Chapter IV

SEDIMENTARY EPISODES

History of Events

General

The evolutionary history of any coastal landscape involves interplay between the continental and oceanic processes operative at 10^3 to 10^5 years scale. These processes, both geomorphological and sedimentological, may get affected by the shifts or changes in climate dynamics, tectonic disturbances and sea level changes (Anderson and Anderson, 2010). The Late Quaternary period of earth history is characterised by changes in climate at various magnitudes. A distinct signature of such change has been observed in terms of relative sea level changes. The resultant oscillations in the sea levels get directly reflected in to the shifts of coastal environment, either sea ward or land ward. As stated earlier, the coastal sedimentary archive receives a significant input from the fluvial systems that drain sediments from the upland areas. During arid climate phases the coastal sediments moves landward due to an increase Aeolian transport. Therefore, it is meaningful to investigate not only the coastal sedimentary archives, but also the coastal fluvial systems to unravel the history of sedimentation during Quaternary time to appreciate overall evolution of the landscape. The study area was earlier investigated to understand coastal evolution by Bhonde (2004) that has greatly helped the present author to integrate coastal events with those recorded in the fluvial sequences. The studies from other parts of the region viz., Kachchh (Shukla, 2012; Prizomwala, 2013) and Mainland Gujarat (Chamyal et al., 2003; Chamyal and Juyal, 2008) have prepared a strong base for understanding overall response of the region to dynamic episodes of Late Quaternary sedimentation. There have been various studies on the Indian subcontinent, in general and western India in particular, which indicate that climatic changes were synchronous with the global changes during the Late Quaternary (Jain and Tandon, 2003). Recently Singhvi et al. (2012) has reviewed the studies on Quaternary environmental changes recorded from a variety of archives spanning from the coasts to the higher Himalayas and also from the Arabia to present a comprehensive understanding on this subject. The present author has based his observations and its evaluation on all these available studies.

Major Events

The long term events comprises of the deposition of sedimentary facies in the fluvial systems as well as in coastal areas. The major events may indicate a long term change observed in the climate or sea level changes (transgression/regression). The fluvial and coastal sedimentary facies in the study area gives a broad picture for the various episodes of deposition during the Late Quaternary that can be enlisted as under.

Event – I

The Miocene transgression is considered as one of the significant higher sea levels in the earth history. This was also a time of docking of the Indian plate with the Eurasian plate and onset of one of the youngest orogenic movement –

the birth of Himalaya. Obviously this was a very dynamic time frame, although remained unrecorded in the early Pleistocene record of the major part of western India. In Saurashtra too, the sedimentation of Quaternary time remained documented either in the form of a large scale weathering, soil formation and peneplanation of the Tertiary/Mesozoic rocks or thin lithified conglomerate units sporadically preserved just above the Dwarka Formation in the Okhamandal in NW and Bhavnagar district in SE.

This geo-surface is overlain by the first event of a significant sedimentation in coastal areas by the miliolite limestone deposits associated with recrystallised shell limestone widely occurring as subdued sheet like deposits covered with red coloured soil. These occur all along the coastal belt between Veraval and Porbandar restricting their outcrops about 5 to 10 km inlandwards and 20m above mean sea level. Unfortunately no dependable dates are available on this unit, but it is correlatable with the M-III (>200 ky) episode of Baskaran et al (1989). This record thus relates with a relatively higher sea level (MIS 7) that also brought onset of normal or increased precipitation in the region. A long period of mechanical weathering during lower sea stand and arid climate has mean while released a lot of coarse grained sediments on the pediment slopes of the highland associated with Gir Hill Range. Onset of wetter climate therefore is recorded in the form of thick gravel (Gt-1 and Gh facies) deposits in the Ojat and Bhader river basins occurring unconformably resting over the Deccan Trap Formation. This event is thus recorded as the GB element in both the rivers depicting higher sediment availability than the stream power.

Event – II

Second event of significant sedimentation took place again after a period of stabilization of fluvial and coastal landscape constituted by the first generation beach ridges, coastal dunes and gravel bedforms. As this was followed by a sea level drop representing MIS-6, which facilitated a wide scale aeolianite deposition, fluvial sequences underwent minor incision and thin soil cover development which is evident by the presence of rhizocretions, as seen at Anandpur in Ojat river. This event representing onset of drier period gave rise to a main miliolite limestone dune deposits due to the availability of wide spread carbonate sand on the retreated shore face and unavailability of enough moisture to stabilize and restrict the same in the vicinity of coast. Episodic landward transportation of these carbonate aeolianites is evident by minor punctuations and reworked clasts of miliolite in younger aeolianites. The fluvial system, however, experienced a period of quiescence.

Event – III

Another prominent event of sedimentation began with last interglacial transgression (MIS-5) which is well recorded in the other parts of the Gujarat and also has well constrained chronology. Some of the well acceptable radiometric and ESR ages of molluscan shells (Bruckner et al., 1987; Juyal et al., 1995) have confirmed this event of higher sea level. In coastal sequences this is recorded as shell limestone and dead coral reefs designated as the Okha Shell Limestone and Aramda Reef Members of Chaya Formation by Bhatt (2000). Recently Kundal et al. (2014) have studied coralline algae from these units and concluded its shallow warm marine condition for deposition. This high sea is also manifested in the form of raised tidal notches on older miliolite cliffs (Bhatt and Bhonde, 2006).

This higher sea level also changed the conditions in the coastal river basins. In coastal areas marine deposits covered the fluvial gravels and sand, whereas increased precipitation associated with change in climate initiated deposition of Gt-2 facies which graded in to Sp and Sm facies with stabilization of climate. Increased moisture also facilitated stabilization of carbonate dunes and even formation of calcareous duricrust over coastal aeolianites and thick soli cover over the inland stabilized miliolites.

Event – IV

This event is accounted to the gradual falling of the sea level that attained its negative level of about -110m during the last glacial maxima (LGM). This took place between 60 and 20 ky period and thus had a long time for overall stabilization and erosion of previous sedimentary sequences. The landscape of Saurashtra almost reached to its present form. Re-reworking of carbonate sand reached to a very long distance from the coast and deposited the farthest occurrences of miliolite limestone e.g. Bamanbor and Chotila. Utmost dry period in the region is indicated by near absence of fluvial record and a wide spread geo-surface characterized by balding of the landscape. This was followed by a rapid rise in the sea level about 17 ky onwards that re-established the Indian monsoon by 13 ky. This is recorded in the form of reworked miliolite sheets containing a lot of fluvial gravels and sand covering the older fluvial sequences on both the banks of Ojat and Bhadar rivers. However, the stream power must have exceeded the sediment supply to an extent that both these river systems entered in to bedrock river form incising its fluvial record for about more than 10 m at certain places.

Event – V

The Holocene record of the study area is made available due to this last event of large scale sedimentation. This was also a period of relative high sea level and prevailing of better monsoon. The coastal record narrates the story through stabilized coastal carbonate dunes and Oyster shell beds associated with younger dead coral reefs, as can be seen at Chikasa and Gosa Bara near Porbandar. Fluvial systems however represent this period in the form of overbank flood plain deposits (Fl facies) and channel gravel deposits which are common in the downstream areas of both, Ojat and Bhadar river basins. The area between Mangrole and Kutiyan conspicuously show wide spread lobe like structure associated with the Ojat and Bhadar rivers, which can be easily seen in satellite images too. This perhaps represents an ancient shore line associated with the Holocene high sea.

Catastrophic Events

The short-term events may record periods lasting from minutes to a few days, such as tempestites, some turbidites (gravitational flow deposits), tsunamites (tidal wave deposits), lava flows and flood deposits. Along the coastal segment of southwest Saurashtra two prominent sites, Chorwad and Ratiya, have the deposits which were misfit in the stratigraphy and could be termed as minor or catastrophic events. These are distinct chaotic deposits represented by assorted boulders derived from the older miliolite limestone forming the shore platform.

Chorwad Site

Boulders along the coastline have been taken a signature of a palaeo-tsunami or an intense storm surge (Whelan and Kelletat, 2005; Barbano et al., 2010; Shah-Hosseini et al., 2011; Knight and Burningham, 2011). The study area in Saurashtra hosts boulders similar to those reported by Whelan and Kelletat (2005). On the basis of their disposition, these boulders can be described as embedded, imbricated and scattered.

The boulders are miliolitic limestone and should have been derived from the shore platform with joints. During a high energy event, jointed miliolitic limestone served as source of blocks that could be detached and transported to the hinterland as boulder deposits. Presence of some inverted boulders along the beach supports this inference. For the magnitude of wave height responsible for detachment and ultimately deposition of these boulder deposits, the dimensions of these boulders was measured (Table 3.1). Accordingly, for a storm to lift and deposit these variably sized boulders, the wave height should range between 2.85m (smallest) and 17.15 m (largest). Contrastingly, the same boulders can be lifted and deposited by a tsunami wave of 0.71 m (smallest) - of 4.28 m (largest). Given the simultaneous presence of all sizes we used the maximum sizes for our analysis. Historical record of storm surges in the Saurashtra coast suggests a maximum storm induced wave height to be about 4 m (1982 and 2001 cyclones). This makes tsunamis as the most likely cause for the movement of these boulders.

Ratiya-Madhavpur Site

High energy deposits in ancient rocks are referred to as 'Tsunamites' (Shanmugam, 2006). Several such deposits have been documented (e.g. Scheffers and Kelletat, 2003; Dawson and Shi, 2000).

Abandoned miliolite limestone quarries between Porbandar and Madhavpur provide unequivocal evidences of a paleo-tsunami event in the form of boulder ridge, boulder floaters and bimodal deposits. Near Ratiya, a boulder ridge occurs as seaward inclined unit about 500 m inland from the present shore was seen. On the quarry face cross sections of these boulders with varied dimensions and shape occur over an erosive surface on shell limestone unit, dipping seawards. At few places some tabular boulders also show imbrications with a mean direction of imbrications due N237^{o}. The base of this boulder bearing unit was traceable for some distance with distinct features arising from sand liquefaction. The boulders were floating in the sandy matrix and were randomly oriented. This unit extends for about 18 km between Ratiya and Pata villages along the Porbandar – Madhavpur coast. Imbrications axes were measured to understand the up current direction that deposited this unit. The boulder geometry in terms of dimensions along three axes (longest, moderate and shortest) and boulder density was measured. The data were used to calculate minimum surge height for both, a tsunami and a storm, using, Nott

(2003). Table 3.2 suggest that in the given a coastal set up, it is more plausible that the boulders were tsunamigenic.

The calculation for required wave height to transport these boulders to its present position under storm and tsunami scenarios, following Pignatelli et al. (2009), suggest requirement of a maximum wave height of about 28m and 7m for Chorwad while 26m and 6m for Ratiya boulders by storm and tsunami surges respectively. Keeping in mind the highest intensity storms recorded on this coastline had a wave height ~ 4 m and the presence of several tsunamigenic sources in the Arabian Sea / northern Indian Ocean, make it likely that a tsunami moved these large boulder deposits.

OSL date of Chorwad beach deposits where these boulders are embedded in sand is 6.6±0.7 ka (Bhatt et al., *In Press*). As the boulders are embedded in these deposits, it can reasonably be suggested that at the time of detachment and placement of these boulders, this beach system was active. Hence this OSL age is the minimum age of emplacement of boulders. To bracket this event, at Madhavpur (i.e. the northward extension of these boulders deposits) the palaeo-beach ridge of beach-dune system where this boulders are embedded was dated. The OSL ages from top and bottom of theses ridges bracketed this event between 7.3±1.2 and 2.7±0.5ka whereas, OSL ages from Ratiya indicate an older event that occurred at 35.4±4.3 ka (Bhatt et al., *In Press*).

If high energy deposits from Chorwad, Ratiya and Mundra are linked to a palaeo-tsunami then the probable source that generated these tsunamis, needs to be addressed. Earlier studies have delineated active zones in the Arabian Sea (Makran Subduction Zone) and Indian Ocean (Chagos Archipelago, Sunda Arc, Andaman-Nicobar Arc) as potential sources for tsunamigenic earthquakes (Jaiswal et al., 2008). In present study the rose diagram plot of the orientation of these boulders shows that at the Chorwad and Ratiya the source could lie to southwest direction, most likely the Owen Fracture Zone (OFZ), a strike slip fault. Although it is known that strike slip faults are not known to produce large tsunamis, but when coupled with on oblique movement of transverse fractures they can produce tsunamis (Jaiswal et al. 2008, Fournier et al. 2007, 2011). Rodriguez et al. (2012) studied the Southern Owen Ridge using multi-beam bathymetry and sediment echo-sounder and reported that it caused most voluminous landslides, two of which moved about 40-45 km^3 of sediments. Other studies have identified submarine landslides as a potential source of tsunami (Henrich et al. 2000; Tappin et al. 2008; Rodriguez et al. 2013; Prizomwala et al. 2015). Out of the two plausible explanations, in this case it must be a huge submarine landslide that took place along the Southern Owen Ridge and generated a tsunami wave with a wave height of ~4 to 5m along the southwestern Saurashtra coast.

Thus, the geomorphology of the coastal rivers and the coast itself in southwest Saurashtra has recorded an interesting story depicted by several depositional and erosional events took place during the Late Quaternary time. Worth mention is that of the preservation of short live events of high energy waves which is unique, and not reported so far from the western Indian coast.