Chapter - 6

LITHOFACIES

VI.1. INTRODUCTION:

The study and interpretation of textures, sedimentary structures, fossils and lithologic association of sedimentary rocks on the scale of an outcrop, well section or small segment of a basin comprises the subject of facies analysis (Miall, 1984). As suggested by Miall (1984), the word facies is used in both, a descriptive and an interpretive sense. According to him, descriptive facies include certain observable attributes of sedimentary rock bodies, which can be interpreted in terms of depositional processes. An individual lithofacies is considered to be a rock unit defined on the basis of its distinctive lithologic features, including composition, grain size, bedding characteristics and sedimentary structures. Each lithofacies represents an individual depositional event, which are characteristic of particular depositional environments. These are commonly cyclic, and form the basis for defining sedimentation models (Miall, 1984). The term is also used in an interpretive sense, for group of rocks that are thought to have been formed under similar conditions, and may refer to a particular depositional environment, encompassing a wide range of depositional processes.

Any objective interpretation of depositional environments, thus, the writer believes, has to begin with lithofacies description, and can then progress after appreciation of lateral facies variations and consideration of modern environments and processes. In most cases, it is only after this stage has been reached that depositional environments can be relatively inferred (Reading, 1978).

According to Miall (1984) with the help of lithofacies studies, one can understand depositional environments and palaeogeography existing at the time a rock unit was formed and can be better placed to make predictions and extrapolations about lateral changes in thickness and composition. Obviously this will be invaluable for correlation purposes, and can make for a much more logical definition of formal lithostratigraphic units. The end product of this work is a palaeogeographic synthesis, depicting an interpretation of the stratigraphic and geographic evolution of the basin through time. Large scale basin fill patterns have been emerged and referred to as depositional environments. The difference between facies interpretation and depositional environment is not clear-cut (Miall, 1984), and hence some overlap between the two is unavoidable.

In the present study, each lithofacies is first defined on purely objective grounds, and is then used as a basis for its inferred depositional environment discussed later. The limited occurrences and poor areal distribution of exposures limit the stablishment of detailed regional facies trends. As a result, the present study is focussed mainly on vertical facies relationships exhibited at each outcrop. The inferred vertical relationship based on the characteristic biogenic structures in each facies is further discussed in detail in chapters - VII and VIII.

In order to gain detailed facies information, stratigraphic sections were measured at the localities given in table no. 8. Lithological correlation was accomplished by 'walking out' the strata and by referring the individual beds to their stratigraphic positions below or above the unconformities identified or important time planes viz. the Astarte bed, the Bivalve Sandstone bed (in the middle part of the Ler Member) and the Dhosa Oolite beds.

The Mesozoic sequence in the study area consists of ten principal lithofacies. This discrimination is based on area of occurrence, lithofacies geometry and stratigraphic position, lithology and texture, physical and biogenic sedimentary structures and on pattern of vertical sequence. Representative lithofacies are shown in fig. 8 and 9. There will be a consideration of the relations among these lithofacies following a brief description and interpretation of each lithofacies. It should, however, be noted that most of these lithofacies are repeated in their vertical extents and also integrate with each other in their lateral extent. The vertical sequence of facies also varies from outcrop to outcrop, and not all facies are repeated at all localities (fig-10).

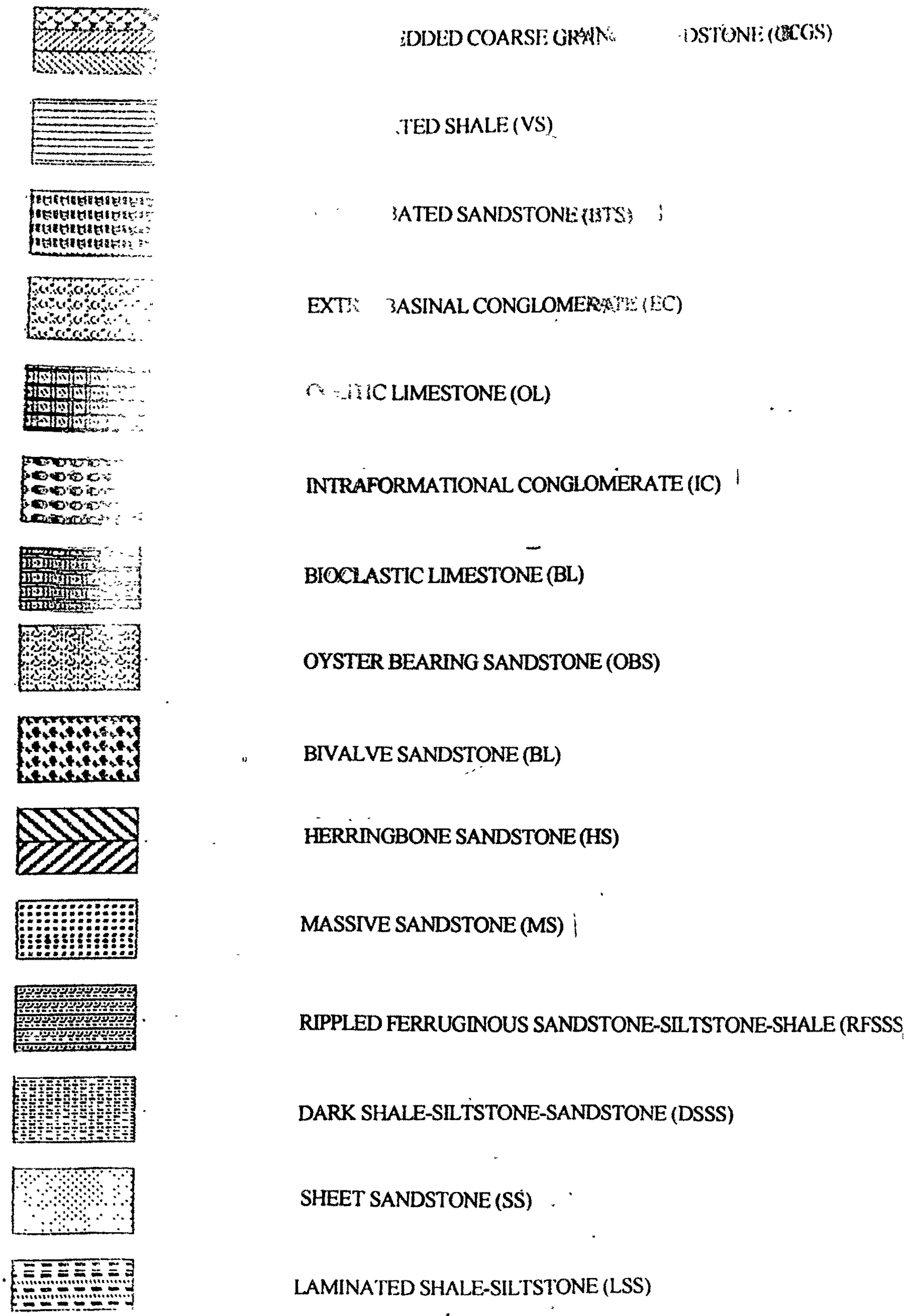


FIGURE - 8 SYMBOLS OF LITHOFACIES

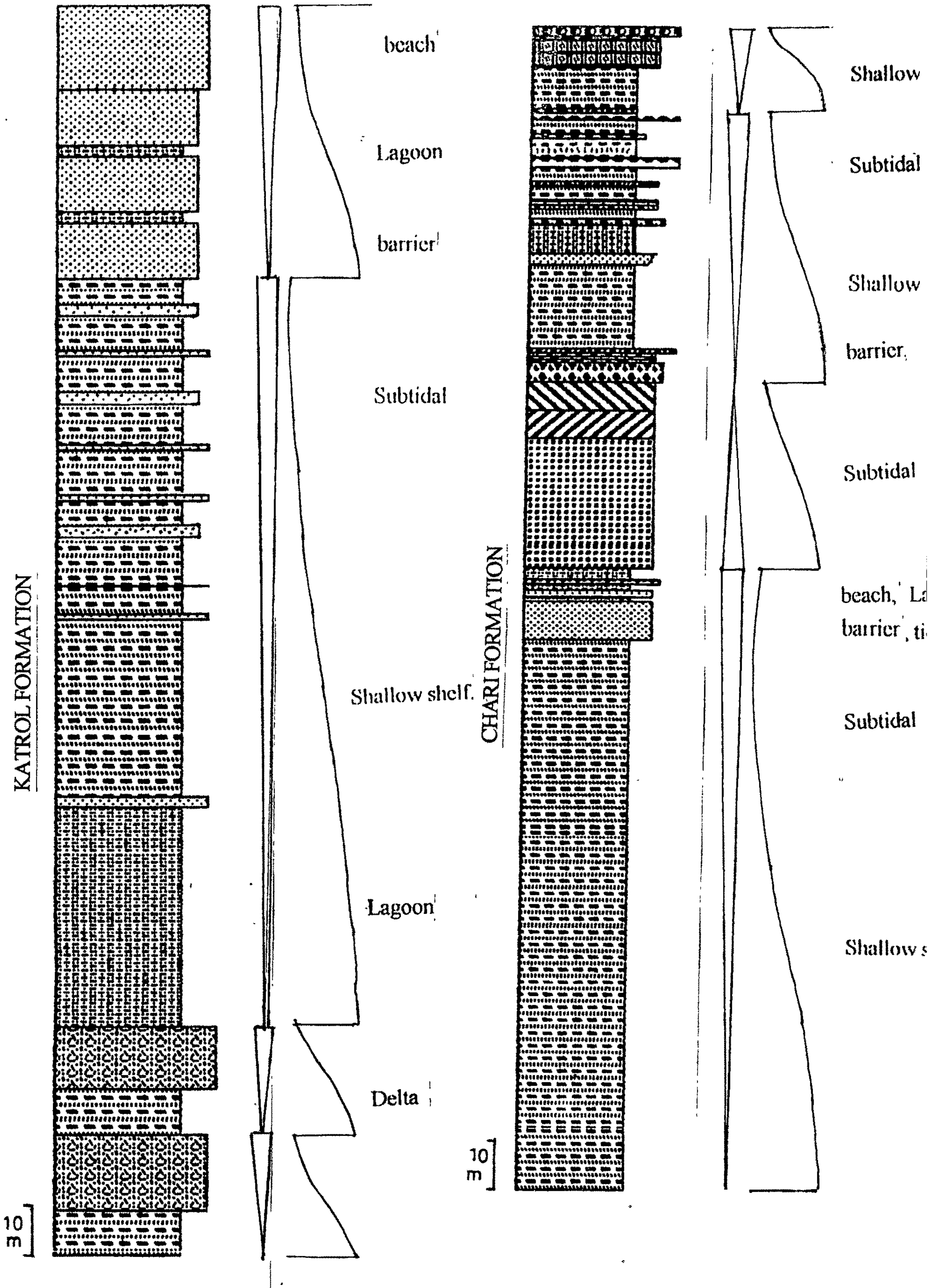


FIGURE - 9a. COMPOSITE STRATIGRAPHIC SECTION OF MESOZOIC SEQUENCE IN THE STUDY AREA - CHARI FORMATION AND KATROL FORMATION

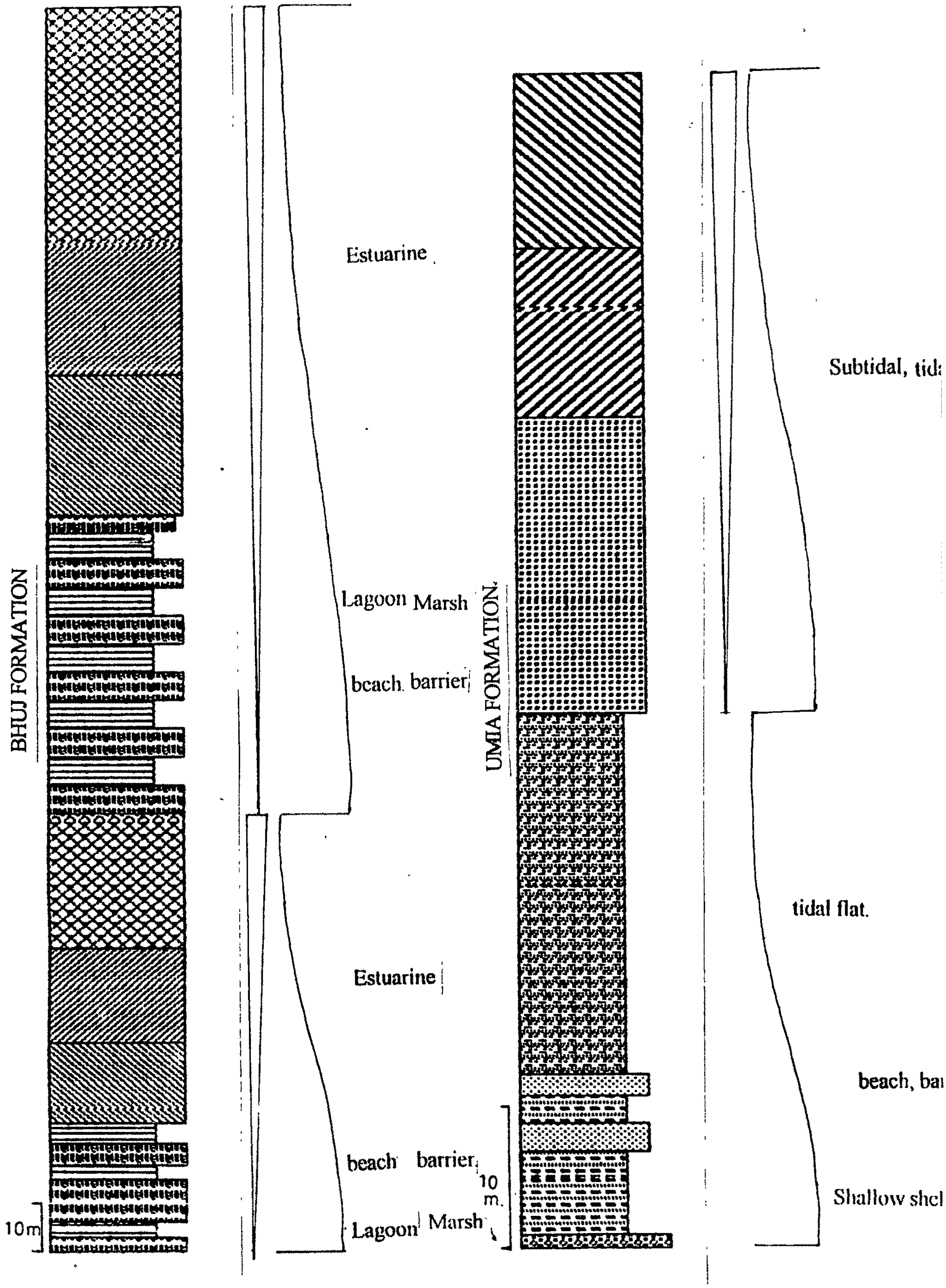


FIGURE - 9b. COMPOSITE STRATIGRAPHIC SECTION OF MESOZOIC SEQUENCE IN THE STUDY AREA - UMIA FORMATION AND BHUJ FORMATION.

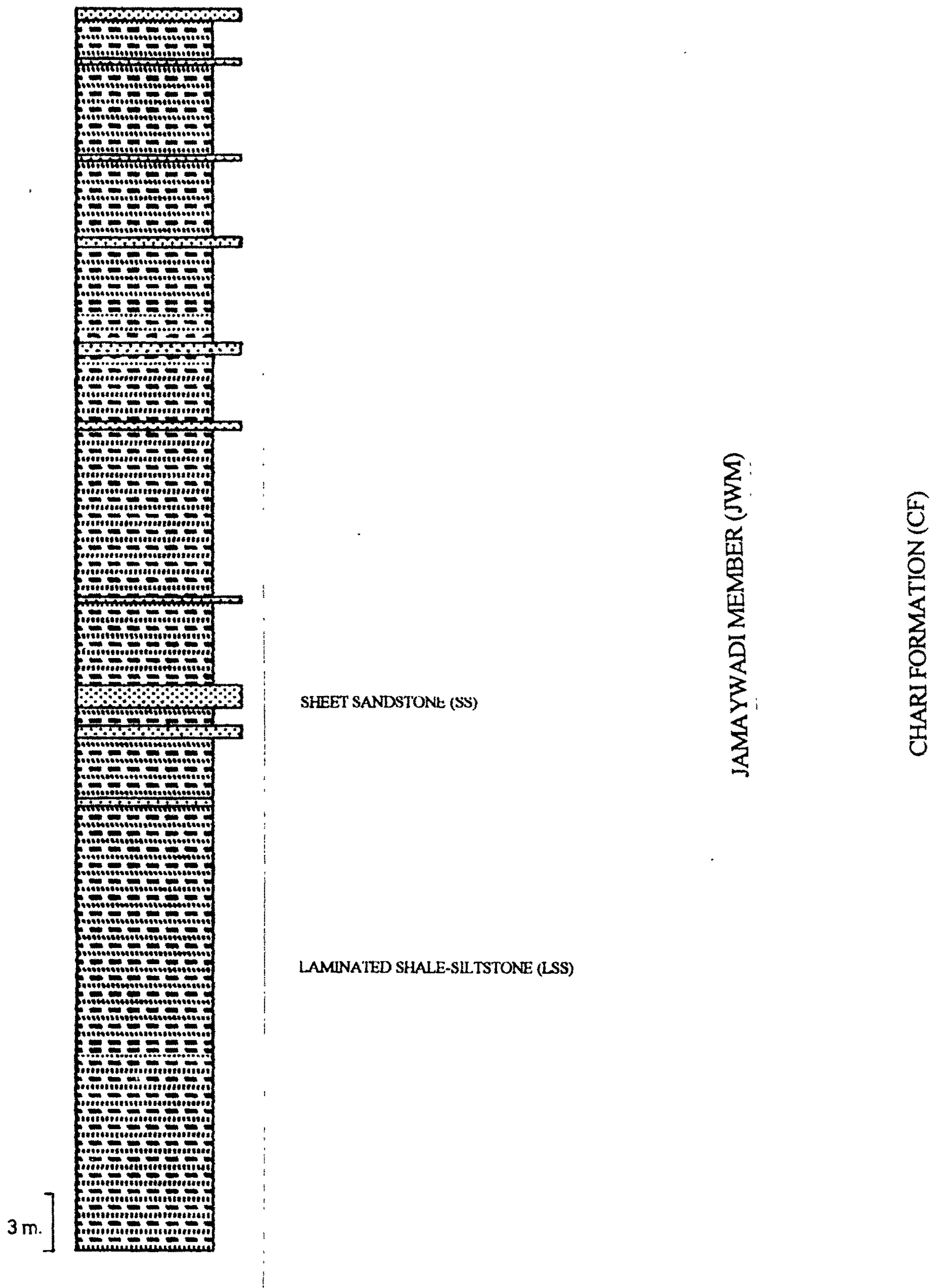


FIGURE - 10a.MEASURED STRATIGRAPHIC SECTION - NEAR JAMAYWADI.

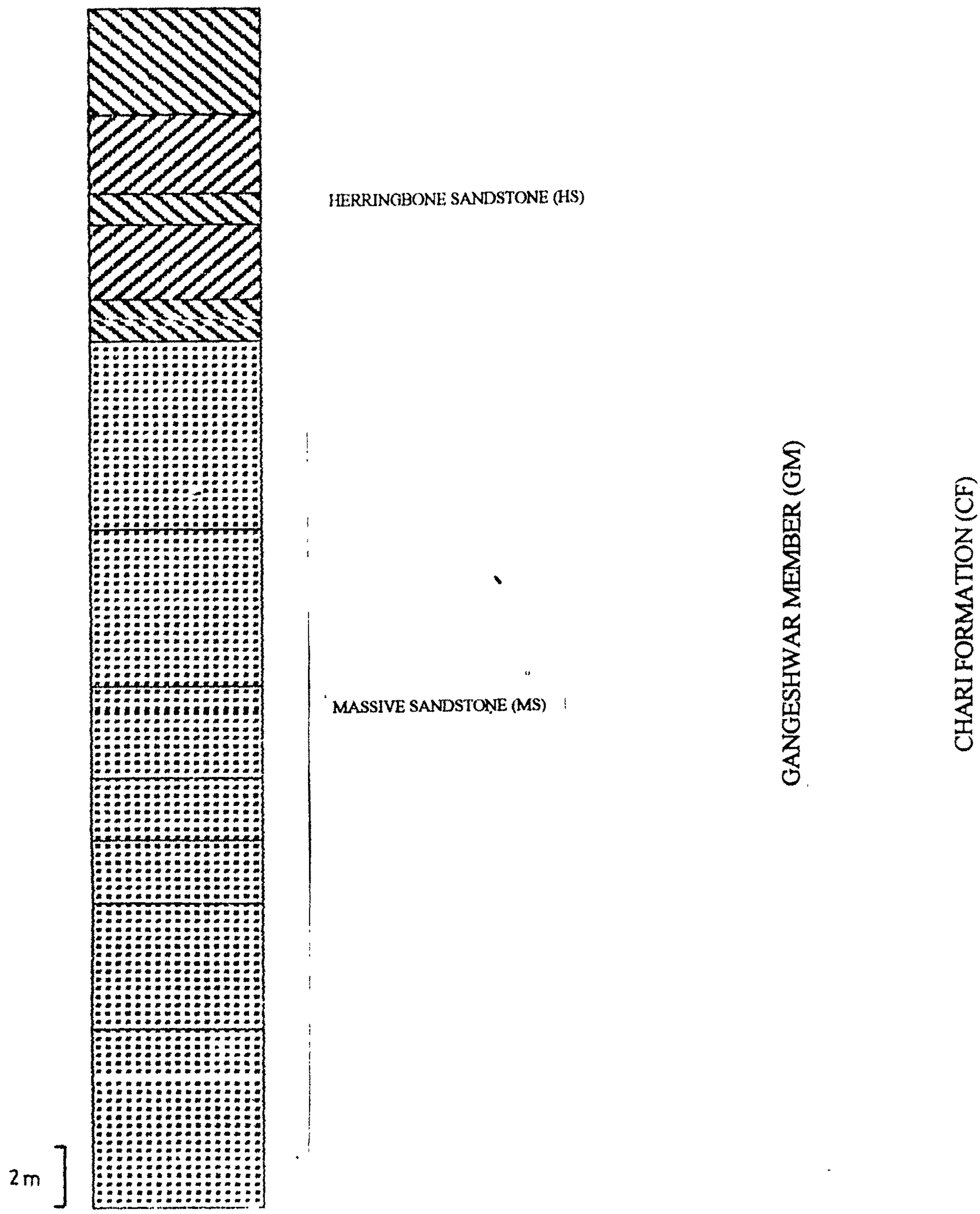


FIGURE – 10b.MEASURED STRATIGRAPHIC SECTION - AT GANGESHWAR.

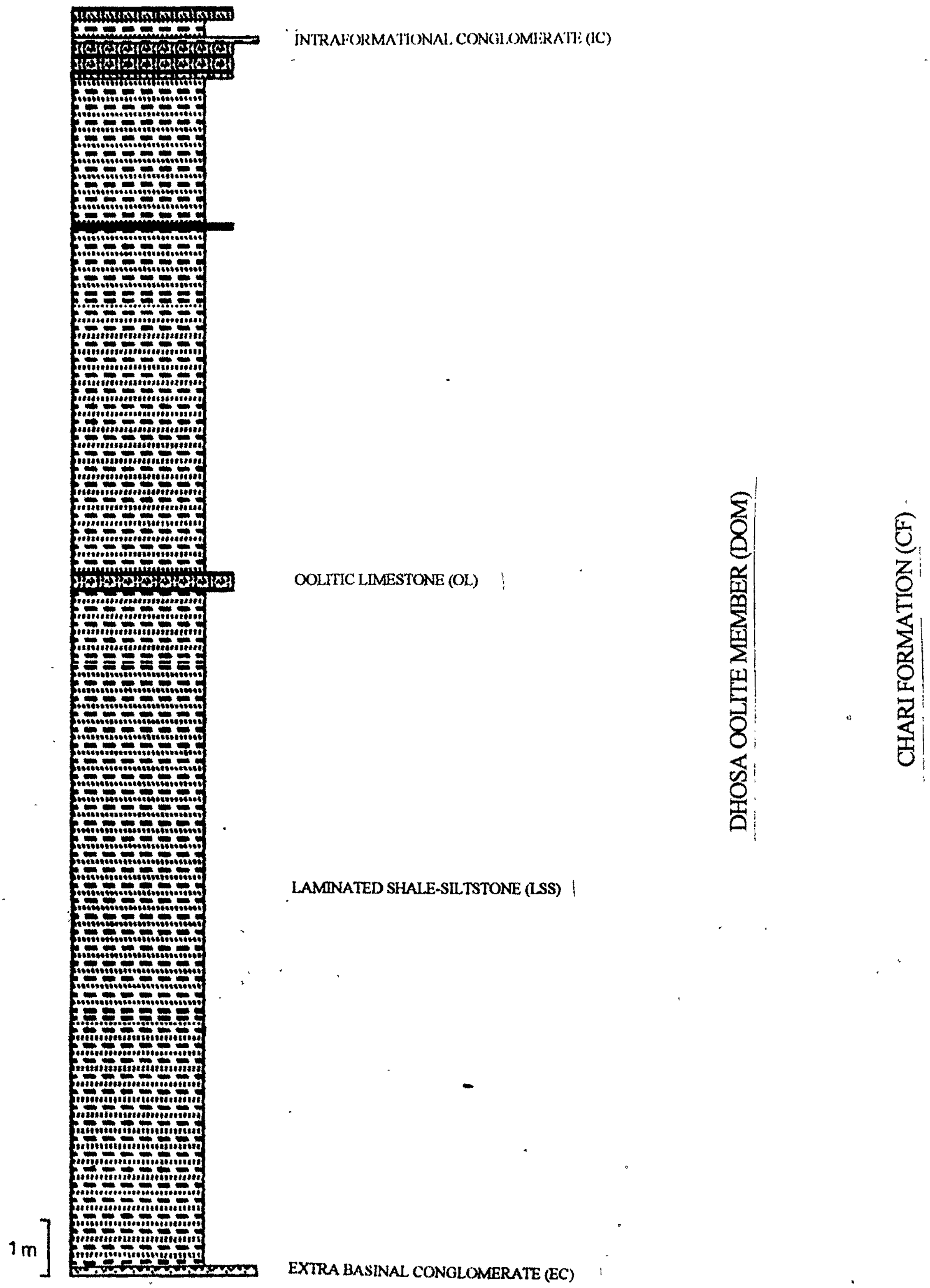


FIGURE – 10c.MEASURED STRATIGRAPHIC SECTION - AT LER (NALA SECTION, LEFT BAN

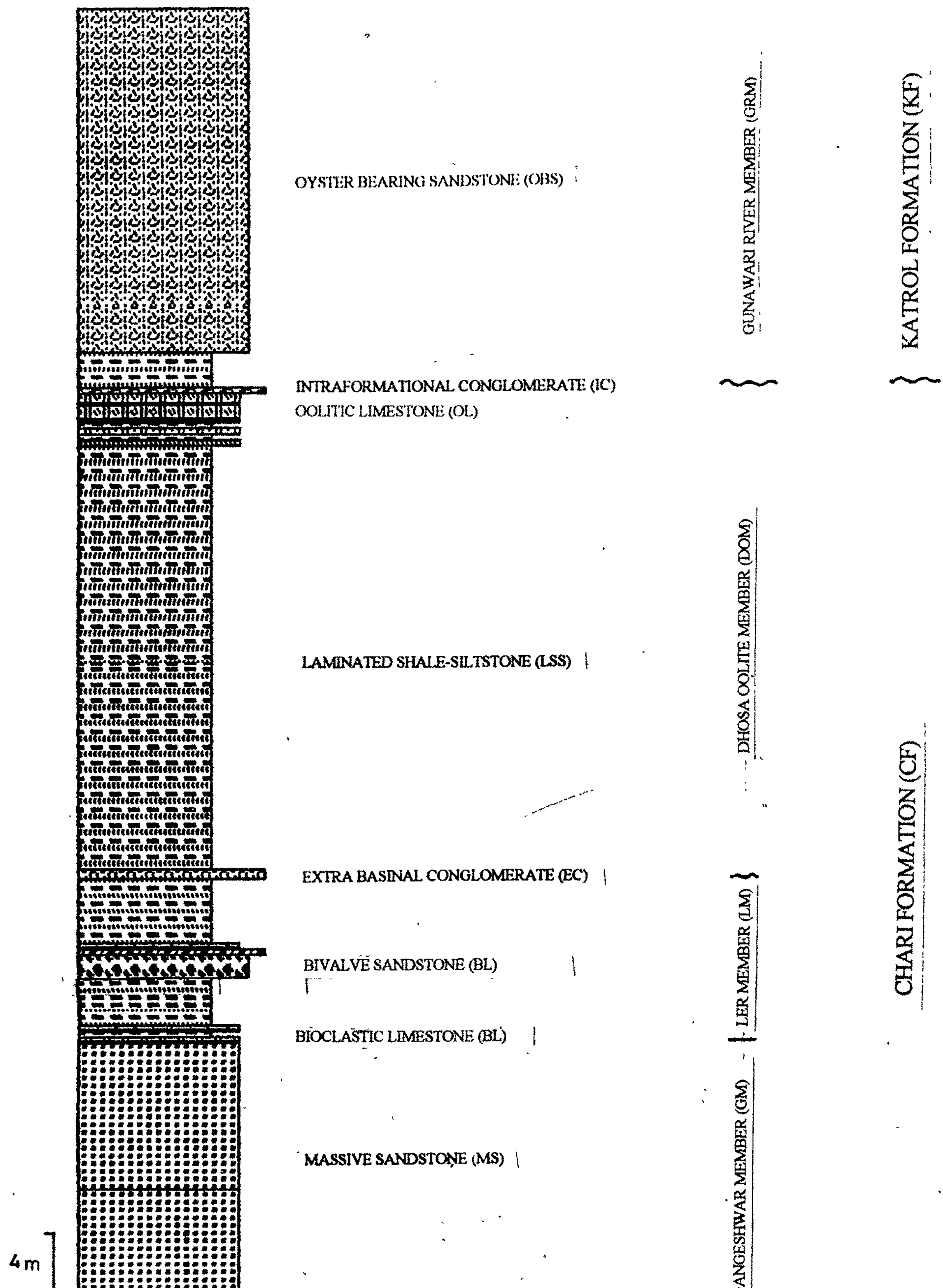


FIGURE – 10d.MEASURED STRATIGRAPHIC SECTION - AT SATPURA DUNGAR

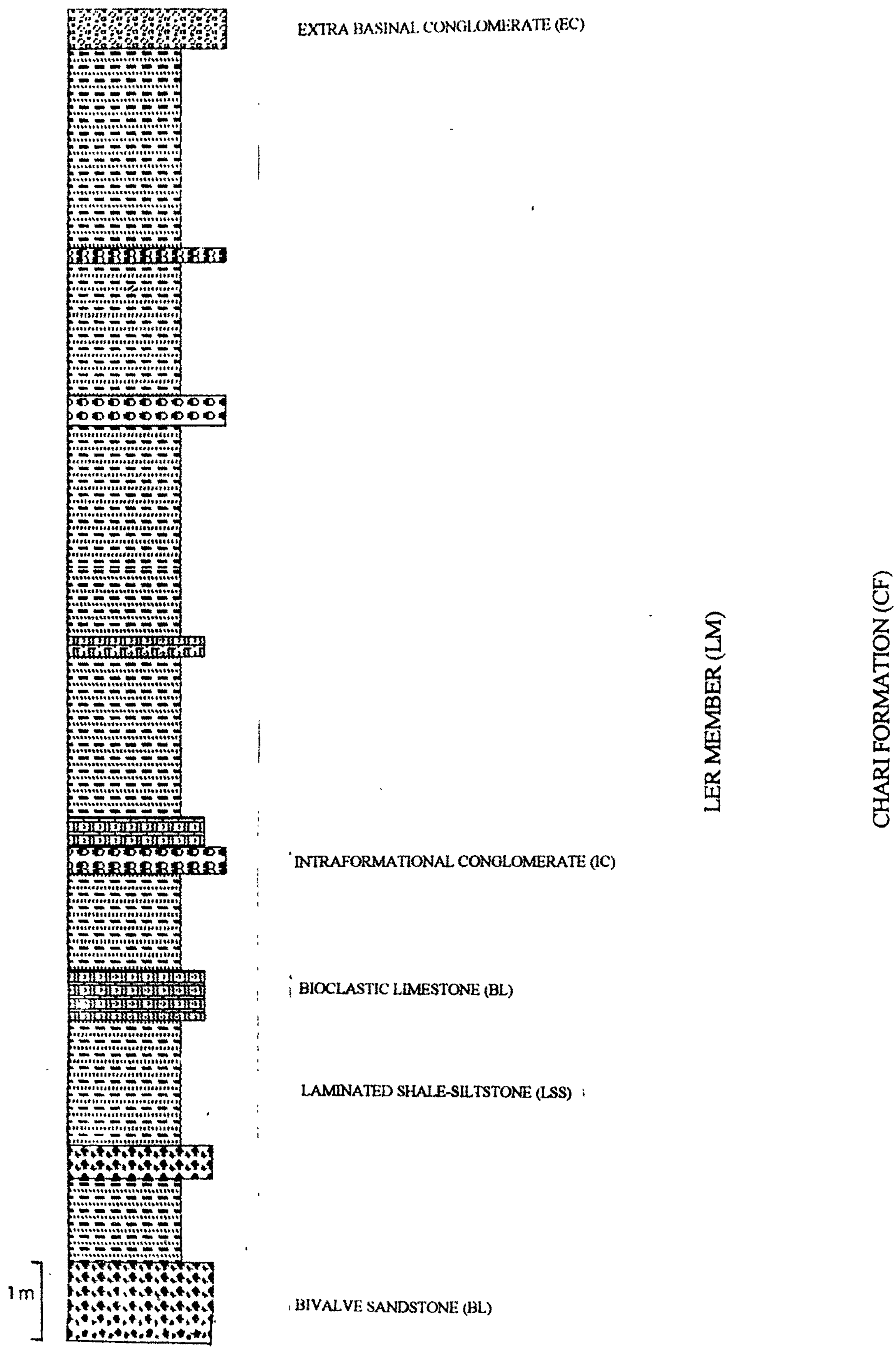


FIGURE – 10e.MEASURED STRATIGRAPHIC SECTION - AT LER
(NALA SECTION, RIGHT BANK)

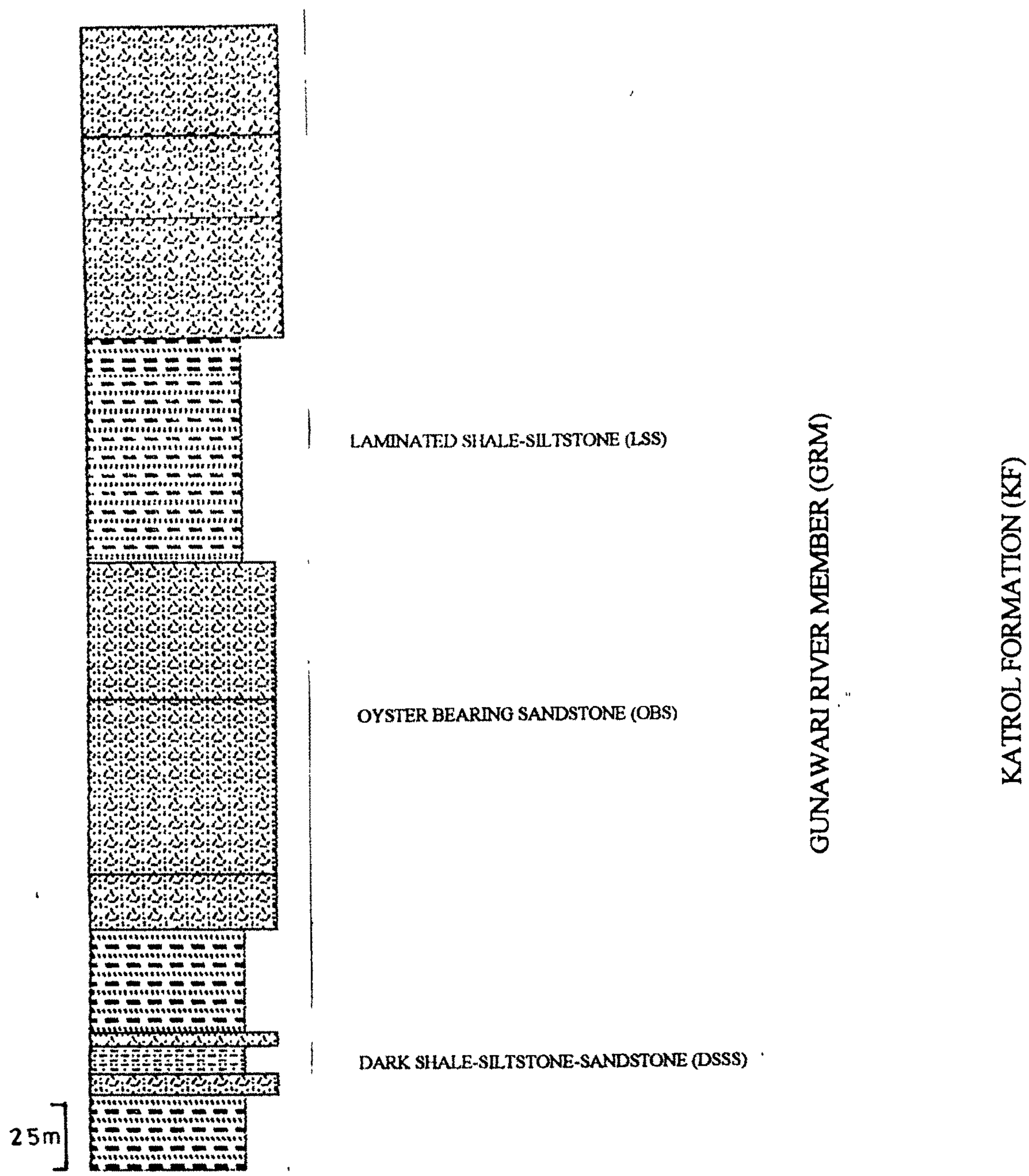


FIGURE – 10f.MEASURED STRATIGRAPHIC SECTION - ALONG GUNAWARI RIVER

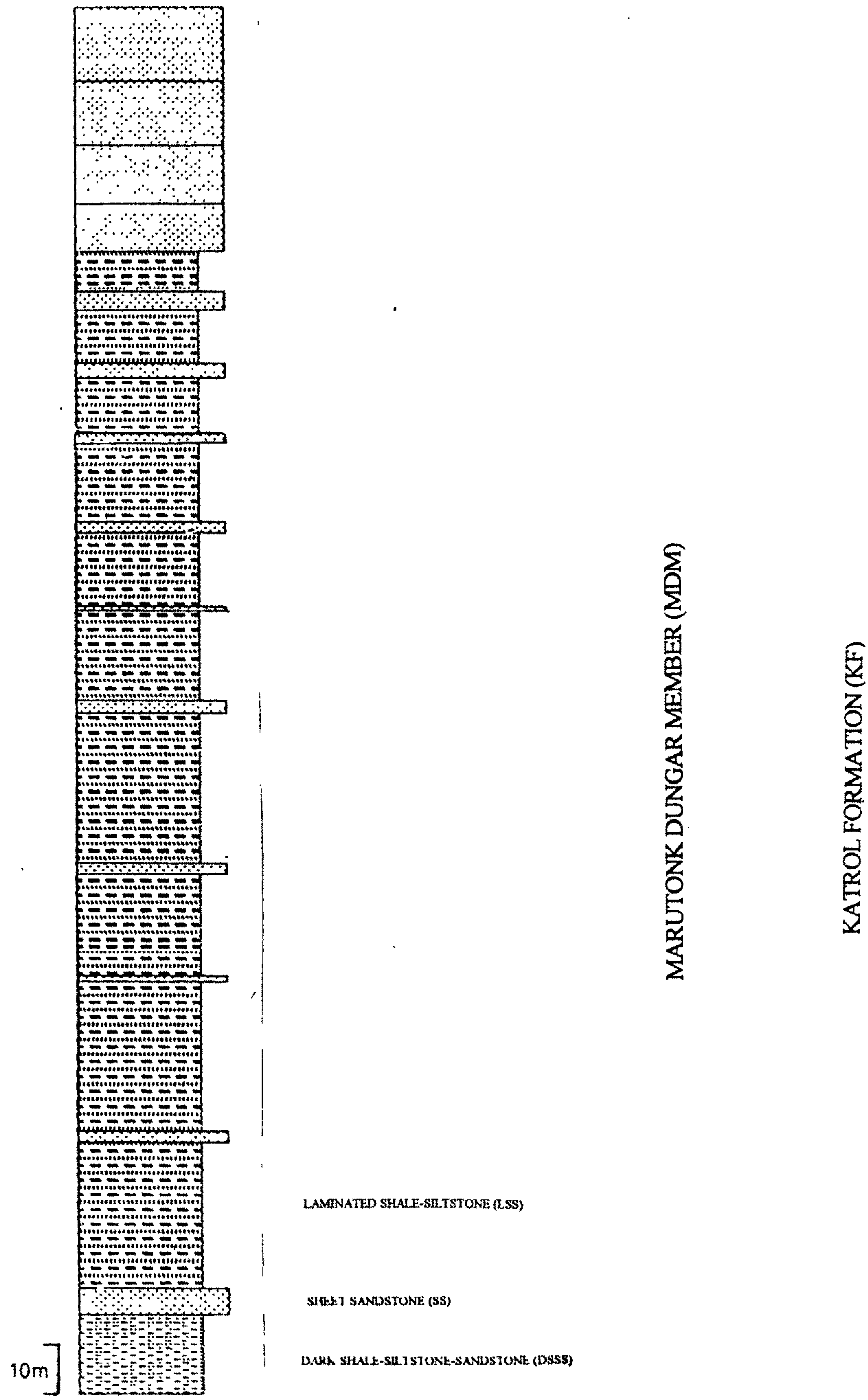


FIGURE – 10g.MEASURED STRATIGRAPHIC SECTION - AROUND MARUTONK DUN

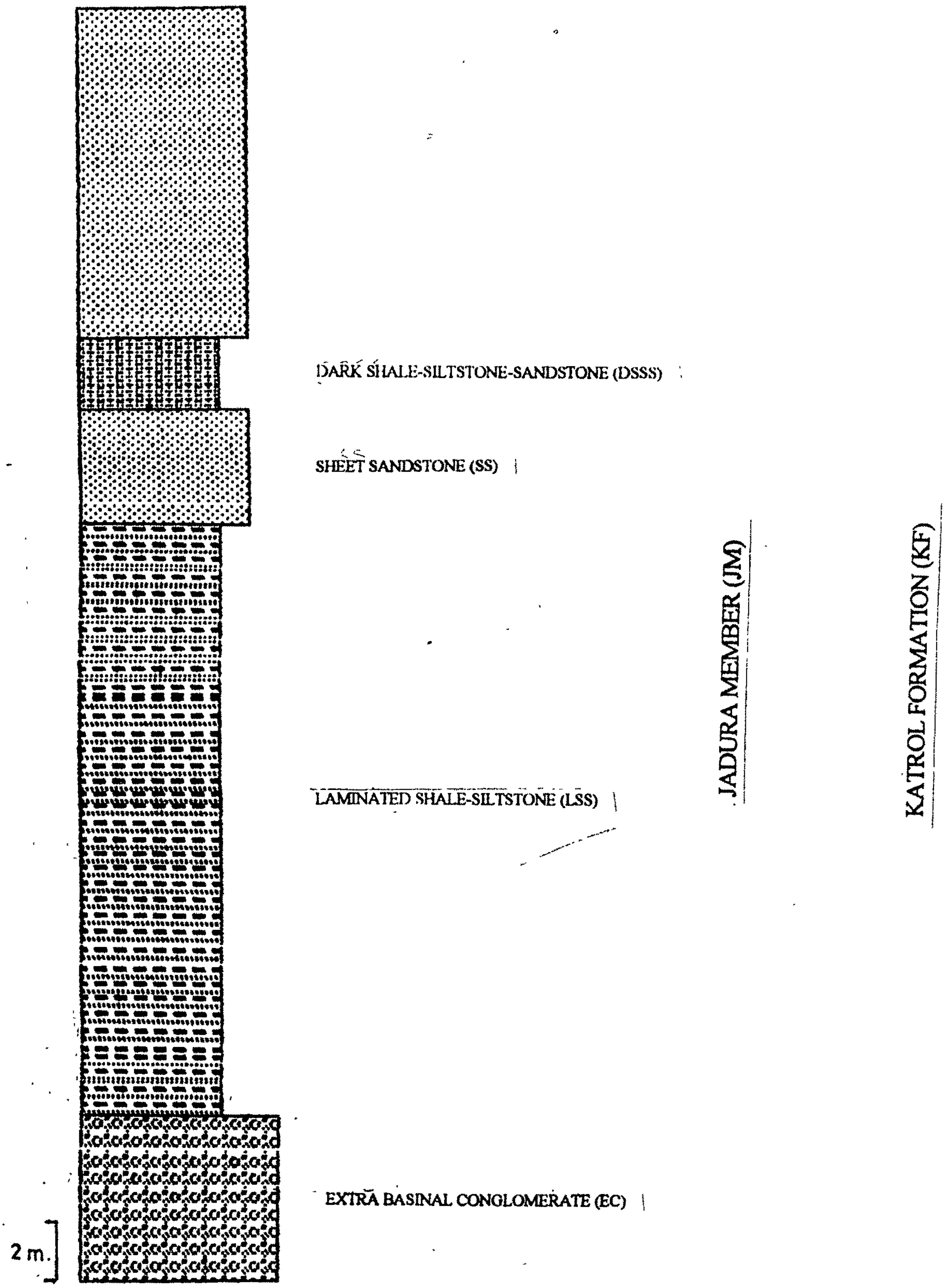


FIGURE – 10h.MEASURED STRATIGRAPHIC SECTION - AROUND JADURA MOTA

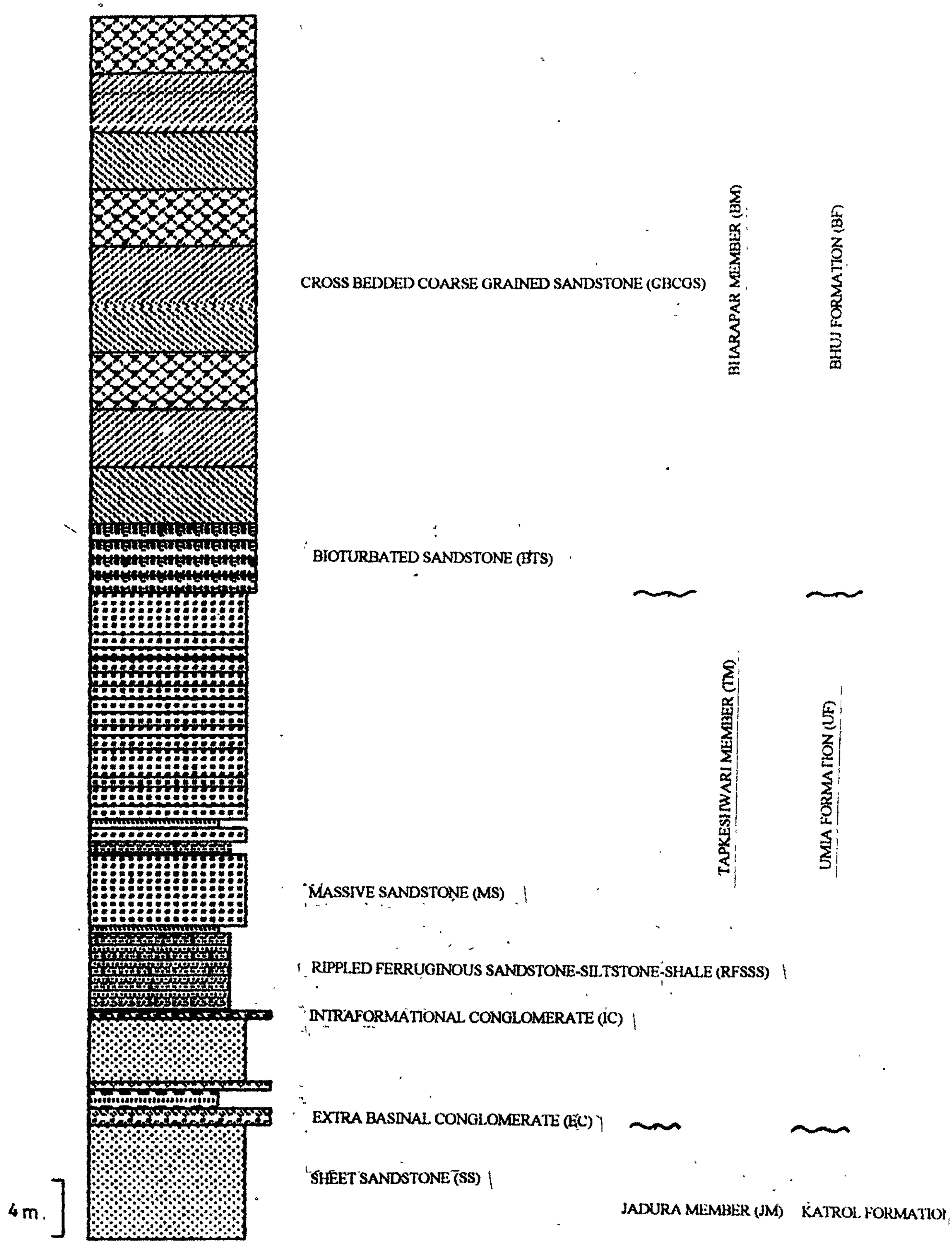


FIGURE - 10i.MEASURED STRATIGRAPHIC SECTION - AROUND JADURA NANA.

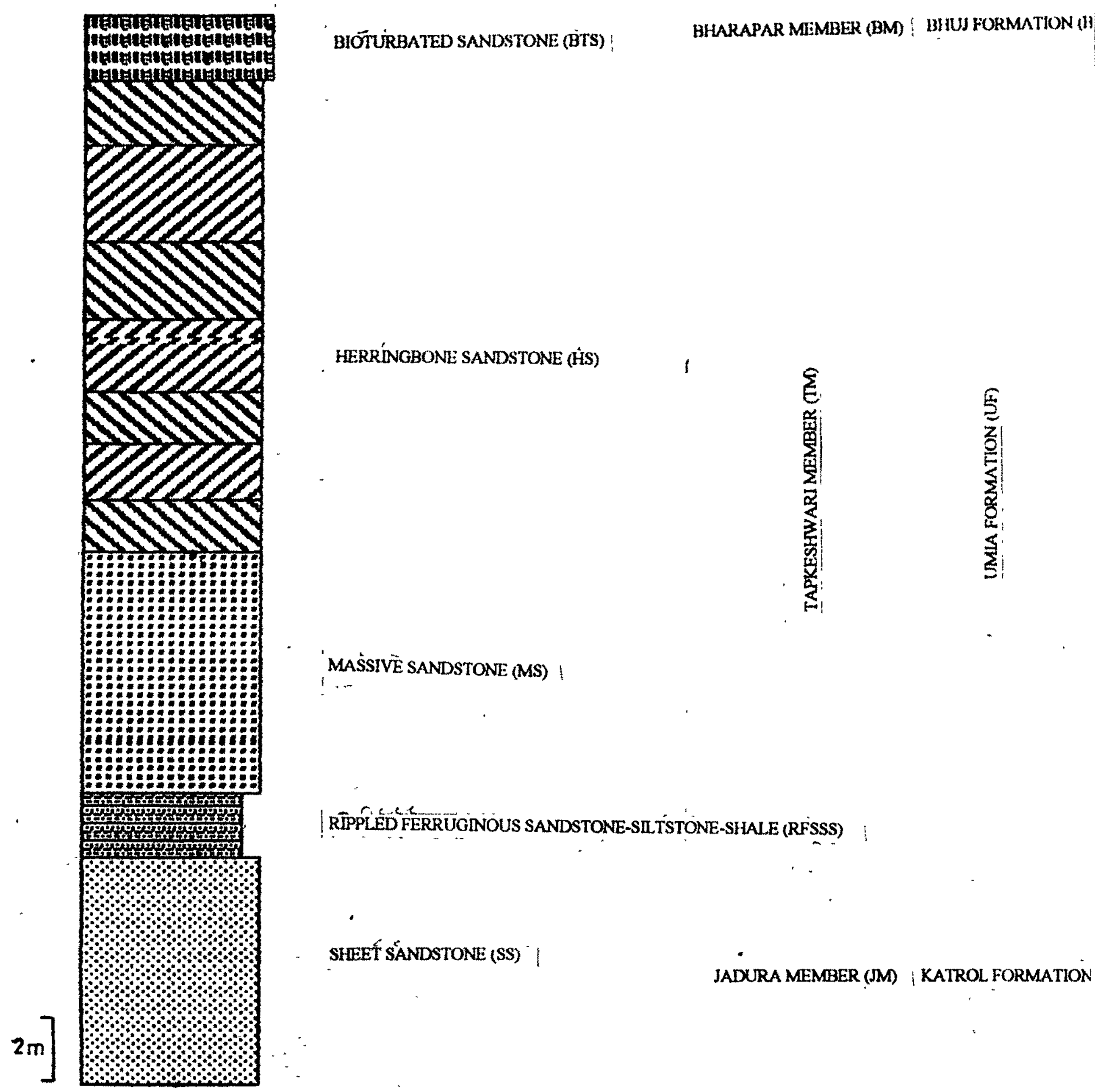


FIGURE – 10j.MEASURED STRATIGRAPHIC SECTION - NEAR BHARAPAR SANATORIUM.

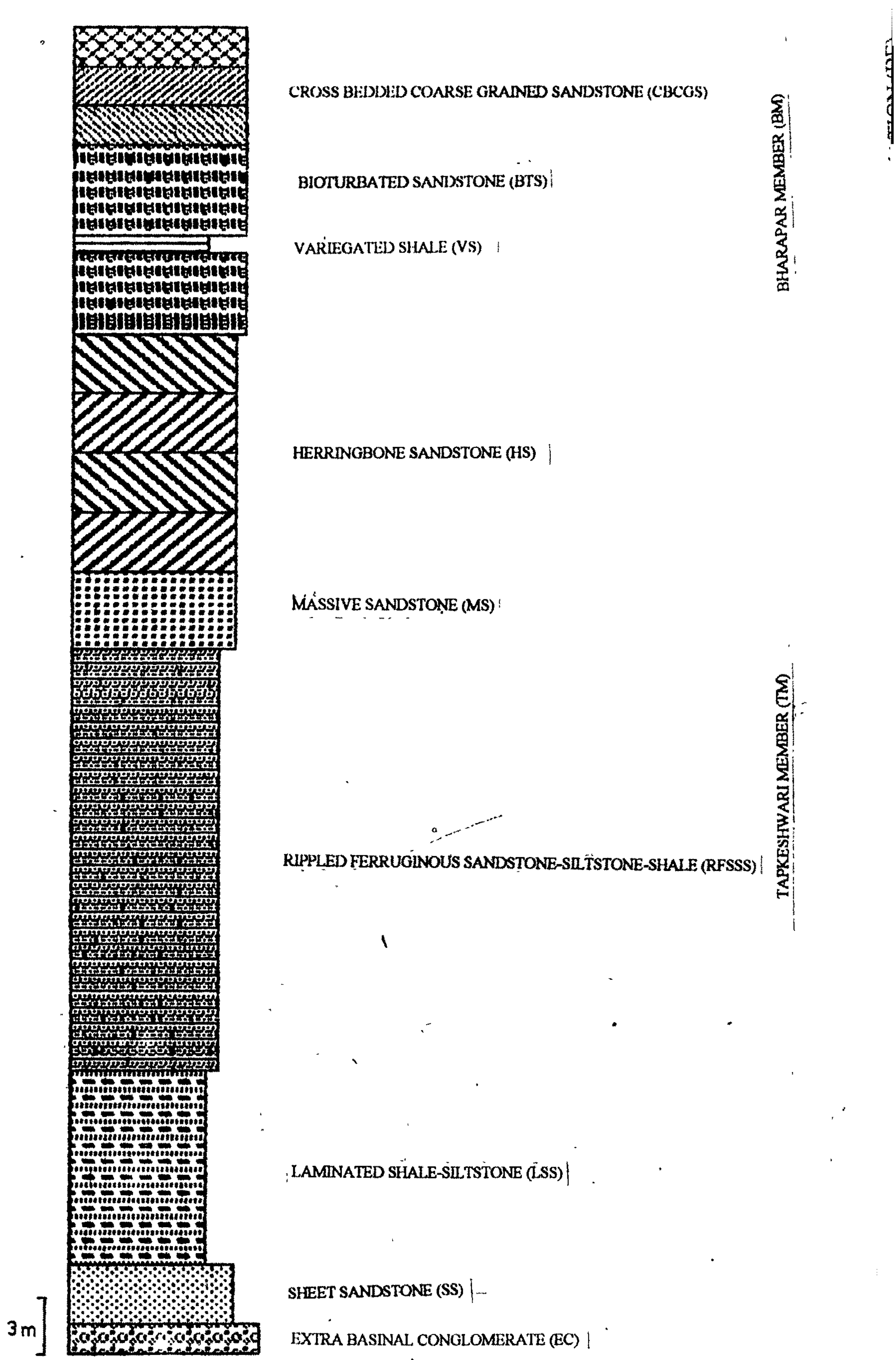


FIGURE - 10k.MEASURED STRATIGRAPHIC SECTION - AT TAPKESHWAR

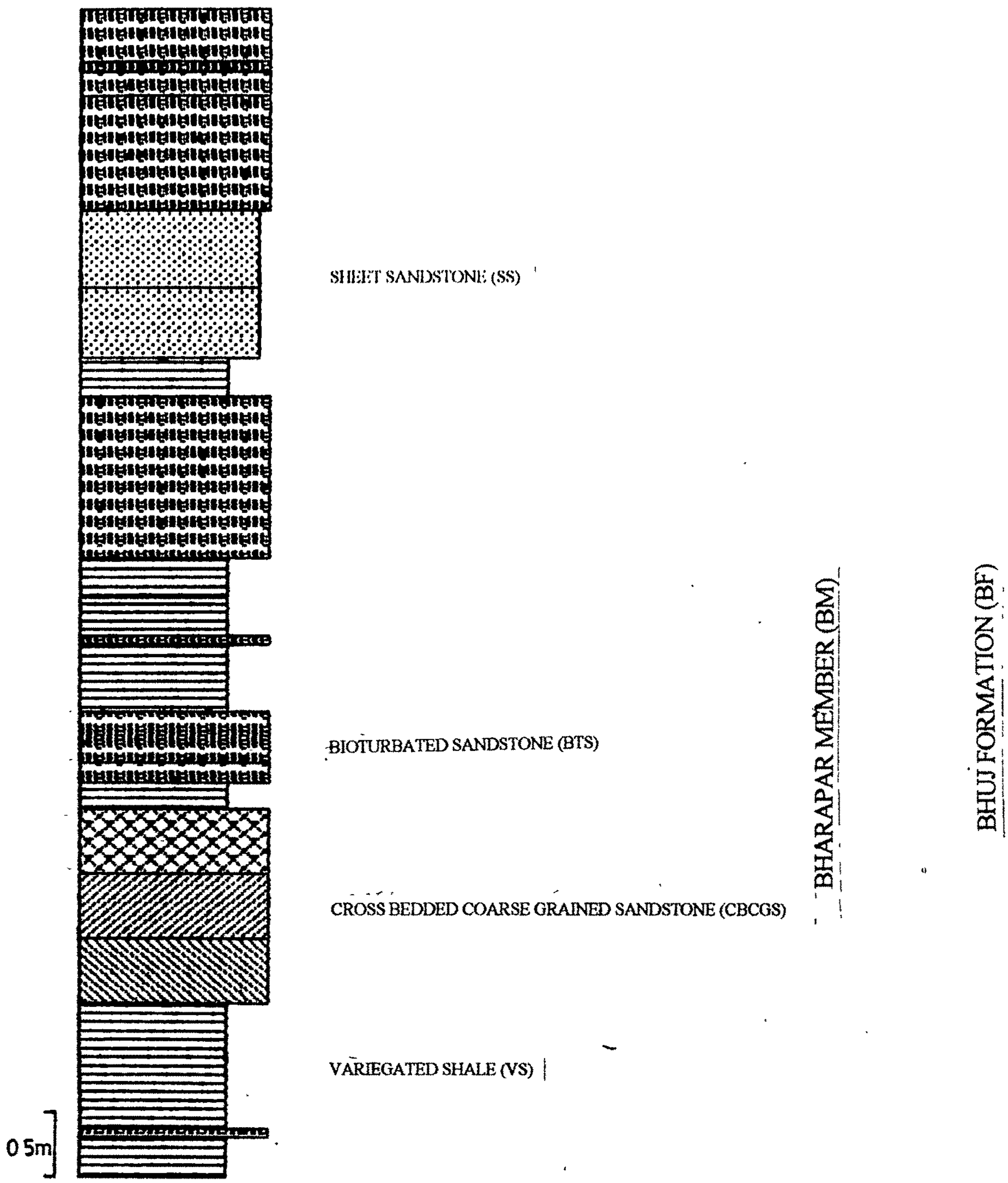


FIGURE 101.MEASURED STRATIGRAPHIC SECTION - NEAR BHANUSHALINAGAR, BHU.

VI. 2. DESCRIPTION OF LITHOFACIES:

VI.2.1. Facies A: RHYTHMIC SHALE SILTSTONE SANDSTONE (RSSS):

This facies is defined on the basis of predominance of argillaceous material overthe silt and arenacous components, where arenaceous material tends to become abundant in upper part of the facies sequence. The facies is found to be well developed in the following Members: viz., Jamaywadi Member (JWM), Ler Member (LM), Dhosa Oolite Member (DOM), Gunawari River Member (GRM), Marutonk Dungar Member (MDM), Jadura Member (JM) and Tapkeshwari Member (TM). Most conspicuous development of it is found in JWM and MDM with maximum thickness of 154 m. in the latter. The vertical sequence of facies varies from outcrop to outcrop and all facies are not represented at all locations.

Four sub-facies are distinguishable within this rhythmic facies sequence. These are: (1) Laminated Shale Siltstone (LSS); (2) Sheet Sandstone (SS); (3) Dark Shale Siltstone Sandstone (DSSS); and (4) Ripple marked Ferruginous Sandstone Siltstone Shale (RFSSS), subfacies.

VI.2.1.1. Sub-facies A.1: Laminated Shale Siltstone (LSS):

Rocks of this facies are thinly laminated shales with thin siltstone bands. The facies is often associated with the Sheet Sandstone subfacies (SS); Dark Shale Siltstone Sandstone subfacies (DSSS); Bioclastic Limestone facies (BL); and Intrabasinal Conglomerate facies (IC). Most of the shaly beds are typically parallel and thinly laminated with intercalated rhythmic sequence of very thin (0.5 cm upto 10.0 cm) khakhi gray red brown calcareous and ferruginous siltstones. Shales are composed of clay material and minute mica flakes with silt size quartz grains and subordinate calcareous material. Fossils are rare.

In different beds, colour of the shales varies from gray yellow khakhi with intercalations of reddish brown or claret argillaceous bands. It is difficult to predict whether colour of these shales has to be assigned to the weathering in the source area, developed through in situ oxidation and reduction at the time of deposition or as a result of diagenetic or weathering process after sedimentation. However, red brown or claret colour can be assigned to the sub-aerial exposure and oxidation of particularly finer sediments, or to the accumulation of oxidized material. Hardening of some of the bands in addition to compaction tells the same story. Gypsum layers are found in entire sequence of facies.

In the lower part of the facies sequence, the shales and siltstones are flat and apparently structureless. But in the upper part, whenever are found intermingled or intermittently located with sheet sandstones, and contain on their top linguoid-, or current-, or symmetrical straight crested-, or interference-, or oscillatory influence ripple marks and, or parting lineations. In such cases, thickness of siltstones reaches upto 30.0 cm and lithologically it approaches to fine medium grained sandstones. Some of the siltstones are richly fossiliferous. *Bivalves* are found in concave up and convex up position in individual layers in a stratified manner. Concave up *bivalves* occur with thin ferruginous layer at the depression of concave part, and also show compactional effects below it. This suggests reworking and setting from suspension.

Thin section study of the intercalated siltstone sandstone reveal that, these are analogous to the rocks of sheet sandstone facies except nonoccurrence of siliceous cement, richer in fragmented fossil contents and less developed thickness.

The fossiliferous bands present in the sequence are often micritic to ferruginous with varying amount of ferruginous material from 0.0% to more than 50%. Such rocks normally contain silt size quartz particles constituting fossiliferous siltstones, silty fossiliferous limestones to silty ferruginous fossiliferous bands. Several unfossiliferous micritic limestones and silty ferruginous bands are also recognised by the author.

Mineralogically, the detrital particles in these rocks are mature, containing less than 5.0% of felspars and unstable minerals, which can be visualised in thin sections. Normally detrital grains, which are angular to subangular are found to float in brownish black ferruginous to dull white calcareous micritic cement. Some times such layers alternate with each other. Such rocks are attributed to the mixed siliciclastic carbonate rocks by Jeffery Mount (1984, 1985). However, due to very thin nature of the bands and negligible proportion of it in comparison to the thick facies sequence, no further comments can be made on these rocks.

Whenever, the LSS is rich in bioclastic material, it contains fragmented *bivalves, brachiopods, bryozoans,* calcareous algal filaments, *echinoid spines, foraminifers, cephalopods* etc. Many of these skeletal fragments are ferruginised and coated by ferruginous or calcareous layer. Also, rounded to elongated ferruginous and micritic peloids occur mostly in genetically related cement. In addition, Glauconitic grains are found in the rocks. Quartz grains are corroded. Muscovite flakes normally occur parallel to the bedding planes. Detrital or reworked calcite grains are found commonly in many sections. Several detrital quartz and calcite grains are coated with ferruginous or micritic material. Fibrous black bituminous material invariably is found in many cases.

In some sections limestone bands are totally composed of yellowish brown micrite with scattered ferruginous material in form of minute grains or rhomb shape ankeritic to hematitic crystals or patches or clusters. Gypsum and calcite veins are found penetrating such rocks which sometimes incorporates host limestones in form of xenolith.

Fossils are, in some cases completely absent, but elongated crystals of micrite and gypsum indicates marine origin (Adams et al, 1984).

In some cases micritic cement shows neomorphism into cleaved sparitic crystals in small scattered clusters.

On the whole, the shale dominate in the lower part of facies but it normally becomes subordinate in upper part. The individual rhythms of shale siltstones are inverse graded and contact is normally gradational. The sequence is commonly coarsening upward. Larger detrital material thickens, while smaller clastics thin out as one approach towards the top. Red brown ferruginous layers occur in lensoid or flaser bedded form above ripple marked top. But when such partings do not contain ripple mark, such ferruginous layers are uniform or may be absent.

Whenever, the siltstones sandstones are bioturbated they contain burrows, trails, insect tracks and markings. Such trace fossils include *Arenicolites, Arthropodichnus, Asteriacites, Asterosama, Beaconichnus, Biformites, Chondrites, Calycraterion, Cochlichnus, Cylindrichnus, Diplocraterion, Granualaria, Gyrochorte, Helminthopsis, Isopodichnus, Keckia, Ophiomorpha, Palaeophycus, Pholeus, Phycodes, Planolites, Rhizocorallium, Thalassinoides, Tisoa, Zoophycos*, etc. Plants remains are also found in some beds.

The LSS sub-facies is found in JWM, LM, DOM, GRM, MDM, JM and TM. In JWM, when traced eastward this facies thins and splits up into a number of tongues which interfinger with the SS facies. Contacts are gradational with siltstone separating the shales from the fine silty sandstones. In some areas sheet sandstones are locally absent, and the laminated shale siltstone facies directly overlie or underlie the Dark Shale Siltstone Sandstone facies. While, in some cases it directly occur overlying or underlying unconformity without development of DSSS or SS. In LM this facies contains marly concretions, indicating early stage of diagenesis.

INTERPRETATION:

When compared with the observations of Selley (1970), Miller and Knox (1985), the LSS indicates deposition under low energy conditions. It is most likely that the lower part of the LSS facies without ripple marked top could have originated below normal wave base on a shallow marine shelf. This shallow shelf condition is depicted by rhythmic occurrence of thin siltstones. While the upper part with ripple marked tops and interfingering with the SS facies indicate deposition in much shallowed condition above normal wave base on an open marine shelf. The part of the facies sequence without ripple marks most probably represents transgressive and standstill conditions followed by regressive conditions marked by frequent intercalations and at times abundance of siltstone sandstone over shales; intermingling of SS facies; and presence of varied ripple marks.

The overall finer material of the sub-facies indicate very slow setting of suspended fine hemipelagic material in a low energy regime marked by the absence of coarse grain sands. The sedimentary structures like varieties of ripple marks are indicate wave action by the migrating currents and bottom currents produced due to breaking of wave that approached the shallow shore. (When normal waves are obstructed by shallower bottoms their up and down vertical movement converts into unidirectional horizontal movements producing currents. Prominent oceanic currents normally are absent in such shallow parts (Elliott, 1978). As postulated by Johnson (1978), interbedded parallel laminated silts and muds which represent suspension depositions, have periodic bottom currents to form ripples (migrating offshore). This is predicted to have followed in the upper part by complex alternations of laminated silts, very fine sands and subordinate shales (mud), mainly regular wavy to climbing ripple cross laminated. The ripple marks thus represent stronger bottom current formed current ripples during higher energy conditions, which were reworked by waves during fair weather periods.

The presence of khakhi colours of the shales is consistent with the rapid alteration between oxic and anoxic conditions below the sediment surface as proposed by Berner (1981). Red brown iron rich sediments imply considerably slower sedimentation and probably indicate longer exposed period in subaqueous oxic condition without burial and without precipitation of calcium carbonates. Following McBridge (1974), the reddish colouration can also be interpreted to have been formed by the decomposition of iron rich minerals to iron hydroxides during pedogenesis, a process that is better developed in semi-arid high temperature environment followed by transportation and deposition in the basin. However, such an interpretation of red colouration is not widely accepted and a late biogenic origin regardless of the original environment can also be proposed, or alternatively the red ferruginous argillaceous bands and red ferruginous cement of the siltstone sandstone may be interpreted to have precipitated by microbial activities.

The uniformity of thickness of intercalated bands/partings/slabs over distant areas suggest gentle gradient of basin and wide development of facies belt paralleling the shore.

The textural composition of the siltstone sandstone indicate their provenance form the proximal part of the basin. Such material is derived by receding tide, and in that way it depicts proximity of shoreline or alternately it shows minutely fluctuating strandline conditions. Much reworking and transportation is suggested from the nature of the sorting of grains and occurrence of megafossils in fragmented form. This possibly was followed by calm period and insufficient current action in general, to rework the final deposits, as indicated by bioturbation or biogenic activities. All these are microscale variations and are not related to turbidity currents or debris flow.

The occurrence of thin limestone bands and calcareous cement in siltstone sandstone indicate precipitation of carbonates in the basin along with ferruginous material at instances, during which argillaceous material supply was limited or negligible.

The detrital silty to fine sandy angular to subrounded monocrystalline quartz, in some cases contain vacuoles and undulose extinction indicate igneous and low temperature hydrothermal origin of the grains. The undulose extinction seen in some of the quartz could be as a result of strain in their parent rock body. The angular to subrounded nature of the grains further indicates nearness of their provenance to the depositional sites.

Several lines of above evidences point to fluctuations in the rate of advance and retreat of the shore line. The local superposition of the marine shales directly on the DSSS facies shows that sometimes the sea transgressed too fast. This may have been caused either by shortage of land derived sediment, or by extremely rapid rise of sea level or subsidence of the land. Overall, facies suggests development along a linear clastic shoreline and deposition in proximal shallower part of an open shelf.

Fossiliferous nature of most of the limestones and several siltstones bands, which show no evidences of bioturbation and undisturbed shells, depicts colonization and in situ reworking of epi and infauna during omission periods. Wearing and tearing of bioclasts, ferruginisation and coating of calcareous and ferruginous material on several fossils prove such reworking and erosional features. While the biota and numerous trace fossils in the siltstones sandstones suggest development and diversity of invertebrate fauna at the time of deposition along with an oxygenated bottom currents. The fossils very often display diagenetic effects in skeletal transformation.

According to Fursich et al., (1992), concretions in LSS facies in LM at Ler are of transgressive early diagenetic origin when sediment influx would be much less and generation of carbonates would be more. According to them, their presence at narrow intervals in LSS in LM represents minor transgressive - regressive fluctuations. This part in the LM depicts overall regressive cycle.

VI.2.1.2. Sub-facies A.2: Sheet Sandstone (SS):

This subfacies as per its name dominates in sandstone. The sandstones in this sub-facies are sheet like separating DSSS facies from previous LSS facies. The individual sandstone layers are normal graded to inverse graded or massive. Thickness of individual sandstone varies from 50.0 cm. to 3.0 m. Such sandstones are found in form of amalgamated sequence of elongated sheet or wedge shape beds or occur isolated intermingled with LSS facies. The thicknessof shales separating two amalgamated sandstone sheets, whenever present, does not exceed 5.0 to 10.0 cm. The sandstones are commonly coarsening upward and thickening upward, i.e. larger detrital material thickens, while smaller clastics thin out as one approach towards the top of a SS sequence. Top parts of the sandstones are capped by argillaceous ferruginous or marly material depicting omission (nondepositional surface) and are ripple marked or parting lineated or flat structureless. Ripple marks are commonly symmetrical oscillatory ripples to interference

Sequence of structures from bottom to top in Sheet Sandstone sub-facies:

Massive, flat bedded, low angle to hummocky cross-stratified and ripple marked.

ripples. Other primary structures are bedding, lamination, ripple lamination, flaser or lensoid bedding, low angle to hummocky cross stratification etc. Normally beds are massive to flat bedded, but in some cases from bottom to top following sequence of structures have been observed: massive, flat bedded, low angle to hummocky stratified, ripple marked (plate-7).

The sub-facies occurs in JWM, LM, DOM, MDM, JM and TM. It is associated with LSS, DSSS, RFSSS, FS, and WRCS facies. Normally it shows gradational contact with LSS and sharp to erosional contact with remaining facies.

These fine to medium flat bedded sands of SS grade down laterally into very fine silty sands. Traced laterally in south and westward, this sub-facies thins and splits up into number of tongues which interfinger with the LSS facies. These interfingering thin partings are yellowish to grayish fine grained calcareous to ferruginous siltstones sandstones. Mineralogically, the grains are mature to immature, containing less than 5% to 20% felspar grains like microcline, plagioclase, orthoclase. Muscovite flakes, few grains of pyroxene, amphibole, garnet, tourmaline, opaque minerals, chert and detrital calcite have been observed in several sections. Glauconite grains are present in majority of the sections. It appears that some of the brownish argillaceous grains are partially oxidized glauconitic grains. Texturally, the sediments are mature to submature, contains about 5% or less amount of matrix, grains are angular to subrounded, many of the grains are elongated - platy, sediments are poor to well sorted but never unassorted. Quartz grains are largely monocrystalline, very few grains are polycrystalline-sutured, quartzitic. Visually more than half of the grains are plain igneous quartz, out of which some grains contain fluid inclusions -vacuoles- suggesting low temperature hydrothermal origin. Other grains show undulose extinction, depicting metamorphic origin or strain effects. Few grains contain fluid inclusion alongwith undulose extinction depicting secondary strain effect. The felspar grains are either fresh or weathered - decomposed or mixture of both fresh and weakened are rather common. Different felspar grains show varying degree of replacement by kaolinitic clays.

Most of the quartz and other mineral grains are corroded and few of them show partial to complete replacement by calcite. Some quartz grains also show over growth or in some cases attain perfect hexagonal shapes as a result of its original crystallinity (?) or indigenous complete over growth.

Microspar coating is found around several grains in many sections, while in few of them hematitic coating is present. In majority of the sections grains float on the cement matrix.

The calcareous sandstones invariably contain skeletal material and microfossils, including fragmented *bivalves, brachiopods, bryozoans, cephalopods, foraminifers,* etc. Some of these show neomorphism. Plant remains are found in some cases in form of black fibrous bitumen. Cement appears to have been recrystallized in majority of the cases.

In many cases, rhomb shape colourless yellowish brownish sometimes zoned dolomite to iron rich ankerite crystals are observed. Some of these crystals have outer lining of brownish red coloured limonite or hematite or siderite. The dolomite indicates diagenetic process which probably altered the previously existing micritic or sparitic crystals. Zoning seen in such cases, most probably occurred due to varying amount of foreign material incorporated in growing crystals or due to variation in chemical composition. Ferruginous hematitic cement that normally occur alongwith calcareous cement in form of disseminated minute rhomb shape crystals (may be siderite), oval elongated peloids pellets or in small patches, within calcareous cement. In certain cases only ferruginous cement occurs. In few cases calcareous micritic peloids-pellets are observed. Pressure solution effects can be seen in several sections. In few cases clay and silt matrix is found in sizable proportion.

It is interesting to note that the thick amalgamated sandstone bands in the upper part of various facies are mineralogically immature to submature, contains about 10% to 25% felspars-microcline, plagioclase, orthoclase. Other minerals like muscovite, amphiboles, pyroxenes, sphene, staurolite, garnet, opaque grains, etc. are found in small proportions. Quartz grains are of igneous origin with few polycrystalline grains and several undulose extinct grains and hydrothermal grains with vacuoles, are also observed.

Texturally, the rocks are moderately sorted to unassorted, contain angular to subangular fine to medium size sand grains with less than 5% to 15% of clay silt matrix. Generally these rocks are matrix supported. The rocks range from quartz and felspathic arenite to quartz and felspathic wacke. Clayey matrix in some cases may have been formed due to decomposition of felspar grains. Original form of such weakened or decomposed grains can still be seen at places in the sections.

Mineralogical and textural maturity and grain size in sediments is found increasing towards the top of the facies sequence. Here, several quartz and detrital grains are coated or corroded or sometimes also shows overgrowth.

Fossils are rare. In thin sections these are mostly unidentifiable. Few beds contain casts of *trigonia*, small *gasteropods*, spines and needles of unknown origin, and *cephalopods* as well as wood and leaf impressions. While in some section, black fibrous wood (bitumen) remains, are seen. Cement is commonly mixer of brown black ferruginous and micritic material. Where as iron containing cement is normally predominant. Few sandstone beds in LM, MDM, JM, and TM are completely micritic, microsparitic to sparitic. Cherty cement with ferruginous material is not uncommon. In several sections dolomitic, ankeritic and sparitic crystals are developed in scattered or patch like form. Gypsum and anhydrite crystals have been observed in few cases. Gypsum layers are present on top parts of certain beds. Ferruginous and micritic peloids and ooids are also present in few sections.

Bedding or stratification is distinct to indistinct in various sections and at times shows gradation and microscopic ripple lamination.

Top parts of several sandstone bands contain tidal gully (small tidal channel) structure in filled by small fossil forms, gritty to silty grains and gravel size host rock fragments. Top part of the lower sandstone sheet in MDM contains megaripples.

The overall nature of the sandstone beds is mostly sheetlike or wedge shaped. In some cases isolated SS facies in from of flat lenses are also seen within LSS facies.

The intercalating shales are gray yellow khakhi clayey in nature. Here, the rocks of SS facies are poor to moderately bioturbated containing burrows, trails and insect tracks. Their trace fossil contents are *Thalassinoides, Chondrites, Calycraterion, Planolites, Palaeophycus, Gyrochorte, Skolithos, Ophiomorpha* etc.

Normally, the thick sandstone sequence contains DSSS facies in between, as in JWM at Gangeshwar & JM at Jadura, while as in JM exposures south of Satellite Earth Station the thick sandstone sequence continues without development of DSSS facies.

INTERPRETATION:

The fossils of the SS facies indicate a marine environment. The vertical sequence of increased grain size and increased sorting is typical of recent barriers and beaches as described by Selley (1970); Johnson (1981). In addition, tidal flats are most probably developed in the study area. Intermittently such barriers and tidal flats are cut along their length by meandering tidal gullies (channels) as pointed out by Armstrong Price (1955); Hoyt and Henry (1967).

Thus, following Selley (1968), the sequence of sedimentary structures, with its massive to regular bedding with dominance of low angle stratification in the upper part of several sandstone sheets can be attributed to their deposition in bars, barriers and tidal flats.

The overall evidences point to a barrier beach to tidal flat environment for SS facies. The channels (gullies) at the top of sandstones were probably cut by tidal currents flowing between open sea and lagoon, or flowing on tidal flat at the time of spring and receding tides.

The intermingled or intermittent massive to flat bedded sandstone sheets with marine fossils, finer grain size, ripple marks and burrows, within the LSS facies depicts ransitional zone between off shore marine zone and barriers. It is clear from the repeated vertical interbedding and lateral interfingering of the two (LSS & SS) facies that deposition could have taken place synchronously in the two environments. The evidences further point to fluctuations in the sea level or rate of advance and retreat of the shoreline.

Alternatively, as postulated by Johnson (1978), siltstone sandstone sheets within marine shales originated during high energy storm condition and represent distal part of storm or catastrophic deposit. The nonoccurrence of cross-stratification and absence of much bioturbation in the sandstone may support this view but symmetrical to interference ripple marks, parting lineations and trails on the top part of sandstone conclusively indicate development in shallower conditions with subaerial exposures under tidal complex rather than deposition under catastrophic stormy event. The occurrence of mega ripples on SS facies in MDM may be due to shoreward migration of megaripples under normal to stormy - catastrophic waves.

The isolated sandstone beds within LSS suggest advancement of the sea so fast that barriers were no sooner formed than they were submerged to form off shore bars and shoals. The location of these was perhaps controlled by palaeohighs on sea floor.

By contrast, quartz and felspathic calcareous arenitic sandstone sheets suggest that from time to time the shoreline was static. High barriers and tidal flats were then developed by the sea on which the sand was continuously reworked and from which the clay was winnowed. This can be seen in JM exposures near Jadura.

The various evidence thus indicate that occurrence of DSSS facies in a regressive sequence in between SS facies depicts development of lagoonal conditions where sandstone bands below the shales of DSSS represents barriers and those above it represents beaches and tidal flats. These successions are found to be capped by unconformity as in JWM, MDM and JM.

On the other hand, in the transgressive sequence reverse is the case and Sheet Sandstone sequence is followed by marine shales gradationally, as can be observed in MDM. While thick sequence of SS facies without occurrence of intervening DSSS facies (as in JM on Mundra Road south of SES, and TM near Jadura due south) suggest development of tidal flats and beaches along a static shoreline where most probably rate of sedimentation and subsidence may be almost equal. Extensive tidal flats were probably developed in the areas of upper intertidal range can be postulated for it as bioturbation is much less.

The detrital grains showing their mix - igneous and metamorphic origin, still majority of the grains belong to an igneous provenance. The angular to subangular nature and undecomposed felspar content suggest proximity of source area. Polycrystalline grains suggest metamorphic origin, while grains with undulose extinction depicts strain effect. More sorting, lesser amount of felspars and subrounded grains in thin sections depicts more transportation and reworking of sediments in distal areas, such reworking is less or absent in proximal sediments of various exposures. Ferruginous and cherty cement and clay and silt matrix depicts derivation from nearby terreginous parts and terrestrial influence, while micritic cement postulates marine influence on sediments and hence more reworking and marine influence can be marked by more calcareous cement and less matrix. Sparite, dolomite and ankerite indicate diagenetic changes.

VI.2.1.3. Sub-facies A.3: Dark Shale Siltstone Sandstone (DSSS):

The facies contains complex quick alternations of shale, siltstone and sandstone. The thickness of individual lithology varies from 2.0 cm to 20 cm. It shows sharp contact with sheet sandstone facies and LSS facies. Laterally it splits into a number of tongues which merge into SS facies. In its overall appearance it is lensoid in shape within SS facies.

DSSS mainly contains dark gray shales often black carbonaceous with complex intercalations of ripple marked yellow to reddish brown siltstones to medium coarse sandstones and flaser bedded to lensoid or rippled marked ferruginous silty to argillaceous laminations. On the top part most of their partings contain thin crust of yellowish to reddish brown fine ferruginous material. Many such partings are darker and not rippled marked as in case of JWM near Gangeshwar and JM near Jadura.

Petrographically these siltstones and sandstones are similar to the sheet sandstones where fossils and calcareous cement are negligible. Cement is mainly ferruginous and in certain cases mix ferruginous and cherty. Clayey matrix is abundant. Fossils are scattered - mainly *bivalves, brachiopods, ammonoids* and *foraminifers*. Sometimes bases of intercalated siltstones consist of casts of *trigonia*, small turritella, *ammonites* and needles of unknown origin. Small *gasteropods* also occur within, in form of clay filled moulds as in their life position. Leaf impressions and wood fossils occur at many places.

The sandstones are coarsening and thickening upward and contain varied trace fossils such as *Tisoa, Scalarituba, Skolithos, Gyrochorte, Thalassinoides, Phycodes, Planolites, Palaeophycus,* etc. In MDM on way to Jadura and JM near SES, it is found directly overlained by or overlying LSS facies.

In some localities at its base the DSSS contains tidal gullies as seen in vertical sections (plate-1). Here, it shows abrupt contact with LSS and abrupt lower contact with SS facies, but upper contact with SS facies is gradational.

Various types of ripple marks like straight crested symmetrical, interference to oscillatory ripples, and lamination, ripple lamination, flaser bedding and subaqueous dehydration cracks etc., have been observed in sandstones and siltstones of this facies. Gypsum layers are common.

INTERPRETATION:

Paucity of structures in this sub-facies makes environmental interpretation difficult, although it appears to have deposited under quiet water conditions. The presence of fossils and trace fossils indicate marine influence and aerobic conditions within saline waters. The intercalated dark to carbonaceous shales depicts restricted anaerobic reducing conditions, possibly a quick aerobic - anaerobic conditions fluctuating condition.

The above inferences as well as the geometry and thickness of the subfacies indicate its development in a shallow narrow open lagoonal condition associated with intertidal flats and a barrier system. The openness of the lagoon averted constant anaerobic conditions giving rise to thin carbonaceous shales in spite of coal beds. Carbonaceous material seems to be derived from nearby terrestrial setting as in situ root portions are completely absent. During nib tide, conditions were most probably anaerobic due to lack of oxygenated water supply, producing and preserving dark to carbonaceous shales without animal traces. Siltstones and sandstones were possibly produced during higher tides which generated aerobic conditions with transportation of sediments from barriers, tidal flats and beaches towards the lagoons. As evidenced by ripple marks, burrows and trails. the siltstones and sandstones were deposited in shallower part of lagoon to lower tidal flats in intertidal areas. Most of the ripple marks show higher energy conditions than those in the dark to carbonaceous shales and nonrippled sandstone siltstone. Symmetrical and interference ripples are common on intertidal sand flats. Occurrence of flaser bedding in lower intertidal sands and in intertidal sediments is common. Burrowing is moderate with subaqueous dehydration cracks depicting uncommon or infrequent subaerial exposures.

The nonoccurrence of ripple marks and trace fossils in sandstones within dark shales depicts its deposition in deeper parts of lagoon under anaerobic conditions. Thickening of rippled sandstones suggests shallowing of lagoon.

The yellowish reddish crust is typical of an omission surface to standstill conditions between two tides. Dehydration cracks and evaporates depend upon factors such as climate and rate of sedimentation (Coleman and Write, 1975). Dehydration cracks suggest squeezing of water due to compaction and in some times shallowing of overlying water column, while gypsum indicates much evaporation under hot and somewhat dry climate.

In conclusion the overall conditions suggests deposition of DSSS in back barrier lagoons and adjoining lower tidal flats, associated within a tide dominated sea.

VI.2.1.4 Sub-facies A.4: Ripple marked Ferruginous Sandstone Siltstone Shale (RFSSS):

This subfacies is developed only in the TM of the Umia Formation. The facies contains intercalated sequence of sandstones siltstones and shales. The sandstones are only 10.0 cm to 30.0 cm thick near the Observatory section, around Kukma railway station on way to Ler, south of Jadura, north of Bharapar Sanatorium, while 1.0 m to 2.0 m thick in Tapkadevi hill and section north of Bharapar. All the sandstones are either straight crested symmetrical ripple marked or interference ripple marked or oscillation ripple marked or parting lineated on top and horizontally stratified to climbing ripple cross laminated to hummocky cross stratified. Many ripple marks are long wave length (10.0 to 15.0 cm) low amplitude (0.5 to 1.0 cm) ripples. Thicker sandstone beds are slightly lighter in colour and in some cases show variegated colours and water movement fronts produced due to movement of ground water. Micrograding is seen in a number of thin sections. Intervening siltstones and shales are only upto 20.0 cm thick, and within thicker beds these are very thin or even absent.

Texturally and mineralogically the sandstones and siltstones are similar to the SS facies - medium, fine grained to silty, well sorted to unassorted, but cement is always ferruginous as a rule, giving it typical reddish brown to black or buff appearance. Amount of fine grained material is less in thicker beds than in thin sandstone beds as seen in thin sections. Cherty patches, sometimes, are observed in thin sections as cement. Thin ferruginous limonitic to hematitic brownish black crust plays an important role in development of such a peculiar appearance to the rock.

The shales are white, gray, yellow, red or black in colour and varied in their composition from felspathic, ferruginous to carbonaceous accordingly.

The facies sequence shows uniform thickness of bands and total thickness of thinner bands is normally about 5.0 m. while that of thicker bands reaches upto 25.0 m.

Only two to three ferruginised fossiliferous bands occur containing *bivalves, gasteropods,* spines, *ammonoids* etc. All other intercalations are devoid of body fossils. Leaf impressions are present on many top parts. Trace fossils on the ripple marked top parts are abundantly present which include *Asteriacites, Arenicolites, Thalassinoides, Rhizocorallium, Beaconichnus, Rosselia, Skolithos, Diplocraterion, Monocraterion, Gyrochorte, Phycodes, Planolites, Palaeophycus, Helminthopsis,* etc. Burrows are comparatively much less in thinner partings than in thicker slabs.

The RFSSS facies is found mostly on SS facies or RSSS facies gradationally. On its top it is followed by FS facies separated by nondepositional surface or storm generated mega wave ripple mark. Near the observatory at the basal section such mega wave ripple beds are conspicuously seen. Here, it also contains small gullies filled with rounded pebbly oligomictic conglomerate. Mud drapes are common in the rocks. Desiccation cracks are present but rare.

INTERPRETATION:

Several characteristics of this sub-facies indicate deposition on a tidal flat. Micro-graded beds and mud drapes record deposition during decreased energy conditions associated with high tide, and few interference ripples possibly reflect diverse directions of water movement during various stages of the tidal cycle. The dominant straight crested symmetrical ripples on the other hand depict oscillatory action during tidal cycles. The variation in bioturbation suggests deposition variation, wherein on the upper portions of a tidal flat burrowing is less intense than the lower portions on the flat where the density of infaunal animals is high, as suggested by Miller and Knox, (1985). The presence of desiccation cracks on thinner partings supports such an interpretation by the author.

In thicker beds shale partings and interbeds are less abundant to almost absent than in thinly bedded sandstones, suggesting their deposition under higher energy conditions in contrast to the thinly bedded sandstones. Flat topped symmetrical ripples with few interference ripples as reported here, are the common features on the intertidal sand flats as suggested by Klein, (1970); Knight and Dalrymple, (1975). Occurrence of hummocky cross stratification suggests undulating depositional surface and winnowing higher energy conditions. In some cases this bedform as suggested by Lindhalm (1987) can be attributed to have produced during upper flow regime conditions in unidirectional flow.

The abundance of ripples, reduction in number of shale interbeds and amount of fine grained matrix as confirmed in thin section study, are indicative of sediment deposition in lower part on a tidal flat. The occurrence of thin carbonaceous shales in between thicker sandstones represent splay deposits into marginal part of a tidal lagoon to lower part of a tidal flat.

The Ripple Index (between 8 to 15) and Ripple Symmetry Index (between 1.0 to 1.5) suggest normal wave to oscillation responsible for the generation of the ripples. Thin fossiliferous bands suggest mild stormy events. Thickness of sandstones suggest moderate to high sand flux from nearby mix igneous and metamorphic terrain. The occurrence of *Skolithos* and *Cruziana* association of trace fossils depicts exact sites of deposition variation on wider tidal flats and suggest long duration of stagnancy of tides, in a tide dominated shore line.

VI.2.2. Facies B: FELSPATHIC SANDSTONE (FS):

The facies is defined on the basis of prominence of arenaceous material in the matrix alongwith occurrence of 5.0% to 20.0% of felspar grains in the rock. The facies is found to be developed in the Gangeshwar Member GM), Jadura Member (JM) and Tapkeshwari Member (TM). Very good exposures are found developed in GM and TM with maximum measured thickness of 47.0 m in the TM.

The sandstones are massive, horizontally stratified to cross stratified. On the basis of its

Channel structure in Tapkeshwari Member molded below the Massive Sandstone sub-facies and incised in RFSSS facies.

prominent bedding variations the rocks are divided into two subfacies namely (1) Massive Sandstone (MS) facies and (2) Herringbone Sandstone (HS) facies.

VI.2.2.1. Sub-facies B.1: Massive Sandstone (MS):

The rocks are mainly massive to horizontally stratified with local occurrences of planar cross stratification to hummocky cross stratification towards the top parts in some beds. Top parts are ripple marked to parting lineated or structureless. The ripple marks are pointed crested straight symmetrical ripples, flat top oscillation ripples to interference ripples. The individual bed varies in thickness from approximately 1.0 m to 7.0 m.

Grains in the rocks are very fine to very coarse and are angular to subrounded. Sorting in majority of the cases is poor but few sections show moderate to well sorting of grains. Grains more or less float in the matrix and/or cement. In some cases grains touch each other. Few grains are slightly corroded. Exsolution phenomena can also be observed in certain cases. Sediments are immature, contains matrix more than 5 %. The felspar content normally ranges in between 15 % to 20 %. Quartz grains are largely plain igneous quartz or grains with vacuoles - hydrothermal variety. But still in some cases considerable number of grains are showing undulose extinction suggesting secondary strain effect within parent body. Other minerals present in the rock are microcline, orthoclase, plagioclase, muscovite flakes, opaque grains etc.

Cement is normally ferruginous, with certain amount of siliceous - cherty material. Presence of micritic material in form of small patches is a common feature. Matrix is mainly clayey to silty. Open pores have been observed in some of the rocks.

Few scattered *bivalves* and micro *gasteropods* are present in sections of top parts. Thin ferruginous to marly crust normally found on top parts of beds. Gypsum layers are present on top of beds.

Internally, the sandstones are found to have a tendency for each of its unit to show the following structures arranged from bottom to top in the sequence: massive, flat bedded, locally cross stratified to hummocky, rippled. Individual sandstone beds varies in thickness and some of the beds vanish completely on different outcrops. The lowermost bed of this facies in GM consists of larger rounded boulders which are calcareous - microsparitic to sparitic and some times containing fossils. Their megascopic features are described in GM. The flat bedded thick sandstones show pebbly coarse sandy single layers at almost regular interval of 20.0 to 30.0 cm depicting distinct bedding plane characters. The facies is many a times found overlying EC facies and normally underlying or in association with HS, LSS, BS & BL facies.

Normally top parts of the beds show mild bioturbation and ripple marked top shows few trails. These include *Skolithos, Diplocraterion, Thalassinoides, Gyrochorte, Planolites* etc.

Channel structure is observed north of Ler in a nala section (plate8) in TM below the MS facies, incised in RFSSS facies, which also indicates minor transgressive event and covering of pre-depositional morphology.

The rocks of the MS facies in JM show palimpset to relict nature where ferruginous, argillaceous to gravelly less compacted sediments with variedly oriented cross stratification showing their terrestrial origin. Here, Extra-basinal Conglomerate occurs underlying MS sub-facies.

INTERPRETATION:

The scarce fossils in the facies suggest that the deposits may have been formed in a marine influenced environment. The occurrence of cross stratified tidal bundles and fossiliferous marine shales and limestone in continuation with the facies also supports the above inference. The occurrence of the MS facies above sharp to erosional surfaces or overlying unconformity or EC depicts that the sandstones were most probably deposited during transgressive episode. This is supported by small channel structure below thick sandstone of the facies in BM, and overlapping sequence of the facies underlying LSS and SS unconformably in GM and JM. The structural sequence of the sandstones in a vertical column which is massive bedded, horizontally stratified, locally trough and planar cross bedded to hummocky stratified, and pointed straight crested symmetrical ripple marked; and sheet like E-W elongated geometry suggest deposition of the rocks in a nearshore onshore region, most probably in a subtidal tidal region.

The massive sandstones in the facies represents reworked beaches, sand dunes and fluviatile deposits by a transgressive sea. Due to the high rate of sand influx, mainly in an encroaching sea, from coastal and related terrestrial sediments (beach, coastal dunes, fluviatile sediments), which is evident by sheet like geometry and thickness of sandstones; it seems that tidal and wave energy must have been subsided to produce any kind of structures in the initial stage. The felspar grains which are liable to be destroyed in constantly agitating tidal marine environment, is present in the facies in sizable amount depicts fast rate of sedimentation. Here, lagoonal facies are not developed probably due to high sand influx and eustatic rise of sea level.

Horizontal stratification occurs in a swash zone (Clifton, Hunter and Phillips, 1971) or back barrier wash over sands (Bridges, 1976; Schwartz, 1975) or lower sand flats in an intertidal zone (Evans, 1965). The occurrence of thin pebbly to coarse sandy layers in the flat bedded sandstones suggest incorporation of beaches and coastal sand ridges by encroaching sea in a regular pulsatory manner.

Low angle cross stratification and trough cross stratification occur in a lower beach face to lower tidal flats to subtidal conditions (Davis, Fox, Hayes and Boothroyd, 1972). While pointed crested large symmetrical ripples generally found in lower tidal to subtidal environments. Finer crust on ripple marked or flat top of beds suggests omission - standstill conditions after depositional phase.

In general the MS sequence probably represents high wave energy beach barrier facies in a transgressive sea. The thick beds in the facies sequence of MS show typical characters comparable to the observations of Elliott (1978), Bridges (1976) and Johnson (1975).

Plate - 9

Wedge shape geometry of individual cross-stratified strata and tidal bundles - Herringbone Sandstone sub-facies.

O - Ophiomorpha

According to these authors very few transgressive barriers have been recognised in the geological record so far, probably due to their tendency to produce relatively thin sequences (Elliott, 1978). Lower Silurian of South West Wales (Bridges, 1976) provides a good example where sandstones and pebble layers, 0.15 - 8.0 m thick, are characterised by subhorizontal lamination, large symmetrical ripples, concentrated layers of granules and small pebbles, which are considered to indicate wave action. Some of these facies are interpreted by Bridges (1976) as proximal washover beach and barrier fans and other as remnants of transgressed barriers. He interpreted the reworked pebble lags at the top of the sandstones to reflect the passage of the surf zone across the area.

Johnson (1975), attributes a wave dominated succession in the PreCambrian of Norway, to the land ward migration of beach. This succession exhibits the general sequence - planar erosion surface -> coarse to medium grained sandstone with parallel lamination and isolated set of cross bedding produced by swash-backwash action on the beach face -> medium sandstone with land ward dipping planar and trough cross bedding reflecting the land ward migration of dunes -> symmetrical ripples with grit and fine gravels. Johnson (1975) argued that the basal erosional surfaces, the upward variations in structures & wave energy, and lateral uniformity of the sequence is formed as a result of land ward migration of beach during a rise in sea level. Its resemblance with present day beach face of Oregon coast according to him resulted from high wave energy conditions on the beach.

In the area investigated, the occurrence of five (TM, Jadura) to seven (GM, Gangeshwar) or more than one bed (two in TM, at Sanatorium & Observatory and else where) depicts repeated development of similar type of conditions in a pulsatory manner in a eustatic to slowly transgressing sea under subsiding basin conditions. The sediments of the facies (as a JM) can be regarded as relict-remnant from an earlier environment and now in disequilibrium (as in GM evident by large sandstone boulders) which are reworked sediment possessing aspects of both its present and former environments.

As mentioned earlier, the boulders are considered as remnants of an underlying bed eroded in a nearshore terrestrial environment most probably under arid semiarid conditions and derived or incorporated in sandstone of GM by transgressing sea. The supporting evidences are provided by the unequal size of the boulders, occurrence of it at different level in the lower part of the sequence, sharp contact with the host sediments, variation in the cement (which is calcareous in the boulders while ferruginous, felspathic to cherty in the host sediments), compactness (boulders are hard and more compacted) etc.

VI.2.2.2. Sub-facies B.2: Herringbone Sandstone (HS):

The rocks of this subfacies, without any exception, are cross stratified graded and fining upward sandstones. The variety of cross stratification and primary structures found in the facies are planar cross stratification, trough cross stratification, climbing ripple cross stratification, flaser bedding, festoon bedding, hummocky cross stratification, graded bedding etc. These cross stratified beds commonly produce herringbone structure due to their diverse directions, which is a normal feature of these sequences and hence lead to the name of the facies. Another common characteristic is the wedge shape geometry of the individual cross stratified strata, when we trace it laterally (plate-9). The HS facies always occurs above the MS facies on scoured reactivation surfaces. Majority of the cross stratified beds commence with the reactivation surface at base and taper against erosional surfaces on top. Very few beds show three sets of cross stratification and ripple marks on top. Thickness of individual cross stratified bed ranges from 5.0 cm to 50.0 cm or more in exceptional cases. Top of the sequence is always bioturbated and flat to slightly uneven. Ripple marks are flat topped to pointed crested straight symmetrical or oscillation and interference ripple marks. The sequence is almost unfossiliferous and without bioturbation except top part.

Thin section studies show that the rocks are submature to mature, where in some cases fine to coarse sand grains occur together, while in others fine or medium or coarse grains are found sorted and separate in various layers. Hence, grains are moderate to well sorted due to graded nature of the sediments. Similar sized grains are arranged in a layer/laminae which shows assorted nature. This shows minutely fluctuating conditions. Grains are subangular to subrounded, matrix is normally less than 5.0 %.

Mineralogically rocks are composed of stable quartz grains. Proportion of unstable felspar grains reaches only upto about 5.0 to 6.0 % visually. Mica flakes are commonly present throughout the sections alongwith few chert, garnet and opaque grains. Quartz grains are mixed from various provenance like igneous, low temperature hydrothermal with vacuoles, to metamorphic or strain affected with undulose extinction.

The cement is sparry calcite and in some cases much ferruginous with abundant felspathic, clayey to silty matrix. Majority of the grains float in the cement, still pressure solution effect can be seen in some of the grains. Almost all the grains are corroded and show coating of calcareous material. Ferruginous material is present through out the sections in form of patches. Trace fossils on the top are mainly *Skolithos, Diplocraterion, Monocraterion* etc.

INTERPRETATION:

The bidirectional cross stratified nature of the sandstone depicts shallow sub-tidal to tidal depositional conditions. The presence ofhummocky cross stratification shows storm generated origin of these bands, while flaser beddings suggest deposition on swells and rises. In mesotidal to macrotidal areas bidirectional planar and trough cross stratification produces herringbone structured sequence in sub-tidal - tidal and beach setup. The herringbone units show distinctive tidal bundles and rare spring nip tide cycles. This suggests deposition on sand flats - shoals under strong tidal influence. The energy level would be much higher. Similar observations for Umia Formation rocks were made by Shukla and Singh (1990). In general the facies represents tide dominated shore line (coast line). The hummocky cross-stratification has been reported by Myrow (1992) in tidal/coastal setting. Typical heights - swale to hummock - for hummocky cross stratification with spacing between 1.0 - 3.0 m are 20.0 - 40.0 cm or less in the study area. This swale to crest heights for the structure is apparently smaller than expected for hummocky cross stratification as indicated in Craft and Bridge (1987). This is considered by the author as a result of deposition associated with low sediment supply of cohesionless (sandy) sediment, under conditions (long wave periods and larger orbital diameter) that would have been capable of generating large continuous hummocky bed forms (Myrow, 1992). There is no consensus on the hydrodynamic conditions under which this stratification forms. The origin is almost surely polygenetic forming under simple or complex oscillatory flow (Harms et al., 1975; Dott and Bourgeois, 1982; Harms et al., 1982; Duke, 1985; Southard et al., 1990) and a variety of combined flows (Swift et al., 1983; Greenwood and Sherman, 1986; Nottvedt and Kreisa, 1987; Arnott and Southard, 1990; Duke, 1990).

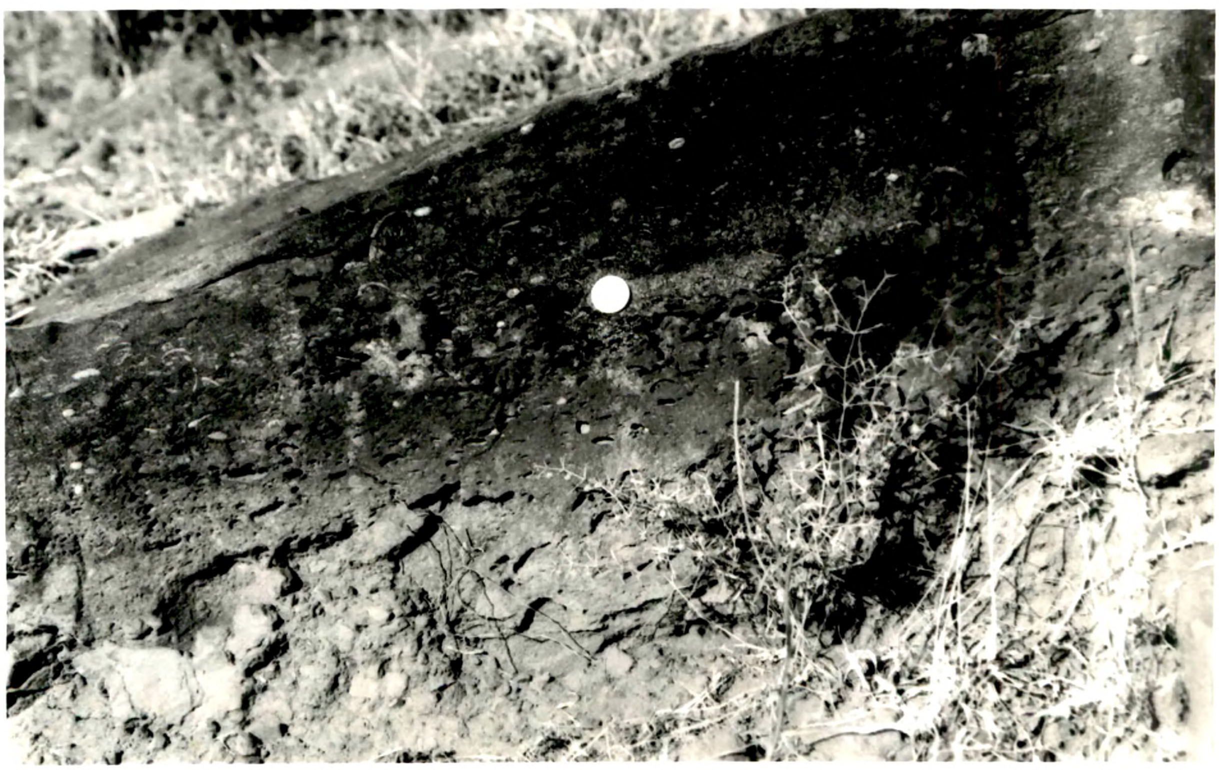
The facies overall represents intertidal, shallow subtidal and beach parts under meso-, macro-tidal environment with storms.

VI.2.3. Facies C: WAVE RIPPLED CALCAREOUS SANDSTONE (WRCS):

The facies is defined on the basis of the presence of wave ripples mark on the top and calcareous material as cement in the rock alongwith presence of abundant fossils. The rocks of the facies occur in JWM, LM and GRM. These rocks are massive, horizontally bedded to cross bedded and graded to inverse graded. The facies is divided into two subfacies: (1) Bivalve Sandstone, and (2) Oyster Sandstone; on the basis of presence of various bivalves in the first (former) and oysters in the second (latter) subfacies, and on the basis of lateral variation in grain size in the rocks. In both the cases wave ripples are present on the top part.

VI.2.3.1. Sub-facies C.1: Bivalve Sandstone (BS):

The facies is characterised by the presence of bivalves. Chief varieties are *Trigonia,*



Convex up and concave up bivalves - (lag deposits under storm conditions) - Bivalve Sandstone sub-facies - exposures near Gangeshwar.

Astarte, and *Oysters*. It shows no lateral variation in the grain size in the exposed sections in different areas and of different Members in which it occurs. The facies is developed in the JWM and LM. It exhibits maximum thickness of 4.0 m in the basal part of the LM. In middle part of the LM, it shows much lateral persistence and can be used as marker horizon. The facies bed in JWM shows local development, might have been eroded laterally.

Thin section studies depicts that the grain size of the rock varies from fine to coarse gritty, pebbly sand. Larger grains are rounded to subrounded, smaller grains and matrix are angular to subangular and in most of the cases moderately to poorly assorted. Elongated disc shape particles are also present in the rocks. Different sections show framework supported to matrix supported textures. Silty matrix varies from 5.0 % to 20.0 %.

Mineralogically sediments are submature - contains about 5.0 % to 15.0 % felspars. Sand size quartz grains mainly shows straight extinction, with small amount of grains showing undulose extinction, but whenever large gritty pebbly grains are present, they show either undulose extinction or polycrystalline nature. Other mineral grains present in the rocks are microcline, plagioclase, orthoclase, muscovite, calcite etc. Majority of the grains are corroded. Exsolution phenomena can be seen in case of large number of grains when rock is framework supported. Cement is micritic to sparitic calcite with scattered dolomitic to ankeritic crystals, in some cases. Ferruginous cement also occurs in form of small patches or disseminated form, which entirely found in few rocks. Certain grains are coated with ferruginous or calcareous material. Few exhumed rock grains of ferruginous sandstones and extrabasinal granitic and quartzitic rock grains also occur in the rock. Occurrence of micritic and sparitic as well as ferruginous material as cement indicates two to three stages of diagenetic effects.

Other fossils present in the rocks are spares *gasteropods, brachiopods, cephalopods, bryozoans, foraminifers, echinoid* and *brachiopod* spines, algal filaments etc. Fossils, in many cases, are neomorphosed.

In many thin sections stratification and sorting of grains can be clearly visible. Few peloids are found in the rock.

In the field, the rocks of the facies shows planar and trough cross stratification, which indicates north and south palaeocurrent direction. The wave ripples on top show SE-NW, N60°W-S60°E, N27°W-S27°E surging direction. The mega ripples, in profile exhibit sharp, rounded to flat topped forms. Plan view exposures display ripple crests characterised by straight to gently sinuous and locally bifurcating crest lines.

Locally the facies shows poor graded nature, as well as within a single bed internal scouring and reactivation surfaces are present. The facies also contains flat pebbles of red to brown ferruginous argillaceous material and dirty white to yellow marl. Such intraclasts are present on the reactivation surfaces in basal, middle and upper parts of the beds. It also contains thin ferruginous argillaceous layers which at places (as near Gangeshwar) display boudinage structure due to stretching of rock. The bivalves are found in concave up and convex up positions at various levels in the facies (plate-10). Larger number of bioclasts are concave upward. The lower part of this lithofacies normally shows uneven scoured contact with the underlying rocks. The rocks are penetrated by calcite veins.

Trace fossils present in this facies are *Skolithos, Thalassinoides* and *bivalve* trails. At places trace fossils are completely absent.

In LM, two successive bands of the facies are found amalgamated with each other in Gangeshwar area, and same bands can be observed separated by thin to 1.0 m thick shales in other areas.

INTERPRETATION:

The unassorted nature, pebbly to gritty grains, flat pebble layers, and mega wave ripples depicts storm generated nature. The cross stratification, which is planar to trough in nature depicts its origin by movement - migration of sediment in form of bed load. The concave up bivalves show their setting from suspension from upper high energy flow regime under subsiding energy conditions. The convex up bivalves depict inversion of bivalves due to prevalent bottom currents originated as a result of compensation to the much water accumulation in nearshore and onshore areas, at the time of or immediately after settling. The lower erosional or scoured surfaces also suggest scouring during initial rising phase of the stormy event. Here, top and bottom parts are not in harmony as the lower part does not show wave rippled surface. The setting of the BS within shales (in JWM and middle part of LM) represents deposition in a shallow marine regressive sequence above storm wave base, while occurrence of BS in initial part of LM, overlying HS facies of GM unconformably, demonstrates commencement of transgression responsible for deposition of LM with stormy events. Deposition of the facies under waves is suggested by the presence of straight and bifurcating crested, symmetrical mega ripples on the top of sandstones. Presence of intrabasinal grains and pebbles suggest exhumation. The intrabasinal flat pebbles such as that described herein is commonly associated with fore shore and near shore zones (e.g. Hart and Plint, 1989). A proximity of fore shore setting might also be suggested by the presence of disc shape particles found in the rocks (Dobkins and Folk, 1970; Bluck, 1967). Further, in such setting the rock normally forms cross bedded units (Cheel and Leckie, 1992), which are found in the facies present in LM. The erosional and reactivation surfaces present within a single bed of the facies suggest that the packages were emplaced periodically by events within short time spans that generated extremely competent currents i.e. storms. Similar rock types have been described by Leckie and Walker (1982), Leithold and Bourgeois (1984), and DeCelles (1987).

A general interpretation of the coarse grained storm beds may be made on the basis of their sedimentology. Within shallow marine environments, normal sedimentation is dominated by mud and silt, where as storm introduce the coarser material (Cheel and Leckie, 1992). Here, the gravel and gritty grains may be delivered to the setting from an area closer to the shoreline, perhaps a gritty, gravelly beach (as indicated by disc shape - platy grains in the study). Further evidence is provided by the physical structure - rill marks indicating water receding on intertidal setting - present on the top of the facies in LM near Ler village.

The stable bed forms during the final phase of deposition were symmetrical mega ripples, preserved capping the BS facies. However, it gives the discordance between the internal cross stratification and the ripple forms, the bed forms that were active during deposition of bulk of the sediment would have been either symmetrical or asymmetrical. If the earlier ripples were asymmetrical, than the change to symmetrical ripples might reflect a decrease in the asymmetry of the oscillatory current below some threshold for the formation of symmetrical ripples. However, internal fabric suggests that the oscillatory currents were not purely symmetrical where mega ripples capping BS facies formed, but indicates the influence of bimodal asymmetrical oscillatory currents. The change in oscillatory current direction can be observed in direction of cross stratification and mega ripples. Cheel and Leckie (1992) have made similar observation for Cretaceous rocks of Canada.

The overall characters suggests the deposition of BS facies in exceptionally strong or long lasting storms.

The characteristics of the facies are (1) sharp (scoured) based sandstone with imbricate intra-, and extra-basinal grains and clasts; (2) bimodal cross stratified nature; (3) symmetrical mega ripples on top; (4) local poor gradation; (5) much lateral extent (except in JWM); (6) mainly concave upward bioclasts (bivalves) with several convex up bioclasts.

VI.2.3.2. Sub-facies C.2: Oyster Sandstone (OS):

The OS is defined by the presence of *Oysters* and vertical and much pronounced lateral variation in grain size (graded nature). The facies is also characterise by its typical outcrop pattern in the field in which rocks are exposed in north to northeast pointing triangular to lobate or elongated shape in plan view, which is wedge shape in vertical section, and grades in to finer clastics laterally. The facies occurs at various levels overlying RSSS facies in Gunawari River Member only. It approaches to a maximum thickness of more than 30.0 m in Satpura dungar.

Thin section studies depict that texturally the rocks are mature to submature, in majority of the sections contain almost equal size grains together, but in few cases silt to grit size grains found together without any regular arrangement. Majority of the larger grains are rounded to subrounded while smaller grains are rounded to subangular. Many such smaller grains are elongated. Grains densely float in the cement or at times produce framework supported texture. Grain size varies from fine sandy to fine gravelly.

Mineralogically the rocks are mature, contains felspar grains upto 5.0 % visually. Most of the quartz grains are showing either undulose extinction or polycrystalline nature, suggesting strain affected to metamorphic origin respectively. Grains are corroded. Other mineral grains present in the rock are microcline, orthoclase, plagioclase, and few opaque grains. Pressure solution effect can be observed in framework supported rocks.

Cement is micritic, to microsparitic with poikilitic texture, to sparitic shows first and second generation diagenetic changes.

Fossils are mainly of *bivalves (oysters), bryozoans,* and *foraminifers* alongwith few *ammonoids, belemnite guards* and algal filaments. Many fossils are neomorphosed. Larger oysters are coated partly by ferruginous material which may be the product of algal activities.

Many grains are coated with ferruginous material. Ferruginous to micritic pellets and ooids have been observed in some sections. Ferruginous cementing material is found scattered in certain sections. Calcite veins and dolomite crystals have been observed in a section where dolomitic crystals are found developed adjacent to the vein.

The rock also shows presence of red brown to yellow ferruginous flat pebbles scattered in it. The sandstones are massive or planar and trough cross stratified. The palaeocurrent direction is due south to southeast and wave ripples present on top shows approx. NE-SW directions. The rocks are coarse grained towards the proximal part. Distal part rocks in the basin are fine grained and massive to flat bedded with ripple marks, bioturbation and thin argillaceous or calcareous crust or gypsum on top parts. These massive beds show increase in thickness in upper part, i.e. thickening upward sequence.

Internally the distal sandstones show graded bedding and a tendency for each unit to show massive bedding followed by flat bedding and ripple marks arranged from bottom to top in the sequence.

Petrographic studies indicate that texturally these represent distal part of the delta sequence (delta front to prodelta) consist of silt size grains to fine sand grains accompanied by well sorting in the lower part, which gradually increase in the upper part to medium and coarse sand with gritty grains on top and moderate to poor sorting of the grains. The grains are angular to subangular with few rounded medium to coarse sand grains. Elongated platy grains are also present in small quantity. Majority of the rocks are compact, framework supported with few examples of floated grains in the cement.

Mineralogically the rocks are submature to immature, contain about 5.0 to 20.0 % of felspar grains visually in various cases. Majority of the quartz grains are plain igneous quartz, in few cases with abundance of vacuoles containing hydrothermal quartz. Amount of polycrystalline or undulose extinction displaying quartz grains, is less. Felspar grains are mainly of microcline with some amount of orthoclase and plagioclase. Mica flakes, garnet and opaque grains are also observed with scattered amphibole and pyroxene grains. In many cases, grains are coated with ferruginous material.

Cement is normally calcareous - micritic to sparitic with certain amount of ferruginous material in form of patches or disseminations. Poikilitic texture is formed in many pseudosparitic (original micritic) rocks. Few sections contain only ferruginous cement. Matrix is normally very less, not exceeding 5.0 %. Stratification and ripple lamination can be seen in some of the thin sections.

Fossils are mainly of *bivalves, bryozoans, ammonoids, belemnoids,* and *foraminifers*. Many fossils are neomorphosed or ferruginised. Black to brown fibrous woody material is present in many thin sections which are also at times ferruginised.

Mud drapes, micritic pellets and fresh to oxidized glauconitic grains are a common feature of many of the sections. Corroded quartz grains are common when they found embedded in calcareous cement. Pressure solution effect can be seen in certain cases. The distal rock contains ferruginous concretions which commonly enclose ammonoids or wood fossils. Many shell interspaces are filled by cement.

The trace fossils present in this facies are *Thalassinoides, Skolithos, Monocraterion, Palaeophycus*.

The facies shows sharp nondepositional to erosional contact with the underlying rocks, and many a times incised into the lower most shales of the GRM in which it occurs, forming channel structure. The distal finer sandstones are normally followed by proximal gritty sandstones directly or many a time shales in between showing ceasing and rejuvenation of delta condition and automatic switching of it by shifting and meandering.

INTERPRETATION:

The sandstone shows a deltaic origin with rejuvenation and automatic switching of conditions in form of repeated coarsening upward sequences. Two distinct fine grained and coarse grained sandstones have been recognised as basin ward and landward representative of the facies. Both the sequence are coarsening and thickening upward but internally the coarser sandstone shows distinct graded nature. The finer sandstones which occur around some of the out pouring centers are more or less uniform in thickness but restricted in lateral extent. The sediments occur overlying shale-siltstone intercalations of LSS facies representing prodelta sediments. All these characters suggest that the deposition was taken place in delta front part overlying prodelta sediments. These sandstones are poor in body fossils and trace fossils. The trace fossils are mainly sparse dwelling burrows. The lower contact is normally sharp nondepositional. Local gutter casts or gully structures have been observed.

The coarse sandstones are massive to trough cross stratified with frequent occurrence of *oysters, belemnite guards, ammonoides* and few *brachiopods*. The sandstones are coarse gritty to pebbly with intraformational clasts. This suggests high energy conditions. The cross stratification mainly shows unimodal palaeocurrent direction. Many a times it shows 25° to 30° depositional dip. This also occurs in form of north to northeast or east pointed triangular or elongated patches around delta mouths. All these characters suggest origin of the sandstone as delta slope deposits associated with delta front. Mega ripples on top of such sequence represent higher energy conditions which might be resulted due to storm.

The cross-stratified nature suggests rapid deposition of the coarser sediments in the upper cycle.

The development of delta front facies depicts dominance of fluvial processes over marine waves and currents leading to net deposition responsible for delta formation. The lack of fossils in the fine sandstones of lower cycle of delta front may be due to uniform and continuous deposition. In the upper coarser cycle the presence of abundant fossils depicts prevalent non-depositional periods and even firm to hard ground development as can be seen from the presence of oysters.

The plant material within the pebbles suggest coating of finer material during transportation and its distribution through fluvial agency. The prevalent high energy unidirectional flows can be predicted by the presence of big cross stratified units and intraformational pebbles which also suggest reworking.

All these details suggest that the fine sandstone in the first cycle of the facies represents distal depositional site on a delta front overlying prodelta sediments while coarse sandstone in second cycle shows deposition on delta slopes associated with delta front in shallower parts.

VI.2.4. Facies D: BIOCLASTIC LIMESTONE (BL):

The bioclastic limestone facies is defined on the basis of occurrence of abundant bioclasts and the calcareous nature of the rock. Development of BL is found in Ler Member (LM) and Gunawari River Member (GRM). In thickness it normally varies from 5.0 cm to 50.0 cm but never found to exceed 1.0 m.

Petrographically, the rock is fine gravelly, gritty, silty to clayey, micritic to sparitic bioclastic limestone. Bioclasts are of *bivalves, brachiopods, belemnoids, echinoids* - spines and plates, *foraminifers, gasteropods, bryozoans* etc. In some cases only a few, while in others majority of these are neomorphosed. Some are corrugated or partly ferruginised, while a few are silicified. Most of these bioclasts are coated with either ferruginous or micritic material and fragmented. Mechanical breaking after deposition is prominent. Internal structure of fossils is retained after recrystallization in a number of cases. Some of the bivalves enclose large amount of yellowish brown ferruginous material which is ankeritic, dolomitic to sideritic with development of minute rhomb shape crystals.

Quartz grains are mixed igneous and metamorphic. Few microcline, orthoclase and plagioclase grains are also present. Grains are corroded. Few of the quartz grains are coated with calcareous material. The larger grains are subrounded to rounded, smaller grains are subrounded to angular. Few glauconitic grains and micritic pellets - peloids are also found. Black fibrous woody (bitumen) material is found present in some of the sections. Calcareous algal filaments also occur.

Micritic crystals in the rocks are elongated and almost un-arranged suggesting its marine origin (precipitation near water sediment interface). The limestones containing ferruginous dark brown to black minute rhomb shape ankeritic, dolomitic, sideritic and hematitic material suggest initialization of diagenesis. In some cases the rock contains one third (1/3) to one half (1/2) amount of red, brown ferruginous material in the total mass of the rock section. Pressure solution effects can be seen on many bioclasts. The rock shows development of disseminated sparitic crystals in micritic mud depicting recrystallization - neomorphism. The specimens collected from adjacent regions near fault zones are completely recrystallised and contain well cleaved sparry calcite crystals.

Total seven bands of BL occur in LM and one in GRM. All but two bands show mega ripple marked top. In two bands ripples are found in harmony showing top and bottom parts in parallel mega ripple form. In other casesbottom is unevenly scoured. Laterally these rocks are persistently found in entire study area, but due to prominent post Callovian - pre Oxfordian erosional event (discussed in chapter - V), the rocks of the facies are well developed in the LM near Ler area, are not found in the western and central part of the study region. Many times such successive bands are found amalgamated on each other, while same bands occur separated by shales on other exposures. The facies is found associated with LSS, BS and IC facies. At places the bioclasts are found in concave up or convex up manner. Cross stratification is observed locally in several stratigraphic sections. The BL rocks are almost devoid of trace fossils. Intraformational pebbles are found in several bands of the facies, mostly at base but not uncommon in other parts of the rocks.

INTERPRETATION:

Majority of the evidences observed in the Bioclastic Limestone show its storm generated origin. The bioclasts are often concave up and convex up, suggest subsiding upper stormy flow regime and an active bottom current respectively. The beds reflect the onset, culmination and waning of water turbulence during the event by distinctive erosional and depositional structures. Lower contact of the facies is erosional and depicts the last generation of a succession of erosional phenomena during onset of a storm event. The storm generated nature is also depicted by the mega wave ripples, unassorted nature, occurrence of smaller to larger detrital grains and bioclasts in the rock, as well as occurrence of intraformational pebbles normally at base and overall gradational nature of the deposits. Coating and corrugated nature of some of the grains and bioclasts and ferruginisation of the fossils depicts some amount of wear and tear and local transportation before deposition. The harmony of top and bottom of some of the bands depicts imprint of oscillatory waves without much migration of crests in almost stationary manner on unconsolidated but cohesive (muddy) sediments almost near the wave base, alongwith deposition of bioclasts in last phase of event. Compensatory bottom currents would be absent in such case. The stable bed forms during the final phase of deposition were symmetrical mega ripples, preserved capping the facies. It suggests deposition of the facies under waves.

The bioclasts were possibly derived by exhumation in the initial phase of stormy event alongwith intraformational pebbles. The variety of bioclasts suggest mixed assemblage of epi- and infauna. The deposition seems to be in situ without much transportation as in case of majority of storm events.

In case of BL without mega ripple marks, it is predicted that deposition to have occurred in much shallower part of the basin where current predominates over waves, and hence wave ripples may not be formed.

The in situ fragmentation of the fossils and pressure solution effects on the rock demonstrates post-depositional but pre-diagenetic compressional effects mostly due to load of overlying sediments. The rounded nature of larger detrital grains shows much transportation but smaller subrounded to angular grains would be the product of attrition and corrasion of the larger grains.

Normally, day to day current velocities are not capable of transporting gravel sized skeletal material (Ball, 1967). Thus, the facies must therefore result from episodic pulses of a higher flow regime during which coarse material could be entrained.

The overall characters suggest deposition of BL under higher energy storm events in marine subtidal environment.

Further, much less thickness of the facies in comparison to large lateral extension is also significant. Here, individual BL bed could be the result of a complete cycle of storm event. The sharp base scoured to erosional surfaces at the base of this facies is thus most likely developed due to storms (Ball et al., 1967; Aigner, 1985), and the overall graded nature is a further evidence of storm generated origin (Ball et al., 1967), suggesting an episodic physical sedimentation.

The coating of several grains and bioclasts and ferruginisation of bioclasts indicate their repeated reworking, while majority of the well preserved fossils suggest rapid winnowing and immediate redeposition during one instantaneous event rather than slow accumulation (Aigner, 1985). Several beds are composite and include the amalgamation of several depositional events (or episodes) within one event. Such composite sheets may be internally homogeneous at one locality (near Satpura Dungar), but when traced laterally, the same bed may be composed of a number of individual (near Gangeshwar), amalgamated layers, separated by discrete bedding planes. Such characters following Aigner (1985) suggest deposition during waning flow. Wave ripples in certain cases suggest interaction of oscillatory flows.

The overall dynamics or kind of storm flows may be speculated on the basis of particular association of sedimentary structures. Possibly wave erosion was most important during initial storm phases (erosional or scoured surfaces at base), followed by a dominance of unidirectional flows (lateral transportation of eroded sediments, bioclasts and pebbles, and influx mostly from short distances), before oscillatory flows became again dominant during storm waning (wave rippled tops), according to Aigner (1985). The third type of storm flows may not be effective every time (particularly in case of coarser rock types such as conglomerates and larger bioclasts) to produce sedimentary structures like wave ripples. Thus, the first two phases, erosional and depositional, were more prominent and effective to record their imprints in certain BL beds, and records of third phase were omitted.

VI.2.5. Facies E: INTRAFORMATIONAL CONGLOMERATE (IC):

The facies incorporates clasts of different size from underlying rocks. The clasts vary in size from 2.0 cm to 23.0 cm in diameter and 3.0 cm to 10.0 cm in thickness. Indistinct bedding structure can be observed in these conglomerates. These are mainly composed of matrix supported flat pebbles of white micritic mudstones (marl) and argillaceous to silty red ferruginous claystone pebbles. The clasts are polymictic to oligomictic and autoclastic. A large number of such pebbles are the fragmented parts of *Thalassinoides* burrows. The flat clasts show no preferred orientation. Many clasts are bored on the upper surfaces, smaller clasts are bored on lower surface as well. *Brachiopods* and *bivalves* are found attached on the clasts. The clasts are rounded or elongated to spherical, oblong to bifurcating in many cases. On the surface of many pebbles subaqueous dehydration cracks are present suggesting dehydration under water at the time of diagenesis.

The facies is developed in LM, DOM, GRM and MDM. Its thickness varies from 7.0 cm to 40.0 cm. Maximum thickness is found in lower part of LM where it reaches 40.0 cm. It is found associated with LSS, BL and BS lithofacies.

Two varieties of intraformational conglomerates have been observed. In one case the rock is polymictic mainly containing gravel and pebble size clasts or red or white or yellowish silty micrite or biomicrite to ferruginous material. The colour of such clasts is due to ferruginous impregnation. The proportion of ferruginous material also vary from 0.0 to 100.0 %. Many of the clasts show two to three phases of their origin, where sharply defined red or white core is covered by a thick layer of ferruginous micritic mud followed on the outer part by ferruginous or sparitic envelop. In such cases clasts are in contact with each other forming clast or framework supported conglomerate. Rarely it shows matrix supported conglomerate. Pressure solution effect can be distinctly seen in the clasts. Bioclasts are abundant in this type of rock. It is observed in the lower part of LM, GRM and MDM. In some cases the facies also contains pebbles of siltstones with brown ferruginous pellet layer, and angular to subrounded pebbles of medium grained microsparitic felspathic sandstone. Bioclasts are abundant in it.

In second type, clasts are mainly oligomictic and larger in size pebbly, cobbly, which are made up of dirty white micritic material. The rocks are mostly matrix supported. Bioclasts are less abundant. Few clasts show their two phase origin where inner whitish core is covered by ferruginous material. First type of clasts are uncommon. This is observed in upper part of LM and DOM. Cement in such case is ferruginous or micritic or mix. Fragmented calcite grains are abundant in the matrix and in some cases scattered to no quartz grains occur. This host sediments are dirty white, pale yellow, reddish to brownish ferruginous hematitic to silty sandy micritic or mix material. Small yellowish brown to dark brown rhomb shape ankeritic, dolomitic, sideritic to hematitic crystals are observed in the cement as well as within fossils. Cement in some cases contains few silty layers. Sparitic crystals are developed within calcareous part and dolomitic crystals suggest two to three generation diagenetic effects. The elongated crystal of micrite suggest its marine origin. Compactional features below clasts and bioclasts suggest that the precipitation of micritic material was contemporaneous to the accumulation of clasts.

Matrix contains silt size to fine gravel size igneous and metamorphic quartz,microcline, plagioclase, fragmented fossils as well as ferruginous and micritic peloids. Detrital calcite grains are abundant in some cases which are micritic, sparitic to fragmented fossils in their origin. Some of the bioclasts have produced rounded to elongated ferruginised pellets due to wear and tear. In some cases matrix is largely made up of peloids.

The bioclasts are of *bivalves, brachiopods, bryozoans, foraminifers, oysters, belemnoids,* calcareous algal filaments etc. Doubtful *ostracods* are also present. *Nodosoria sp.* have been observed in one section (section no. 60). Majority of the fossils have preserved their original structures, but few of them show neomorphism. *Foraminifers* and *bryozoans* are filled by ferruginous material. In some sections all the fossils are highly ferruginised.

Trace fossils are absent except in some micritic clasts where *Chondrites* traces and borings are present. Gypsum veins are present in some cases.

INTERPRETATION:

The overall characters of the IC facies is indicative of exhumation of concretions under stormy conditions in shallower subtidal part where due to interaction with substrate, waves were converted in to unidirectional currents and hence in such part current dominated over wave action. Such an evidence is depicted in the alignment of pebbles and absence of wave induced structures like symmetrical wave ripples and migratory ripple generated cross stratification and by erosional scoured base. The pebbles in the conglomerates are interpreted as being of concretionary origin.

The lithofacies in case of oligomictic intraformational conglomerates represent predominant and last of the number of higher energy storm events. Here, due to successive storm events, the smaller pebbles (exhumed concretions) are overturned several times, and bored and encrusted one by one for all sides during calm times between two such events. In this way it represents multiple event beds. According to Aigner (1985), boring and encrustation of the pebbles from several sides attest to repeated reworking and colonization. On the other hand larger pebbles are mostly bored and encrusted on top, depict no overturning after exhumation. The larger size of the clasts as well as repeated overturning of smaller one demonstrates that the accumulation and overturning would be the result of in situ exhumation by number of storm episodes which are represented in individual IC facies. In short, the bands of the IC facies represent cannibalism and preservation of several highest energy events.

According to Ball et al., (1967) and Aigner, (1985) the sharp contact, mostly scoured at the base of the facies is most likely due to erosional episodes during storms.

During the storms, the micritic and ferruginous mud along with quartz and other detrital grains and fragmented material seem to have produced mud dominated bottom regimes. Due to the cohesive nature, at the time of waning energy conditions, which is seemingly settled along with exhumed concretions - pebbles and bioclasts, - formed matrix and cement of the conglomerate and provided setting grounds for pebbles and cobbles, while finer argillaceous clayey sediments probably transported elsewhere along with storm generated currents.

Not only the clasts but later on the surrounding matrix and cement in the facies found bored, suggest early diagenesis and formation of hard grounds. Lack of fresh sediment supply and omission periods following the storm episodes likely to be responsible for early diagenesis, formation of hard grounds and borings.

Occurrence of *Chondrites* in pebbles, and fragmented *Thalassinoides* suggest deep event erosion, as *Chondrites* belongs to a deep infaunal tier and *Thalassinoides* at mid level tiers, which is normally more than 10.0 cm to 1.0 m. Similar observations were made by Aigner (1985) based on characteristic vertical zonation of trace fossils (Wetzel, 1979; Ausich and Bottjer, 1982) within sediments, for Muschelkalk of Europe.

The overall characters of the intraformational polymictic conglomerates are almost similar to the Bioclastic Limestones without mega ripple marks. The only difference is that in case of the BL facies, proportion of pebbles is much less in comparison to bioclasts, while in case of IC, proportion of bioclasts is much lass in comparison to pebbles. Hence, the conglomerate has similar origination as the BL, i.e. storm generated in much shallower substrate conditions, where in upper regimes of storm flow dominated.

VI.2.6. Facies F: OOLITIC LIMESTONE (OL):

This facies is characterised by the presence of ooids in various proportion. It occurs only in Dhosa Oolite Member of Chari Formation in form of 0.2 m to 1.5 m thick bands. Such bands varies in number from three to seven, in the study area. It is found associated with LSS and IC facies.

The facies contains varied types of lithologies which ranges from oolitic bioclastic calcareous sandstone siltstone to oolitic micritic or sparitic limestone. The detrital particles in the rock are mainly angular to subrounded silty to medium size quartz sand with few microcline, plagioclase and orthoclase grains. Majority of the grains are corroded and few are coated with either ferruginous or calcareous material. Some times two to three quartz grains are steak together by coating.

In some bands detrital grains are almost rounded to subrounded and mainly of hydrothermal quartz with fluid inclusions - vacuoles-, in others igneous quartz become abundant.

When abundance of detrital grains produce sandstones in these oolitic bands, such rocks are mineralogically mature with 5.0 to 7.0 % of microcline, orthoclase, plagioclase and few grains of tourmaline and garnet. Mica flakes and black opaque grains are commonly found in such rocks.

Texturally the rocks are submature to immature, contain rounded to subrounded grains but uneven in size, varying from silt to small gravel, and scattered in micritic mud. Such grains are corroded. Larger grains are normally found embedded in silty to sandy matrix.

In some cases few polycrystalline grains, calcareous and ferruginous siltstone and sandstone grains, and granophyric grains are observed. Normally same rock section shows framework to matrix supported fabric, where pressure solution effect can be observed. Some of the grains in such rocks are partly or wholly covered - coated - by micritic, sparitic or ferruginous material. In such cases, micritic to ferruginous rounded to elongated pellets-peloids are present with micritic mud coating. Here, few immature ooids with only two to three concentric layers are located

The cement is, in most of the cases, micritic to microsparitic, but in some cases cherty and/ or ferruginous patches have also been observed alongwith well developed ankeritic or dolomitic crystals. Many times, micro- or pseudo- sparite produce poikilitic texture. Sparitic cement is also not uncommon.

Whenever facies bands are more in number, the lower bands are commonly sandy, but when only three bands are present, all are oolitic limestones.

The sand (detrital grain) rich lithologies occur only in the lower bands of facies in DOM. The limestones in the lower bands of facies also contains peloids and immature ooids with two to three concentric layers. The ooids gradually converts in, the upper bands of the facies, to mature ooids with more concentric layers and supermature aggregate grains. The pellets/ peloids are mostly made up of micritic material, in few cases of ferruginous material (? mud drapes) without showing any type of layered concentric arrangement or in few cases depicting thin coating of calcareous or ferruginous material partly or completely.

The ooids are of various origin - some of them are made up of micritic material and coated by similar type of material with inner part slightly neomorphosed, recrystallised, and showing radiating arrangement in several cases. Second type of ooids are micritic, coated by yellowish brown ferruginous concentric layers, few of them partly recrystallised. Other type of ooids are brown ferruginous with various number of concentric layers may be ferruginous or micritic or microsparitic. In some cases radiating fibrous calcareous material in the core is found covered by thick micritic layer, followed in the outer part by thin micritic to ferruginous layers.

Inner part of many of the ooids show development of cracks, in few cases filled by ferruginous or micritic material.

Micritic ooids contain either quartz grains or fragmented fossils or pellets or rectangular ferruginous material in the core. Some ooids contain very thin coatings around any such nuclei. Some of them contain large, fibrous,brown black opaque almost rectangular (?woody) material in the center. Few ooids contain complex structures incorporating two to three or more fragments at the kernel. Few of the ooids are seem to be much elongated. Many ooids are formed around fragmented algal mates. While, many ooids exhibit shrinkage features. Such shrinkage are likely to have occurred after lithification of the sediments, as the void space is not seen to have not collapsed. On the other hand, the occurrence of ooids without any surface features and ooids with shrinkage features in different but adjacent specimen indicate that shrinkage took place very early during diagenesis, even before reworking because this type of features are also found in the reworked clasts, pebbles and boulders.

Aggregate grains are made up of irregular aggregates of a small number of recognisable particles of ooids, peloids, intraclasts, oncoids, fragmented fossils, detrital grains, etc., cemented together by micrite or fine sparite or ferruginous material. Some times such cement also shows concentric arrangement. These are similar to grapestones of modern sedimentary environments. Black woody fibrous material (bitumen) can also be observed.

Few of the ooids enclose microfossils of *ostracodes* or spores. Intraclasts (reworked bioclasts with coating and without concentric layers, or coated bioclasts) are present in the sections with oncoids (reworked bioclasts with concentric layers). Coating is of various material, i.e. micritic, sparitic to ferruginous.

Bioclasts are mostly smaller in size - almost unaltered to completely recrystallised - neomorphosed. These are mainly *bivalves, brachiopods, cephalopods, foraminifers, bryozoans, gasteropods, calcareous algal filaments, echinoid plates, echinoid and brachiopod spines, coral polyps, crinoid stems* and some unidentified elongated plates. Algal filaments and mates, and embryoical belemnoids are abundant in the upper bands of the facies.

Peloids - pellets are micritic, muddy, in some cases ferruginous, perfectly rounded, oval to elongated. some times cracks are found developed within it, and mostly coated by thin micritic layer. Few glauconitic, altered glauconitic, ferruginous and black bituminous grains and detrital calcite grains are found in some cases. Some of such peloids are gypseous in composition, some times partly or almost completely replaced by ferroan micrite, sparry calcite or ferruginous material. Some peloids, mud drapes contain fragmented fossils and fine sand grains as nuclei.

Many aggregate grains are coated with thick calcite layer. Few ooids show their typical development where core part - micritic, sparitic, ferruginous, quartz grain, fragment of fossil, algal mate or detrital calcite - surrounded by calcareous layer, followed by corrosion and again surrounded by ferruginous and then calcareous - micritic or sparitic layer. Few ooids also developed around ferruginous siltstone nucleus. Ooids are mature in the upper part with much size variation. In some cases, elongated ferruginous fibrous material is present which may be of algal or plant origin.

Microripples, rippled or wavy lamination can be observed in certain cases. Aggregate grains some times host micritic veins in the fractures indicating fracturing and penetration of cement. The overall nature of limestones of the facies are micritic, few patches are recrystallised to form sparitic crystals. Few patches of ferruginous material are also present. Some times it is microsparitic with poikilitic textures incorporating detrital grains and ooids. Micritic crystals are elongated suggest marine origin, and it may be magnesian rich.

Three to four types of lithologies can be distinguished in the uppermost band of the lithofacies by the colour and crystallinity, proportion and presence of peloids, detrital grains as well as ooids and aggregate grains. These vary from micritic sandy limestone with scattered ooids and fossils, to micritic to oomicritic, to biooomicritic. Complex relationships developed due to successive periods of erosion, induration, omission and deposition - precipitation. Calcite veins are present in many cases.

The topmost band of the lithofacies in the sequence is capped by ferruginous gritty to conglomeratic rock. Top of the limestone band is bioturbated which can be observed in the field as well as under microscope. The ferruginous gritty conglomeratic rock mainly contains rounded to elongated grit to small gravel size recrystallised bryozoan fragments with few elongated *bivalves, brachiopod* fragments, some of these are bored and filled by microcrystalline ferruginous material. Few silty limestone fragments are also present. Fossil fragments show perfect rhomb shape calcite cleavage, depicting secondary stress effect. All the fragments are corroded. The rock is bounded by dark brown to black ferruginous material, mainly composed of rhomb shape sometimes twinned crystals and rounded subrounded pellets with subordinate sparry micritic calcite. Also contains few ooids, *foraminifers* and quartz grains. Normally above these ferruginous crust and oolitic limestone, IC facies occurs. Bands of the oolitic limestone facies show gradational upper and lower contacts except the topmost band which always shows erosional upper contact. The trace fossils present in the facies are the varieties of *Chondrites* and *Zoophycos.*

INTERPRETATION:

The interpretation of Oolitic Limestone facies has been made following Fursich et al. (1992) and Singh (1989). The main features of the OL facies are indicative of prolonged phases of omission and frequent erosive intervals leading to very slow rate of net sedimentation. This suggest an environment far away from terrigeneous input. The wide geographical distribution of these features also point to an off shore position well below fair weather wave base. While the iron ooids probably were derived from a near shore source, the carbonate components, largely bioclasts, formed locally by biological or mechanical degradation of shells. The dominance of *Zoophycos* and *Chondrites* traces among the ichnofossils suggest generally low energy conditions with oxygen depleted interstitial water at the on set of the facies.

Erosion most likely was caused by off shore currents which winnowed finer sediment leaving lag deposit behind. However, formation of extensive under cuts can not have been the result of winnowing alone. These features were probably produced by the scouring action of exceptionally strong storms which also might have distributed the iron ooids across the basin. Deposition of Oolitic Limestone facies, thus took place in a relatively uniform off shore setting, well below fair weather wave base, but still within the reach of singular storms. The uniform conditions and the negligible sediment input most likely reflect a transgressive phase which persisted throughout the Oolitic Limestone facies deposition.

This interpretation is in contrast to Bayer et al. (1985) and Hallam (1988), who stress the importance of erosion processes in the formation of shell lags and reworked concretion layers. According to them such layers form as "roof beds" on top of regressive cycles and are interpreted to reflect maximum regression. Similarly, Einsele (1985) postulates that extensive marine erosion occurs only if sea level fall is faster than subsidence, that is during regression, or in sequence stratigraphic terms, during the formation of low stand system tracts. However, the lack of shallow water features, such as primary sedimentary structures, and the presence of features characteristic of condensation (e.g. iron crust, hard grounds) are more in agreement with the interpretation of the facies as transgressive horizons.

Oncoides (oncolites), according to Wilson (1975) are typical of shallow, relatively quiet back bank environments, where they form on the edge of ponds and channels, normally landward to the oolitic grainstone belt (back bank environments). Further beds of ooids and oolitic pack to grainstone are most common along shore parallel belts with shoal bodies as per observations made by Vollrath (1955a) and Hagdorn (1982) in upper Muschelkalk of Europe. Thus ooids and oncoides show their origin on shoals and banks in very shallow agitating water (Aigner, 1985), from where, due to some exceptionally strong event, they derived in shelf environment of Oolitic Limestone.

Insitu logs of trees - Bharapar Member near Bhuj.

VI.2.7. Facies G: EXTRABASINAL CONGLOMERATE (EC):

The facies derives its name from the oligomictic quartz pebbles and gritty coarse sand beds, the material of which is most probably derived from out side the depositional basin. The facies occurs at the bases of DOM, JM and TM above unconformities between LM and DOM, MDM and JM, and JM and TM respectively. Rocks of the facies are normally less than 1.0 m, but thickness upto 5.0 m is observed on way to Jadura, 1.0 km north of Jadura mota. In the same way, it is found completely absent in overlapping sequences of JM and TM, as near SES in JM and south of Suteshwar Mahadev on way to Kotada-Chakar from Kukma in TM. Many a times it loses its typical conglomeratic character and is thus represented by loose mixture of red brown clays, siltstones and sandstones containing scattered pebbles as in exposures of JM towards 1.5 - 2.0 km SSE of Tapkadevi.

Megascopically the rocks of the facies are red, brown, ferruginous to yellowish, calcareous with haphazard arrangement of gravels, pebbles, sands and silts. The rocks are well compacted to almost loose and contains few, red ferruginous, yellowish marly, to white clayey flat pebbles of intrabasinal origin. The rocks are deposited on erosional uneven surface. The EC lies unconformably on SS subfacies or LSS subfacies and is followed gradually by FS facies or LSS subfacies.

Thin section studies depicts that the rocks are mineralogically mature containing mixed, monocrystalline and polycrystalline, igneous and metamorphic quartz grains. One or two sections from JM, facies shows 10.0 - 15.0 % felspar content.

Texturally rocks of EC are immature, where angular to rounded silty, arenaceous and fine rudaceous quartz grains are found together in an unassorted manner. Chert, detrital micrite, limestone and granophyric grains are also present in the rock. Muscovite flakes are common. Larger grains are found floated in cement/matrix or rock may be grain supported. Local sorting in form of elongated patched is found in some thin sections. Many grains are corroded and most of them are coated by brown ferruginous or yellow brown sideritic or micritic material. Few grains in rocks of facies in JM also shows over growth.

Majority of the fossils are ferruginised to neomorphosed. The fossils are *bryozoans, bivalves, brachiopods, cephalopods, foraminifers*, vertebrate teeth, algal filaments, fibrous bituminous plant material etc. Fossils in several cases show micritic or ferruginous coating.

Ferruginous and micritic peloids with coating of similar or heterogeneous material is observed in many cases. Cement is either dark brown black ferruginous or yellowish to dirty white micritic or locally sparitic. In the same section all such variation can be observed producing complex lithology, or individual sections can show prominence of one type of cement. Sparitic crystals are very large in certain cases almost producing sparitic limestone or giving appearance of marble.

In several cases distinct ferruginous and calcareous (micritic) cement layers are observed in conglomerate. When its detrital material is absent, thin layers of ferruginous or micritic material are produced within the rock. These layers may be a part of algal mates. Minute rhomb shape crystals of sideritic and ankeritic material are present in abundance in few sections. In some cases cherty cement has also been observed. Micritic crystals are elongated indicating its marine origin and magnesian rich nature. In the same way, elongated crystal casts in ferruginous cement suggest replacement of micrite. Pores are present in few sections. Trace fossils are absent.

INTERPRETATION:

The occurrence of the facies on uneven denuded unconformable surface depicts transgressional deposition on an unconformity. The presence of such conglomerate characterizes an unconformity, containing mix - terrigeneous and marine originated material.

Further, The rock has no uniform composition over larger area and it shows perfect oligomictic, matrix supported (para-conglomeratic) nature-, to large proportion of intraformational grains, pebbles and fragmented corroded fossils; to almost argillaceous in nature with few extra- and/ or intrabasinal clasts.

Thickness of the facies is uneven, and at places it is completely absent.

The rock when overlies hard rocks like sandstones unconformably, it contains larger proportion of sand size to pebble size angular subangular quartz and rock fragments of sandstones, quartzites as well as in few instances granites. On the other hand, when it is found capping shales, here also not in a conformable manner (unconformably), it largely contains detrital calcite grains of varied (bioclastic to lithoclastic) origin, intraformational grains and pebbles, and fragmented corroded bioclasts mainly of resistant nature like *brachiopods (Terebratulids* and *Rhynchonellids), oysters* and *belemnite guards*. Such material probably settled in loose to hard, red to dark brown, ferruginous material, to yellowish to brownish mix calcareous and ferruginous material. The rocks are further texturally immature. The cement seems to be mainly of marine origin.

All the above characters either directly or indirectly suggest origin of EC characteristic over unconformity, at the time of invasion of sea.

The framework and matrix of the conglomerates suggest that it could be residual material on denuded land surfaces. This is supported by mixed bioclasts like teeth, woody material, algal filaments, minutely fragmented bones (pers. comm. Ghevaria) along with marine invertebrate fossils.

VI.2.8. Facies H: BIOTURBATED SANDSTONE (BTS):

The facies consist of coarse grained highly ferruginous sandstones characterised by abundant bioturbation, which has obliterated primary sedimentary structures of the rocks. This facies can be marked from a distance by its typical dark brown black colour, bioturbated nature and uniform thickness over distant areas. Individual beds in this facies shows thickness variation from 0.50 cm upto 2.0 m. Thickness of amalgamated sequence of identical beds of the facies reaches upto 20.0 m, e.g. exposures in northern facing cliffs, half kilometer south of Bhanushali nagar, Bhuj. The occurrence of this facies is known from BM of Bhuj Formation. It occurs in association with Variegated Shale facies (VS) and Cross Bedded Coarse Grained Sandstone facies (CBCGS) constituting complex alternations. The alternate sequence of BTS, VS, and CBCGS frequently alongwith SS, is cut across by small tidal gully structures, filled by cross bedded sandstones. The lowermost bed of the facies in the BM occurs capping FS (HS) facies developed in the TM with nondepositional flat to uneven surfaces or disconformity. The lower junction of the beds of the facies is normally abrupt scoured uneven or with load casts and related structures, while upper junction is bioturbated or ripple marked. The ripple marks are straight crested symmetrical to asymmetrical or in some cases current ripple marks. Ripple marks when present are much obliterated by bioturbation.

The sandstones of the facies show large leaf impressions as well as algal mate structures (e.g. Tapkadevi hill top), and in situ logs and root portions of tree (e.g. near Bhuj, plate-11).

Horizontal stratification and planar cross stratification has been observed in field which are highly obliterated by bioturbation. Linear structures (plate-5) produced by uneven erosion under prevalent wind has also been seen on upper surface of a bed on top of Tapkadevi hill. (Strong winds blowing over damp or slightly cohesive sediment can lead to erosional forms reminiscent of flute but showing a positive relief on the upper surface. A blunt end points upwind with a tail streaking out down wind. In the facies, the structures are 1.0 to 3.0 cm wide and upto 30.0 - 35.0 cm long and they occur in groups. Similar observations are made by Collinson and Thompson, 1989, p.47). This facies is iron rich and can be referred to as ferruginous bands, concretionary hematitic or limonitic with spongy or nodular weathering as suggested by Biswas (1977).

Small tidal gullies and symmetrical straight crested ripple marked shallow tidal swell structures have been observed on top of the facies bands (e.g. near Bhuj on Mundra road).

Thin section studies reveal that the rocks are coarse sandstones to pebbly grit, are moderately sorted and in majority of the cases framework supported alongwith clay, silt and fine sand matrix filling interstices. Few sandstones are unassorted. Coarse grains are rounded to subrounded, matrix is subangular to angular.

Mineralogically the rocks are mature, contain rare felspar grains. Matrix normally contains upto 5.0 % felspar. The quartz grains are of mix origin. Plain quartz, undulose extinct quartz and polycrystalline quartz grains almost occur in equal proportion. Few of the grains are chertified. Clayey pellets have been observed in certain sections. Fossils are totally absent except fibrous black brown wood (bitumen) material.

Cement in majority of the cases is dark brown black hematitic (ferruginous) with small proportion of micrite in form of patches, microveins and hairlike fracture filling. Some of the hematitic sandstones are hardened due to chertification and gives vitreous lustre. Cherty cement is also present in form of patches in several sections. In many cases grains are coated by ferruginous or micritic or in rare cases clayey material. Overgrowth of quartz grains have also been observed in several cases. Many framework supported rocks are cemented together by ferruginous coating only, where open pores are found in abundance or such spaces are found filled by clay silt matrix. Thin sections many a times show layering.

Trace fossils are mainly *Diplocraterion, Monocraterion, Skolithos, Arenicolites, Thalassinoides, Rosselia* etc.

Burrows in the sandstone do not extend downward in to the shales of VS facies or cross bedded sandstones of CBCGS facies. The dense burrowing, coarse grain size, and extreme weathering make it difficult to examine individual burrows. The upper bedding planes on these densely bioturbated beds sometimes show mound and crater topography, representing the original sediment surface. By comparing this with modern burrowing organisms, it can be said that the depressions could have formed at the incurrent limb and the mounds at the excurrent limb of the U - shape burrows.

Gypsum layers and crystals have been observed on top beds of this facies. Crystals are of selenite variety.

About 2.0 - 2.5 km northeast of Bhuj, near Suralbhit, the sandstones of the facies show megaripples with NE-SW & N-S palaeowave direction. Here, two different sets of megaripples are superimposed to form megainterference ripples. Megaripples have also been observed opposite to Bhanushali nagar in vertical section in the facies.

INTERPRETATION:

Highly burrowed rocks reflect deposition in areas where wave and current stratification is over shadowed by biological reworking (Howard, 1972). Such conditions with slow to negligible rate of sedimentation could have existed either offshore, or in a protected shoreline environment such as back barrier lagoon. Burrowing in some modern lagoonal sediments is also intense as suggested by Warme, 1971; Reineck & Singh, 1973; Ronan, 1975. The extensive burrowed texture and sheet like geometry of the Bioturbated Sandstones of the BM put constraints on the environments in which they may have been deposited. First, the overlying or interstitial water must have been brackish, or more likely, of near normal marine salinity. Studies of bioturbation in modern estuarine environments have shown that the abundance and diversity of biogenic structures increases seaward, especially in estuaries with fresh water influx (Howard, 1975); sediments deposited in low salinity environments (e.g. inner estuaries) generally are not extensively bioturbated (Dorges and Howard, 1975).

The extensive burrowing in the Bioturbated Sandstone (BTS) facies, therefore, suggests near normal marine salinity and an area protected enough to allow biogenic reworking to dominate over wave and current stratification. Such conditions occur on a subtidal to lower

Micro-ripples in CBCGS facies, Bharapar Member near Kera.

part of intertidal region. Much less lateral variation in thickness, more lateral extension, sheet like geometry and absence of channel structure denies deposition in a tidal channel or estuary. Mostly, such horizontal stratification and perpendicular abundant bioturbation depicts very gentle gradient of the depositional basin and development of extensive tidal flats.

The coarse grain size of the sandstones rules out deposition under lagoonal conditions, but moderate sorting to unassorted nature, pebbly to coarse grains and scoured erosional bottom surfaces suggests that the rocks are probably storm lag deposits, which later on reworked by tidal currents and biogenic activities during long continued stable agitating conditions. The storm or high energy origin is also supported by the occurrence of mega wave ripples in the facies. It is considered that storm period waves scour the shore face, temporarily suspend the sediment, and redeposit it as laminated sands as the storm wanes. Then, during fair weather periods, burrowing organisms and/or lower energy waves rework the upper part of the laminated sand. Identical beds, termed 'sub-littoral sheet sands' or 'storm lag deposits', have been described in ancient shelf facies associations (Goldering and Bridges, 1973; Brenner and Davies, 1973).

Based on the above evidences it can now be interpreted that the burrowed sandstones were deposited in a subtidal - tidal (offshore - shore face) transitional environment, in similar manner as the burrowed sands in modern environments evidenced by Howard, (1972). These bioturbated sandstones are further capped many times by the trough cross bedded sandstones which could be typical of lower shore face deposits as further suggested by Howard (1972), and Reineck and Singh (1973).

In situ wood fossils and root portions which have been found behind Lalan college, Bhuj, in the thin layer of the facies supports storm generated deposition of the sandstones. This could be in a stormy transgressive encroaching sea, which have incorporated near shore coastal terrestrial region or tidal marshy region, suggested by preservation of root portions and in situ logs in form of ferruginised internal moulds. The occurrence of gray coloured mud and gypsum below this band supports pre-existing marshy conditions. Here, bioturbation is comparatively less. The association of the facies with lagoonal to marshy VS facies and CBCGS facies depict superimposing of various geomorphologic features associated with subtidal - tidal coastal environments by the storm generated and later reworked BTS facies.

Alternatively, the deposition of it could have occurred during mesotidal or macrotidal shoreline conditions in form of tidal lags.

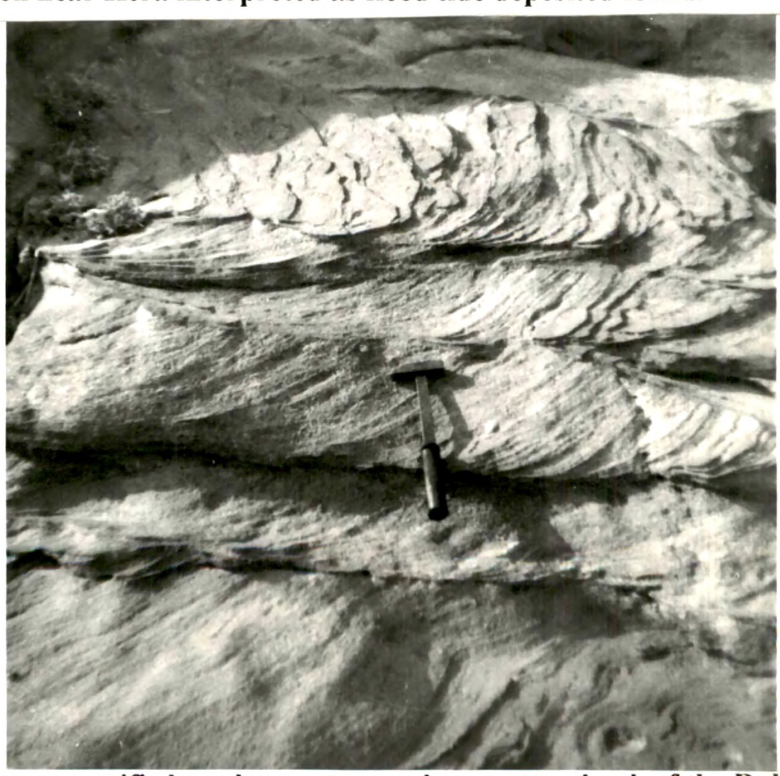
VI.2.9. Facies I: VARIEGATED SHALE (VS):

The facies is defined on the basis of occurrence of variegated silty shales and muds. The rocks are massive to laminated, fissile to nonfissile and moderately compacted to loose. The colour of the rocks varies from white, gray, yellow, red, brown to black. Composition of it varies from felspathic, ferruginous, clayey to carbonaceous. Thickness ranges from 0.1 m upto 2.0 m and occurs in form of elongated beds and lenses. It is found associated with BTS and CBCGS facies and occurs only in Bharapar Member of Bhuj Formation. It normally shows quick gradational lower contact and gradational, abrupt to erosional upper contact. Trace fossils are moderate in some and rare to completely absent in other beds and include only vertical, oblique and horizontal burrows (*Skolithos, Calycraterion, Arenicolites,* etc.). Leaf impressions and plant fragments are abundant, but no root structures were observed. Body fossils are totally absent. Burrows, when present have disturbed lamination of the rock. Many a times, facies is represented by siltstones, which in some cases shows trough and planar cross stratification and symmetrical to asymmetrical ripple marks on top.

Carbonaceous shales with abundant leaf impressions and burrowed ferruginous shales are commonly found in the lower part of the facies sequence in the BM, while felspathic shales and mudstones are more in upper part.

Near Observatory, on Tapkadevi hill top as well as near Reha village, yellowish red and brown

a. Northwardly directed cross-stratified sandstones exposed on western bank of the Rukmavati river section near Kera interpreted as flood tide deposited forms.



b. Southernly dipping cross-stratified sandstones exposed on eastern bank of the Rukmavati river section near Kera interpreted as ebb-tide deposited forms.

Channel structure incised within estuarine facies.

ferruginous shales and siltstones with bioturbation has been observed. Behind Lalan college, Bhuj, ferruginous, felspathic & carbonaceous shales and mudstones have been observed. While on Mundra road, near 4 km milestone, mudstone and cross stratified siltstone bed occurs. Commonly carbonaceous shales, several mudstones and siltstones are richer in leaf impressions and plant fossils. While in ferruginous shales and siltstones, burrows have been observed. Gypsum layers have been observed in mudstones. The facies occurs in form of complex alternations with BTS and CBCGS facies.

INTERPRETATION:

Paucity of structures in this facies makes environmental interpretation difficult, although it appears to have deposited under quiet water conditions. Rarity of biogenic structures may be due to, in part, poor exposures rather than solely to lack of trace producing animals as can be seen in felspathic and carbonaceous shales and mudstones. Occurrence of biogenic structures in ferruginous shales depicts favourable conditions for infaunal elements and oxygenated aerobic conditions. Trace fossils, whenever present depicts marine influence in a coastal setting.

It is interesting to note that, in modern coastal settings, fine grained sediments are deposited in a variety of environments. Lagoonal sediments accumulating landward of barriers consist of shales and fine silts which commonly are burrowed and which may also be laminated (Elliott, 1978). Fine grained sediments are also deposited in estuarine marshes and interdistributary bays (Morgan, 1970). The VS deposits may be settled in a gradational transition from back barrier to interdistributary environments. Silts and clays of these were probably deposited in intertidal flats associated with barrier systems.

The ferruginous bioturbated shales and siltstones with horizontal stratification are most probably originated in landward side of barriers to intertidal setting. Mudstones and cross-stratified siltstones presumably deposited in intertidal flats associated with barrier systems.

Here cross stratified siltstones are typical of tidal (shoreface) environment.

Variegated Shale facies in the BM do not have desiccation cracks, root impressions or any other indication of subaerial deposition. But, as evaporite deposits, bioturbation and abundant leaf impressions are present, a lagoonal to intertidal origin for the shales can be postulated.

Alternatively, the carbonaceous shales with leaf impressions were parts of coastal marsh or swamp conditions, is possible like most of the modern coastal peat deposits.

The facies is associated with subtidal - tidal flat deposited BTS facies and migrating bar deposited CBCGS facies also supports the above interpretations. The frequent repetition of these facies in the stratigraphic record indicate slowly subsiding basin giving rise to repetitive phases of shallowing by sedimentation, and evaporation in partially enclosed water bodies.

VI.2.10. Facies J: CROSS BEDDED COARSE GRAINED SANDSTONE (CBCGS):

The facies is defined on the basis of abundance of coarse grained sandstones which are characterise in majority of the cases by large scale planar and trough cross stratification. The facies is developed only in Bharapar Member of Bhuj Formation. It depicts a maximum thickness of 150.0 m in the upper part of BM. Individual bed of the facies normally show thickness variation from 0.5 m to 5.0 m. The facies is found associated with BTS and VS facies. The facies differs from BTS facies by the much less occurrence of burrows, sorted nature and abundant occurrence of cross stratification in the former in comparison to bioturbated nature, poor to moderate sorting and dark brown hematitic to lateritic composition of later. Trace fossils present in the facies are only few in form of escape structures or in form of *Ophiomorpha*, *Skolithos* and *Strobilorhaphe* burrows.

Thin section studies depicts that, texturally the rocks are mostly moderate to well sorted, but poorly sorted to unassorted sandstones have also been observed. The grains are very coarse sand size with frequent occurrence of small pebbles. The larger grains are subangular to subrounded. In moderate to well sorted rocks, which are framework supported, matrix varies from negligible proportion to abundant and occupies open spaces only. The matrix varies from silt to medium sand size. Poor to unassorted rocks are matrix supported where matrix is clayey to sandy. The matrix is angular to subangular.

Mineralogically the rocks are mature with abundance of plain and undulose extinction grains, and with presence of several polycrystalline quartz grains. Felspar content is only 5.0-8.0 % in certain cases, to almost absent. Opaque grains and mica flakes are found present. Many grains are coated either with ferruginous or light brown to black clayey material or in few cases by micritic or sparitic material. Woody material is present in several cases.

Cement also varies from ferruginous, micritic to sparitic or siliceous or may be completely absent and compacted by matrix only. Few rocks are fractured, and micritic to sparitic microveins have been observed in such fractures.

Megascopically colour of the rocks varies from white, pink, yellow, gray, buff, red to brown. The facies occurs in isolated cross bedded sheet form or linear elongated ridge like form within complex alternate sequence of BTS, VS and CBCGS facies; or it produces thick amalgamated sequence of cross stratified beds.

Some times (as in river section near Kera) very thin - upto 10.0 cm - trough cross stratified fine sandstone beds have been observed. Thin (only 10.0 - 15.0 cm) isolated ferruginous to clayey shales with current and asymmetric ripple marks have also been observed, in thicker sandstones. Microripples produced by surface expression of small scale trough cross bedding have also been seen (plate-12).

The facies shows large scale to small scale planar cross-stratification, trough cross-stratification, torrential bedding, climbing ripple cross lamination, slumping and contorted bedding, graded bedding, herringbone structure, small sandstone dykes etc.

When the facies occurs alternating with BTS and VS, it mainly contains planar cross stratification and torrential bedding. The planar cross stratification depicts east to northeast palaeocurrent direction. The torrential bedding shows southernly palaeocurrent direction. When amalgamated sequence of planar cross stratification is exposed, it mainly shows southernly palaeocurrent directions with few sets of cross stratified units showing northerly directions and some producing herringbone structures pointing northern and southern palaeocurrent directions (e.g. in river section near Kotada and Kera and in hill south of Jadura). Large scale trough cross stratified beds occur in form of channel fills cutting through planar cross stratified beds and shows southeast, south to southwest palaeocurrent directions. Small scale trough cross stratification show southernly palaeocurrent directions.

Moulds and casts of bivalves are observed in the facies exposures south of Jadura nana village, while silicified coral fragments are observed in the facies south of Lalan collage, Bhuj.

Lower contact of the beds shows reactivation surfaces and upper contacts are erosional. Ripple marks are hardly found preserved on top surfaces. Pebbly conglomerate layer occur in form of toe sets in cross stratified or torrential beddings. The amalgamated sandstones occur in form of larger channel fill deposits where beds occur in form of sheets or broad lenses tapering against erosional channel contacts.

INTERPRETATION:

The thick sequence of CBCGS facies seems to be deposited in an estuarine depositional system. The estuarine set up is judged on the basis of lateral and vertical variation in the physical structures and geometry of the beds observed in the facies. Here, herringbone structured sequence as exposed near Chakar is indicative as resulting from flood and ebb tides in an estuarine set up. Each bed commence with the reactivation surface and tapers on top by erosional surface. Such features are characteristic of the flood tides and are associated with normal storm events (Leckie and Singh, 1991; Dalrymple, Zaitlin and Boyd, 1992).

The compound cross beds, reactivation surfaces and superposed reversing cross bed sets are suggestive of deposition by tidal currents. There is no evidence of subaerial exposure in cross stratified units (roots, tidal flat muds, swash lamination etc.), and the deposits are inferred to have been deposited sub-tidally.

Further evidence regarding the estuarine condition is provided by exposures of the facies in river section near Kera. Here, two separate courses of flood and ebb tides has been inferred from northerly directed planar cross stratified units exposed on western bank of the Rukmavati river, and southernly directed cross stratification on eastern bank of the same river (plate-13 & 14). The opposite directed structures are only few tens of meters away from each other. Further the cross stratification on western bank shows 0.5 to 1.0 m thickness, while structures on eastern bank show few decimeter to half meter thickness. This indicates variation in the flood and ebb tide energy conditions. In several modern estuaries (e.g. Bristol channel, U.K.), ebb and flood tidal currents occupy mutually exclusive areas within the estuary resulting in spatially segregated zones of sediment transport (Harris, 1988; Harris and Jones, 1988; Coleman et al., 1988; Harris and Collins, 1985).

Small asymmetric to linguoid ripple marks on thin siltstones and shales as well as minute trough cross stratification alongwith microripples are interpreted as deposits of weaker ebb tide flows or fluviatile flows in between two flood tides. These small scale structures depicts prominent southernly palaeocurrent direction.

Large scale planar cross stratified units near Kotada with a thickness of more than 1.0 - 1.5 m and showing secondary physical structures like slumping, contorted bedding, micro faulting, sandstone dykes, mud and siltstone drapes etc., and torrential bedded units predominantly pointing southward palaeocurrent directions are interpreted as flood deposits within estuarine conditions with catastrophic sedimentation at the time of higher precipitations during rainy season. Secondary physical structures support the faster rate of sedimentation. Large scale planar cross stratification with contortion has been interpreted as flood deposits by Collinson and Thompson (1982). Here, palaeo-seaward directed southernly palaeocurrent direction of planar and torrential bedded flood deposits rule out the deposition in tidal channel.

Further, channel cut and fill structures containing trough cross stratified sandstones and oriented in a meandering manner and showing SE to SW palaeocurrent directions are considered as fluviatile channel deposits (plate-14). As a result the rocks are found cutting bimodal planar and trough cross stratified rocks (interpreted as estuarine deposits). Such observations were made by Raaf and Boersma (1971) for Pleistocene estuarine facies in Holland.

Massive to large scale cross stratified sandstones with monodominant *Ophiomorpha* could be interpreted as elongated bar or tidal ridge within relatively deeper parts of estuarine channels. Similar interpretations are made for the Tertiary beds of England by Bosence (1976). This may be dumping of sand at the fresh and saline water interfaces in estuaries.

The CBCGS facies found interbedded with BTS, VS and SS facies in BM represents barrier and/or shore face deposits. This is inferred on the basis of much lateral elongation of the facies in east-west direction and occurrence of planar cross stratification in the rocks, and association with shoreline deposits of BTS, VS and SS facies.

The bimodal cross stratification, meandering channel fill structures, sandstones with *Ophiomorpha* etc., point to an outer marine dominated to central mixed energy (river and marine processes) part of an estuary. Such a situation is proposed in a perspective model of estuaries, based on physical processes and structures by Dalrymple, Zaitlin and Boyd (1992).

In this inferred set up by the author, there was possibly considerable tide and wave energy which constantly reworked sediment and made conditions inhospitable for burrowing organisms, thereby accounting for the lack of bioturbation and general absence of mudstones. Similar interpretations are also made by Leckie and Singh (1991) for Albian Estuarine deposits in Canada.

In many modern estuaries, the coarsest sediment, typically cross bedded, is generally found at the mouth or lower middle portion of the estuary and are described from Ossabaw Sound, Georgia (Howard et al., 1975; Dorges and Howard, 1975), Morton bay, Queensland (‘‘marine tidal delta’’, Harris and Jones, 1988), Chesapeake bay (‘‘bay mouth shoals’’ Coleman et al., 1988) and Bristol channel, U.K. (Harris, 1988). The CBCGS facies of Kutch therefore indicate similar set ups during its deposition.