Chapter III

SEDIMENTARY ARCHITECHTURE

Facii and forms of sedimentation

Sedimentary Facies

The term facies *(plural facii)* was introduced by the Swiss geologist Amanz Gressly in 1838. The term *facies* is derived from a Latin word which implies a facial expression characteristic of a particular condition (Sengupta, 2007). Sedimentary facii are used to study large scale climatic or eustatic changes for a particular region. The sedimentary facies is studied by sedimentologists for various purposes, such as petroleum reserves, fossil assemblages, tectonic disturbances, chronology, etc. All of the above studies involve a detailed analysis of the various sedimentary packages that are found in a particular basin. The word facies is used in both descriptive and interpretive sense, where the descriptive facies include lithofacies and biofacies and could be used to interpret depositional or biological processes (Miall, 1999). So far lithofacies is concerned, it is an individual unit defined on the basis of mineral composition, grain size and sedimentary structures. The sedimentary facies has proved to be an anolog for the future studies to study the modern environments. The last few decades have witnessed a compilation of huge amount of data, both from the continental and oceanic regions leading to the better understanding of terrestrial and marine processes.

The present study is focused on such kind of strategy to envelope the various sedimentary facii from the fluvial systems and contemporary coastal segments. Since the Saurashtra Peninsula is a horst (Biswas, 1971), the overall drainage pattern appears to be radial. The entire region is drained by several short distance coastal streams along with some major long distance rivers such as Bhadar, Ojat and Shetrunji. The Bhadar and Ojat Rivers flow towards the western margin whereas the Shetrunji River arising in the Gir Hills takes a path towards the eastern margin of Saurashtra to meet the Gulf of Khambhat at Sartanpar. These rivers must have witnessed the climatic fluctuations and sea level changes occurred on the western margin of India. The geological signatures expressing these effects should be noticed in the sediments laid down by these rivers. Since the study area lies in on the south western part of Saurashtra Peninsula, two major fluvial systems viz; Ojat and Bhadar rivers that were investigated.

Fluvial sequences

The term "fluvial architecture" was used by J.R.L. Allen in his keynote address during the First International Symposium on Fluvial Sedimentology held at Calgary in 1977, to encompass the geometry and internal arrangement of channel and overbank deposits in a fluvial sequence. The main criteria used for defining the facies follow those of Miall (1978, 1996, 2006), which principally concern grain sizes and sedimentary structures, the geometry of sedimentary bodies, and presence or absence of identifiable plant remains. The codes used for facies also agree with those used by Miall (1996). The analysis of the sedimentary architecture generally follows the approach of Miall (1985, 1996), but the features visible to an outcrop-scale are identified and described more simply for clarity.

The river basins Ojat and the Bhadar are documented in detail for their geomorphic variations and geological constituents. The vertical and lateral logging was done at various locations (according to accessibility) in both the fluvial systems. Table 3.1 summarises various lithofacies identified in the study area, whereas table 3.2 enlists all fluvial facies and its interpretation proposed by Miall (2006).

Table 3.1 Facies identified in the fluvial sequences of study area.

Lithofacies code	**Facies Description**
Gt	Trough cross bedded gravel
Gp	Planar cross bedded gravel
Gh	Horizontally bedded gravel
Sp	Planar cross bedded sand
Sm	Massive sand with no stratification
Fl	Floodplain facies
P	Palaeosol facies

Table 3.2 Fluvial sedimentary facies classification. (after Miall, 2006)

Facies code	**Facies**	**Sedimentary structures**	**Interpretation**
Gmm	Matrix-supported, massive gravel	Weak grading	Plastic debris flow (high-strength, viscous)
Gmg	Matrix supported gravel	Inverse to normal grading	Pseudoplastic debris flow (low strength, viscous)
Gci	Clast-supported gravel	Inverse grading	Clast-rich debris flow (high strength), or pseudoplastic debris flow (lowstrength)
Gcm	Clast-supported massive gravel	-------	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits
Gt	Gravel, stratified	Trough cross-beds	Minor channel fills
Gp	Gravel, stratified	Planar cross-beds	Transverse bedforms deltaic growths from older bar remnants
St	Sand, fine to very coarse, may be pebbly	Solitary or grouped trough cross-beds	Sinuous-crested and linguoid (3-D) dunes
Sp	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Transverse and linguoid bedforms (2-D dunes)
Sr	Sand, very	Ripple	Ripples (lower flow regime)

	fine to coarse	cross-lamination	
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination parting or streaming lineation	Plane-bed flow (critical flow)
Sl	Sand, very fine to coarse, may be pebbly	Low-angle (< 15°) cross-beds	Scour fllls, humpback or washed-out dunes, antidunes
Ss	Sand, fine to coarse, may be pebbly	Broad, shallow scours	Scour fill
Sm	Sand, fine	Massive, or faint lamination	Sediment-gravity flow deposits
Fl	Sand, silt, mud	Fine lamination very small ripples	Overbank, abandoned channel, or waning flood deposits
Fsm	Silt, mud	Massive	Backswamp or abandoned channel deposits
Fm	Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
Fr	Mud, silt	Massive, roots, bioturbation	Root bed, incipient soil
C	Coal, carbonaceous mud	Plant, mud films	Vegetated swamp deposits
P	Paleosol carbonate (calcite, siderite)	Pedogenic features: nodules, filaments	Soil with chemical precipitation

Ojat River Basin

The sedimentary packages of the Ojat River comprises of three gravel facies namely; Gt (trough cross bedded gravel), Gp (planar cross bedded gravel), Gh (clast-supported, horizontally stratified gravel) and three sand facies namely, Ss (silty sand), Sp (planar stratified sand) and Sm (massive sand) are distinguished and described as per Miall (2006). The sediments derived from the upper reaches (catchment zone) of the Ojat river was the major source for the monsoon fed discharge which transported the sediments to deposit them in the channel or on to the floodplains. These sediments seem to be deposited in such environments that reveals the climatic conditions in the region during the late Quaternary and has played significant role for the geomorphology of the basin. This basin is a nest of several tributaries along with the main channel of the Ojat river, those flowing along the outer periphery of an igneous complex, the Mount Girnar.

The various sections measured vertically and laterally along the Ojat River are Khambhaliya, in the upper reaches; Anandpur, Dhanphuliya and Shapur in the middle reaches and Piplana in the lower reaches (Fig. 3.1).

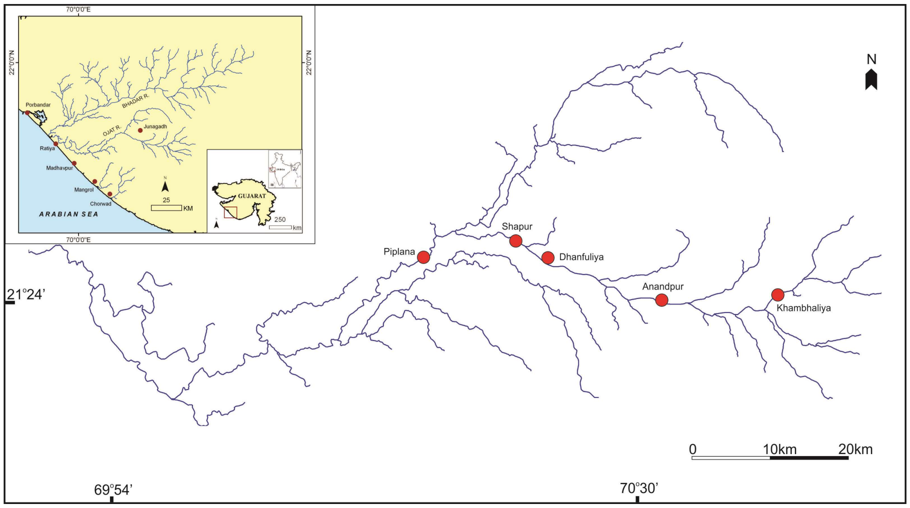

Figure 3.1 Map showing the Ojat river basin and the various sites of logging.

Anandpur

Anandpur village (Lat: 21°24'3.98"N; Long: 70°31'2.05"E) is located on the banks of Ojat river at a distance of 20 kms to the SE of Junagadh (Fig.3.2 and 3.3). The 8-9 m incised cliffs on the right bank of Ojat river at Anandpur exposes the entire sequence of Quaternary sediments non conformably lying on Decaan basalt. This fluvial sequence comprises of various lithofacies like Gt, Gp, Fl, Gh, Sp and Sm (Table 3.1).

Figure 3.2 Google earth image of Ojat river showing log locations at Anandpur.

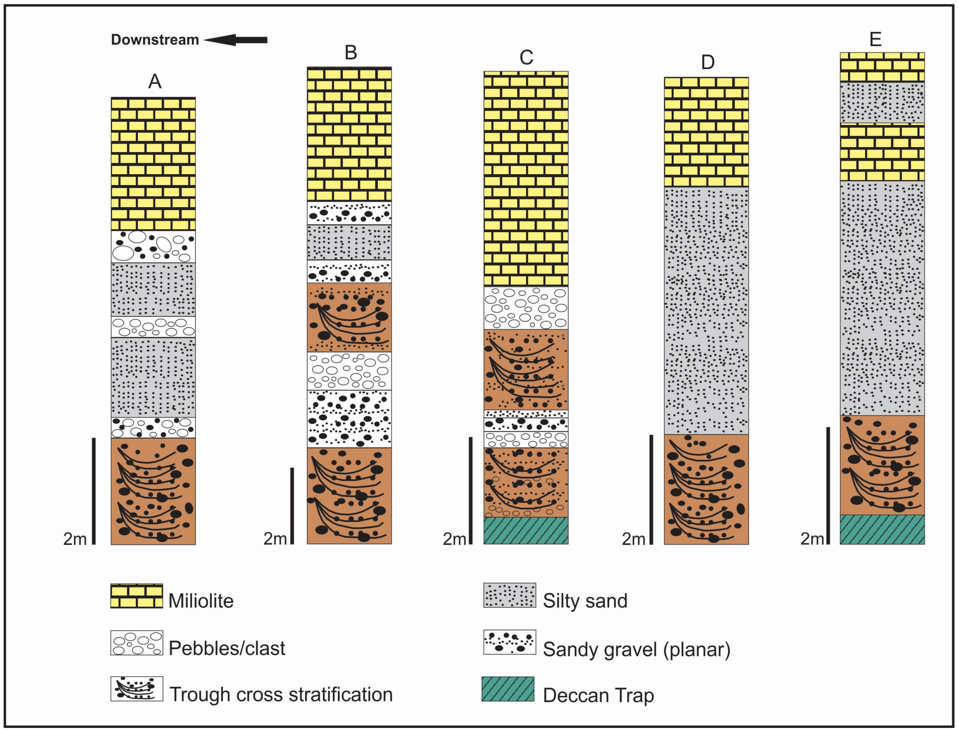

Figure 3.3 Lithologs showing lateral relationship between various fluvial facies at Anandpur.

Lithofacies Gt: Trough cross-bedded gravel

The trough cross bedded gravel (Gt) facies is observed at two different stratigraphic levels and has been named as the Gt-1 and Gt-2 (Fig.3.3 and 3.4 a). At Anandpur the maximum and minimum thickness of Gt-1 facies is observed to be 2 m and 1m respectively, whereas the Gt-2 facies is maximum 1.2 m in thickness.

Lithofacies Gh: Horizonally stratified Gravel (Clast-supported)

This lithofacies was first defined as Gm by Miall (1978) but later replaced by Gh to avoid the confusion in the use of the lowercase letter m (Miall, 2006). It consists of clast-supported pebble and cobble gravel of various dimensions with crude horizontal stratification. This facies is observed to be overlain unconformably on the Deccan Trap basalts. Individual beds are a few decimeters thick but the bed contacts are obscure because of lack of well defined bedding (Fig.3.4 b).

Lithofacies Sp: Planar cross-bedded sand

At Anandpur section, the entire fluvial sequence is capped by the 4 m thick Sp lithofacies (fig.3.4c). This 4 m thick bed is miliolitic in nature. The upper and lower bounding surface is typically flat. This lithofacies is formed by the migration of 2-D dunes (Miall, 2006). The planar cross bedded sand facies characterised by gently downstream ward and bears thin layers of calcrete. The thickness of this unit varies spatially from a maximum of 4.5m to a minimum of 0.5m. This unit is observed to be a major lithofacies in the Ojat river basin. The major occurrence of this facies is at Anandpur and is slightly pedogenised in the upper part. The sedimentary characteristics and the bounding surface suggest it to be the floodplain deposits that might have followed the topography.

Lithofacies Sm: Massive sand

This lithofacies is observed in the middle of Ojat at reach Shapur and lower reach at Piplana. Its maximum thickness is observed 3m. It is characterised by the massive Sandstone beds. It may have been developed by post-depositional modification or as a result of the sediment gravity flows (Miall, 2006).

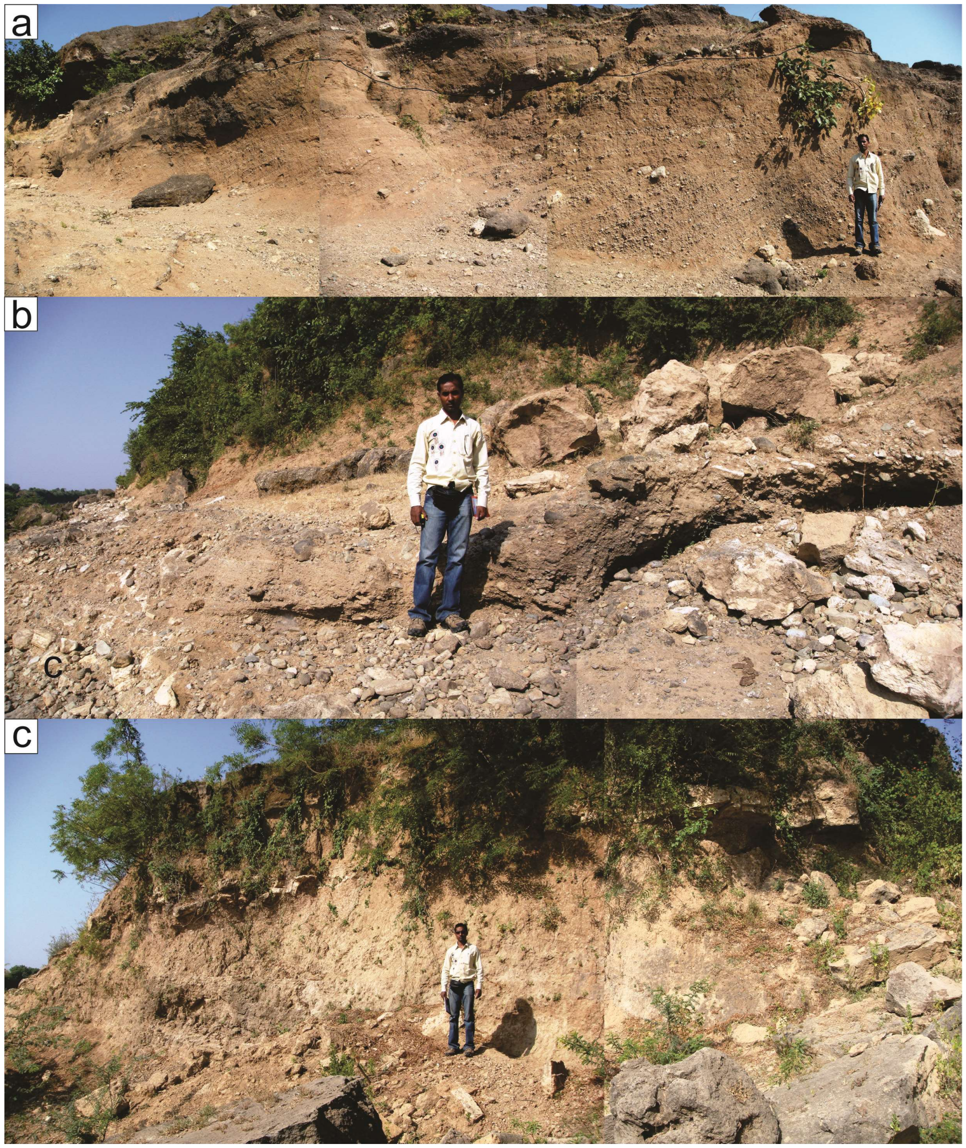

Figure 3.4 Field photographs showing dispositions of (a) Gt , (b) Gh and (c) Sp facies in the Ojat river section at Anandpur. Height of person standing is 165 cm.

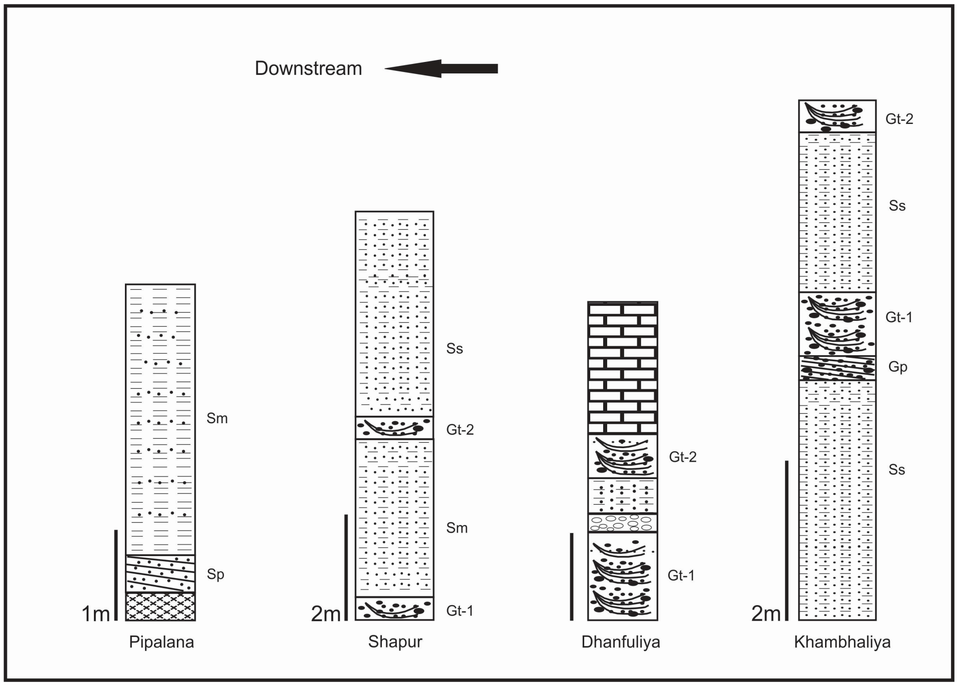

Figure 3.5 Lithologs observed at locations downstream of the Anandpur along the Ojat river.

Some other sections in the Ojat river basin were observed, measured and logged for the vertical and lateral variations of lithofacies (Fig.3.5). The upper reaches included a section near the village Khambhaliya on the way to Visavadar at a distance of 40 km to SE of Junagadh. The middle reaches include sections at Dhanfuliya and Shapur, whereas in the lower reaches Piplana village has a cliff of moderate height in the Ojat river.

Bhadar River basin

Bhadar is the longest river of Saurashtra peninsula, and its basin covers an area of about 4143.75 km^2. The river originates near Jasdan and flows towards west about 185 km to meet the Arabian Sea near Navibandar. Basalt and other magmatic derivatives belonging to Deccan trap Formation.

The locations covered in Bhadar river basin are Survo dam-site, confluence point of Survo and Bhadar, Paanchpipla, Supedii, Upleta, and Chhatrava (Fig.3.6). The vertical and lateral facies variations are identified and logged along with its lateral continuity.

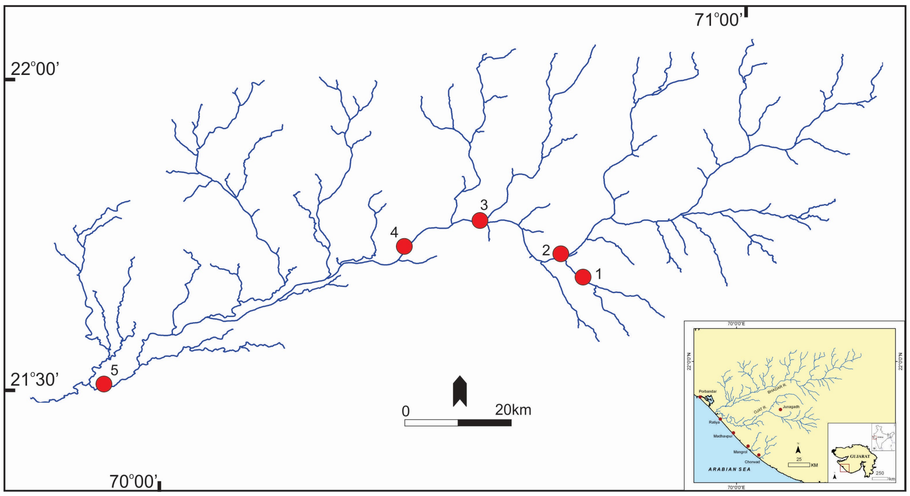

Figure 3.6 Map showing the Bhadar river basin and the locations of logging. Locations downstream wards are 1.Surva dam, 2.Surva-Bhadar confluence, 3.Panchpipla, 4. Upleta, 5. Chhatrava

(Late Cretaceous) dominate the geology of the basin. Fluvial sequences are exposed in riverbank cliffs of moderate height (8-10 m) downstream of the Bhadar dam. The gravelly units can be categorized in trough cross-bedded gravel (Gt) facies and crudely bedded gravel (Gh) facies while the sandy units chiefly exhibit massive sand (Sm) facies and planar cross-bedded sand (Sp) facies. These facies, in general, are overlain by silty sand facies that is designated as flood plain deposits (Fl facies). The contact between the adjacent lithofacies is sharp, and in places feeble to moderate degree of pedogenesis (P facies) is observed in the lower units. Figure 3.7 summaries the facies variations in Bhadar river basin as logged at various locations.

Palaeosol facies (P)

The prominent breaks in fluvial sequences of Bhadar basin can be seen in the form of palaeosol layers that has been designated as P-facies. Based on its stratigraphic occurrence, palaeosol developed over the pre-Quaternary substrate is referred to as P1 facies and other palaeosol layer that caps the lower gravelly unit as P2 facies. The P1 facies in Bhadar river is developed on Deccan Trap basalt, and is dark greyish brown in colour. It shows vertisolic characters with numerous fractures, and subangular to angular blocky soilpeds. The fractures, in places, are filled in by calcareous matter but, the overall nature of soil is weakly calcareous as it gives very little reaction with mild HCl. The contact with substrate is clear and its lateral continuity is wavy.

Trough cross-bedded gravel facies (Gt)

The trough cross-bedded gravel facies is the most dominant lithofacies in the study area. Stratigraphically, two units Gt1 and Gt2 have been identified. The Gt1 facies, 1-4m thick, occurs unconformably either over Deccan Trap

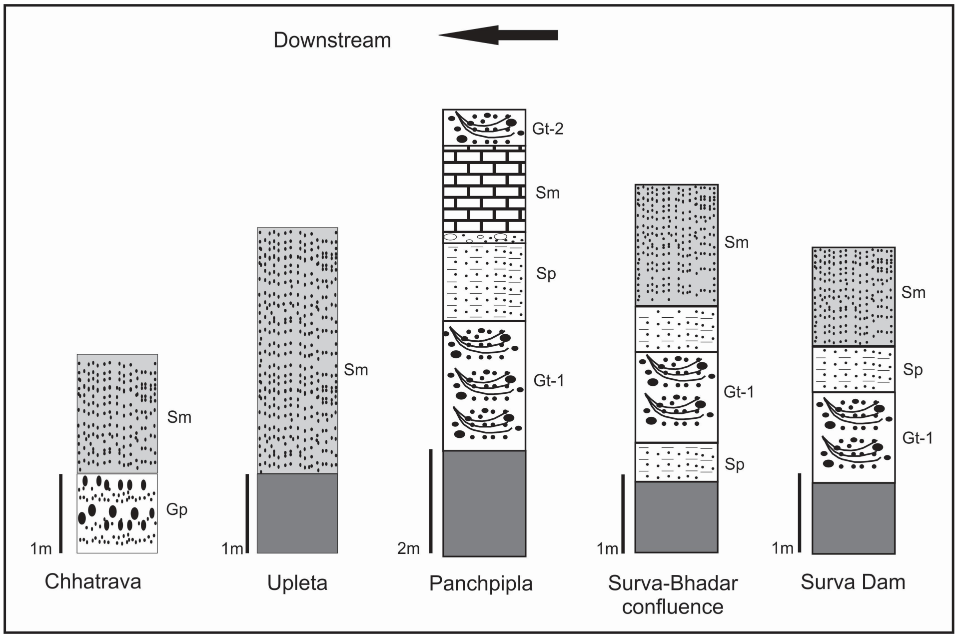

Figure3.7 Lithologs at various sections in the Bhadar river.

Formation or over the palaeosol developed on it. The trough axes are oriented in 300°-120° direction. The average size of clasts, dominantly basalt, constituting this facies is about 2.5cm. Individual foresets in Gt1 also show normal grading. The thickness of individual strata ranges from 2cm to about 20cm and the average dip of all the foresets is between 18°-28°. The Gt2 facies is distinctly different from the Gt1 facies both, compositionally and geometrically. This younger unit rests over the pedogenetically altered top (P2) of the Gt1 facies and planar cross-stratified sand (Sp) facies that overlies the Gt1. The thickness of individual strata ranges from 2 to 7cm. The average dip amount of the foresets is about 28°. Locally, the Gt2 facies grades into planar cross-stratified sand (Sp) facies. Both, the Gt1 and Gt2 facies show multistoried stacking of the troughs (Fig.3.8).

Crudely bedded gravel facies (Gh)

The gravelly sequence also consists of a clast supported, crudely bedded and unsorted facies, which is designated as Gh facies. The clast size ranges from 1cm to 15cm but, few boulders larger than 60cm are also observed. The majority of the clasts are angular to sub-angular and elliptical in shape. Basalt and other magmatic rocks are dominant clast constituents; however the larger fragments consist of limestone. Locally, the clast imbrication is in the 220° direction. The thickness of this unit ranges between 0.5m and 1.5m. Stratigraphically this unit is equivalent to the Gt2 facies as it occurs over the same bounding surface.

Planar cross-stratified sand facies (Sp)

The sandy unit that unconformably lies over the pedogenetically altered top of Gt1 or Deccan Trap basalt, is characterized by the presence of very gently dipping, planar cross-stratified sand (Sp) facies (Fig.3.8). In general, it consists of medium to fine sand. However, locally it grades into gravelly sand that occurs as a shallow scour fills (Ss facies). This unit ranges in thickness from 1 to 2m and its top is pedogenetically altered. The palaeosol layer (P2 facies) capping this unit is relatively lighter in colour and contains few rhizocretions.

Massive sand facies (Sm)

Another significant unit of the fluvial sequences of the Bhadar river is massive sand (Sm) facies that overlies the Sp facies or Gt2 facies with a sharp contact. This unit, 1.5 to 2m thick, comprises medium to coarse sand with faint horizontal laminations (Fig.3.8). This sand facies is characterized by significant amount of biogenic carbonate sand along with the dark coloured trap sand and other detrital constituents. In places, this unit shows horizontal cylindrical, branching and non-branching burrows with an average diameter of 2.5cm. Texture and composition wise this unit is similar to impure miliolite limestone. The miliolite limestone (*per se*) is very fine to medium grained, well rounded to subrounded, well sorted sand (dominantly allochemical, subordinately intraclasts) deposit that can be designated as massive sand (Sm) facies and planar cross-bedded sand (Sp) facies due to its texture and structure, when it is found forming a part of fluvial sequences.

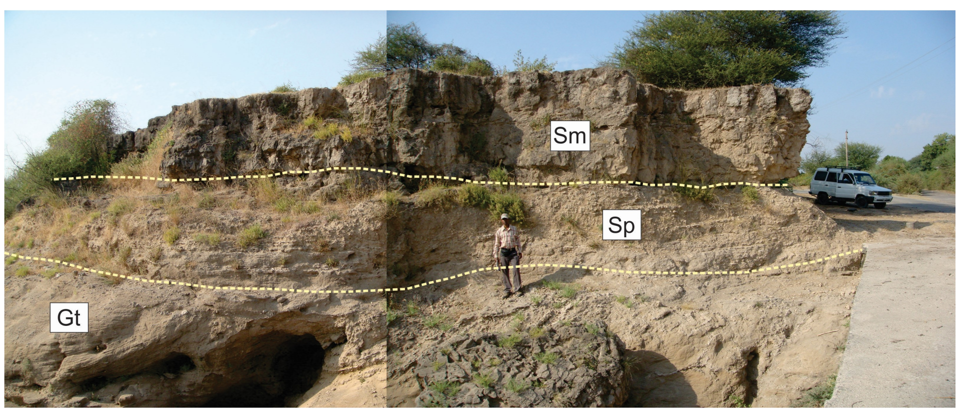

Figure 3.8 Field photograph showing typical fluvial facies in the Bhadar river basin as seen at Panchpipla. Height of person standing is 165 cm.

Basic Architectural Elements of the Study Area

The various straight and curved channel reaches and large areas of exposed mud, sand or gravel termed as bars are the component depositional elements of a river and the sediments that comprise them are termed as the architectural elements. The architectural element may be defined as a component of a depositional system equivalent in size to, or smaller than a channel fill, and larger than an individual facies unit, characterized by a distinctive facies assemblage, internal geometry, external form and (in some instances) vertical profile (Miall, 2006). The recognition of architectural elements, their characteristics and their relationships allow an interpretation of local and regional processes of fluvial evolution of the basin (Miall, 1978a; Miall, 1978b; Allen, 1983; Yu et al., 1992; Than, 2012).

The present study of the Facies exposed at Ojat and Bhadar river have revealed three architectural elements; Element GB, SB and FF; that are bounded by the 3rd to 5th order bounding surface.

1. *Gravel bars and Bedforms (Element GB)*: Lithofacies Gh, Gp and Gt define three main kinds of mesoforms which are common complexly interbedded and thus it is important to understand the varying water and sediment discharge leading to rapid lateral and vertical change in the lithofacies architecture (Miall, 2006). The nature of gravel transport strongly affects the development of these forms in the gravel-bed Rivers. During high water and sediment discharge, the Gh sheets grows upwards as well as in the downstream by the addition of the clasts and form the horizontally stratified gravel sheets (Gh) also known as the longitudinal bars. The trasverse bar growth from the remnant bars generates the planar cross stratified gravel sheets (Gp) while the lithofacies Gt represents minor channel fills

2. *Sandy bedforms (Element SB)*: The sandy bedforms element represents the Channel floor dune fields. The transverse bedforms and sand waves are commonly developed in the shallower parts of channels, including the tops and flanks of the macroform elements like bars. These sheet generate the planar cross-beds (Lithofacies Sp).

3. *Flood plain fines (Element FF)*: Lithofacies Ss and Sm represents the Element FF which indicates km long extent of the fine sheet which shows a slow continuous deposition of the sediments. This element represents the flood plain deposits.

The whole basin consists of major GB elements commonly containing thin stringers of cross bedded sandstone of element SB and few macroforms draped by thin silty sand lenses representing the abandonment or preservation of the FF deposits. These represents the proximal gravel-bed rivers and braid deltas in which sediment gravity flows are absent and shows consisting of a shifting network of unstable, low sinuosity channels in which a variety of gravel bedforms is deposited. Ojat and Bhadar rivers are predominant of element GB and consist of tabular bodies and varying assemblages of gravel traction current deposits (lithofacies Gh, Gp, Gt). The channels were abandoned at low stage, in which case the thin lenses and wedges of sand have been deposited comprising the element SB; and the thin sandy bar tops (lithofacies Ss and Sm) by the runoff comprising element FF have been formed.

The sedimentary facies and the interbedded elements at the individual lithofacies set scale suggest an alluvial fanglomerateand the sheetflood deposits below the fan intersection point (Packard 1974) in the Ojat and Bhadar river basins. Typically, the Ojat and Bhadar river basins represents predominantly element GB and the element SB comprises about 5% of most fluvial successions which identifies it to be a "Shallow Gravel-bed braided river".

Coastal Sedimentary Sequences

The Saurashtra coastline is characterised by a variety of geomorphic features such as sandy beaches, rocky coast and cliffy coast. The western Saurashtra coastline, from Porbandar to Kodinar in the south, is almost straight with sandy beaches and rocky shore platform at places. The southern Saurashtra coast has cliffs in Miliolite limestone all along coastline upto Gopnath on the eastern margin. The coastal segment between Chikasa and Chorwad was investigated for the identification of various depositional events resembling short term or either long term climatic changes and the catastrophic events as well.

The coastal belt is characterized by two distinct coast parallel ridges separated by a shallow depression that is partially covered by the dune sand (Fig.3.9). The dune sand has been stabilized using casuarina plantation at several places which is reflected by distinct red linear feature on the satellite imagery. On either side of the road near Raitya (N 21^{o} 23' 58.02" & E 69^{o} 50' 14.23"), Balej, Mocha, Pata etc. villages several shallow quarries expose medium to coarse grained, poorly sorted shell limestone which are overlain by typical aeolianite constituted by miliolite limestone (Fig.3.10).

At Navibandar right on the coast, the shell limestone occurs forming a prominent coast parallel ridge of about 4-5m height. In a dug well the poorly sorted conglomeratic base of this unit occurs at about 3m depth having

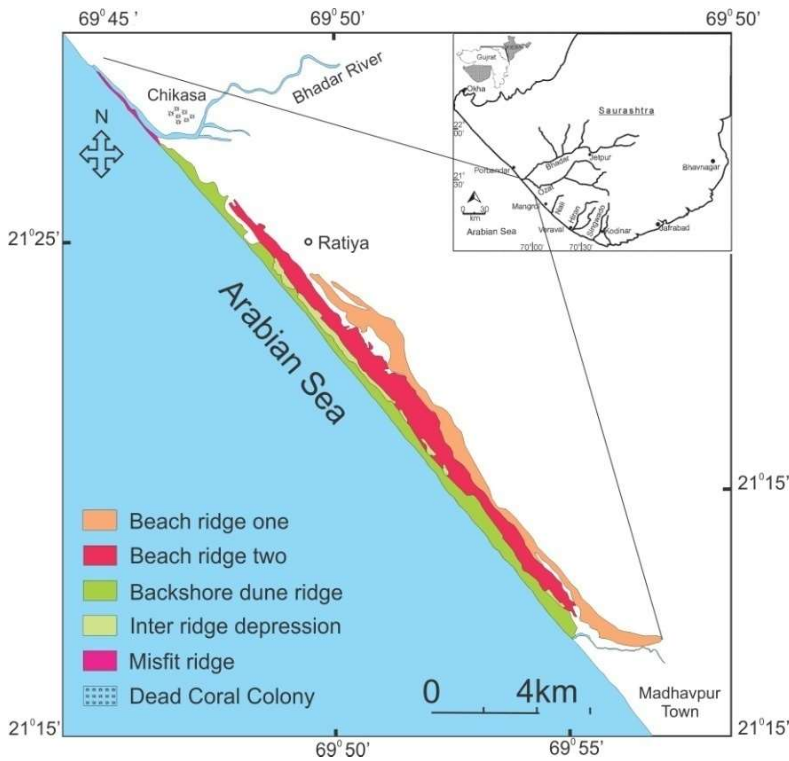

Figure 3.9 A geomorphological map of the coastal belt between Chikasa and Madhavpur showing distinct beach ridges of miliolite limestone.

approximate thickness of 2.5m. This unit possesses dominant composition of well rounded to sub-rounded clasts of Deccan Trap derived material that is cemented by the carbonate (Fig.3.11). The upper part has relatively less dominance of such detrital material, but is coarse grained, porous and shell rich in nature. On the eastern side of Navibandar, a shallow depression that is covered by black coloured sandy alluvium separates another prominent ridge on which the road to Veraval runs. In shallow wells dug in this depression cross-stratified pinkish coloured miliolite limestone has been encountered at a depth of 1-2m. The miliolite limestone that constitutes the second ridge are white to dirty white coloured, moderately sorted, cross-bedded having slightly duricrusted recrystallized exposed surface. Here the rocks also show presence

Figure 3.10 Field photograph showing characteristic nature of miliolite limestone in coastal sequences.

Figure 3.11 A close up of shell limestone on Navibandar coast showing high amount of detritals derived from Deccan basalt.

of thin layers of trap sand and occasionally biogenic structures like trails and burrows. As the base of this unit is not exposed anywhere in this area, the thickness has not been estimated.

Near Balej about 10km south of Navibandar, in a road side quarry a conspicuous thickness of shell limestone is exposed. The rocks are moderately sorted and in general coarse to very coarse grained in nature. They show gentle sea ward dips, but on eastern side the dips are in landwards. The thickness reaches to about 5m and the base has sharp contact with the below lying miliolite limestone. The thickness reduces towards the eastern side where these deposits abut against a prominent ridge of miliolite limestone – second ridge that reaches the elevation of about 30m. Scattered, unsorted, tabular and irregular blocks of this second ridge limestone have been encountered floating into the younger shell limestone unit (Fig.3.12). The same unit extends southward and encountered at several places like Mocha, Singaria and Pata on the road side. Near Pata the road turns closer to the present shore and runs over the sandy, semi-consolidated ridge that connects to Madhavpur. More than one parallel to semi-parallel ridge occurs between Balej and Pata, which are made up of miliolite limestone. However, in absence of prominent depression characterized by different facies of deposits and bounding surface to differentiate litho-units, such occurrences in a very narrow belt of 500m width are considered representative of a common sea level.

Although, a prominent coast parallel linear ridge runs about 3-4km inlandwards where upon the Kadachh and Mander villages are situated. As mentioned earlier this ridge is partially covered under the alluvium, but the exposures of its constituent miliolite limestone have been encountered in the dug wells. The rocks are pinkish coloured, cross-bedded and duricrusted. This ridge abuts about a kilometer south of Mander against a low lying flat alluvial plain north of Madhavpur. Near Madhavpur a distinct truncation in the thus occurring coast parallel ridges can be seen in a form of flat, low lying, triangular area that is under the dense agricultural practice separated from the sea by about 200m wide present day beach ridge over which the road is passing. The triangular low lying area can be distinctly seen on the satellite datasets. This part is drained by a small seasonal stream called Madhuvanti Nadi. The stream is highly irregular in shape and controlled by the topography that is formed by the so described limestone ridges.

The coast between Mangrol and Chorwad is again marked by a prominent ancient beach ridge reaching up to 15m height, and is composed of the shell limestone. The intertidal zone however, exposes the miliolite rocks of second ridge to form abrasion platform. The coastal highway (Porbandar-Veraval road) runs on the top of the first beach ridge that is characterized by comparatively recrystallized very coarse grained to gravelly, cross-bedded shell limestone. The attitudes of bedding planes in this unit distinctly shows two opposite dip directions i.e. SW (seaward) and NE as well as SE (landward). This substantiates its beach ridge morphology as well.

At Mangrol coast the third ridge appears as conspicuous ridge hosting several quarries of shell limestone. Here, it attains height of about 10-12m running parallel to the coast just above the High Water Line (HWL). In few abandoned quarries, maximum thickness of this unit has been estimated to be about 5-6m. The rocks are typical calcirudites dominantly composed of broken and complete molluscan shells, coral fragments and gravels of older miliolites. At the depth of about 1.5m in a quarry situated near Mangrol Bandar, a conspicuous occurrence of dead coral reef has been encountered. It exposes mainly massive coral belonging to the genus *Favia* along with other biogenic remains characterizing a reef assemblage (Fig.3.13). This unit unconformably rest on abraded surface of the older miliolite limestone that constitute another ridge behind it towards the land. In this quarry the shell limestone unit (third - ridge) is of about 3m thickness and exhibits low angle planar cross-stratifications showing sea ward dips (N 135°/ 5° due WSW). This ridge is overlain by about 2-3m thick stabilized carbonate dune sand. At a slightly lower level than this quarry towards sea a massive sand unit, that is semi-consolidated and devoid of any appreciable stratification, is overlain by about 1m thick porous, partly consolidated and stratified, very coarse, carbonate sand unit occurring about 3m amsl. This unit is distinctly bio-turbated and shows numerous feeding burrows characterizing its intertidal deposition.

The second ridge miliolite limestone that underlain the shell limestone also get exposed forming abrasion platforms on present day shoreline. The

Figure 3.12 Photograph of an abandoned quarry showing boulders floating in the shell limestone unit at Ratiya.

Figure 3.13 Photograph showing a characteristic presence of dead coral reef associated with the shell limestone unit at Chikasa.

typical ridge form of this miliolite limestone is obliterated due to extensive quarrying at Mangrol Bandar. However, 10-15m high ridge at about 600m away from the present shore can be seen northward from this place. This ridge is second ridge made up of aeolianites (miliolite limestone) that rest on typical beach facies, and described so far. The Mangrol town is situated on southward extension of the first ridge on which the Porbandar – Veraval road runs. A distinct depression of about 1km width separates this ridge from the second ridge that is situated nearer to the sea. This depression is characterized by reddish coloured kankary and loamy soil that supports agricultural fields and orchards. In few dug wells the first ridge limestone can be seen at a depth of 2-

3m underlying the soil. This limestone unit is a bit recrystallized and cavernous.

At Chorwad Bandar, about 5-8m deep stone quarry exposes very coarse to gravelly, poorly sorted, porous shell limestones showing gentler seaward dips of planar and locally trough cross-bedded sequence. There also occurs a scattered large fragment of gastropod and pelecypod shells and corals. On the coast of Chorwad Bandar behind the holiday camp, this shell limestone unit occurs as 0.5-1m thick patches of sheets resting unconformably over the pinkish coloured miliolite limestone of the older ridge. The miliolite limestone also forms low cliffs of about 1-2m and extends seawards in the form of the abrasion platform.

Catastrophic events

Unfortunately no report (geologic records documented) exists for the catastrophic events on the Saurashtra coastline. Although there are many storms/cyclones reported along this coastline, but no signatures are found the stratigraphic column.

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). The study area possesses sedimentary records of such events in the form of chaotic deposits which are described bellows.

Chorwad-Mangrol coastal stretch

The one major tsunami event mentioned in historical documents and well documented by many is the 1755 Lisbon tsunami that destroyed the Port at Lisbon. Whelan & Kelletat (2005) have reported tsunami boulder occurrences on the Spanish Atlantic coast, Cabo de Trafalgar, which are related to the 1755 AD Lisbon Tsunami. Similar sort of boulder deposits are observed in the intertidal region along the rocky coastline near the Chorwad Holiday Camp, Chorwad (Fig.3.14). These boulders are derived from the shore platform made up of the well known miliolite limestone. In this rock some well developed joints can be seen and these joints has played an important role in the whole process of boulder transportation because the boulders are detached along this joints only and have been transported inland by the giant tsunami waves. These boulders are angular, triangular and tabular in shape, and varying size. Some abrasive marks and chaotic dump debris can be seen over the top of the cliff. Quite a few boulders are found in the inverted position as indicated by the erosive marks of shore platform and vermitid colonies on its lower side instead of upper side. These boulders were also measured for their dimensions and similar to those of the Madhavpur area, related wave heights were calculated (Table 3.1).

Figure 3.14 Field photograph showing scattered limestone boulders on Chorwad coast. These boulders are partially buried under dune sand on its landward side.

Table 3.3: The details of boulder dimensions from Chorwad Holiday Camp coast and required wave heights calculated after Pignatelli et al. (2009).

Sr. No.	**a-axis (cm)**	**b-axis (cm)**	**c-axis (cm)**	**Volume (cm^3)**	**Weight (kg)**	**H_s (m)**	**H_t (m)**
1	68	49	23	76636	210	6.69	1.67
2	82	74	30	182040	500	8.06	2.02
3	84	67	31	174468	479	8.26	2.06
4	91	58	36	190008	522	8.95	2.24
5	92	48	26	114816	315	9.04	2.26
6	83	63	47	245763	675	8.16	2.04
7	96	86	39	321984	885	9.44	2.36
8	86	78	28	187824	516	8.46	2.11
9	100	73	55	401500	1104	9.83	2.46
10	125	128	60	960000	2640	12.29	3.07

11	146	136	28	555968	1528	14.35	3.59
12	108	70	32	241920	665	10.62	2.65
13	100	54	27	145800	400	9.83	2.46
14	113	66	61	454938	1251	11.11	2.78
15	110	92	29	293480	807	10.81	2.70
16	141	133	32	600096	1650	13.86	3.47
17	113	112	41	518896	1426	11.11	2.78
18	119	165	51	1001385	2753	11.70	2.92
19	114	132	42	632016	1738	11.21	2.80
20	149	92	32	438656	1206	14.65	3.66
21	136	96	37	483072	1328	13.37	3.34
22	146	86	26	326456	897	14.35	3.59
23	114	54	32	196992	541	11.21	2.80
24	180	113	46	935640	2573	17.70	4.42
25	188	149	87	2437044	6701	18.48	4.62
26	150	82	107	1316100	3619	14.75	3.69
27	210	95	58	1157100	3182	20.65	5.16
28	238	110	65	1701700	4679	23.40	5.85
29	157	148	97	2253892	6198	15.44	3.86
30	254	151	43	1649222	4535	24.97	6.24
31	154	113	46	800492	2201	15.14	3.79
32	243	143	70	2432430	6689	23.89	5.97
33	182	184	51	1707888	4696	17.89	4.47

34	248	130	48	1547520	4255	24.38	6.10
35	192	151	45	1304640	3587	18.88	4.72
36	208	160	38	1264640	3477	20.45	5.11
37	181	87	80	1259760	3464	17.79	4.45
38	214	139	47	1398062	3844	21.04	5.26
39	133	123	24	392616	1079	13.08	3.27
40	286	219	51	3194334	8784	28.12	7.03
41	218	164	31	1108312	3047	21.43	5.36
42	163	118	38	730892	2009	16.03	4.01
43	210	164	42	1446480	3977	20.65	5.16
44	218	142	48	1485888	4086	21.43	5.36
45	190	148	43	1209160	3325	18.68	4.67
46	256	190	46	2237440	6152	25.17	6.29
47	216	105	38	861840	2370	21.24	5.31

Density of boulder = 2.75 gm/cm^3 H_t- tsunami wave height; H_s-storm wave height

Madhavpur-Chikasa section

Along the western Saurashtra coastline between Chikasa and Madhavpur, abandoned quarries of the miliolite limestone / shell limestone exhibit profound evidence of a palaeo tsunami event in the form of boulder floaters and bimodal deposits (Fig.3.12). On the surface these boulders occur as seaward inclined unit at about 500 m inland from the present shore. On the quarry face cross sections of these boulders having varying dimensions and shape can be seen. The boulders are floating in the sandy matrix and are oriented randomly. However, at few places some tabular boulders also show imbrications with a mean direction of imbrications due 237^o. The base of this boulder bearing unit can be traces for some distance showing distinct features related to the sand liquefaction. This bimodal sediment unit extends for about 18 km between Ratiya and Pata villages along the Chikasa – Madhavpur coast.

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 (Fig. 3.15a). 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 (Fig. 3.15b). The boulders were floating in the sandy matrix and were randomly oriented. On closer scrutiny the effect of scouring, flowing of liquefied sand exhibited typical flame pattern (fig. 3.15c). 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 density of was measured. The data were used to calculate minimum surge height for both, a tsunami and a storm, using, Nott (2003).

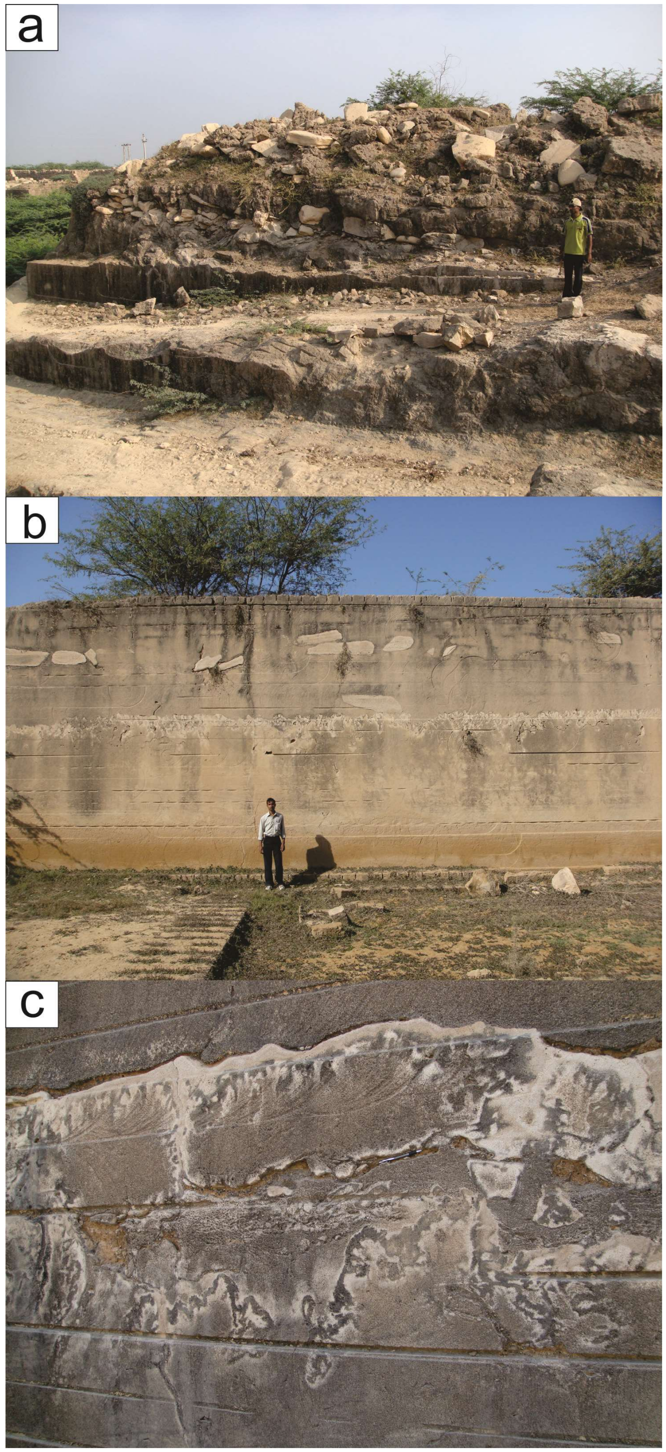

Figure 3.15 (a) Seaward dipping unit of boulders at Ratiya, (b) Scouring and partial liquefaction features at the base of this boulder unit and (c) a closer view of same exhibiting flame like structure.

The Chikasa-Madhavpur segment of the western Saurashtra coastline is especially important because the signatures for multiple events of sea level changes and catastrophic (tsunami/storm) events have been preserved exclusively in the coastal deposits. These signatures tell us about how these records got in the place of preservation and have not been removed by natural agencies. Table 3.2 suggest that in the given a coastal set up, it is more plausible that the boulders were tsunamigenic.

Table 3.4: Dimensions of boulders from the Ratiya-Pata coastal stretch along with required wave heights for tsunami and storm origin (calculated after Pignatelli, et al., 2009).

Sr. No.	**a-axis (cm)**	**b-axis (cm)**	**c-axis (cm)**	**Volume (cm^3)**	**Weight (kg)**	**H_s (m)**	**H_t (m)**
1	110	95	26	271700	747	10.81	2.70
2	108	82	20	177120	487	10.62	2.65
3	90	82	30	221400	608	8.85	2.21
4	114	80	32	291840	802	11.21	2.80
5	92	80	42	309120	850	9.04	2.26
6	65	60	24	93600	257	6.39	1.60
7	70	58	25	101500	279	6.88	1.72
8	53	16	14	11872	32	5.21	1.30
9	146	88	40	513920	1413	14.35	3.59
10	135	110	45	668250	1837	13.27	3.32
11	130	120	66	1029600	2831	12.78	3.20

12	150	145	46	1000500	2751	14.75	3.69
13	120	100	50	600000	1650	11.80	2.95
14	145	108	60	939600	2583	14.26	3.56
15	140	127	55	977900	2689	13.76	3.44
16	120	88	40	422400	1161	11.80	2.95
17	114	102	60	697680	1918	11.21	2.80
18	106	80	34	288320	792	10.42	2.61
19	145	76	36	396720	1090	14.26	3.56
20	132	116	35	535920	1473	12.98	3.24
21	106	76	30	241680	664	10.42	2.61
22	118	107	24	303024	833	11.60	2.90
23	131	70	18	165060	453	12.88	3.22
24	130	90	30	351000	965	12.78	3.20
25	112	75	32	268800	739	11.01	2.75
26	114	100	25	285000	783	11.21	2.80
27	120	110	32	422400	1161	11.80	2.95
28	122	76	24	222528	611	11.99	3.00
29	126	78	34	334152	918	12.39	3.10
30	96	52	22	109824	302	9.44	2.36
31	103	68	24	168096	462	10.13	2.53
32	105	94	40	394800	1085	10.32	2.58
33	180	176	50	1584000	4356	17.70	4.42
34	168	126	60	1270080	3492	16.52	4.13

35	158	142	40	897440	2467	15.53	3.88
36	144	84	28	338688	931	14.16	3.54
37	182	144	42	1100736	3027	17.89	4.47
38	123	77	31	293601	807	12.09	3.02
39	164	65	42	447720	1231	16.12	4.03
40	274	160	50	2192000	6028	26.94	6.73

Density of boulder = 2.75 gm/cm^3 H_t- tsunami wave height; H_s-storm wave height