Chapter V

SEDIMENTOLOGICAL STUDIES

5.0 INTRODUCTION

The contents of this chapter forms a part of field investigation, dealing with the study of the Quaternary sediments that occupy the various cliff-sections exposed all along the major river channels such as the Kim, Tapi and Mindhola as well as their tributaries, in the study area, in order to bring out a systematic record of the stratigraphy, spatial distribution pattern and sedimentary characteristics. The sedimentological studies include the identification of various lithological units, their vertical and lateral relationships with the adjacent units and their lateral mapping, in order to understand their continuity and extent. Along with the mapping of the lithological units, due emphasis has been given on the identification of primary as well as secondary structures wherever observed. The representative samples of each of the lithological units have been collected by means of trenching of the entire cliff-sections, for further laboratory investigations.

Although, the sedimentological studies have been attempted for the lithological units exposed along the cliff-sections, however, an attempt has been made to incorporate the bore-hole information so as to understand the sub-surface details of these sediments and to bring about the overall Quaternary basin configuration.

The succeeding pages of this chapter, provides the location-specific sedimentological details of the lithological units exposed along the river cliffs in the study area (Fig. 5.1).

5.1 SEDIMENTOLOGICAL DETAILS OF CLIFF-SECTIONS

5.1.1 – Kim River

This river basin forms the northern limits of the study area, comprising illustrative cliff-sections exposed along the main channel, consisting of Quaternary sediments, resting on the Tertiary basements. Five important cliff-sections have been studied at various locations (Fig. 5.1), the details of which are furnished below:

(a) Dungri ($73^0 09'$; $21^0 32'$):

This location is on the left bank of the main river channel, 100m upstream of Mangrol – Valia road bridge. The exposed cliff-section comprises sediments having thickness varying from 10 to 12m. The lithological succession is mainly dominated by the presence of clay units which are yellowish to grayish brown in appearance, fractured and at places, sticky in nature. The upper horizons of these units are characterized by pedogenic features such as root casts, burrows etc. and shows intercalations of silt and fine sand lenses.

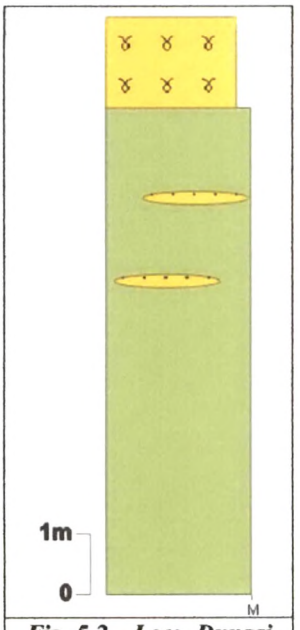


Fig. 5.2 – Loc:- Dungri

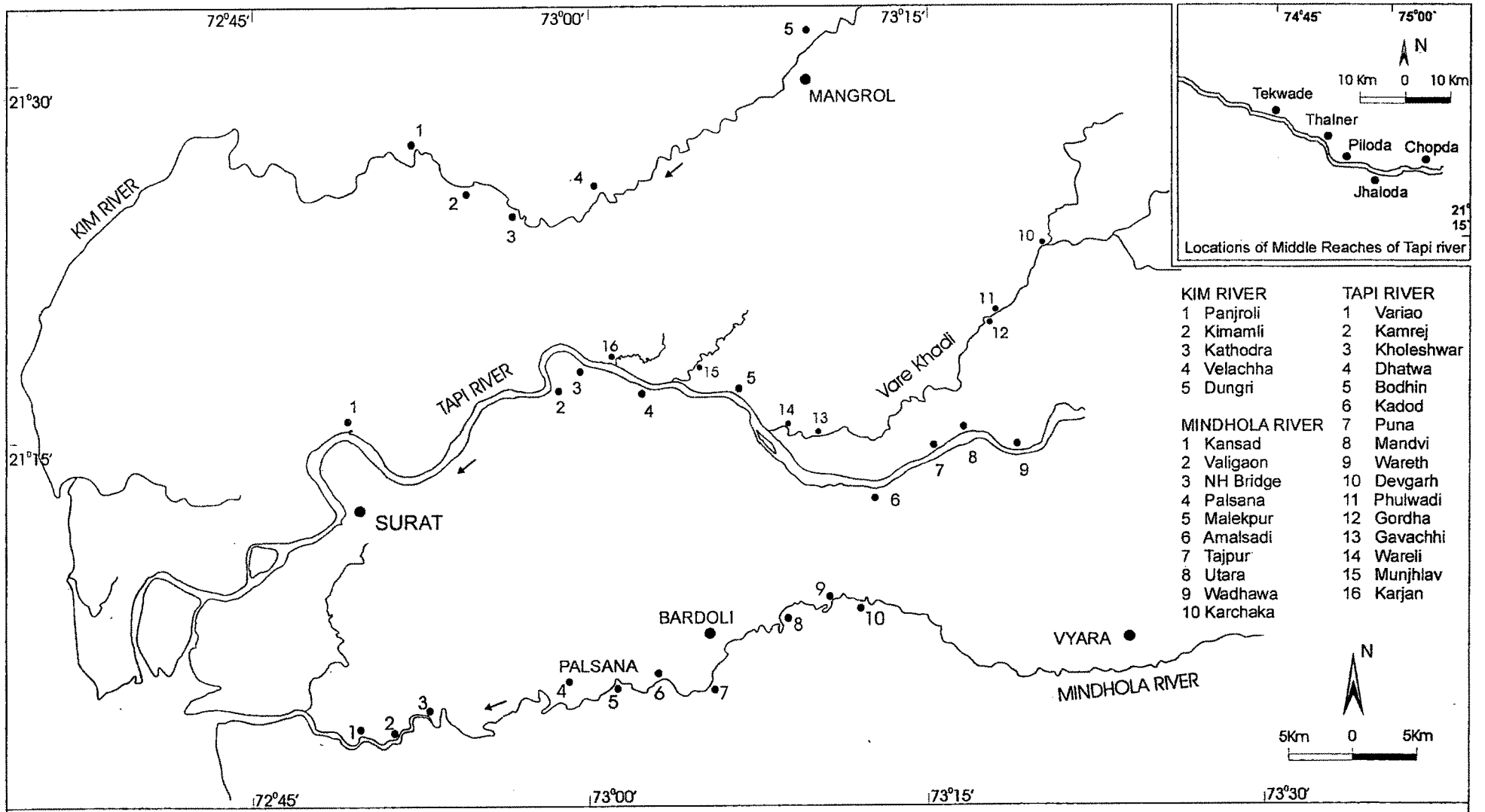


Fig. 5.1 Locations Of The Inventoried Cliff-Sections Along The Kim, Tapi, Vyare Khadi (A Tributary Of Tapi River) And Mindhola Rivers. Inset Figure Shows The Locations Along The Middle Reaches Of Tapi River.

The present-day black cotton soil represents the top of the succession. The overall nature of the lithological succession represents deposition of sediments under low energy conditions with temporal phases of high energy conditions, at places.

(b) <u>Velachha – (73^{0}01'; 21^{0}26')</u>.

This location is marked by the presence of cliffs consisting of Quaternary sediments, exposed on the right erosional bank at the main river channel and located about 8km before Kosamba. The maximum height of the cliff is about 11m and is characterized by the presence of two planation surfaces. The Quaternary sediments that occupy these cliffs are seen disconformably overlying the yellowish colored and highly weathered outcrops of fossiliferous limestone, belonging to the Kand formation of Miocene age (Gadekar, 1975). The overall succession represents single cycle of sedimentation (Fig. 5.3) and commences with a gravelly sand unit, which is about 1m in thickness comprising of poorly sorted clasts of varying composition. The sand particles are sub-angular to sub-rounded in nature and show moderate to poor sorting. This lithological unit is followed upward by the presence of 2m thick silty clay unit, showing occasional presence of gravelly lenses within it. The silty clay unit grades upward into a brownish mud unit, which is highly blocky and fractured in nature and characterized by the presence of pedogenic features such as burrows, which at places, is filled with secondary materials. The variations in the grain-size of the sediments observed throughout the succession, represents an overall fining upward nature of the sediments, indicating there formation under channel and floodplain conditions. Although, the

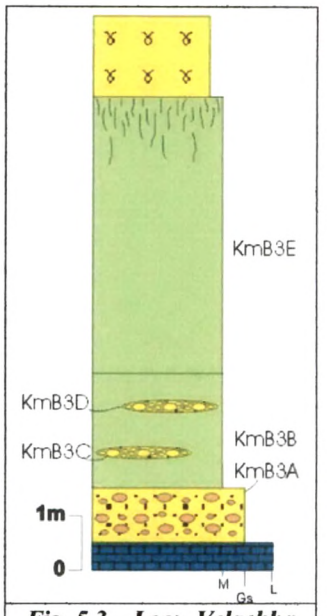


Fig. 5.3 – Loc:- Velachha

sediments are devoid of any primary sedimentary structures however, at places, feeble laminations have been observed.

(c) Kathodra ($72^0$56'; $21^0$26'):

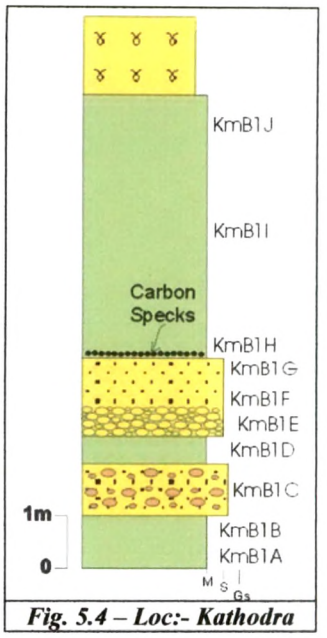


Fig. 5.4 – Loc:- Kathodra

This location is demarcated by the presence of cliff-sections comprising Quaternary sediments exposed along the left bank of the main river channel, north east of Kathodra, near the railway bridge. The cliffs show two distinct planation surfaces with an overall altitude of 10m. The sedimentary succession shows three cycles of fining upward sequences (Fig. 5.4) wherein the bottom most cycle comprises of sticky clay unit followed by a 0.5m thick brownish mud horizon. The second cycle of sedimentation is marked by a gravelly sand horizon (1m) comprising dominantly sand clasts with associated gravel clasts of trappean composition. This unit is succeeded by brown colored fractured mud unit (0.5 – 1m), which is blocky in nature and marks the end of this cycle. The third cycle resting on the brown mud is represented by gravel horizon, followed by coarse to medium sand, which gradually fines upward and grades into a 5m thick mud layer, which is fractured in nature and demarcates the end of the sedimentary cycle. A thin layer consisting of discontinuous specks of organic carbon is observed at the contact of fine sand and mud units. The close observation of the entire sedimentary succession in this location reveals the absence of any important primary sedimentary structures except the presence of feeble lamination at places. The overall nature of the sediments and the vertical variation in the grain size indicates the deposition

of these sediments under fluvial conditions, representing channel – point bar – floodplain deposits.

(d) Kimamli ($72^0$55'; $21^0$26') :

The cliff-sections comprising Quaternary sediments (Fig. 5.5) are exposed on the left bank of the channel, downstream of Kathodra. The maximum altitude of the cliffs is about 4 – 5m consisting of sediments disconformably resting on the weathered outcrops of Tertiary limestone belonging to Kand Formation of Miocene age (Gadekar, 1975). Two distinct planation surfaces are observed in this location, with the T_1 planation surface, marked by the outcrops of Tertiary limestones, whereas T_0 represents the present day planation surface.

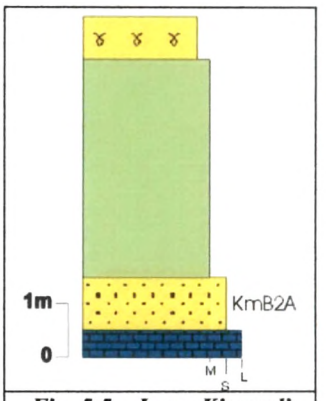


Fig. 5.5 – Loc:- Kimamli

The Quaternary sedimentary succession commences with a laminated medium to fine sand unit (1m), comprising sub-angular to sub-rounded trappean clasts embedded in siliceous matrix and shows moderate to poor sorting. The sand unit further grades into a 4m thick fractured and laminated mud horizon that marks the end of this succession.

(e) Panjroli ($73^0$54'; $21^0$27'):

This location lies west of Kosamba, where the main river channel shows a considerably amount of width and bifurcates on account of the presence of mid-channel bars. The left bank of the channel shows the presence of appreciable cliff-sections having height of 10m.

The Quaternary succession in this location shows two cycles of sedimentation (Fig. 5.6), the first cycle beginning with 1m thick brownish mud unit, followed by 3m thick yellowish colored mud, which at places is sticky in nature and also appears to be compact and blocky. This horizon is fractured, partly calcretised and consists of thin intercalations of laminated silts. The second cycle begins with the coarse to fine sand unit (1m) comprising sub-angular to sub-rounded trappean clasts, moderate to poorly sorted and in turn, is overlained by a 3m thick unit of mud with lenses of silts, at places. Based on the variation in grain size, the succession seems to exhibit deposition under a channel – point bar conditions in a fluvial regime.

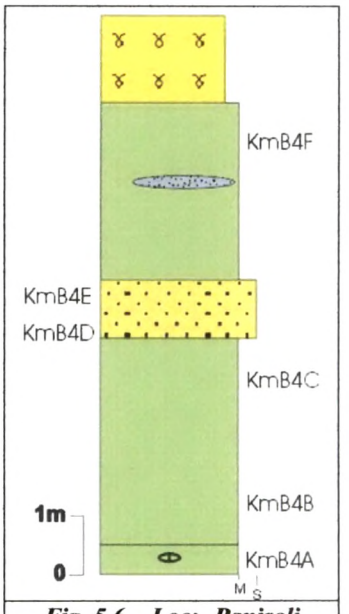


Fig. 5.6 – Loc:- Panjroli

5.1.2 – Tapi River

The Tapi River, along with its numerous tributary streams, represents one of the mega fluvial systems that drain the study area. The main channel as well as its tributary streams, cuts across the vast accumulation of Quaternary sediments which represents the deposits of palaeo-Tapi and its tributaries during Quaternary times. It is observed that the present-day Mindhola river and its tributaries, which forms a part of study area, also drains through and cut across these deposits. All along the present-day Tapi river channel and its tributaries in the study area, numerous cliff-sections are seen exposed comprising of Quaternary sediments (Fig. 5.1). The present investigation, although aims to study the Quaternary sediments of lower reaches of Tapi river basin, however, in order to ascertain the regional picture on the continuity and the nature of disposition of these sediments, the sedimentological

investigations have been extended to the middle reaches of Tapi river also, in the adjoining state of Maharashtra. The following paragraphs furnish a detail account of the sedimentological studies of the illustrative cliff-sections exposed in the middle as well as lower reaches of Tapi river basin.

5.1.2.1 Middle Reaches Of Tapi River

(a) Chopda ($74^0 49'$; $21^0 18'$):

This location comprises Quaternary cliffs exposed on the right bank of Tapi river, 100m upstream of Chopda – Amalner bridge (Plate 5.1). The maximum elevation of these cliffs is found to be 6m and is characterized by the presence of two planation surfaces. The sedimentary succession observed in these cliffs represent singe cycle of sedimentation (Fig. 5.7) beginning with a basal gravelly sand horizon showing bimodal nature consisting of gravel and sand clasts. The gravel clasts comprise fragments of detrital quartz, cryptocrystalline silica and trappean rocks, showing rounded edges and consistent elongations. The long axes of these clasts are, in general oriented in E – W direction. The sand clasts represent grains, which are medium to fine in nature and show planar to trough cross-stratifications with an azimuth of 25^0 due WNW. This basal gravel horizon is followed upward by medium to fine sand unit, intercalated occasionally with silt and gravel bands. This unit is characterized by the presence of elongated burrows giving a strong indication of bio-turbation, presently seen occupied by secondary calcites. The sand unit is followed upward by silty horizons, which are highly

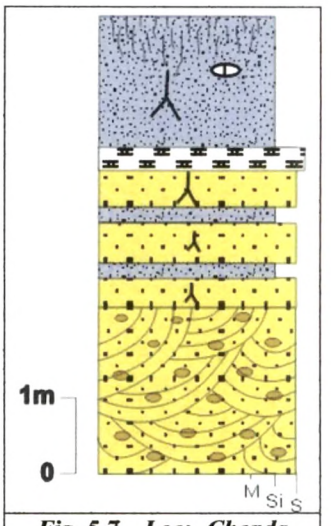


Fig. 5.7 – Loc:- Chopda

pedogenised and distinctly shows the presence of bands of calcrete and gypsum forming anastomosing networks. Looking to the overall characteristics of the sediments and their fining upward nature, they seem to represent their deposition in a fluvial regime.

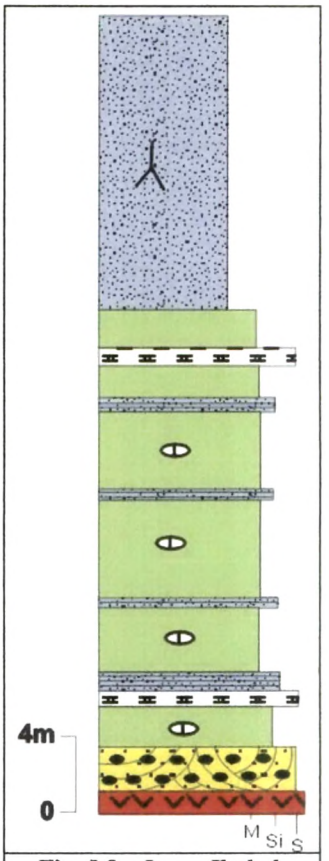


Fig. 5.8 – Loc:- Jhaloda

(b) <u>Jhaloda ($75^0$02'; $21^0$19'):</u>

This location is significant from the point of the presence of a 40m cliff-section, comprising the Quaternary sediments exposed on the left bank of the Tapi river channel (Plate 5.2). The entire cliff shows an inclination of 25^0-30^0 in the upstream direction and also displays the evidences of sediment deformation in terms of the lateral displacement of the order of 2m (Plate 4.6). This section forms the thickest occurrence of the exposed Quaternary sediments observed in the present study. The sedimentary succession shows two cycles of fining upward sequences (Fig. 5.8), the bottommost cycle, comprising gravel horizon marked by the presence of sub-angular to sub-rounded trappean clasts, well cemented by calcareous materials. This gravel unit grades upward into a thick mud unit having alternating silt and clay layers with occasional intercalations of calcretic horizons. The second cycle of sedimentation shows repetition of the lithological units observed in the first cycle, however the mud units, unlike the first cycle is highly fractured and blocky in nature, showing brownish appearance with ample pedogenic features, possibly reflecting a palaeosol horizon (?). The end of this cycle is marked by the presence of thick (10m) calcretised brown to buff colored silt horizon. The detrital grains are well sorted in nature,

reflecting the aeolian nature of the sediments. Interestingly, the complete succession is devoid of primary structures except the presence of laminations. The nature of the sediments observed in this section, their mode of occurrence and sedimentary characteristics very will reflects the fluvial nature of their genesis under low energy condition, over which the present-day aeolian action is noticed.

(C) <u>Piloda ($74^0 48'$; $21^0 20'$)</u>:

Near Piloda, the cliffs consisting the Quaternary sediments attains an elevation of 30-40m, on the right bank of the river channel, similar to that observed at Jhaloda in the upstream, however, this location is featured by the presence of voluminous outcrops of trappean rocks within the river bed. The trappean outcrops are mainly andesitic in composition and are delineated by the presence of E – W set of joint planes. The Quaternary cliff-sections that rest unconformably on the trappean outcrops show an inclination of 15^0 due west and also displays the evidences of local sediment deformations in terms of the undulating calcretic bands oriented in the E – W direction. In this location, the cliff-sections exposed on the left bank of the main channel near the confluence of river Aner (a tributary of Tapi river) have been studied (Plate 5.3). These cliffs attain an elevation of 15m (Fig. 5.9) and comprise two fining upward cycles with gravel horizons at the base subsequently followed by the silt and the clay units with occasional intercalations of calcretic bands.

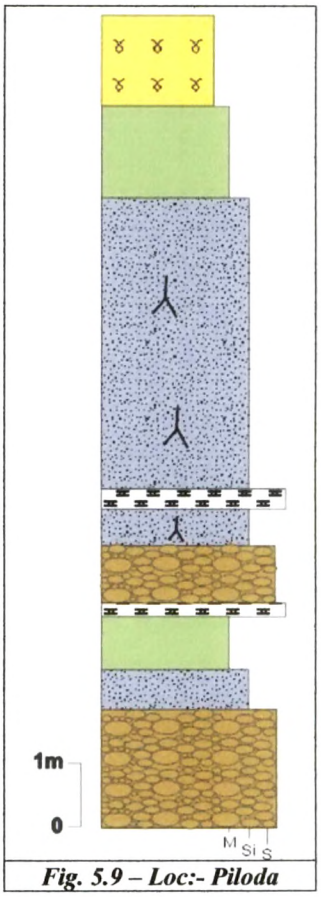


Fig. 5.9 – Loc:- Piloda

Plate 5.1 - Field Photograph Of An Excavated Trench Giving A View Of Disposition Pattern Of Coarse And Fine Sediments (Loc: Chopda, Tapi River).

Plate 5.2 - Field Photograph Showing An Inclined Cliff (Loc: Jhaloda, Tapi River).

Plate 5.3 - Field Photograph Depicting The Cliff-Section Exposed At River Aner (Tributary of Tapi River).

Plate 5.4 - Field Photograph Depicting Laminated Silt And Clay Units (Loc: Thalner, Tapi River).

(d) Thalner ($74^0$47'; $21^0$21'):

The cliff-sections comprising Quaternary sediments near Thalner, downstream of Piloda, represent an elevation of 20m (Fig. 5.10) and exhibit two paired terraces. The sediments dominantly comprise laminated silt and clay layers. Alternating layers of loosely compacted and poorly sorted gravelly sands (1 – 1.5m), with presence of broken shell fragments are observed within the clay horizons. Owing to the disarticulated and broken nature of the shell fragments the identification could not be made. The sedimentary structures include the presence of well developed laminations within the silty layers (Plate 5.4), whereas the clay horizons are highly fractured in nature. Taking into account the dominance of mud units throughout the succession with intercalations of gravelly sands, it is likely that the overall succession represents its formation in a quiet aqueous condition with feeble currents, perhaps representing ponding conditions.

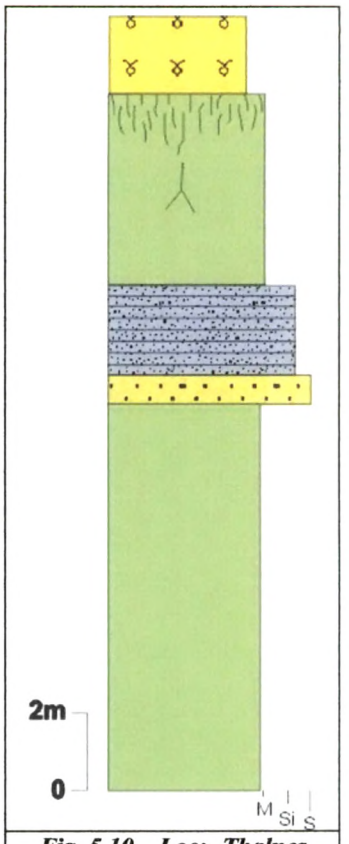


Fig. 5.10 – Loc:- Thalner

(e) Tekwade ($74^0$44'; $21^0$22'):

The Quaternary sedimentary succession exposed along the Tapi river near Tekwade represents a cliff having height of 25m on the erosional bank (Fig. 5.11). The cliff shows an inclination of 20^0 due NW and the lithological units are characterized by the presence of deformational features, such as thrusting of layers on a local scale. The sedimentary sequence in general, depicts two cycles of fining

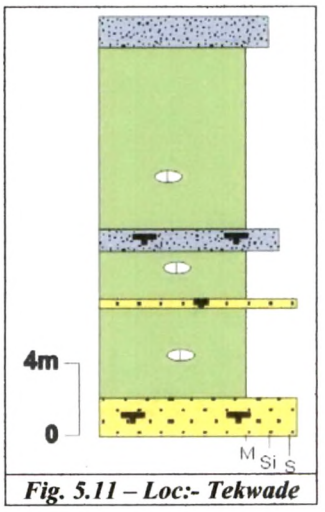


Fig. 5.11 – Loc:- Tekwade

upward nature, beginning with a compact gravelly horizon comprising trappean clasts, followed by the muddy units, which are calcretised in nature. The second cycle is marked by a medium to coarse sand unit that shows planar cross-stratifications and comprises sub-angular to sub-rounded detrital grains, showing moderate sorting. At places, thin lenses of gravels are also observed. The sand unit grades upward into mud horizons, which are calcretised. The calcretes are represented in the form of bands and nodules. Interestingly, towards the top of this succession, specks of thin charcoal layers are observed within the mud units. The presence of charcoal layer probably indicates a warm and humid climate, towards the final stages of sedimentation. The top of the succession is demarcated by the presence of present-day dunal sands.

5.1.2.2 Lower Reaches Of Tapi River

(a) Wareth-Petia ($73^0 20'$; $21^0 16'$):

This location represents one of the important areas for the occurrence of Quaternary sediments within the lower Tapi basin,. It is located in the downstream of Kakrapar weir, characterized by the presence of Quaternary cliff-sections on the right bank of the main river channel, whereas the left bank is occupied by the outcrops of Deccan Traps. The cliffs show gentle inclination of 10^0 towards west and attain a maximum height of about 15m distinctly showing three unpaired planation surfaces.

The Quaternary sediments show three cycles of fining upward sequences (Fig. 5.12) and are found resting on the outcrops of Deccan Traps. The succession commences with an extensively calcretised mud unit, having brownish appearance and occurs in the form of a bench. The calcretes in this unit occur as nodules, tubes and at places branching in nature.

The length of the calcretic tubes has been found to be varying from 0.5 to 2m and indicate their formation by the capillary action under vadose condition representing non-pedogenic origin (Plate 5.5). The second cycle begins with a gravelly sand horizon comprising highly angular gravel clasts of trappean composition, embedded within the matrix of sub-angular to sub-rounded sand clasts. Planar as well as trough cross stratifications marks their presence within this unit showing azimuths of $N/20^0$ and $W/10^0$ (Plate 5.6). A calcretised laminated mud unit marks its presence resting above gravelly sands and represents the end of this cycle. The succeeding third cycle commences with a poorly sorted conglomerate horizon comprising mainly sub-rounded clasts of trappean fragments of varying sizes, embedded in a siliceous matrix and represents its oligomictic nature. This horizon is followed upward by a gravel unit, which comprises sub-angular to sub-rounded clasts of trappean composition. This gravel unit is followed upward by the intercalations of laminated silt and clay layers, with occasional presence of pedogenic features, such as root casts, burrows, which are presently occupied by calcareous constituents, overall showing the effect of calcretisation. The top of the succession is marked by the present-day alluvium.

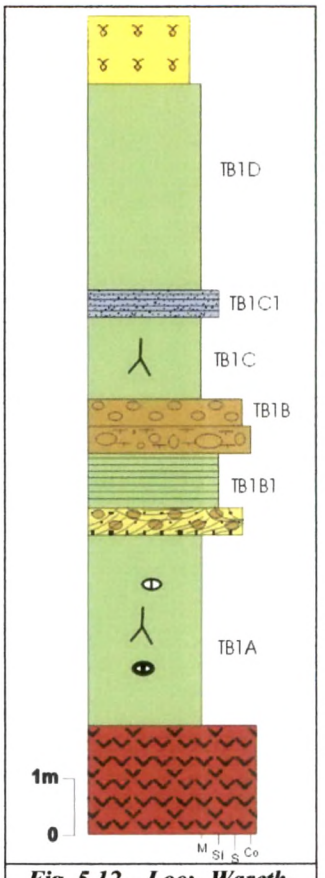


Fig. 5.12 – Loc:- Wareth-Petia

(b) <u>Mandvi ($73^0 17'$; $21^0 15'$):</u>

Likewise the cliff-sections exposed near Wareth-Petia, illustrative sections, comprising Quaternary sediments are also exposed near Mandvi bridge on the right bank of Tapi river

(Plate 5.7). The cliffs are inclined by 20^0 to 25^0 due west, represent two erosional planation surfaces and are seen resting on the trappean outcrops, attaining a maximum elevation of 10m. The outcrops of trappean rocks are also found to be inclined westward and show presence of criss-cross joints, which are presently occupied by E – W running andesitic dykes.

The Quaternary sedimentary succession consists of one cycle of fining upward nature (Fig. 5.13). The sequence begins with a gravelly horizon, comprising clasts of trappean composition embedded within the sandy matrix. This unit is followed upwards by a thick laminated silty unit (Plate 5.8), which shows evidences of calcretisation in the form of nodules, tubes and powdery varieties, however, unlike Wareth-Petia; the intensity of calcretisation in this unit is comparatively less. A 6m thick horizon of clay follows the silty unit, showing feeble laminations, calcretised at places and shows intercalations of silty horizons.

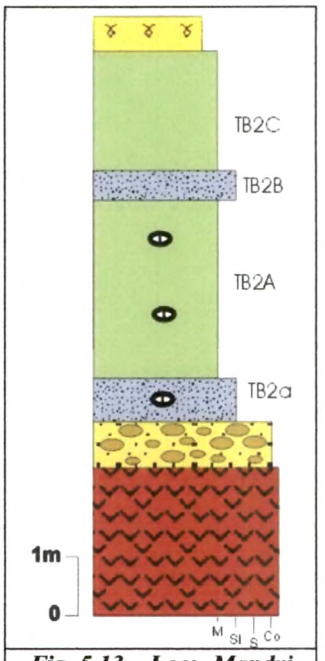


Fig. 5.13 – Loc:- Mandvi

(c) Puna - ($73^0$08'; $21^0$15'):

In the downstream of Mandvi, the right bank of the Tapi river channel shows consistent disposition of cliffs, comprising Quaternary sediments extending up to a lateral distance of 6km. These cliffs show three distinct unpaired planation surfaces and are occasionally dissected by low-order feeder streams, running perpendicular to the main river channel. Illustrative examples of an exemplary cliff-section have been studied near Puna village, on the right bank of Tapi river (Plate 5.9).

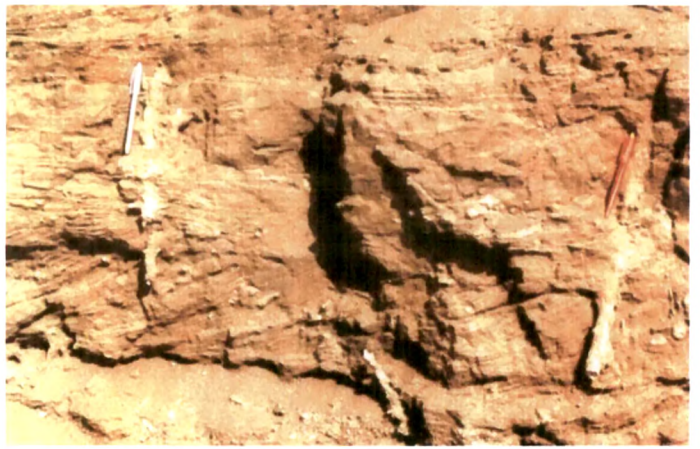


Plate 5.5 - Field Photograph Showing Presence Of Calcretic Tubes Within The Mud Unit (Loc: Wareth-Petia, Tapi River).

Plate 5.6 - Field Photograph Showing The Cross-Stratified Sand Unit (Loc: Wareth, Tapi River).

Plate 5.7 Field Photograph Depicting The Cliff-Sections (Loc. - Mandvi, Tapi River).

Plate 5.8 - Field Photograph Showing Laminations Within Silt Units (Loc: Mandvi, Tapi River).

In this location, the cliff-section attains a maximum elevation of about 18m (Fig. 5.14) and displays the presence of two distinct cycles of fining upward sequences. The base of these sedimentary successions is not exposed however, the observed section commences with a conglomerate horizon, containing sub-angular to sub-rounded clasts of trappean composition, varying in size from 1.5 to 12cm in diameter and are poorly sorted and moderately compacted with siliceous cement. Interestingly, these clasts show imbrications with their longest axis oriented in NE direction.

The conglomerate unit grades upward into a well-compacted siltstone horizon which shows a gentle inclination towards WNW. This unit is dirty white to grey in appearance, consisting of silt grade detrital sediments, embedded in siliceous matrix and cemented by calcareous materials. This unit is characterized by the presence of stray occurrence of broken shell fragments, karstification features and organic structures such as burrows and tubes, presently filled with clay and silt materials.

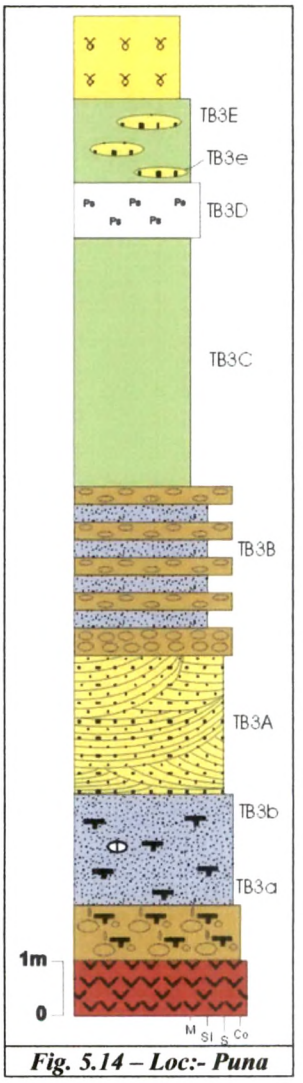


Fig. 5.14 – Loc:- Puna

The second cycle of sedimentation commences with gravelly horizon having trappean clasts embedded within a sandy matrix. Within this unit, alternating lenses of medium to coarse sands and silts are observed. The sand lenses show lateral extension and exhibits the presence of planar cross-stratifications having azimuths $N210^0/20^0$ and trough cross-sets with azimuths $N210^0/20^0$ and $N40^0/30^0$. A thick (7-8m) mud unit, which is fractured and pedogenised, vertically follows the gravel horizon. This unit is represented by the presence of intercalations of sand and mud lenses,

associated with a brown, highly fractured, blocky clay unit, possibly representing a palaeosol horizon (?). The top of the succession is marked by the presence of recent dunal sands.

An attempt has been made to map the various litho-units observed along the cliff-sections, in order to obtain their lateral as well as vertical extent. To comprehend this information, the mapping of various litho-units was carried out from the cliff-section at Puna village, further downstream covering a lateral distance of 3km (Fig. 5.15). The inferences obtained from the above mapping have been found to be interesting and are cited below.

(i) The mapping of the cliff-sections has clearly demonstrated the uniformity in their elevation and overall thickness of sedimentary successions, ranging from 16 to 18m;

(ii) The vertical successions are represented by two well-developed cycles of sedimentation overlying the trappean basement. They have been continuously traced through out the profile and distinctly represent the dominance of coarser units towards the lower portion of the sequence and mud units towards the top, indicating the gradual decrease in the grain size as well as energy conditions.

(iii) The presence of sand lenses within the top mud unit, suggest the temporal changes perhaps indicating an increase in the energy conditions.

(iv) The inferred palaeosol unit shows lateral continuity probably representing sub-aerial exposure of the sediments for a short duration, during the sedimentation.

(v) A significant observation made during the lateral mapping shows the sudden disappearance of trappean basement between 100m and 2875m and after 3150m points. This type of appearance and disappearance of trappean basement is attributed to the local tectonics of the area.

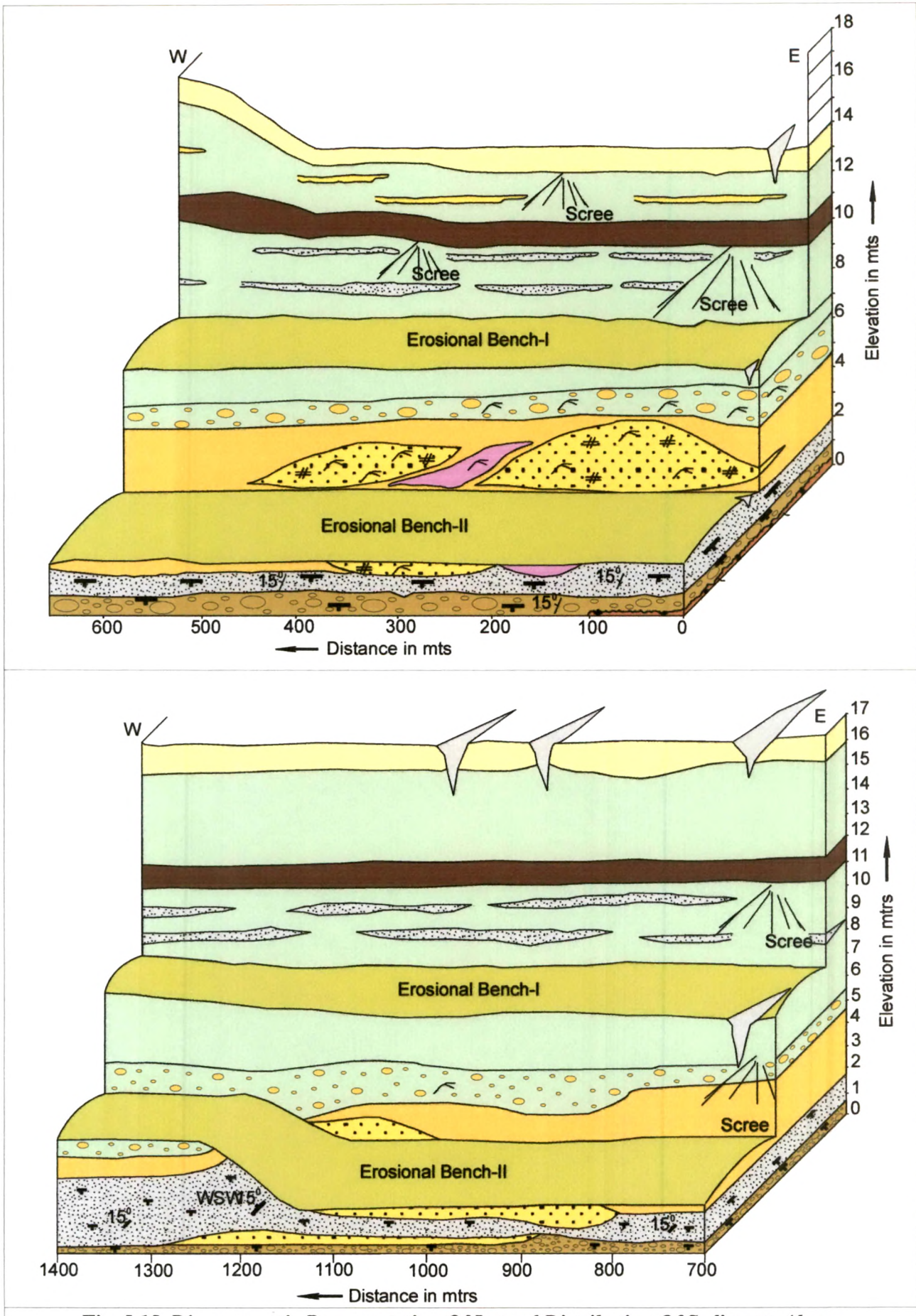
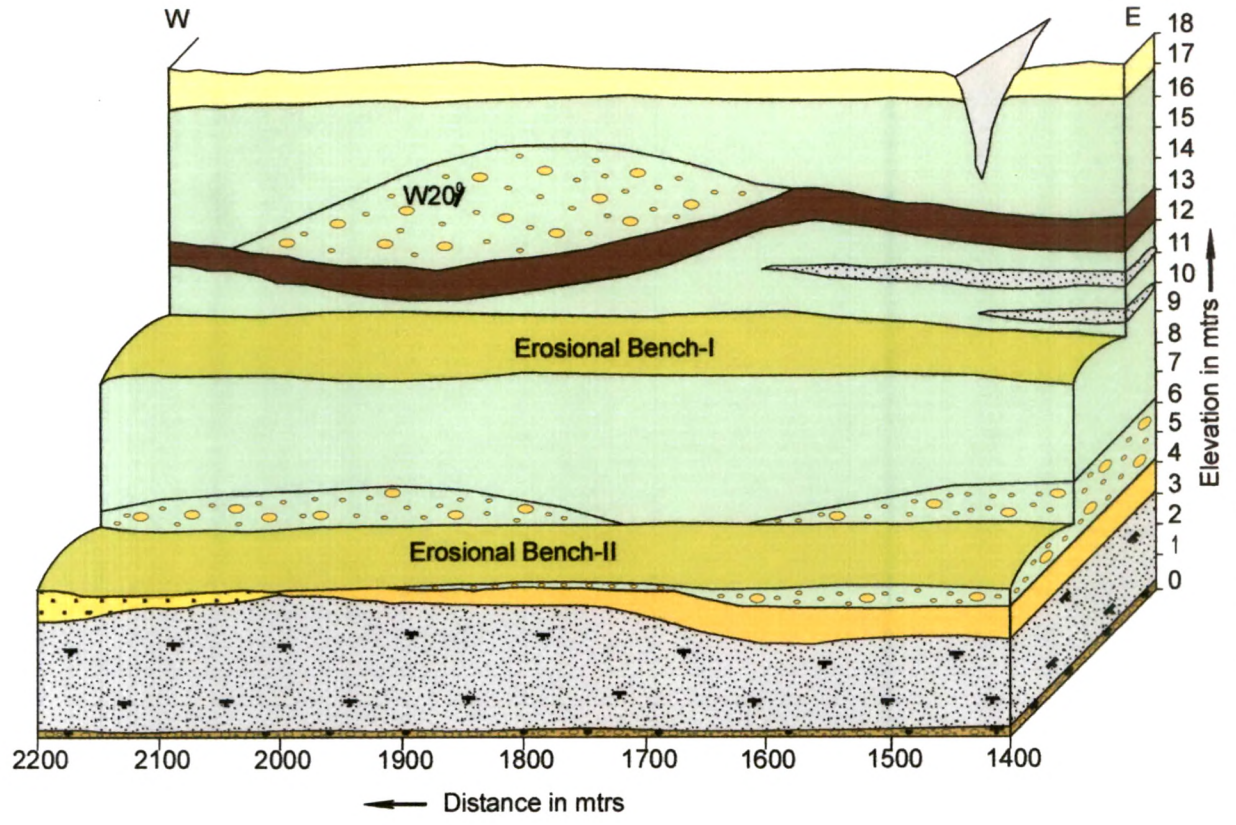


Fig. 5.15 Diagrammatic Representation Of Lateral Distribution Of Sediments Along The Cliff-Sections (Loc:- Puna).



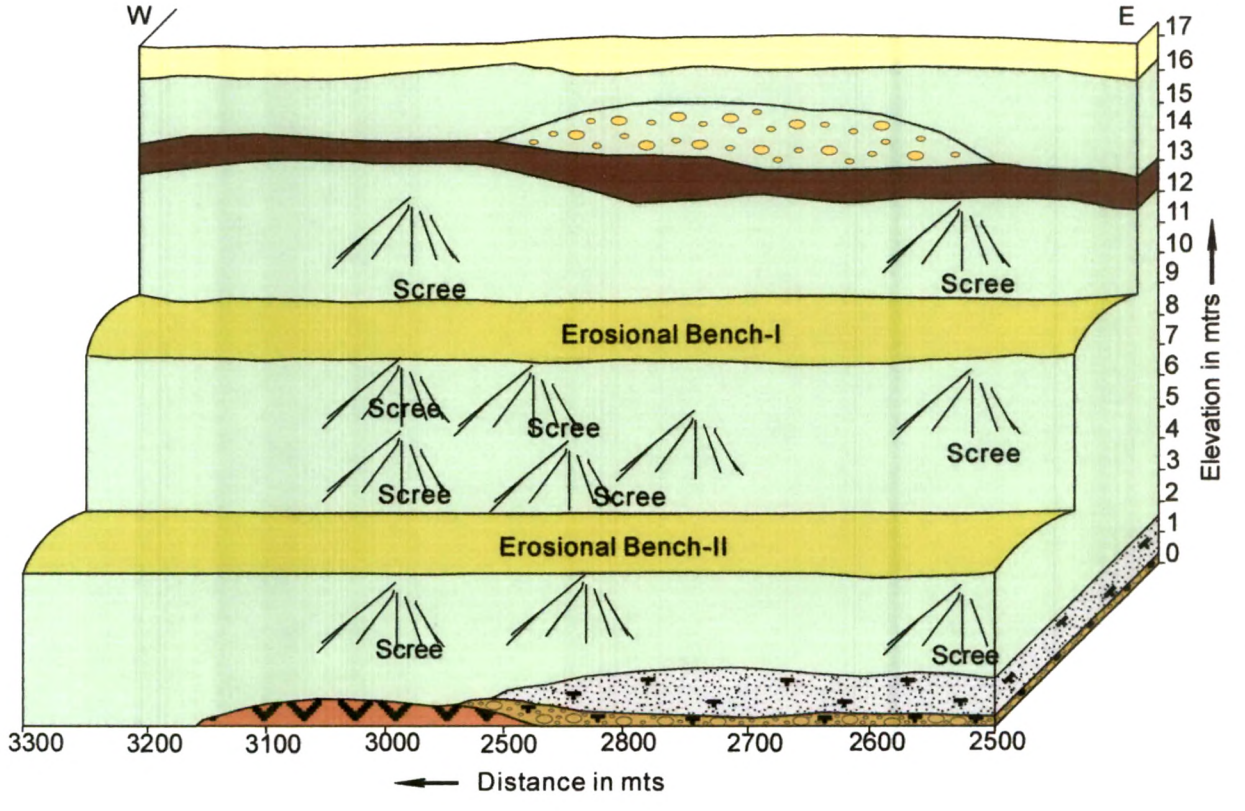


Fig. 5.15 - Continued.

(d) Bodhan ($73^0 07'$; $21^0 17'$):

Unlike the cliff-section well-developed on the right bank of Tapi river in the upstream areas up to Kadod, in the downstream side from Bodhan village, cliff-sections are exposed on the left bank of the main channel. The Bodhan village is around 6-7km downstream of Kadod. This complete stretch, all along the river channel, including the cliff-sections, is marked by the presence of trappean outcrops, which are inclined towards west direction by an amount of $15^0 - 20^0$.

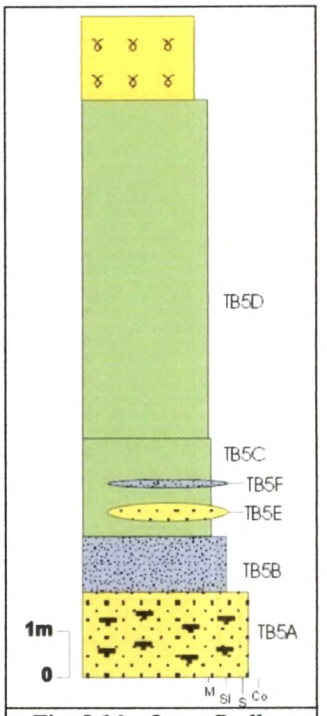


Fig. 5.16 – Loc:- Bodhan

Quaternary sediments (10-12m) occupying the cliff-sections, are observed 1km downstream of Bodhan, (Fig. 5.16) and represents one complete cycle of fining upward sequence. A close observation of this succession suggests that the sedimentary sequence commences with a consolidated fine to medium sand unit, showing well-developed laminations. The base of the sand unit is not exposed. The clasts comprising the sand unit are basaltic in composition, sub-rounded to rounded in nature and shows moderate to well sorted nature. This sand unit further grades into 1m thick silt horizon, which also shows lamination. The end of this fining upward cycle is demarcated by the presence of 8 – 10m thick unit of mud, dominated by clayey sediments, however lenses of laminated silt and fine sand are occasionally observed within the clay unit. Towards the top, the mud unit acquires a blocky nature and is fractured, showing evidences of pedogenic activities. The top of this mud unit is marked by the presence of recent alluvium.

(e) ***Dhatwa (73^{0}00'; 21^{0}17'):***

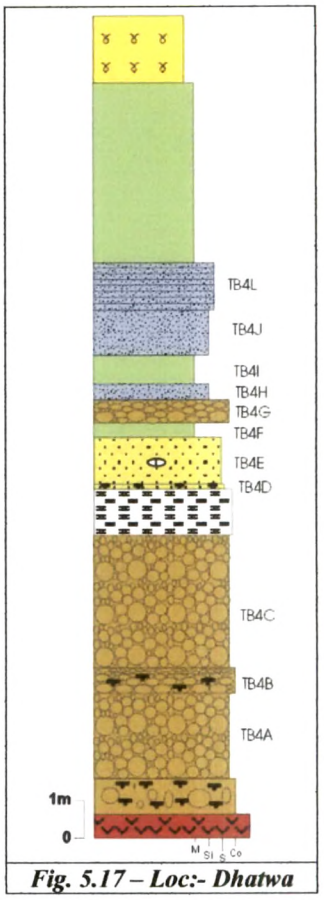


Fig. 5.17 – Loc:- Dhatwa

This location is further downstream of Bodhan and is delineated by the presence of cliffs along the river channel attaining a maximum elevation of 20m (Plate 5.10). These cliffs comprises of Quaternary sediments resting on the trappean basement having three distinct cycles of fining upward nature (Fig. 5.17). The bottom most cycle of the Quaternary succession commences with a conglomerate unit (0.5m) having sub-angular to sub-rounded clasts of trappean composition, poorly sorted in nature and are cemented by siliceous materials. This unit is followed upwards by a yellowish to red colored gravel member comprising sub-angular to sub-rounded clasts of trappean compositions, embedded in a silty matrix. This unit is succeeded by the presence of a gravelly sand member distinguished by the presence of gravel clasts having varying sizes while the sand fraction comprises medium to coarse sand size grains. Overall this unit shows poor sorting, however, it is moderately to well compacted and exhibits the presence of planar cross-stratifications having azimuth 25^0 due S.

The second cycle is again marked by the presence of a gravel member with sub-angular to sub-rounded trappean clasts, poorly sorted and shows evidences of calcretisation. It is observed that the intensity of calcretisation gradually increases, towards the top of this unit, leading to the formation of a calcrete bench having a thickness of 1m. A coarse to medium sand member with poorly sorted, sub-angular to sub-rounded grains follow the calcretic unit upwards. The end of the second cycle is marked with the presence of

intercalating silt and clay horizons, brownish in appearance and shows intense pedogenesis.

The third cycle of sedimentation is again marked by a gravelly sand horizon with gravel clasts embedded in sand matrix. The gravels are sub-angular to sub-rounded, poorly sorted however sands are fine to medium in nature. This unit is followed upwards by a brownish mud horizon, which is highly fractured, blocky and mottled, showing evidences of intense biogenic activities such as burrows, calcretic nodules; root casts and probably represents a palaeosol horizon (?). Although this unit dominantly comprises of clayey sediments, however intercalations of thin laminated silts are also observed. The top of the entire succession is marked by the presence of recent alluvium.

(f) Kholeshwar ($72^0$57'; $21^0$18'):

In the downstream of the Tapi river, about 5km from Dhatwa location, the cliff-sections maintain an elevation of 18-20m and are exposed on the left bank, near Kholeshwar (Fig. 5.18). These cliffs are found occupying the Quaternary sediments distinctly showing two cycles of sedimentation. The first cycle is demarcated by the presence of a 4m thick brownish colored, fractured and blocky mud horizon, characterized by pedogenic features, such as burrows filled with calcareous materials.

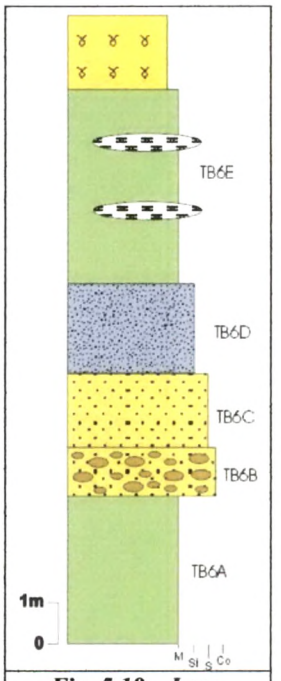


Fig. 5.18 – Loc:- Kholeshwar

The second cycle of sedimentation is typically fining upward in nature beginning with a gravelly sand unit. This unit is bimodal in nature, comprising gravel clasts and sand clasts. The gravel clasts vary in size from 3-4cm in diameter, trappean in composition and are sub-rounded to rounded in habit, embedded

in a sandy matrix. The sand clasts represent more than 80% of the unit and comprises medium to coarse sand sized particles, which are poorly sorted in nature. The gravelly sand unit grades further into a sandy horizon, consisting of medium to coarse size grains, which shows poor sorting and is delineated by the presence of organic structures such as burrows, which are presently filled with calcareous materials. A thick mud unit, consisting of alternating layers of silt and clay, forms the topmost unit of the second cycle. This unit is also represented by the presence of thin calcrete layers of varying thickness. The end of the complete succession is demarcated by the presence of recent soil and alluvium cover.

Further downstream of this location, near Gaypagla, an interesting observation has been made. The Quaternary sediment successions in this location are exposed on the right bank of the main river channel and comprises poorly sorted gravelly sands and alternating silt and clay units. In one of the tributaries that meets the main channel, these sediments are well exposed and are found disconformably resting over the shales and limestones belonging to Kand Formation of middle to upper Miocene age (Plate 5.11). Throughout the study area, this is the sole location wherein a clear contact between the Tertiaries and Quaternary sediments is clearly discernible.

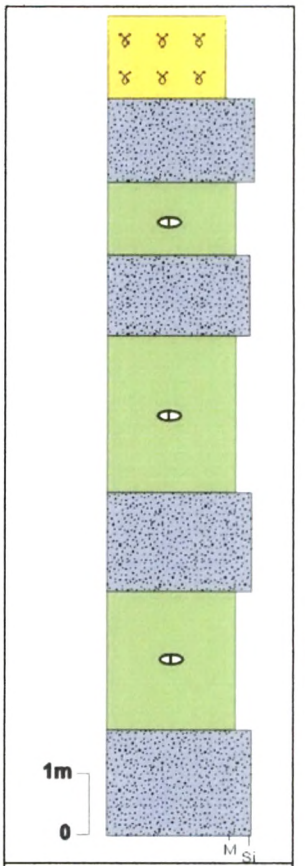


Fig. 5.19 – Loc:- Kamrej

(g) <u>Kamrej ($72^0$56'; $21^0$16'):</u>

This location is further downstream and demarcates the upper extremity of the present-day Tapi river estuary. The left bank of the main river channel in this location comprises

cliffs consisting of the Quaternary sediments and attains a maximum elevation of 15m (Fig. 5.19). This location is characterized by the presence of two distinct planation surfaces on the left bank of the river whereas the right bank represents only one planation surface, overall pointing to their unpaired nature. The cliffs show an inclination of 25^{0}-30^{0} towards the upstream direction. Interestingly, the right bank of the river is devoid of the Quaternary cliffs and rather represents the present-day site for the development of point-bars.

The complete succession observed on the left bank, represents an intercalated sequence of laminated silts and clays representing a single cycle of sedimentation. The laminated silt and clay units are found to be inclined with an attitude of $N60^{0}/20^{0}$ due SE and are characterized by the presence of pedogenic features, such as burrows and calcretes, in the form of thin consolidated benches and also as concretions and nodules. The succession is overlain by the presence of present-day alluvium.

(h) Variao ($72^{0}50'$; $21^{0}15'$):

In the downstream of Kamrej along the Tapi river, the cliffs show a gradual decrease in their elevation and at number of locations they are found to be concealed by the retaining walls. However, at Variao, on the right bank of the river, a cliff attaining 8m elevation is exposed comprising Quaternary sediments, dominated by laminated silt and clay units, occasionally calcretes in the form of nodules and thin benches are observed within this unit and are at places, shows gentle inclinations, which is ascribed to the local slumping.

Plate 5.9 - Field Photograph Of A Cliff Giving A View Of The Inclined Siltstone Unit And Planation Surfaces (Loc: Puna, Tapi River).

Plate 5.10 - Field Photograph Showing River Cliff Sections (Loc: Dhatwa, Tapi River).

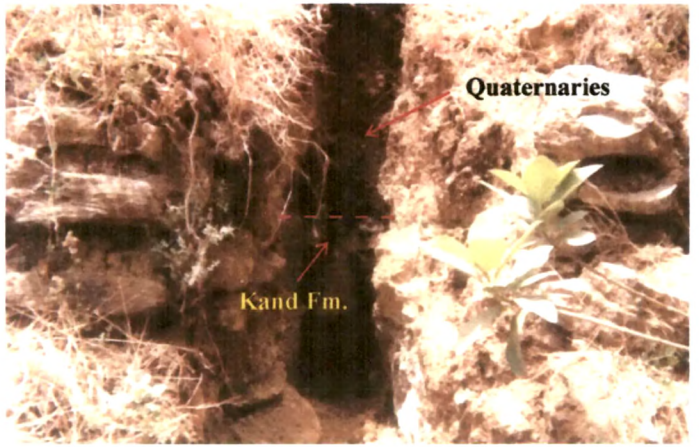


Plate 5.11 - Field Photograph Depicting The Contact Between Quaternary Sediments And Kand Formation (Loc: Gaypagla, Tapi River).

Plate 5.12 - Field Photograph Depicting The Cliff-Section Exposed At Gordha Location, Vyare Khadi.

Further downstream of Variao, right up to the mouth of Tapi river, no appreciable cliff-sections are noticed on account of the present-day settlements and construction activities. However, the bore-hole records obtained from the Surat Urban Development Authority (SUDA) for Surat city and its adjoining areas that represents the mouth of Tapi river, have been studied, in order to understand the sub-surface distribution of these sediments and their lateral continuity. Figure 5.20 shows the fence diagram prepared on the basis of bore-hole records.

The fence diagram clearly indicates the occurrence of thick Quaternary succession in the sub-surface, varying in thickness from 110 to 310m; however the base of these sediments is not known. The Quaternary sediments dominantly consist of laminated fine sand and silt units with comparatively thin intercalations of clays and occasional presence of gravel lenses. The presence of calcretes within these units is found to be limited to few locations. Overall, the sub-surface sequence represents the lateral continuation of their counterparts, exposed in the other location all along the Tapi river channel.

5.1.2.3 Vyare Khadi (Tributary of Tapi river)

The exposed cliff-sections comprising the Quaternary sedimentary record all along the Tapi river channel represents a part of the study area, however to pursue a complete understanding of the distribution of these sediments, the cliff-sections along tributary streams of higher order have also been investigated.

A close observation along some of the important tributary streams of Tapi river particularly those meeting the main stream along the right bank, has revealed the presence of an interesting assemblage of Quaternary sediments.

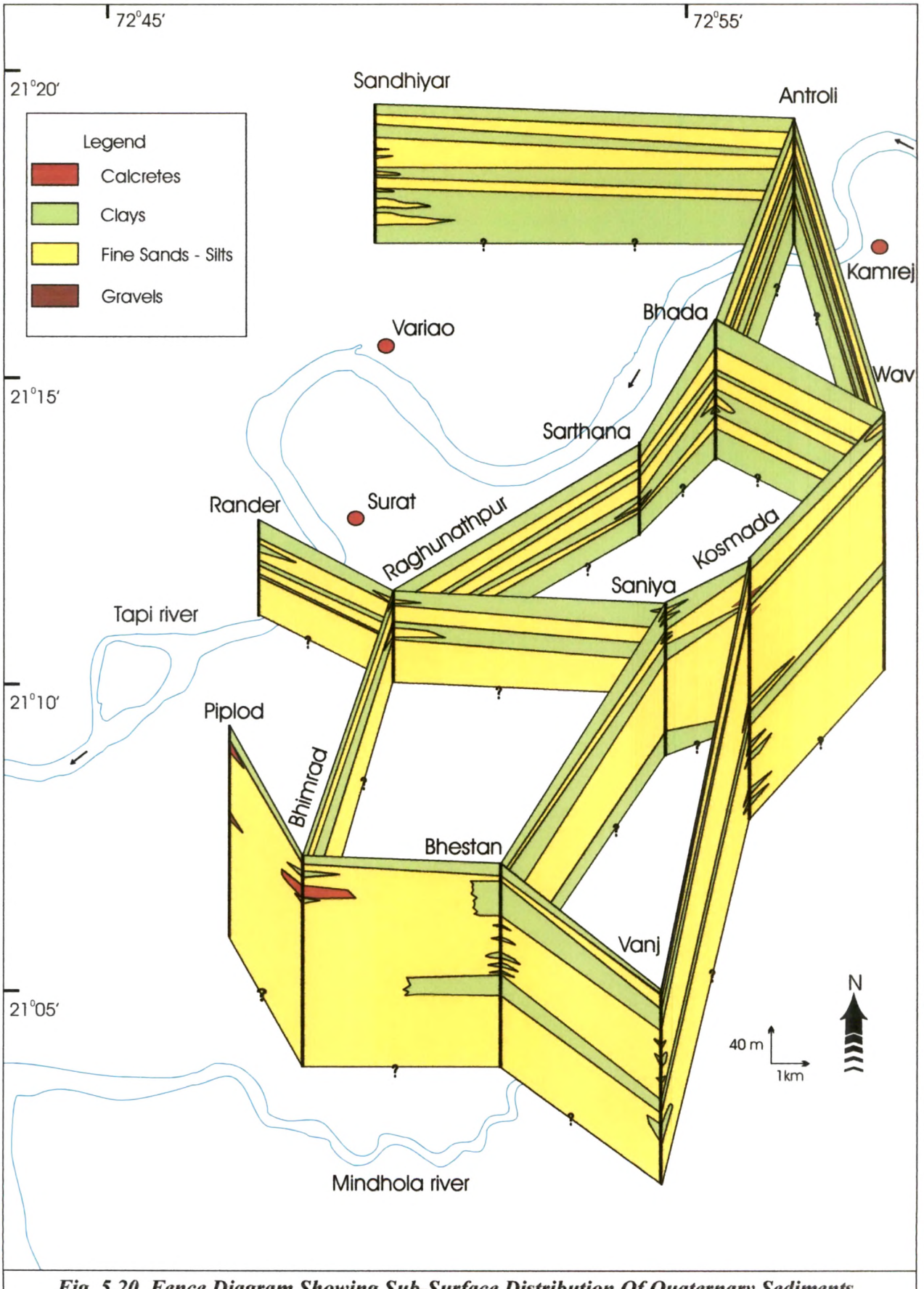


Fig. 5.20 Fence Diagram Showing Sub-Surface Distribution Of Quaternary Sediments In And Around Surat City.

Owing to this, an attempt has been made to investigate the Quaternary cliff-sections exposed along Vyare Khadi, which forms the largest tributary stream of Tapi river and practically drains through the trappean terrain (Fig. 5.1), cutting across the pockets of Quaternary deposits. Interestingly, the Quaternary deposits exhibits restricted occurrences along the segment between Devgarh and Gavachhi. The following paragraphs provide location-specific descriptions of the Quaternary successions observed along Vyare Khadi.

(a) <u>Devgarh ($73^0 21'$; $21^0 23'$):</u>

The area in the upstream of Devgarh, all along the stream bed is occupied by trappean outcrops, devoid of any signatures of Quaternary deposits. However, in the downstream, the cliff-sections on the right bank comprising Quaternary sediments attain a maximum elevation of 10m and are characterized by two cycles of fining upward sequence resting on trappean basement (Fig. 5.21).

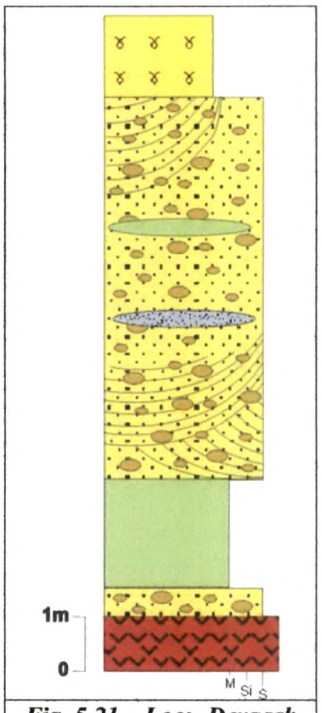


Fig. 5.21 – Loc:- Devgarh

The Quaternary succession commences with a well compacted gravelly sand unit, comprising gravel and sand clasts cemented by calcareous materials. The detrital grains exhibit poor to moderate sorting and are trappean in composition. The successive silt and clay units that follow upward are reddish in appearance, show evidences of fracturing and are associated with nodular calcretes. Similarly the second cycle of sedimentation is marked by a poorly compacted and moderately sorted gravelly sand unit, exhibiting the presence of primary sedimentary structures such as trough cross-stratifications. At places, intercalations of silt and clay lenses are observed within this unit.

(b) Phulwari ($73^0$18'; $21^0$21'):

The area around Phulwari dominantly shows excellent outcrops of trappean rocks all along the streambed and cliffs, however, few meter downstream of this location, on the left bank near Gordha village ($73^0$17.5'; $21^0$20'), cliff-sections attaining elevation of about 8m are observed consisting of Quaternary sediments (Plate 5.12), resting on the Deccan traps. The succession of sediments is similar to the one observed at Devgarh and represents the lateral continuation of the two cycles of fining upward sequences (Fig. 5.22).

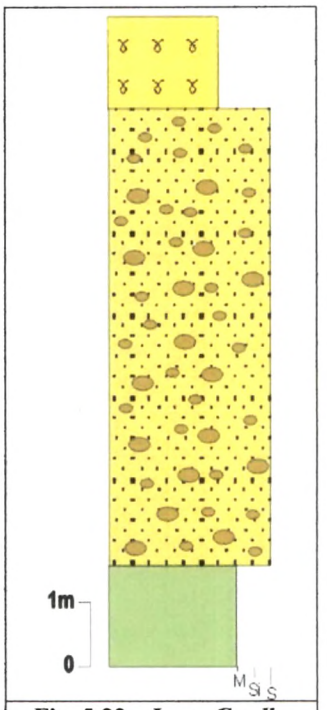


Fig. 5.22 – Loc:- Gordha

Interestingly, in the downstream side of Gordha, the Quaternary sediments show their marked absence and that the streambed as well as the cliffs is occupied by trappean outcrops. Near Gavachhi ($73^0$10'; $21^0$16'), these traps conspicuously show a tilting of about 25^0 to 30^0 due west, and continues further right up to the confluence of this stream with the main Tapi river channel near Wareli village ($73^0$7.5'; $21^0$16'). Throughout this segment, the stream bed shows the presence of number of rapids and local pool conditions.

5.1.3 Mindhola River

The Mindhola River Basin (MRB) constitutes an important and integral portion of the study area i.e., LTRB and provides vital information regarding the nature and disposition of the Quaternary sediments exposed at various locations. The present-day Mindhola river, although forms a separate basin, however, this river seems to have originated later than Tapi river and along with its tributary streams, it is found dissecting the Quaternary deposits already

developed by the drainage network of palaeo-Tapi and its tributaries. Presently the Mindhola river, originating from the trappean highlands in Maharashtra, shows similar trend as Tapi river. All along the alluvial plains, this river is characterized by winding loops and deep entrenchments, before it finally flows westwards and debouches in the Arabian sea.

Within the MRB, the Quaternary sediments are found restricted along the cliffs mainly confined to the right bank of the main river channel and also along the tributaries at places. Some illustrative cliff-sections exposed at various locations (Fig. 5.1), have been investigated for the present study, the details of which are furnished in the following paragraphs.

(a) <u>Karchaka ($73^0$11.5'; $21^0$8.5')</u>:

This location is in the upstream of the Mindhola river, east of Bardoli and is characterized by the presence of cliffs along the river channel, attaining a maximum elevation of 12 – 14m (Plate 5.13). The sediment succession comprising these cliffs rests unconformably on the trappean basement and represents the dominance of 7 – 8m thick clayey horizons, with intercalations of laminated silts and calcrete layers (Fig. 5.23). The clay units are brownish in appearance, mottled in nature, shows fractures and blocky appearance and are intensely calcretised. The effects of calcretisation are also noticed in the silty layers. Particularly the calcrete layers (15 – 40cm) have been noticed at the top of clay units throughout the succession. The overall observation indicates that the calcretes occur in various forms, such as branching, nodular, honey comb, tubular and as sheets. The end of the

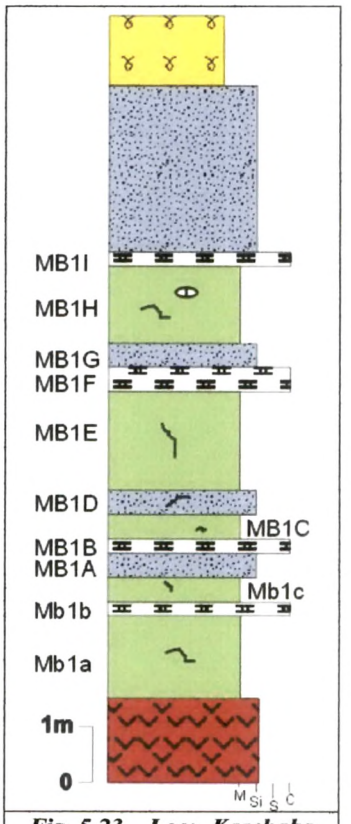


Fig. 5.23 – Loc:- Karchaka

sedimentary succession in this location is delineated by the presence of silty units (3 – 4m) resting on the uppermost calcrete layer and in turn is overlained by the present-day soils and alluvium.

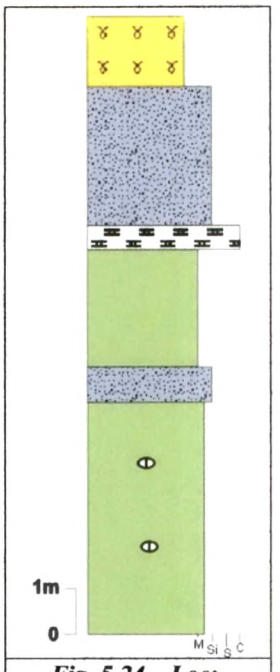


Fig. 5.24 – Loc:- Wadhawa

(b) Wadhawa (73°11'; 21°08'):

In the downstream side of Karchaka, at a distance of 2 – 2.5km, Quaternary sediments are exposed along the river cliffs around Wadhawa (Fig. 5.24). The cliffs attain a maximum elevation of about 10m and that the lithological succession is exactly similar to that of Karchaka, showing the lateral continuity, however degree of calcretisation in this succession is found to be comparatively less.

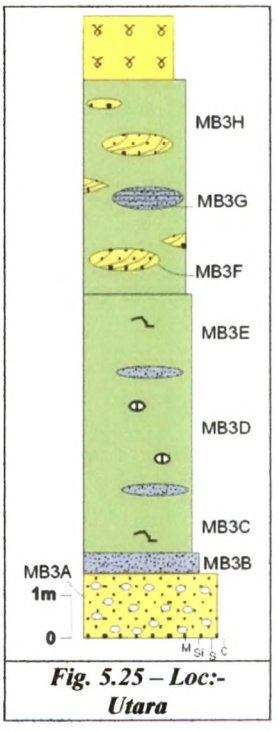


Fig. 5.25 – Loc:- Utara

(c) Utara (73°09'; 21°6.5'):

In this location, the cliff-sections comprising Quaternary sediments are exposed on the right bank of the main river channel and attain a maximum elevation of 15m.

These cliff-sections are gently inclined towards north and at places, are seen dissected by southerly flowing sub-streams/rivelutes that meets the main river at right angles. The sedimentary streams exhibit straight course, deep entrenchments and reflects their orientations along the N – S fractures, within the study area. The overall Quaternary succession around Utara, represents two distinct cycles of fining upward sequences, however the base of the succession is not exposed (Fig. 5.25). The

first cycle of sedimentation commences with a gravelly sand horizon, bimodal in nature and characterized by the presence of gravel clasts and sand clasts, showing trappean composition. This unit is gradually followed upwards by thin laminated silts and a thick clayey horizon, showing intense calcretisation. The second cycle of sedimentation is dominated by clayey horizons, however lensoidal bodies of sands and laminated silt horizons intercalating with clays are observed. These sand lenses show maximum length of 11m, with a width of 2m and are characterized by the presence of planar cross-stratification having azimuth of NW/14^0. The fore-set beds are found to show a thickness of about 30cm while the cross-stratification show a maximum length of 65cm. Pedogenic features such as the burrows, tubes etc. are seen associated with clay and silt units. The complete succession is overlain by the present-day alluvium. The sediment characteristics, associated structures and the fining upward nature of sediments, points to their deposition by fluvial agencies particularly under a meandering – channel point bar – floodplain conditions.

(d) Tajpore ($73^0 06'$; $21^0 04'$):

This location is on the left bank of Mindhola river, 3km before Sarbhan, on the Bardoli – Navsari road and represents an important location from the nature of disposition of Quaternary deposits. The cliff-sections are restricted on the left bank of the river and attain a maximum elevation of 18m. These cliffs comprise weathered outcrops of trappean rocks, having thickness of 12m (Fig. 5.26) and are unconformably overlained

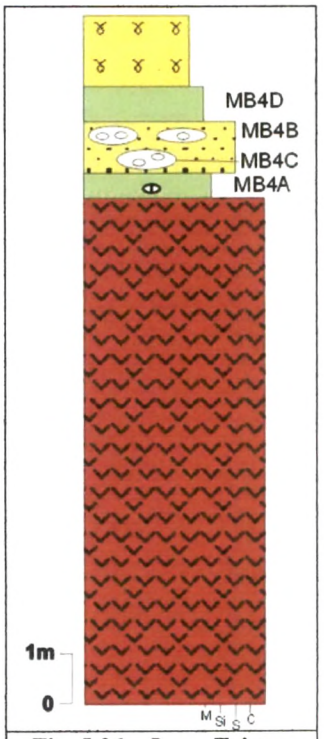


Fig. 5.26 – Loc:- Tajpura

by a 3m thick succession of Quaternary sediments. These sediments consist of laminated silt and clay units with occasional presence of gravel lenses within them. These sedimentary sequence as well as the trappean rocks and are tilted with an inclination of 15^0 to 20^0 towards SW. The presence of trappean rocks, in this location, particularly occupying the left bank of the river and their marked absence on the opposite bank, is quite significant. The sudden outcroppings of Deccan Traps, tilting of the basalts and the overlying Quaternary sediments as well as the presence of rapids in the present-day river channel, possibly points to the upliftment of this segment along the NW – SE lineaments.

(e) Amalsadi ($73^0 04'$; $21^0 05'$):

In the downstream of the Mindhola river, on the right bank near Amalsadi, the Quaternary sedimentary successions are represented in the form of cliffs (Plate 5.14), having a considerable thickness of 15m and exhibits two distinct cycles of fining upward sequences (Fig. 5.27). The first cycle comprises dominantly of yellowish brown colored clayey horizon with thin intercalation of silts and gravelly sands. These lithological units are calcretised, showing the presence of calcretic bands and thin sheets. The second cycle commences with a gravelly unit comprising sub-angular to sub-rounded clasts of trappean rocks and crypto-crystalline silica, varying in sizes from 0.5 to 3.0cm and shows imbrications in SW directions. These clasts are poorly sorted and are embedded in a

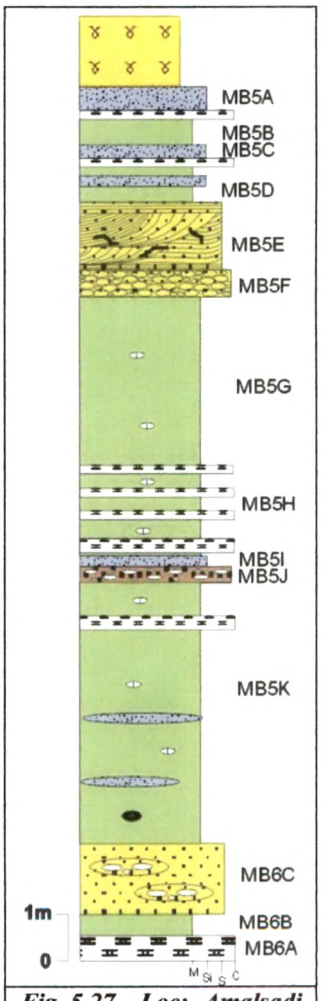


Fig. 5.27 – Loc:- Amalsadi

sandy matrix. The succeeding unit comprises medium to fine sands, mainly trappean composition and is delineated by the presence of planar as well as trough cross-stratifications showing NW/15^0 and NE/15^0 and NW/10^0 orientations respectively (Plate 5.15). The length of the troughs has been found to be varying from 1 – 6m. At places, the sand unit shows the presence of broken shell fragments. The sand unit grades upward into laminated silt and clay sequence, which is highly calcretised in nature. The calcretes occur as thin layers, intercalating with the silt and clay units and also as irregular nodules and tubes varying in sizes with a maximum length of 40cm and diameter of 3cm and at places, are found cutting across the bedding units (Plate 5.16). Along with the calcretes, the clay and silt units are also associated with the presence of burrows, having different forms, such as branching, tapering and at times irregular, filled with calcareous materials. The end of the sedimentary succession is marked by the present-day soil cover.

(f) Malekpur (73^{0}02'; 21^{0}4.5'):

Illustrative cliff sections comprising Quaternary sediments are exposed on the right bank of Mindhola river near Malekpur, which is in the downstream of Amalsadi. The sediment characteristics observed on these cliff-sections are similar to those in Amalsadi, however unlike the later, the cliff-sections at Malekpur represents three distinct cycles of fining upward sequences. The gravelly unit of the bottommost cycle, which is absent at Amalsadi, is clearly depicted in this location resting on the clayey units. The entire sedimentary succession is found resting on the calcrete bench, which is presently submerged under river water.

Plate 5.13 - Field Photograph Depicting The Cliff-Section Exposed At Karchaka Location, Mindhola River.

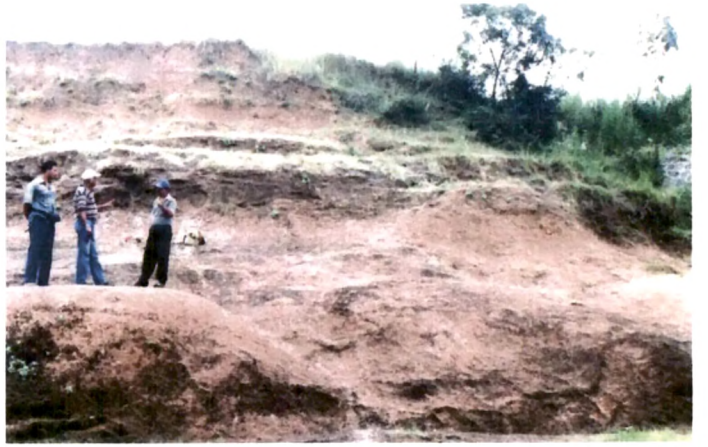


Plate 5.14 - Field Photograph Showing River Cliff And Planation Surfaces (Loc: Amalsadi, Mindhola River).

Plate 5.15 - Field Photograph Showing The Cross-Stratified Sand Unit (Loc: Amalsadi, Mindhola River).

Plate 5.16 - Field Photograph Depicting The Presence of Calcretic Tubes Within The Intercalating Silt And Clay Units (Loc: Amalsadi, Mindhola River).

(g) Palsana ($72^0$59'; $21^0$4.5'):

This location constitutes one of the important areas of occurrence of Quaternary deposits within the Mindhola river basin. In this location, two distinct planation surfaces are observed and the present-day river channel shows deep entrenchments and sprawls in the form of hair-pin bends and tight winding loops. Cliff-sections comprising Quaternary sediments are exposed along the Mindhola river and its tributaries near Palsana. One such exemplary cliff attaining an elevation of 20m along the tributary stream on the northern bank of main river channel has been studied in detail (Fig. 5.28). The nature of sediments observed in this cliff-section represents three distinct cycles of fining upward sequences.

The bottommost cycle comprises exclusively a yellowish brown clay unit characterized by pedogenic features, streaks of organic carbon and bentonite and in turn is marked by the presence of calcrete horizon towards the top. The second cycle of sedimentation begins with medium to coarse sands, comprising sub-angular to sub-rounded trappean clasts, which are moderately sorted in nature. The laminated silt and mud units, follows the sand horizons, represented by the occurrence of intercalated cross-stratified sand layers, at places. The silt and clay units are calcretised and shows pedogenic features, such as burrows, filled with the secondary calcareous materials. The third cycle of sedimentation commences with a gravel horizon, which gradually shows a progressive decrease in the grain size, representing a medium to coarse sands. Both these units comprise clasts of trappean composition, which are moderately to poorly sorted and shows the presence of cross-stratifications. The end

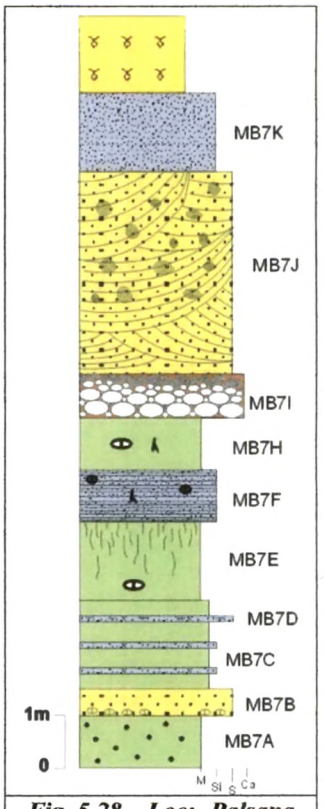


Fig. 5.28 – Loc:- Palsana

of the cycle is marked by the presence of a thin laminated silt unit, over which the present-day soil cover is observed. Taking into account the textural maturity of the sediments, and their fining upward nature, it is very much evident that the entire sequence represents the deposition by fluvial action under a meandering – channel bar – floodplain conditions.

(h) National Highway Bridge (72°58'; 21°03'):

This location is further downstream of Mindhola river representing partly the sedimentary succession observed at Palsana (Fig. 5.29). It comprises medium to coarse sands with presence of large scale trough cross-stratifications having orientation 20^0 due north and 24^0 due south. The sand units are followed upward by laminated silt and clay units, representing intense calcretisation and pedogenic features. The calcretes occur as irregular nodules and also as tubular forms, having a maximum length of 40cm and 6-8cm diameter. The pedogenic features are exhibited in the form of burrows filled with the calcareous materials and their appreciable presence imparts a honey comb nature to the sedimentary units.

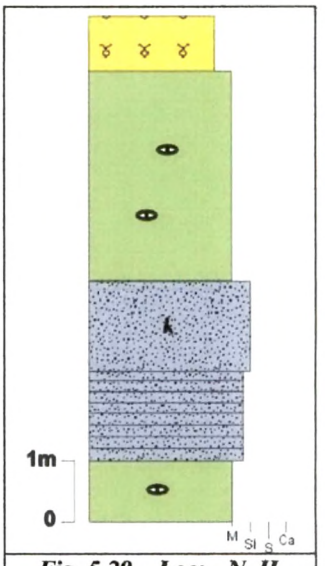


Fig. 5.29 – Loc: - N. H. Bridge

(i) Kansad (72°53'; 21°03'):

Further downstream of Mindhola river, the overall elevation of the cliffs gradually decreases however, the proportion of finer

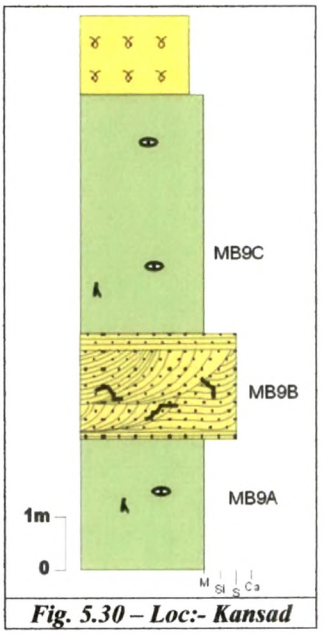


Fig. 5.30 – Loc:- Kansad

sediments (clay units) increases accordingly. One such observation has been made along a cliff-section at Kansad, near the mouth of the Mindhola river. The cliff attains a maximum elevation of 8m and its erosional surface exhibits a thick accumulation of intercalated laminated silt and clay horizons with a 2m thick silty sand horizon, almost in the middle of the succession (Fig. 5.30). Trough cross-stratifications have been observed in the sand units showing azimuths of 18^0 due SW and 24^0 due NE. evidences of calcretisation are observed in this succession, wherein the calcretes occur as irregular nodules, bands and branching tubes that cut across the entire succession vertically.

5.2 CALCRETES

Duricrusts (Woolnaugh, 1927), has been defined by Goudie (1973) as "a product of terrestrial processes within the zone of weathering in which either iron and aluminium sesquioxides or silica or calcium carbonate or other compounds like manganese have accumulated in and/or replaced a pre-existing soil, rock or weathered material, to give a substance which may ultimately develop into an indurated mass." These duricrusts, depending on the chemical compositions, have been classified in to Calcretes (comprising calcium carbonates); Ferricretes (comprising oxides and hydroxides of iron); Silicretes (composed of silica) and Gypsicretes (composed of gypsum).

Calcretes are a form of duricrusts, defined as "a terrestrial material composed dominantly, but not exclusively of $CaCO_3$, which occur in states ranging from nodular and powdery to highly indurated and result mainly from the displacive and/or replacive introduction of vadose carbonates in to greater or lesser quantities of soil, rock or sediments within a soil profile" (Watts, 1980). The study of calcretes is demanding in a way that they help in deciphering the past climatic changes.

Although, calcretes are developed almost every where in the Tapi river basin, there complete sequence of calcretisation is not ubiquitously seen. However, the calcrete profile observed at Dhatwa section displays an illustrative sequence of calcretisation beginning from calcified soil to highly indurated forms (Plate 5.17). Owing to the objectives of the present study, an in-depth study of these calcretes has not been done, however a complete genetical classification (Goudie, 1983) has been attempted based on their physical characteristics and sequence of development.

As seen in figure 5.31, the lower most (first) gravelly sand member does not show any feature of calcification. However, in the second gravelly sand member, the calcretes are well developed in the form of nodular calcretes. The size of these nodules and the intensity of calcretisation increases towards the upper portions within the same litho-unit, finally giving rise to the formation of a honeycomb calcretes. The nodules observed in the lower portion are soft and irregular in shape, occurring within a sandy matrix, whereas the nodules observed in the upper portions of this horizon are hard, discrete and well rounded in shape and are occurring within a predominantly powdery calcretic matrix (sand matrix < 50%). The honeycomb calcretes, representing the topmost portion of this horizon, is pinkish in appearance and has formed by virtue of carbonate accretion and recementation. Due to the coalesced nature of honeycomb calcretes, the matrix content is very less. This horizon is capped by the development of a massive,

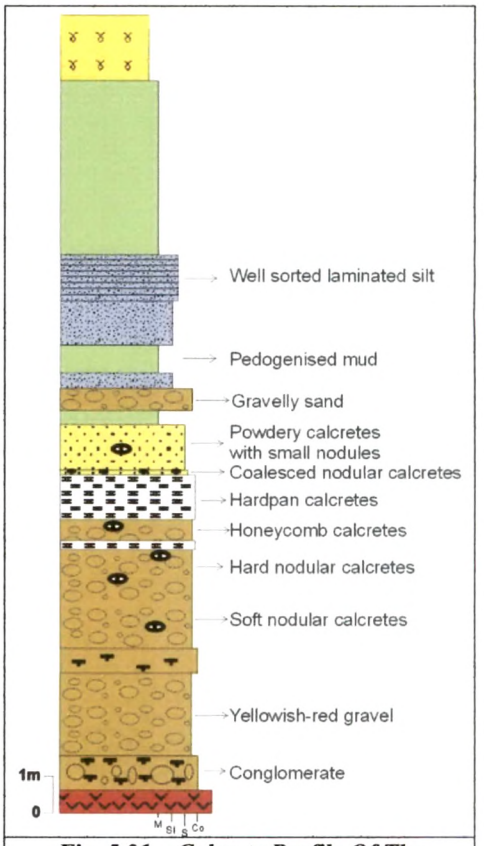


Fig. 5.31 – Calcrete Profile Of The Exposed Cliff-Section (Loc:- Dhatwa)

compact hardpan calcrete (1.0m thick), which is also pinkish in color and merge progressively with the underlying nodular calcrete horizon.

The hardpan calcrete is followed upward by a sand unit, which shows considerable features of lime redistribution in the form of powdery calcretes. These powdery calcretes constitute fairly compacted and cemented fine grained sands, along with silt sized calcite grains, which mainly accommodates the pore spaces within these detrital grains. This unit also shows occasional presence of small nodules. A thin band of a transitionary coalesced nodular variety of calcrete occurs between this powdery calcretes and the underlying hardpan calcretes. The powdery calcretes has a sharp boundary with the underlying nodular calcrete horizon. Further these types of features of lime redistribution are not deciphered in the various litho-units occurring above this horizon.

The field characteristics as well as the sequence of calcrete development suggests that dominantly these calcretes represent non-pedogenic origin, developed on account of the lateral seepage of through flowing streams as well as ground waters. However, at certain locations stray evidences of pedogenic origin is also noticed towards the top of the stratigraphic successions.

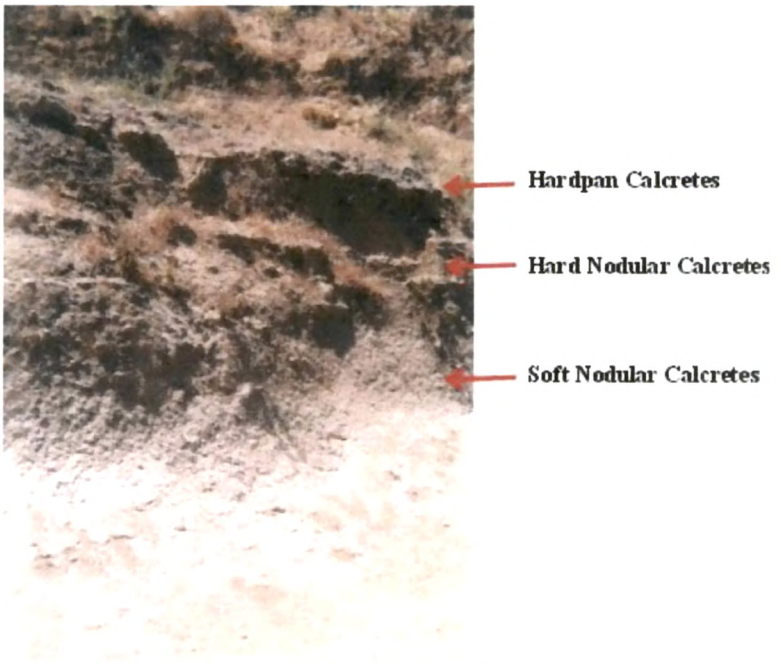


Plate 5.17 –Field Photograph Depicting Sequence Of Calcretisation (Loc: Dhatwa, Tapi River).