations made by workers from the continental record (Prasad et al., 1997; Enzel et al., 1999; Laskar et al., 2013), and the marine records (Tiwari et al., 2006; Chauhan et al., 2010) from western India.

(c) Phase-III (20−0 cm; 1838−1500 cal yr BP)

During this phase, an increasing trend in detrital proxies is observed which suggests slight reduction in arid condition. Considering that the uppermost Unit-III is desiccated, it implies that the surface remained free from tidal ingression after 1500 cal yr BP. This is also indicated by the expansion of salt tolerant mangrove species like *Avicennia marina* and *Suaeda* sp suggesting that site was well above the tidal ingression. Evidence of reduced aridity punctuated with short monsoonal spells during this period have been inferred from the Nal Sarovar lake sediment (Central Gujarat) by Prasad (1997).

## 3.1 Stable isotope variations and their implication

### *3.1.1 Nitrogen isotopes*

In the marine environment the biologically mediated reduction reaction for the conversion of nitrogen from nitrate takes place with various intermediate products such as nitrate to nitrite to nitrous oxide to nitrogen and then the ammonia (Sachs, 2007). The $\delta^{15}N$ in the marine organic matter usually ranges between 3 to 12 ‰ (mean: 5 to 7‰) as derived from phytoplankton which normally use dissolved nitrate (Brandes and Devol, 2002; Lamb et al., 2006)

While in case of terrestrial plants, the $\delta^{15}N$ value for the organic matter derived from nitrogen fixing land plants has around zero value, while in case of those plants that utilises only mineral N from soil $NO^{-}_{3}$ or $NH^{+}_{4}$ usually have positive $\delta^{15}N$ values. In general, the $\delta^{15}N$ values for the river suspension is usually lower than oceanic values (Maksymowska et al., 2000; Gaye-Haake et al., 2005). Low values of $\delta^{15}N$ in the rivers probably due to the contributions from forest and soil nitrogen as the terrestrial plant have low $\delta^{15}N$ (Gao et al., 2012).

### *3.1.2 Carbon Isotopes*

The carbon isotopic variation for the organic matter occurs as a consequence of photosynthesis (Wickman, 1952). Based on the photosynthesis pathways the terrestrial plants are divided in to three major groups viz. C3, C4 and Crassulacean acid metabolism (CAM) (Khan et al., 2015). The intrinsic isotopic variation for each plant types depends on the way in which the plant fixes carbon. The $\delta^{13}C$ values for the C3 plants ranges from –32 ‰ to –21 ‰ (Deines, 1980) while for C4 plants ranges from –17 ‰ to –9 ‰ (Chmura and Aharon, 1995). The $\delta^{13}C$ for the CAM plant covers the range between –28 ‰ to –10 ‰ (Deines, 1980).

In case of aquatic organisms (phytoplankton, algae, seagrasses) some of them uses C3 pathway but the $\delta^{13}C$ values differs from that of terrestrial C3 plants (Khan et al., 2015). Such difference results due to the slower $CO_2$ diffusion in water and ambient $CO_2$ availability (Fogel et al., 1992). The preferential uptake of dissolved $CO_2$ by the aquatic organisms takes place until the source is exhausted, and the low availability of $CO_2$ (–8 ‰) in the oceans will result in the uptake of $HCO_3^-$ (~0 ‰). Hence the $\delta^{13}C$ values for the phytoplankton ranges between –30 ‰ to –18 ‰ (Degens et al., 1968). Due to the high dissolved $CO_2$ concentration compared to $HCO_3^-$ in the river water, variations in the $\delta^{13}C$ for the marine (–24‰ to –18‰) and freshwater (–30 ‰ to –25 ‰) phytoplanktons are observed. Similarly the $\delta^{13}C$ values for the algae (freshwater: –30‰ to –26‰; marine: –23‰ to –16‰) (Khan et al., 2015) and seagrasses (–21‰ to –6‰) (Hemminga and Mateo, 1996) also reflect its use of $CO_2$ relative to $HCO_3^-$.

### *3.1.3 Nitrogen and Carbon isotopic variation in the relict mudflat (VV)*

The $\delta^{15}N$ and $\delta^{13}C$ for the relict mudflat Vasoj (VV) vary from 5.89 to 9.56 ‰ and -22.54 to -19.89 ‰ respectively (Fig. 3–6). $\delta^{15}N$ followed a similar trend like $\delta^{13}C$, wherein the values mainly varied between 4 to 8 ‰ with no significant fluctuation except for a sudden depleted value (1.3 ‰) observed between 3180–2495 cal yr BP. The average values of $\delta^{15}N$ and $\delta^{13}C$ for the mudflat sediment are 6.85±0.61‰ and -23.87 ± 0.58‰ respectively (Yang et al., 2013). Similar values for nitrogen and carbon isotopes are observed for the relict mudflat section which is further supported by the presence of mangrove pollen found during the palynological study of the litho section (Banerji et al., 2015).

### 3.2 Geochemical and palynological response towards land sea interaction

The relict mudflat deposits, overlying the miliolites of Southern Saurashtra coast provide evidences of Holocene climatic and sea-level changes. Various stages of climate and sea-level changes are depicted in Figure 3–8.

*Phase-I:* During 4710–2825 cal yr BP interval, the region witnessed rich and diverse mangrove forest with less salt tolerant species as evidenced by the palynological data. A noticeable percentage of freshwater taxa along with enhanced $Al_2O_3$ indicate persistence terrestrial flux due to enhanced monsoon as the region is deprived of perennial river. The presence of marine elements implies marginally high sea level in the region. Overall, the area experienced an extended estuarine environment.

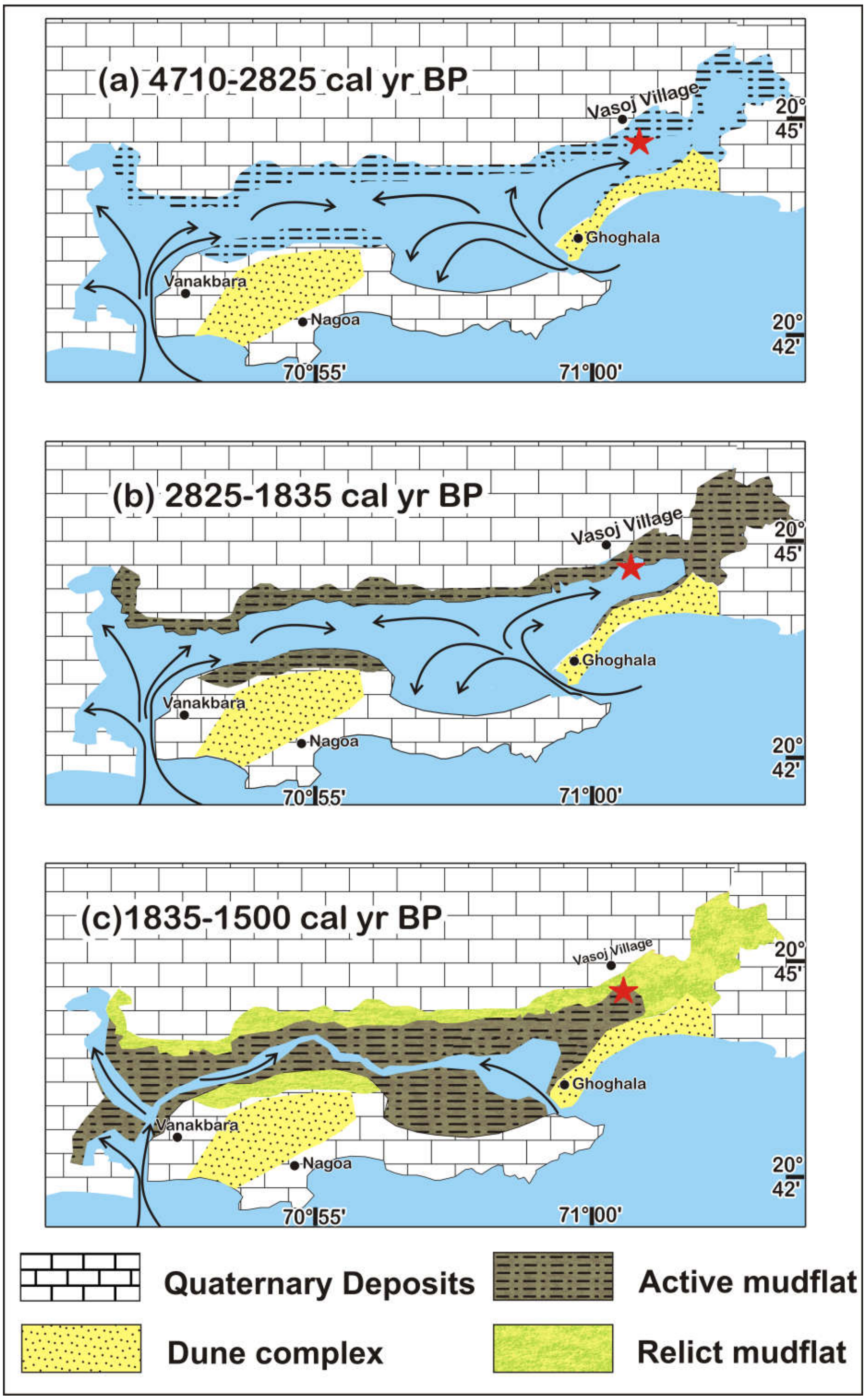



*Figure 3-10. Phases of decline in the tidal ingression since 4710 cal yr BP. The study area is marked as red star; (a) Phase-I: High sea-level (tidal ingression) during 4710−2825 cal yr BP associated with humid climate; (b) Phase II: tidal regression (marginal sea-level lowering) associated with aridity during 2825−1835 cal yr BP; (c) Phase-III: Regression in the sea and slight reduction in the aridity after 1835 cal yr BP. The present configuration of the mudflat was attained after ~1500 yr cal BP.*

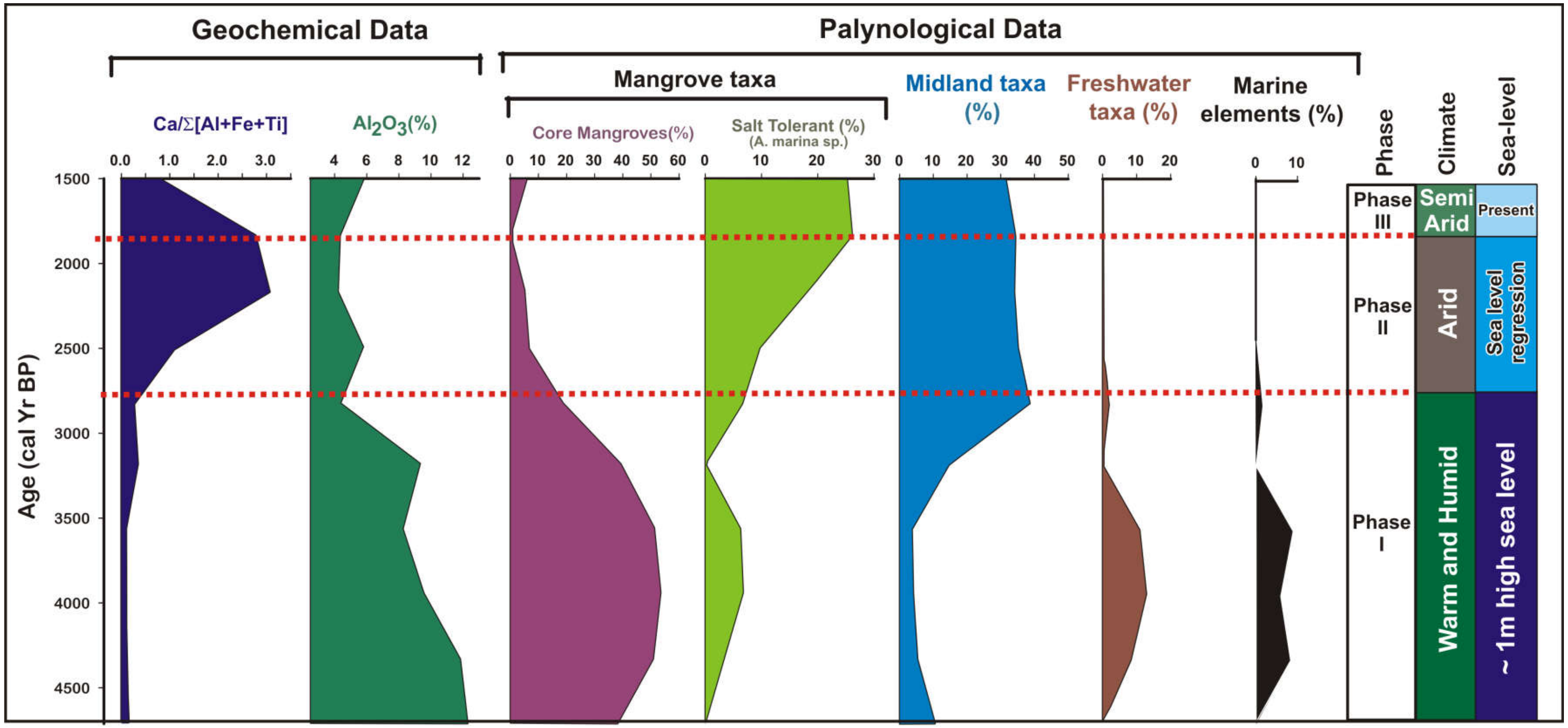



*Figure 3-11. A comparative diagram of geochemical proxies with that of the palynological data for the lithosection VV of Vasoj Village. Also shown, the inferred climate and sea-level during the mid-Holocene.*

*Phase-II:* During 2825−1835 cal yr BP decrease in the $Al_2O_3$ along with the fresh water taxa and core mangrove are indicated by the geochemical and pollen proxy respectively. Moreover, enhanced salt tolerant species with increased Ca/Σ[Al,Fe,Ti] indicated a drier climate (Mueller et al., 2009). The enhanced midland taxa and decreased marine elements imply a regressive phase in the sea (Pandey et al., 2014). Therefore the region experienced drier climate with a marginal regression in the sea level.

*Phase-III:* During 1835-1500 cal yr BP marginal increase in the $Al_2O_3$ with reduced Ca/Σ[Al,Fe,Ti] indicated the presence of humid climate in the region, whereas with the increased percentage of midland taxa along with high salt tolerant mangrove species, the area became free from tidal and the present coastal influence.

### 3.3 Mid-Holocene land level changes

Radiocarbon dating of the oyster bed in the Rupen River near Diu located at an elevation of 2 m above the present day sea-level (Fig. 3–12) indicated a high sea-level during 3.4 ± 0.05 ka (Juyal et al., 1995). The above observation accords well with the present study suggesting prevalence of marginally high sea-level during this period. However, considering that the Diu and adjoining areas experienced pulsating uplift during the late Quaternary period (Pant and Juyal, 1993), the sea-level changes during the mid-Holocene cannot be viewed as an artifact of the volumetric changes in the water mass only. Therefore, for realistic estimate of sea-level lowering, it is essential to ascertain the tectonically induced land-level changes (Lambeck et al., 2004; Ramirez-Herrera et al., 2007). This question may be addressed by examining the miliolite dominated raised notch morphology. A tidal notch has a recumbent v-shaped profile and its vertex represents the mean sea-level. Presence of tidal notch is a good indicator of coastal stability and any change in land or sea-level tend to modify the notch morphology (Pirazzoli, 1978) particularly the notch platform (intertidal platform).

There are two tidal notches preserved near Vankwara (Diu) (Fig. 3–12). The older notch-2 lies ~3 m above the present day sea-level and is assigned the mid-Holocene age (Pant and Juyal, 1993; Juyal, et al., 1995), whereas the younger (modern) notch-1 is carved just below the notch-2 platform (Fig. 3–12). According to Pant and Juyal (1993), if there would have been a gradual lowering of the sea following the development of notch-2, the notch platform would have been destroyed or pushed it back to the cliff face. The emergent scenario, therefore, is phase of landform stability prevailed during the formation of notch-2, when the sea-level was ~3 m high than the present day sea level. Following this, a phase of landform instability led to an up throw of ~1 m. This would imply that the effective sea-level high during the mid-Holocene was ~2 m. The well-developed modern notch-1 with extended intertidal platform and vertex suggests the landform stability.

### 3.4 Climate and land–sea interaction during last 4700 cal yr BP

The geochemical evidences and the palynological study from the relict mudflat around Diu (southern Saurashtra coast) suggest that during the past 4710 cal yr BP, climate fluctuated between warm and humid to drier conditions. During this period, sea-level fluctuated marginally and was responsible for the temporal changes in the mudflat sedimentation.

More specifically, beginning of mid-Holocene marked by relatively humid climate with marginally higher sea-level (Fig. 3–10a). Estimates based on the extent of the relict tidal flat sediments suggest that the tidal ingression was ~2 m higher than the present extent. The climate began to ameliorate which culminated into the onset of aridity after 2825 cal yr BP. This phase also witnessed slight lowering of the sea-level (Fig. 3–10b).

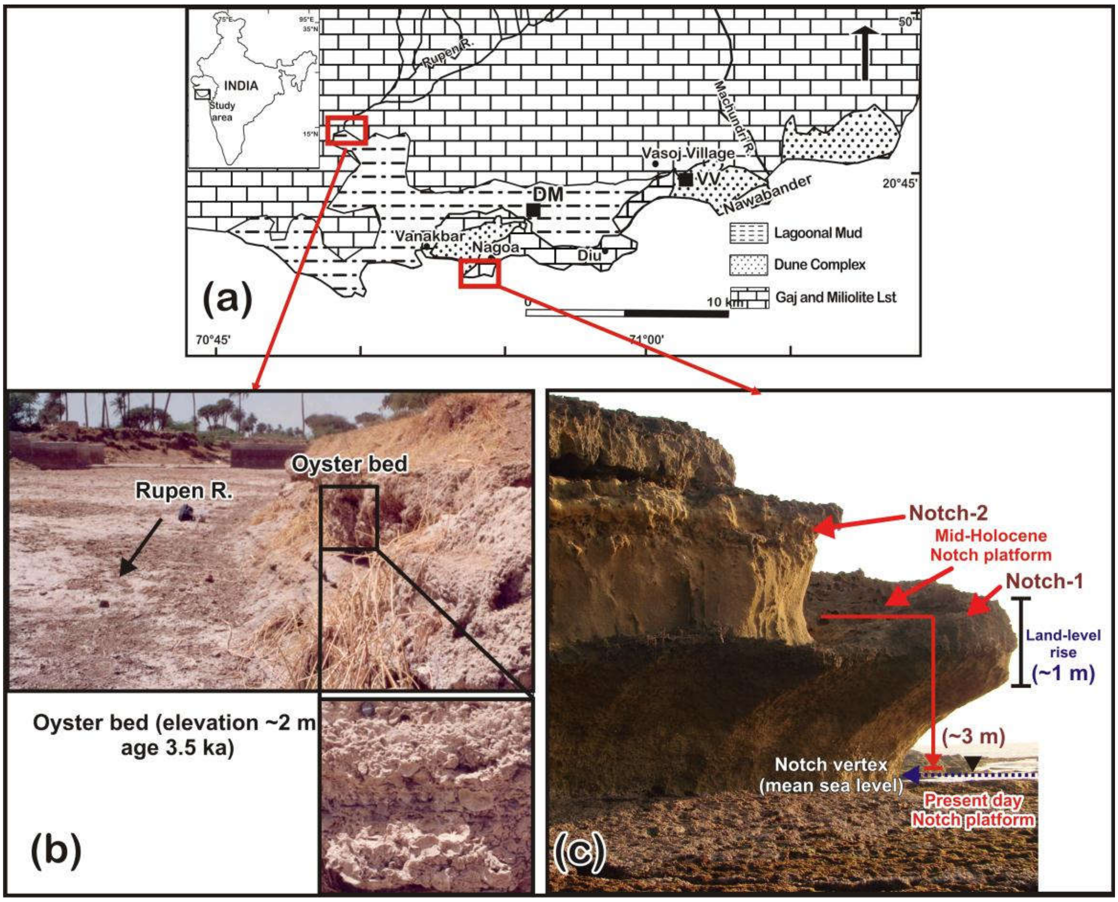



*Figure 3-12. (a) Geological map of southern Saurashtra showing sample locations; (b) exposed oyster bed near Rupen river with an elevation of 2 m amsl that yielded an age of 3.5 ± 0.05 ka (Juyal et al., 1995); (c) Tidal Notch-1 and 2 exposed near Nagoa; notch-2 has preserved a well-developed platform at 3 m. Thickness of the platform is ~1m implying a land-level rise which outpaced the sea-level low.*

However, there was marginal reduction in the aridity after 1835 cal yr BP and probably similar climatic conditions to present day were attained by the region along with significant reduction in the magnitude of tidal inundation. The studied location was fully exhumed from the frequent tidal ingression after 1500 cal yr BP (Fig. 3–10c).

### 3.5 Sedimentary records of paleoredox conditions at relict mudflat of Vasoj Village (VV)

The coastal lagoons being isolated from the sea get nutrient input from both land and sea, therefore, they are highly productive eutrophic zones along the coast (De Wit, 1999). In today's scenario, coastal lagoons experience oxygen deficient environment which is caused by natural as well as anthropogenic factors. In oxic environments, aerobic organism utilise ambient dissolved oxygen and interstitial waters for the organic matter degradation. With continued decomposition of organic matter resulting in oxygen depletion, the organism tends to utilise secondary oxidant sources such as nitrate, manganese oxide, iron oxides, oxyhydroxides and sulphates (Froelich et al., 1979). The continued depletion of oxygen results in anoxic conditions (No free $H_2S$) and under extreme oxygen depleted conditions causes euxinic conditions with free $H_2S$ in the water column. Thus, classification of the redox conditions in the sedimentary environment can be broadly divided in to four divisions as described in Table 3–1.

*Table 3-1. Classification of redox conditions in a depositional environment, after Tyson and Pearson (1991)*

| **Redox conditions** | **Oxic** | **Suboxic** | **Anoxic (No free $H_2S$)** | **Euxinic (With free $H_2S$)** |
|---|---|---|---|---|
| Oxygen concentration ($mlO_2/L\ H_2O$) | $[O_2]>2$ | $2.0>[O_2]>0.2$ | $[O_2]<0.2$ | $[O_2]=0$ |

The sea water comprises various trace elements either in soluble form or adsorbed onto particle whose removal from the water column to the sediment occurs via biotic or abiotic processes (Tribovillard et al., 2006). Biotic process include consumption of trace elements by the phytoplankton which acts as micronutrients. In oxic environment, abiotic processes are limited, however, under suboxic conditions enrichment of the elements can takes place via diffusion of dissolved trace elements from the water column across sediment–water interface or via remobilisation along the redox gradient with in the sediments (Tribovillard et al., 2006). Therefore, study of trace element distribution in sediment profile can help in deciphering the level of redox condition persisted during the deposition of the sediments.

Generally, coastal regions in tropics are inhabited by mangrove forest which accumulates large quantity of organic matter resulting into high in-situ productivity (Chmura et al., 2003), as monitored by the local hydrology, geography and topographic settings (Alongi, 2008; Perry et al., 2008). Mangrove ecosystem response towards local sea level changes and hence local sea level oscillations (Horton et al., 2007) influences the origin and amount of organic matter (Cahoon and Lynch, 1997) in the intertidal region. The mangrove ecosystem acts as a barrier against cyclones and coastal erosion and provides a nursery ground for commercially important coastal organism (crabs, prawn, fishes etc) (Selvam et al., 2003). In the western Indian coast, major wetlands are present in the Gujarat, wherein Gulf of Kachchh consists 77 % of Gujarat mangroves, while remaining are found along Gulf of Khambhat (Singh, 2003). Present day mangroves along the Saurashtra coast from Dwarka to Rajula are mainly confined to mudflats and creeks near Dwarka, Porbandar, Mahuva, Diu, Jafarabad, Bhutharai, Pipavav Bandar and Narera Bet. These mangrove forests are sparse, scrubby and consists of mainly *Avicennia* sp. (Kalubarme, 2014). However, based on palynological and geochemical evidences carried out along the southern Saurashtra coast, an extensive mangrove forest during mid-late Holocene period has been suggested with varied diversity in mangrove species which got depleted with the simultaneous sea regression (Banerji et al., 2015). The present study aims to investigate the paleo-redox conditions persisted along the southern Saurashtra coast that experienced rich and diverse mangrove forest during mid-late Holocene period (Banerji et al., 2015).

### *3.5.1 Control of redox conditions on trace elements*

#### I. Vanadium (V)

Vanadium in the oxic environment exists as vanadium (V) in vanadate ionic species ($HVO_4^{2-}$ and $H_2VO_4^-$) (Sadiq, 1988) which under mild oxygen deficient conditions leads to production of vanadyl ions ($VO^{2+}$) related hydroxyl species or an insoluble hydroxides with the conversion of V(V) to V(IV). In the presence of humic and fluvic acids, reduction of vanadate to vanadyl is being facilitated (Wilson and Weber, 1979). Under strong reducing conditions in the presence of free $H_2S$ gas, vanadium is further reduced to V(III) which precipitates as solid oxide ($V_2O_3$) or hydroxide ($V(OH)_3$) (Breit and Wanty, 1991).

#### II. Molybdenum (Mo)

Mo usually gets enriched in organic rich sediment and the transfer of molybdate ($MoO_4^{2-}$) to the sediment water interface is being promoted via adsorption on to the humic substance (Brumsack, 1989) or particulate Fe–Mn oxyhydroxides and hence it is associated with the redox cycling of Mn and Fe (Magyar et al., 1993). Under anoxic conditions, the decay of organic matter through sulphate reducing bacteria results in the release of molybdate and Mo (VI) is reduced to Mo (V) or Mo (IV) species (Calvert and Pedersen, 1993). Under euxinic conditions, rapid uptake of Mo by authigenic sulphides (produced from the free $H_2S$) can takes places (Morse and Luther, 1999).

**III. Manganese (Mn)**

Under oxic conditions, Mn forms highly insoluble Mn (III) or Mn (IV) hydroxides or oxides which deposits as particulate form (Calvert and Pedersen, 1993). In case of anoxic conditions, reduction Mn takes place and Mn (II) is formed which is a soluble cation ($Mn^{2+}$ or $MnCl^{+}$). As the dissolved Mn is not readily taken up by the organic matter or sulphide phase, it diffuses upwards till the oxic condition is attained. In the sediments, Mn depletion may occur under reducing conditions until the fixation of manganese in carbonate mineral doesn't takes place (Hild and Brumsack, 1998).

**IV. Zinc (Zn)**

In oxic environment, Zn is present as soluble $Zn^{+2}$ cations or $ZnCl^{+}$ but generally it forms complexes with humic and fluvic acids (Calvert and Pedersen, 1993). With the decay of organic matter, the Zn is released from organometallic complexes to pore waters (Tribovillard et al., 2006). Under reducing conditions especially in the bacterial sulphate reducing conditions Zn may be incorporated as ZnS or it may also form its own sulphides (Sphalerite) (Morse and Luther, 1999; Tribovillard et al., 2006).

**V. Nickel (Ni)**

With ambient oxygenated environment, Ni remains as soluble cation ($Ni^{2+}$) or $NiCl^{+}$ but mostly it remains as soluble nickel carbonate ($NiCO_3$) or adsorbed on to humic and fluvic acids (Calvert and Pedersen, 1993). With decay of organic matter, Ni is released back to pore-water from the organometallic complexes (Tribovillard et al., 2006). Under moderately reducing conditions in the absence of Mn oxides and sulphides, Ni gets recycled from sediments to overlying water (Tribovillard et al., 2006). But under euxinic condition in the presence of sulphides, Ni gets incorporated as insoluble NiS in to pyrite (Morse and Luther, 1999).

In order to access the correlation among the geochemical parameters, Pearson's correlation coefficient for the geochemical data were calculated which included comparison of trace elemental concentration (V, Mo, Ni, Zn and Mn), $Al_2O_3$ normalised trace elements, TOC, $CaCO_3$, $CaO/Al_2O_3$ (Table 3–2).

### 3.5.2 *Behaviour of redox sensitive elements in relict mudflat of Vasoj village (VV)*

The Vasoj section is divided into three units representing distinct climatic and sea level phases. The Unit–I (100–40 cm) of 60 cm thick is represented by high organic carbon rich sediment with *Turritella* shells at the top 20 cm. Unit–II (40–20 cm) represents marly calcareous mud following which Unit–III (20 cm– surface) represents desiccated clay. The lithology of the relict mudflat section is described in Banerji, et al. (2015).

In the relict mudflat V, Mo, Ni, Zn and Mn concentration ranges between 102–2565 ppm, 0.4–24 ppm, 36–55 ppm, 19–124 ppm and 239–980 ppm respectively. $V/Al_2O_3$ and $Mo/Al_2O_3$ showed a gradual decrease during 4710–1500 cal yr BP with an enhanced value between 3945–2824 cal yr BP. $Ni/Al_2O_3$ and $Mn/Al_2O_3$ showed an increasing pattern with low values between 4710–3200 cal yr BP and gradual increase after 3200 cal yr BP till 1500 cal yr BP. $Zn/Al_2O_3$ consistent but low values between 4710–4000 cal yr BP following which a marginal increase between 4000–3200 cal yr BP is observed. After 3200 cal yr BP the $Zn/Al_2O_3$ showes an increasing tread with fluctuating values till 1500 cal yr BP.

The redox sensitive elements such as vanadium and molybdenum are of minimal detrital influence (Tribovillard et al., 2006). Simultaneous enrichment of Mo and V with depletion of Mn between 4710–3200 cal yr BP (Fig.3–13) suggests changes in the redox conditions occurred during 4710–3200 cal yr in the relict mudflat. But during 3200–1500 cal yr BP, Mn showed enrichment while Mo and V showed depletion in the both concentration and $Al_2O_3$ normalised values (Fig.3–14). In anoxic conditions Mn forms soluble Mn (II) which diffuses upwards and precipitates as $MnCO_3$ or Mn-Ca Carbonate (Calvert and Pedersen, 1993). Therefore, $Mn/Al_2O_3$ showed a strong correlation with $CaCO_3$ (0.97) and $CaO/Al_2O_3$ (0.88) and a negative correlation with $V/Al_2O_3$ (-0.81) and $Mo/Al_2O_3$ (-0.82) (Table 3–2).

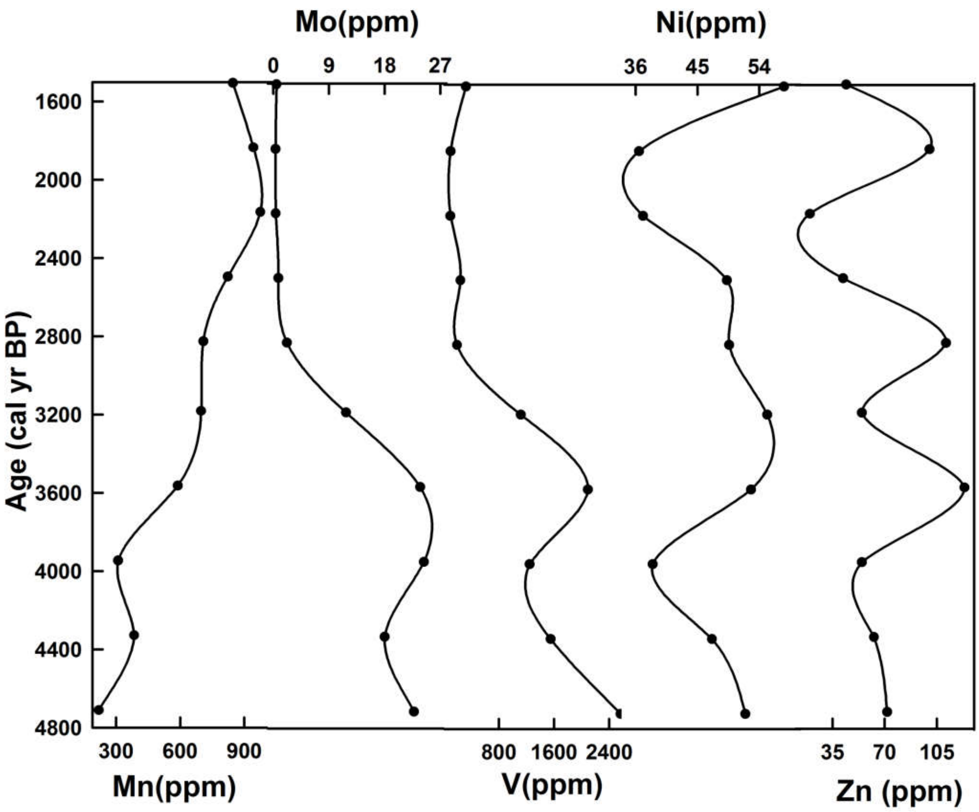



*Figure 3-13. Trace elemental variation for the relict mudflat section near Vasoj village.*

The palynological study of the same (relict mudflat) section suggested an extensive mangrove forest with core mangrove species (*Rhizophora* sp., *Brugeuria* sp, *Sonneretia* sp.) in the region during 4710–3200 cal yr BP (Banerji et al., 2015). Mangrove forests are highly productive tropical ecosystem that plays a significant role in supporting coastal food webs and nutrient cycle. High productivity may result in ambient oxygen deficiency which in turn might create suboxic, anoxic or euxinic conditions in the region depending on the oxygen demand and supply. Therefore, TOC plays a crucial role in monitoring the ambient redox conditions.

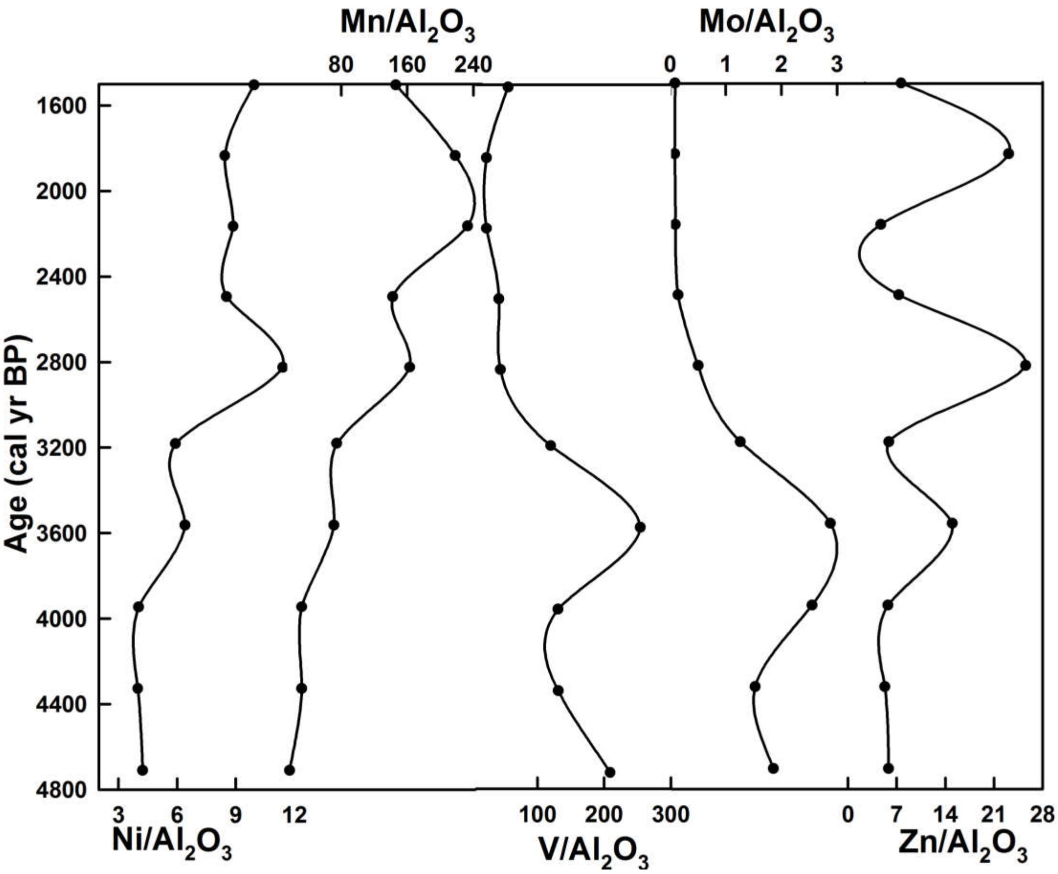



*Figure 3-14. $Al_2O_3$ normalised trace elemental variation in Vasoj section (VV); enhanced values of $V/Al_2O_3$ and $Mo/Al_2O_3$ suggests euxinic conditions.*

Throughout the litho section, $Mo/Al_2O_3$ and $V/Al_2O_3$ shows strong correlation with each other (0.88) but weak correlation with TOC (0.22) (Table 3–2.).

Nevertheless, during 4710–4000 cal yr BP, TOC, Mo/$Al_2O_3$ and V/$Al_2O_3$ show enriched concentration. Under anoxic conditions (non sulphidic), V shows strong correlation with TOC suggesting that V being resident mainly in TOC while in euxinic conditions V resides predominantly in sulphidic fraction and indicates strong correlation with Mo (Algeo and Maynard, 2004). Therefore, it can be suggested that anoxic conditions persisted between 4710–4000 cal yr BP following which the lagoon experienced euxinic conditions between 4000–3200 cal yr BP.

*Table 3-2. Pearson's correlation coefficient for trace element, $Al_2O_3$ normalised trace elements, TOC, $CaCO_3$ and CaO/$Al_2O_3$ for the Vasoj relict mudflat*

| | **TOC** | **$CaCO_3$** | **CaO/ $Al_2O_3$** | **Mn** | **Ni** | **Zn** | **V** | **Mo** | **Mn/ $Al_2O_3$** | **Ni/ $Al_2O_3$** | **Zn/ $Al_2O_3$** | **V/ $Al_2O_3$** | **Mo/ $Al_2O_3$** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TOC** | 1.00 | | | | | | | | | | | | |
| **$CaCO_3$** | -0.41 | 1.00 | | | | | | | | | | | |
| **CaO/$Al_2O_3$** | -0.41 | 0.93 | 1.00 | | | | | | | | | | |
| **Mn** | -0.53 | 0.89 | 0.79 | 1.00 | | | | | | | | | |
| **Ni** | 0.02 | -0.43 | -0.61 | -0.16 | 1.00 | | | | | | | | |
| **Zn** | -0.21 | -0.21 | -0.32 | -0.16 | 0.12 | 1.00 | | | | | | | |
| **V** | 0.28 | -0.85 | -0.69 | -0.85 | 0.33 | 0.28 | 1.00 | | | | | | |
| **Mo** | 0.42 | -0.90 | -0.72 | -0.89 | 0.12 | 0.26 | 0.92 | 1.00 | | | | | |
| **Mn/$Al_2O_3$** | -0.49 | **0.97** | **0.88** | **0.93** | -0.39 | -0.11 | -0.87 | -0.90 | 1.00 | | | | |
| **Ni/$Al_2O_3$** | -0.42 | 0.74 | 0.49 | **0.81** | 0.06 | 0.08 | -0.80 | -0.86 | **0.83** | 1.00 | | | |
| **Zn/$Al_2O_3$** | -0.37 | 0.34 | 0.14 | 0.32 | -0.13 | **0.80** | -0.33 | -0.32 | 0.44 | 0.57 | 1.00 | | |
| **V/$Al_2O_3$** | 0.22 | -0.84 | -0.70 | -0.74 | 0.39 | 0.40 | **0.96** | **0.91** | -0.81 | -0.69 | -0.22 | 1.00 | |
| **Mo/$Al_2O_3$** | 0.35 | -0.87 | -0.71 | -0.80 | 0.12 | 0.36 | **0.86** | **0.97** | -0.82 | -0.76 | -0.20 | 0.91 | 1 |

Unlike Mo/$Al_2O_3$ and V/$Al_2O_3$, Ni/$Al_2O_3$ during 4710–4000 cal yr BP showed depleted values with marginal enrichment observed between 4000–3200 cal yr BP, while after 3200 cal yr BP an increasing pattern till 1500 cal yr BP has been observed (Fig. 3–14). Though there persisted redox conditions between 4710–4000 cal yr BP, depletion of Ni/$Al_2O_3$ suggests that Ni is not scavenged by settling organic particles (Tribovillard et al., 2006). Additionally, Ni/$Al_2O_3$ during 4710–4000 cal yr BP showed low values throughout the litho section. This is attributed to the fact that during organic matter degradation, Ni is released from the organometallic complexes in to the pore waters (Tribovillard et al., 2006). It also gets recycled from sediment in to the overlying waters in the absence of sulphides and Mn oxides (Tribovillard et al., 2006). Similar to $Mo/Al_2O_3$ and $V/Al_2O_3$, a marginal increase in the $Ni/Al_2O_3$ during 4000–3200 cal yr BP indicates that under euxinic conditions Ni might have formed insoluble sulphides that can be taken up by authigenic pyrite (Algeo and Maynard, 2004). However, Ni uptake is kinetically slow which in turn tends to limit its concentration in the authigenic sulphides (Morse and Luther, 1999; Algeo and Maynard, 2004; Tribovillard et al., 2006). Therefore, unlike $Mo/Al_2O_3$ and $V/Al_2O_3$, $Ni/Al_2O_3$ does not show high values during euxinic conditions between 4000–3200 cal yr BP. Low values of $Zn/Al_2O_3$ between 4710–4000 cal yr BP (Fig. 3–14) suggests that with the decay of organic matter, Zn is released in to the pore water from the organometallic complexes. While during 4000–3200 cal yr BP, under euxinic conditions, Zn might have been incorporated as ZnS as solid solution phase in the pyrite or it might have formed its own sulphides (Daskalakis, 1993; Morse and Luther, 1999) which resulted in marginal increase of $Zn/Al_2O_3$ during 4000–3200 cal yr BP.

### 3.6 Redox conditions during 4710–1500 cal yr BP at Relict mudflat of Vasoj village

The Relict Mudflat of Vasoj village, southern Saurashtra coast has recorded a climatic and sea level history during 4710–1500 cal yr BP. The study suggested high sea level of nearly 2 m along the southern Saurashtra coast masked by 1 m of tectonic component (Banerji et al., 2015). Such high sea level has also being inferred based on corals and oyster beds along Diu and adjoining areas (Juyal et al., 1995). Palynological study carried out on the relict section suggested extensive mangrove forests with presence of core mangrove species. With the simultaneous sea regression, reduction in the mangrove forest occurred during 4710–1500 cal yr BP (Banerji et al., 2015). The present study is an attempt to understand the variations in the paleo redox conditions persisted in the mangrove forest during last 4710 cal yr BP in the lagoon of Vasoj village of southern Saurashtra coast. In the present study, high TOC with enhanced $Mo/Al_2O_3$ and $V/Al_2O_3$ during 4710–4000 cal yr BP is observed suggesting anoxic conditions (non–sulphidic condition) persisted in the lagoon caused by the presence of mangrove forest (Fig. 3−15A). However, during 4000–3200 cal yr BP, highest value $Mo/Al_2O_3$ and $V/Al_2O_3$ with no major change in TOC (Fig. 3–15B) suggests that though there persisted euxinic conditions but it was not triggered by the degradation of organic matter rather it was due to the restricted water mass renewal from the adjacent sea or due to the stagnation of water in the region (Tribovillard et al., 2006).

As the region was experiencing a high sea level during 4710 cal yr BP with regression till 1500 cal yr BP, probably during 4000–3200 cal yr BP, there existed a phase when the region experienced last lagoonal conditions with low ventilation of water resulting in development of euxinic conditions. After 3200 cal yr BP, the coastal/ mudflat environment began to persist and the region experienced oxic conditions (Fig. 3−15 C and D) till the sedimentation process ceased (till 1500 cal yr BP) in the region.

The transformation of lagoon in to mudflat due to sea regression is further supported by the presence of *Turritella* shells which is usually found along the coast where the sea swashes the coast in the intertidal marine environment (Desai and Patel, 2008).

Various stages of redox conditions corresponding to relict mudflat lithosection is shown in Figure 3-16. Based on the reconstructed redox conditions it can be suggested that the bottom part of the weathered dark brown clay representing unit–I deposited under anoxic conditions following which euxinic conditions persisted till the broken *Turritella* shells were encountered at nearly 3000 cal yr BP of Unit–I (Fig. 3−16). Later on the entire lithosection (Unit–II and Unit–III) of Vasoj experienced oxic conditions till the surface got exposed due to sea regression, resulting in termination of sediment deposition in the region.

### 3.7 Phases of redox conditions during 4710 cal yr BP at relict mudflat

The present study attempts to decipher the paleo redox conditions during 4710−1500 cal yr BP. The study is in continuation with the previous study carried out at the relict mudflat of Vasoj village which suggested marginally high sea level with extensive mangrove forest with core mangrove species in the region (Banerji et al., 2015). Based on redox sensitive elements and their behaviour, the present study suggests that the region experienced anoxic conditions between 4710–4000 cal yr BP, following which euxinic conditions persisted during 4000–3200 cal yr BP. Thereafter, oxic conditions existed till the sedimentation process ceased with the sea regression. Additionally, the study also points that the euxinic conditions was not the resultant of organic matter degradation rather it was caused due to the low ventilation of water or due to stagnation of water from the adjacent sea caused by regressive phase of the sea in the region.

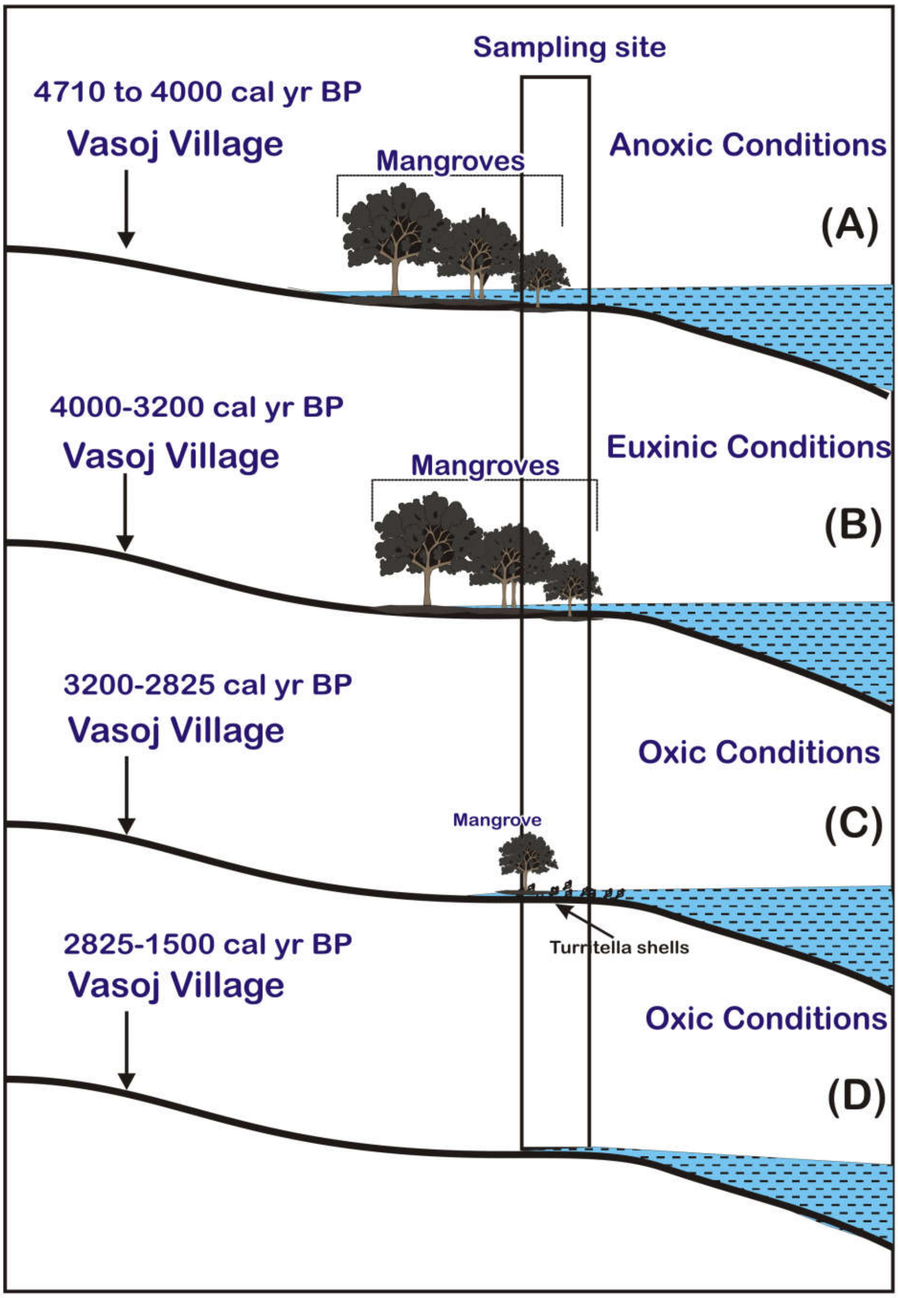



*Figure 3-15. Schematic view of the study area during last 4710 cal yr BP constructed based on varying redox conditions. (A) shows anoxic conditions persisted between 4710-4000 cal yr BP due to mangrove forest;(B) shows euxinic conditions existed between 4000-3200 cal yr BP due to lowering of sea in the region. (C) and (D) represents oxic conditions persisted after 3200 cal yr BP till the sedimentation in the region got ceased.*

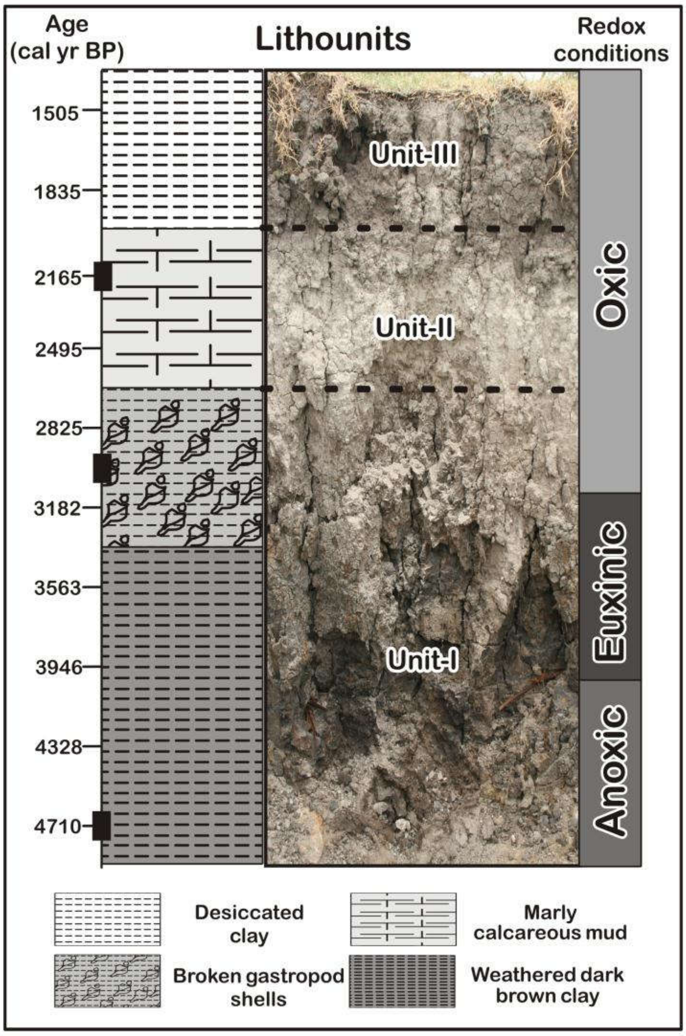



*Figure 3-16. Relict mudflat lithosection representing various stages of redox conditions. Filled rectangle represents the location of C-14 dates obtained for the lithosection.*

# CHAPTER 4
# PALEOMONSOONAL RECORDS FROM THE PARTIALLY ACTIVE MUDFLAT OF DIU ISLAND