CHAPTER 5
SEDIMENTARY FACIES

5.1 INTRODUCTION

The term and concept of "facies" was first introduced by Gressly (1838), observing the characteristic lateral changes in Jurassic rocks of the Jura region of southern France. In the late twentieth century, it gained significant importance, especially in sedimentology, in which sedimentary facies refer to the sum of the characteristics of a sedimentary unit (Middleton, 1973). The facies characteristics include the dimensions, sedimentary structures, grain sizes, color, and biogenic content of the sedimentary record (Nichols, 2009). In modern-day research, various terms are used, such as "Lithofacies," "Biofacies," and "Ichnofacies," emphasizing the physical and chemical characteristics of a rock; fauna and flora present and/or on the trace fossils, respectively description (Miall, 1984). These facies are used in a descriptive and interpretive sense (Miall,1984) and hence form the basis for reconstructing the depositional sequence's paleoenvironments.

According to Miall (1984), descriptive facies include specific observable attributes of sedimentary rock bodies on the outcrop defined based on its distinctive lithologic features, including composition, grain size, bedding style, fossil content, and sedimentary structures. Each lithofacies represents an individual depositional event, characteristic of particular depositional environments and can be interpreted in terms of depositional processes. These different facies form a facies association that reflects the depositional environment (Reading and Levell 1996). The author attempted to analyze the various lithofacies from the Bagh Group sequence of the WLNV and grouped them into facies association according to the depositional environment.

5.2 DESCRIPTION OF THE FACIES

The Bagh Group succession of the WLNV is exposed at different places and characterized by variable sedimentological characters. Total eleven sections (Fig. 5.1) are studied in detail which include, Navagam (324 m), Bhadarwa hill (81 m), Uchad village (47 m), Devaliya (19 m), Songir (130 m), Karvi (11 m), Mohanfort-Kara River (26 m), Mathwad Nala (34 m) and Vajepur section (24 m), displaying the vertical as well as lateral lithological variations. Lithofacies analysis was done based on field and laboratory studies that include sedimentary structures, texture, composition, and petrographic variation. It comprises a large variation in textural and mineralogical composition that revealed three different facies association including siliciclastics, mixed siliciclastic-carbonate, and carbonate rocks and classified according to Dott's (1964), Mount (1985), and Dunham (1962), respectively. These are further grouped into shallow marine and fluvial environments.

5.2.1 FLUVIAL FACIES

The initiation of intracratonic rifting during the Early Cretaceous period created the space for the deposition of the continental sediments. The high relief area of Precambrian supplied the coarse clastic sediments by ephemeral streams on the slope either in an alluvial fan environment and/or sheet deposits. The initial deposits rest unconformably over the Precambrian granites, quartzites, phyllites, and schists. The common feature of the deposits observed is their gravelly nature in the lower part, which progressively becomes a coarse sand-dominated sequence. The proportion of gravel is highly variable and poorly sorted in nature, but mostly subangular to subrounded in nature and randomly oriented. Further, the upper part of the sequence is characterized by planar and trough cross-stratification, which marks the change in depositional conditions. The fluvial deposits of the Narmada basin show the facies variation, which is the result of the change in flux and environment and depicts four different lithofacies including conglomerate, Planar and Trough Cross-Stratified Sandstone, Parallel-Laminated Sandstone, and Massive Sandstone.

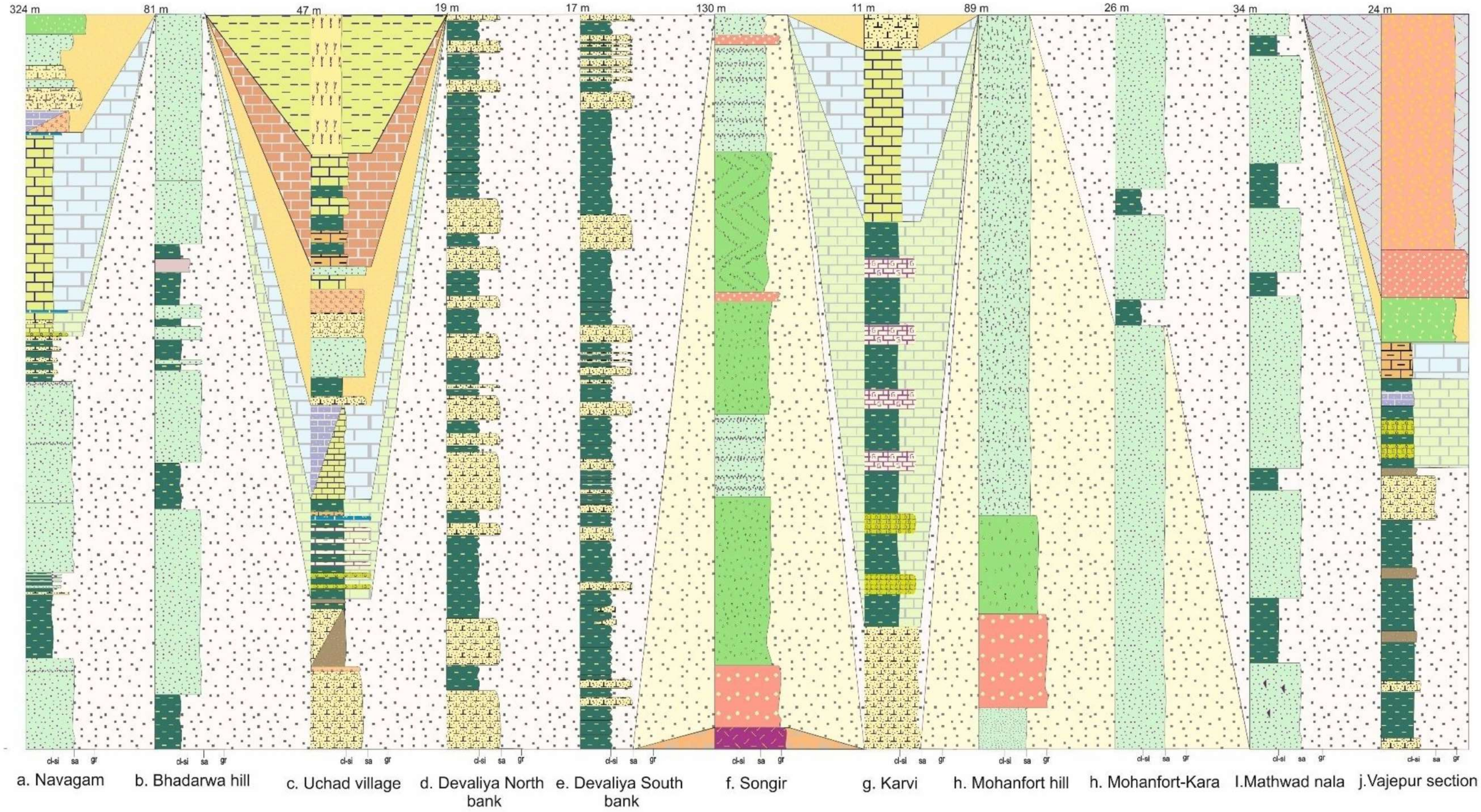
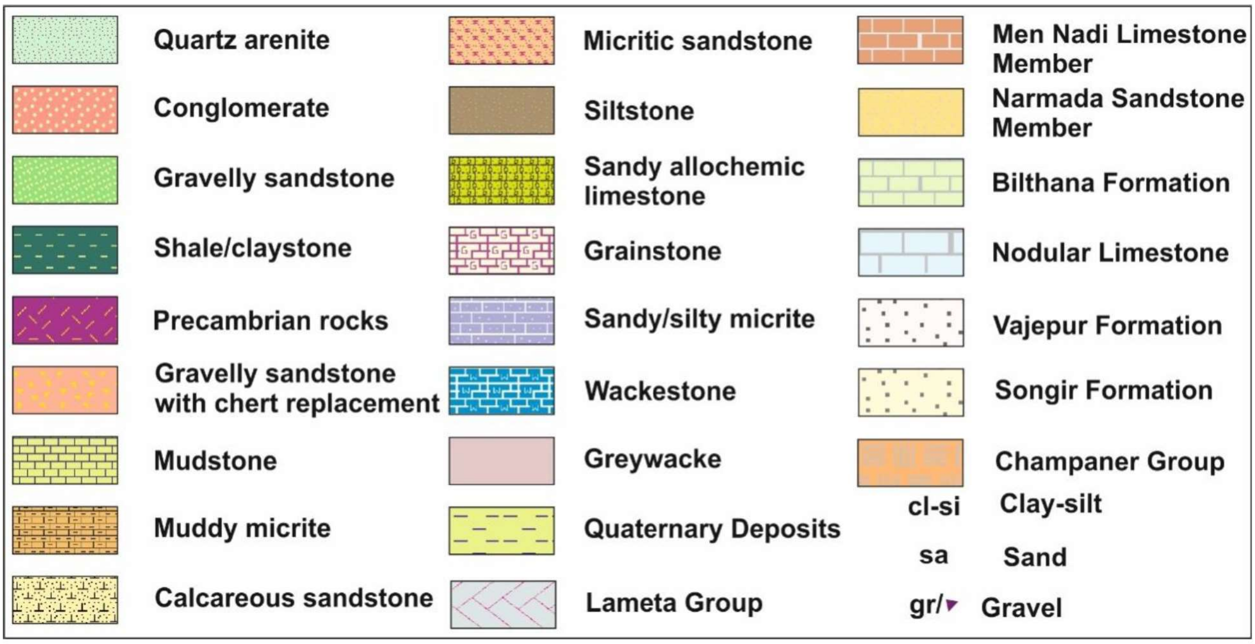


Figure 5.1 Two-dimensional strip log correlation of the WLNV sections.



Legend represents the symbols used in the present study.

5.2.1.1 Conglomerate facies

Description: This facies is well developed in the lower part of the Songir Formation and exposed in Ghantoli, Naswadi, Songir, Chosulpur, Vajeriya, and Mohanfort areas. The thickness of the unit is highly variable at different places; it comprises different sizes of gravels as well as a varying proportion of the clast and matrix ratio, further grouped into four subfacies, clast-supported conglomerate, matrix-supported conglomerate, planar stratified gravel, and clast-supported conglomerate with sandstone. The identification of four subfacies was based on their texture, framework, sedimentary structures, external geometry, and nature of contacts. The conglomerate subfacies of the Songir Formation are highly variable within and between individual outcrops, dependent upon the distance between sources and depositional sites and specific environments of deposition.

Clast Supported Conglomerate Subfacies: The clast supported conglomerate with thicknesses up to 2 m are observed, which can be laterally traced to more than 50 m. It comprises granules to cobbles-sized grains of quartzite, which are mainly white colored but occasionally red-, green- and orange-colored gravels. Clasts are subrounded to rounded, poorly sorted, and randomly oriented (Plate 5.1a-d). The clast-supported conglomerate laterally and vertically grades into matrix-supported conglomerates; the layers of clast supported conglomerates are very often interbedded with sandstone and pinch out at a short distance. The facies often interbed with the trough cross-stratified sandstone facies but have a distinct upper and lower boundary.

Plate 5.1 Field photographs of the conglomerate. a. Conglomerate with rounded to subrounded clasts, Songir-Chosalpura section. b. Conglomerate with angular to rounded clasts, Songir-Chosalpura section. c. Massive conglomerate at Mohanfort section. d. Imprints of pebble and cobble on clast-supported conglomerate, Songir-Chosalpura section.

Matrix Supported Conglomerate Subfacies: The matrix-supported conglomerate shows highly variable thicknesses; maximum 4 m thick band is observed in the Ghantoli area, which can be laterally traced to more than 100 m. This unit also shows the varying proportions of gravel and matrix ratio; the gravels are identical in composition to the clast supported conglomerate. It comprises gravels ranging from granules to cobbles (Plate 5.2a-b) but subrounded to rounded pebble-sized clast are abundant, displaying well sorting as compared to clast supported conglomerate. This subfacies also grade into the clast supported conglomerate and sandstone, and very often, it is observed to be interbedded with sandstone.

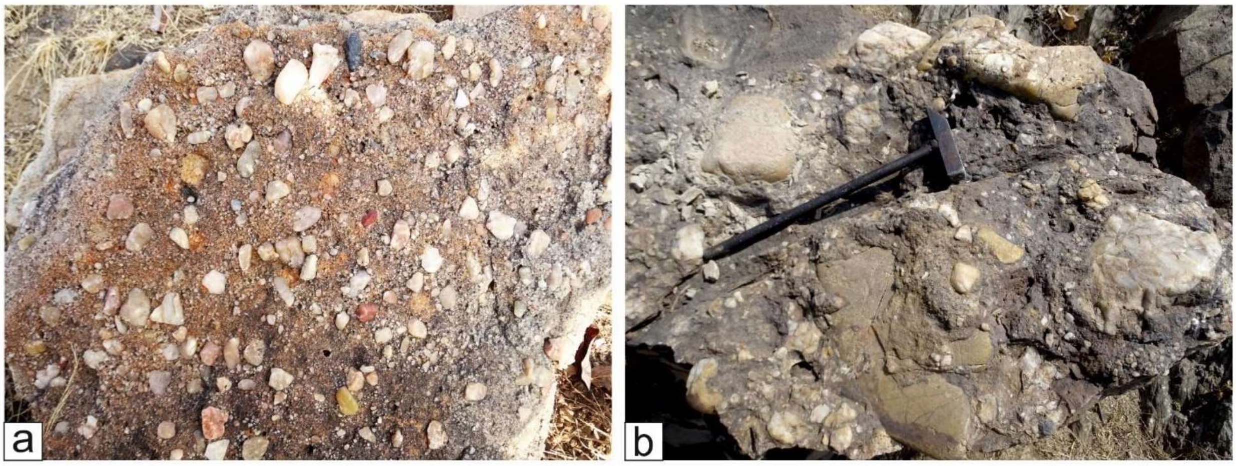


Plate 5.2 Field photographs of the matrix-supported conglomerate. a. Conglomerate with angular to subangular clasts, Mohanfort section. b. Conglomerate containing boulder to pebble-sized angular to subrounded clasts, Ghantoli section.

Clast Supported Conglomerate with Sandstone Subfacies: This facies interbeds between the clast supported pebbly conglomerate with sandstone (Plate 5.3a-c) and is observed in the middle and upper part of the sequence around the Songir-Chosalpura area. The clast supported conglomeratic beds are up to 30 cm, while the interbedded sandstone layers are thicker and have maximum a thickness up to 35cm.

The clasts are subangular to subrounded, poorly sorted, and tightly packed; they are unevenly distributed, and their proportions is highly variable. Sandstone is characterized by coarse-grained particles with an appreciable amount of medium-grained quartz, which are subangular to subrounded and poorly sorted. The beds are usually massive and seldom show faintly developed low-angle planar stratifications. These conglomerate and sandstone layers pinch out at short distances and show the contrasting grain size at the same level laterally.

Planar-Stratified Gravel Subfacies (Gp): The planar-stratified gravel facies is matrix-supported and comprised of poorly-sorted, oligomictic conglomerate possessing planar cross-bedding (Plate 5.3d). It shows up to 2m thick brown colored, planar-stratified gravel, which abruptly terminates. The subfacies show well-preserved solitary, wedge-shaped cross-bedding. It is composed of predominantly white-colored, angular, granule to pebble-sized quartz grains in a sand-dominated matrix observed in the Songir-Chosalpura area. The facies contain minor interbands of sandstone and is associated with parallel-laminated sandstone facies.

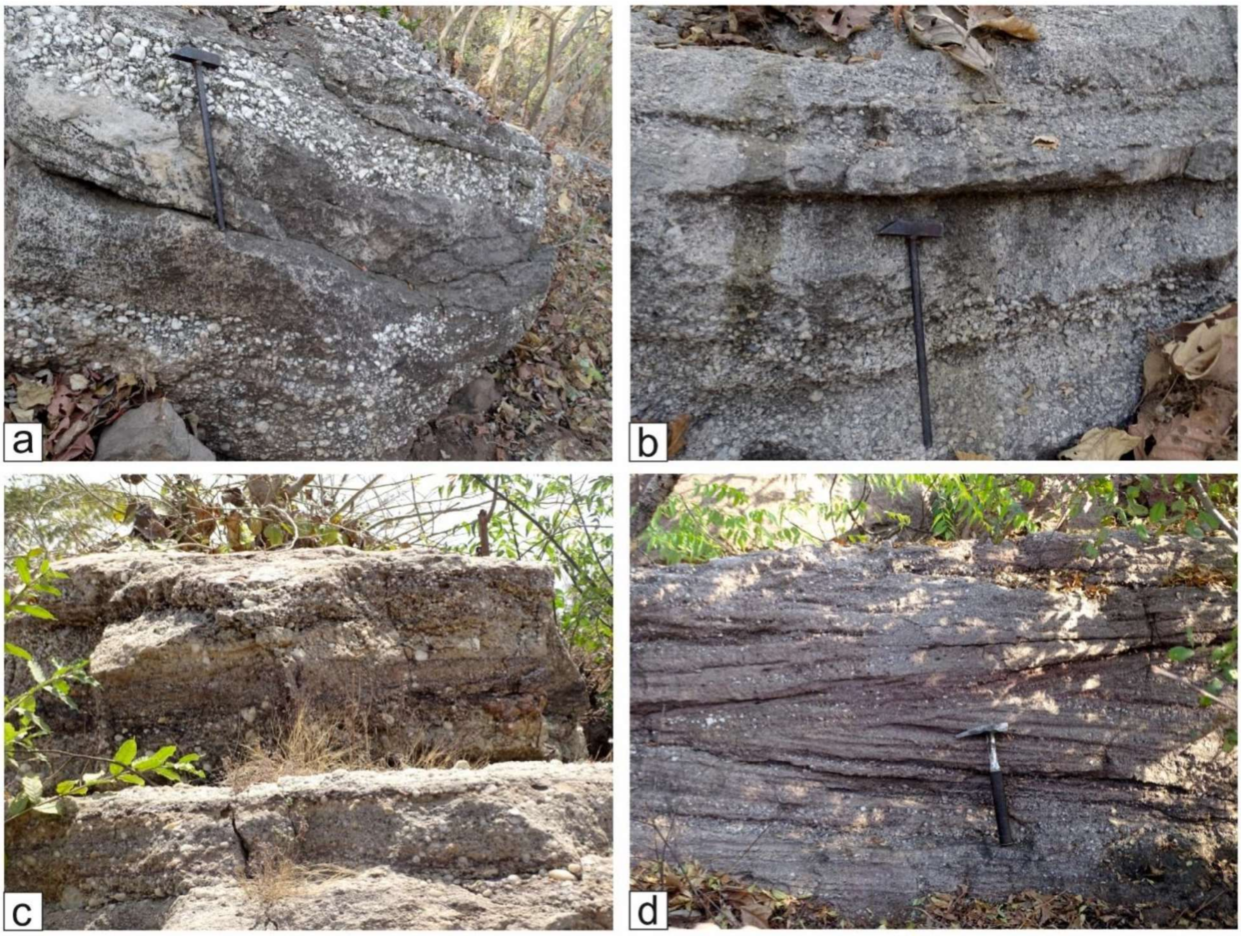


Plate 5.3 Field photographs showing conglomerate interbedded with sandstone and cross-stratified gravels. a-b. Clast-supported massive pebble conglomerate interbedded with trough cross-stratified sandstone, Vajeriya section. c. Fine pebbly matrix-supported conglomerate, Ghantoli section. d. Planar-stratified gravel, Chametha-Chosalpura section.

Interpretation: The conglomerate facies marked the beginning of the sedimentation in the Narmada Basin during the initial rifting phase characterized by transported grains. The proportion and size of the grains are highly variable laterally and vertically, which marks the change in sediment influx over time and space, and the high sediment supply points to the development of an alluvial fan environment. Massive conglomerates, which are either clast supported or matrix-supported, planar stratified, and interbedded with sandstone marked the braided channel deposits in the alluvial fan environment.

The clast-supported conglomerate occurs as a sheet or massive body, unevenly distributed and lacks continuity. It is poorly sorted; grains are up to boulder size and are dominated by subangular fraction indicating the early development of fan on foredeep of the Precambrian igneous and metamorphic rocks. Sheet like conglomerate observed at the Chametha-Chosalpura section are the products of catastrophic flows, while the horizontally stratified conglomerates at the Mohanfort section suggests winnowing by strong currents at the top of the erosion surface or as lags on the channel floor (Collinson, 1996)

Matrix-Supported Conglomerate occurs as a massive body and comprises rock fragments up to boulder size (Ghantoli area) and is pebble dominated in Mohanfort, which marks the change in depositional processes. The large-sized gravels in the Ghantoli area lack imbrication and internal bedding, which suggests it to be a product of cohesive debris flows (Nemec and Steel, 1984). The fine gravels of the Mohanfort area suggest varying transport of grains during the waning water stage (Steel and Thompson, 1983) in the middle part of the alluvial fan.

Planar-Stratified gravel of the Songir-Chosalpura area is characterized by low-angle, large scale cross-stratified conglomerate characteristic of the middle part of an alluvial fan. The foresets are wedge-shaped, inclined at 6-20^0, and pebbles are evenly distributed at places, but some-cross beds lack uniformity in the distribution of pebbles, suggest high-density flow in catastrophic floods.

Clast-supported conglomerate interbedded with sandstone is observed at Mohanfort, Ghantoli, Songir-Chosalpura, and Vajeriya villages. The crudely-stratified deposits at Mohanfort, Vajeriya and Ghantoli section are the characteristics of the braided stream deposits. Thin strata (a few cm's thick) of conglomerate typically result from rapidly shifting, shallow braided channels, from the shallow flow on the tops of sand sheets, or from unchannelised flooding on the lower reaches of alluvial fans. The clast-supported conglomerate at the Songir-Chosalpura section lack stratification and imbrication and is interpreted to be deposited during high stages of transport, while the intermediate stratified sandstones represent the waning flow deposits.

5.2.1.2 Planar and trough cross-stratified sandstone facies (PCS)

Description: This facies is observed in Songir Formation around Mohanfort, Vajeriya, Chametha, Songir, Chosalpura villages. It comprises coarse-grained sandstone with varying cross-stratification classified into two subfacies, planar stratified coarse-grained sandstone and trough cross-stratified sandstone (St).

The planar cross-stratified sandstone subfacies (Sp) is well developed in the Kara River near Mohanfort and attain a thickness of 25 m. The individual planar cross-stratified package is up to 1m thick, it also occurs as tabular-shaped, stacked one above the other, and occasionally scattered fine-grained gravels are observed at Mohanfort and in the Kara River section (Plate 5.4a-c). It is whitish to brownish, mainly comprised of coarse-grained sand-sized particles of quartz with scattered granules and fine-grained pebbles. Petrographically, the sandstones are composed of subangular to subrounded, medium- to coarse-grained quartz grains, polycrystalline quartz, and occasional gravels bonded with the siliceous and argillaceous matrix. The quartz grains show the presence of overgrowth. The upper and lower contacts of the facies are sharp. The beds pinch out abruptly but are laterally persistent in the Mohanfort area.

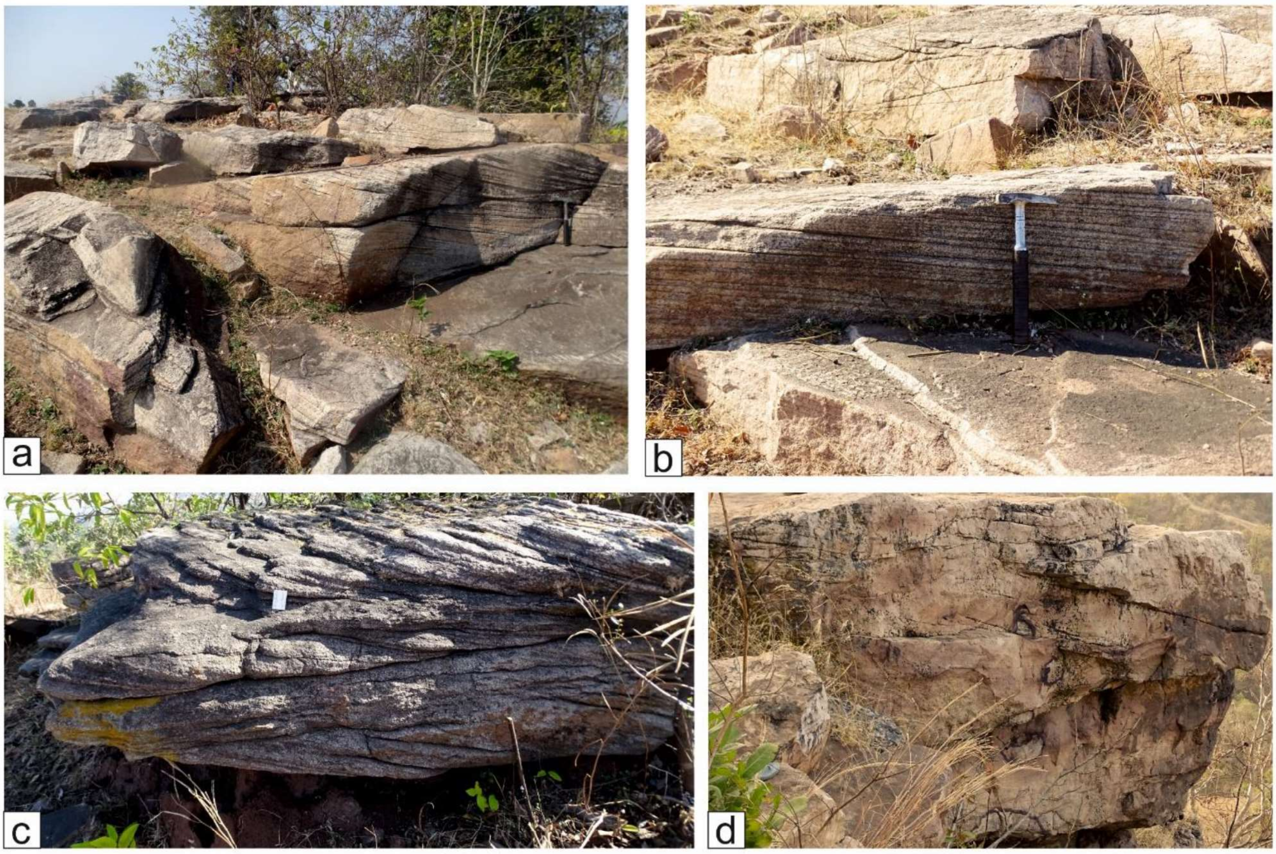


Plate 5.4 Field photographs of planar cross-stratified sandstone. a. Large-scale cross-stratification, Kara River section. b. Large scale cross-stratification, Kara River section. c. Coarse-grained cross-stratified sandstone with gravels; Mohanfort section. d. Trough cross-stratified sandstones; Songir Formation, Vajeriya section.

Trough cross stratified sandstone subfacies (St) is characterized by yellowish colored medium-grained sandstones. It is observed at the top of the Vajeriya section. The sandstone beds are about 1 m thick and show faint trough cross-stratification. The beds show sharp upper and lower contacts and consist of moderately curved, concave-up reactivation surfaces. The trough cross-laminae occur as medium-scale sets, about 15-20 cm thick (Plate 5.4d). This subfacies occur in association with the laminated sandstone and clast supported conglomerate. Petrographically, the sandstones are composed predominantly of medium-sized, subangular to subrounded grains, monocrystalline quartz with a minor proportion of polycrystalline quartz and feldspar. Trough cross stratified sandstone subfacies comprises relatively finer grains compared with planar cross stratified sandstone subfacies.

Interpretation: Planar cross-stratification suggests the migration of 2-D bedforms like sand waves in a high-energy condition (Miall, 1996). The planar cross-stratified sandstones are deposited from traction by unidirectional currents, and the migration of subaqueous dunes along transverse rather than longitudinal bars in a lower flow regime (Boggs Jr., 1987). The lack of bioturbation, coarse-grained deposits, unidirectional flow and high energy conditions of deposition suggest the facies was deposited in fluvial influenced processes. The large-scale planar cross-stratified cosets in a multistoried sequence suggest of sand dunes in shallow water stream channels (Fambrini et al., 2017), as observed in the Mohanfort section (Plate 5.4a). The planar cross-stratified sandstone suggests the migration of channel bedform in fluvial transverse bars of braided rivers (Miall, 1996). Trough cross-stratification suggests migration of 3-D bedforms like sand waves in high-energy condition (Miall, 1996). The trough cross-stratified sandstones are deposited from traction by migration of subaqueous dunes in a lower flow regime (Miall, 1977). The high frequency of trough cross-stratified facies suggests low energy and low discharge (Fambrini et al., 2017).

5.2.1.3 Horizontal-thinly Bedded Sandstone Facies (Sh)

Description: The horizontal-bedded sandstone facies is 0.5 m – 2.0 m thick and occurs in the upper part of the sequence exposed around the Songir-Chosalpur and Vajeriya area (Plate 5.5a-d). It is yellowish in color and consists of centimeters thick, horizontal, individual beds with scattered fine white pebbles. This facies mainly comprises coarse-grained, subangular to subrounded sand and fine pebbles of monocrystalline quartz. Plane-lamination is characteristic to the facies but faintly developed planar cross stratifications are also observed; the beds have tabular geometry with sharp planar contact and an erosive base. It vertically grades to the matrix-supported conglomerate subfacies where parallel beds become obscure.

***Interpretation*:** The horizontal thinly-bedded sandstones of Songir-Chosalpura and Vajeriya sections are produced on a plane bed surface of the middle and distal alluvial fan. The mixture of sand-dominated debris with minor proportions of fine gravels suggests high density and viscosity of the fast-moving laminar flow with the low water level. Such type of flow covers large land surface where the gradient decreases or flow loses water content; deposition of plane bed takes place on the middle and distal reaches of the alluvial fan. This type of condition is usually a result of the sudden high debris flow of ephemeral streams on a plane surface of the alluvial fan.

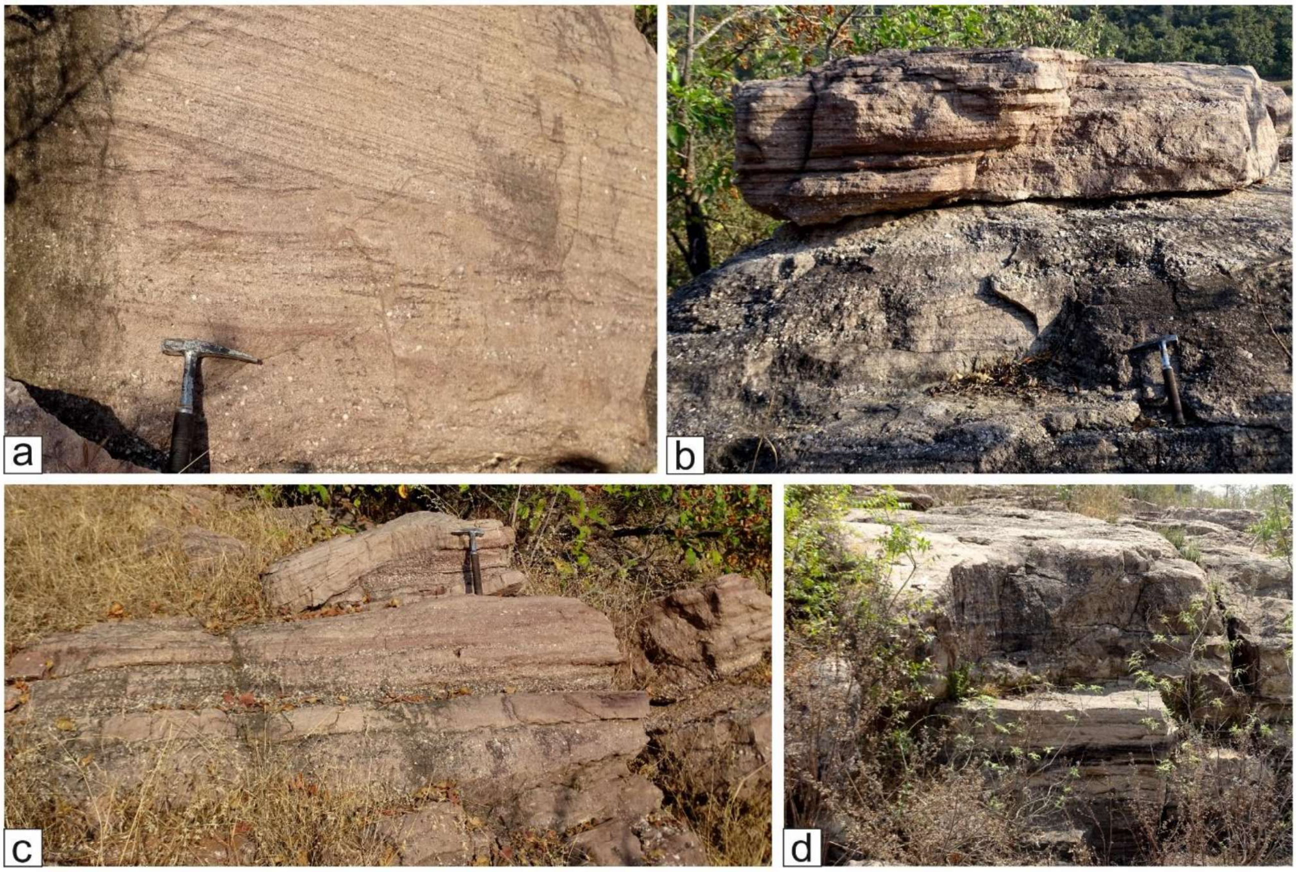


Plate 5.5 Field photographs of horizontally bedded sandstone facies. a. Thinly bedded sandstones with scattered fine pebbles, Songir Formation, Chametha-Chosalpura section. b. Coarse-grained sandstones with gravels; Songir Formation, Chametha-Chosalpura section. c. Laminated coarse-grained sandstones interbedded with fine pebbly conglomeratic layers; Songir Formation, Chametha-Chosalpura section. d. Fine to medium-grained laminated sandstone; Songir Formation, Ghantoli section.

5.2.1.4 Massive sandstone facies

Description: This facies is characterized by white to brown colored massive sandstones occur in the upper and middle part of the Songir Formation exposed around the Mohanfort area. The individual beds show variable thickness, the maximum being 1 m thick. The sandstone beds have a sharp base and tabular geometry and show very faint lamination or planar cross-stratification laterally. The thickness of the beds varies laterally (Plate 5.6) vertically the sandstone bodies grade to with parting lineations (Plate 5.6a). Scatter fine pebbles are observed throughout but never form a distinct layer. Petrographically, the facies is composed of coarse-grained, subangular to subrounded, monocrystalline quartz grains with scattered granules.

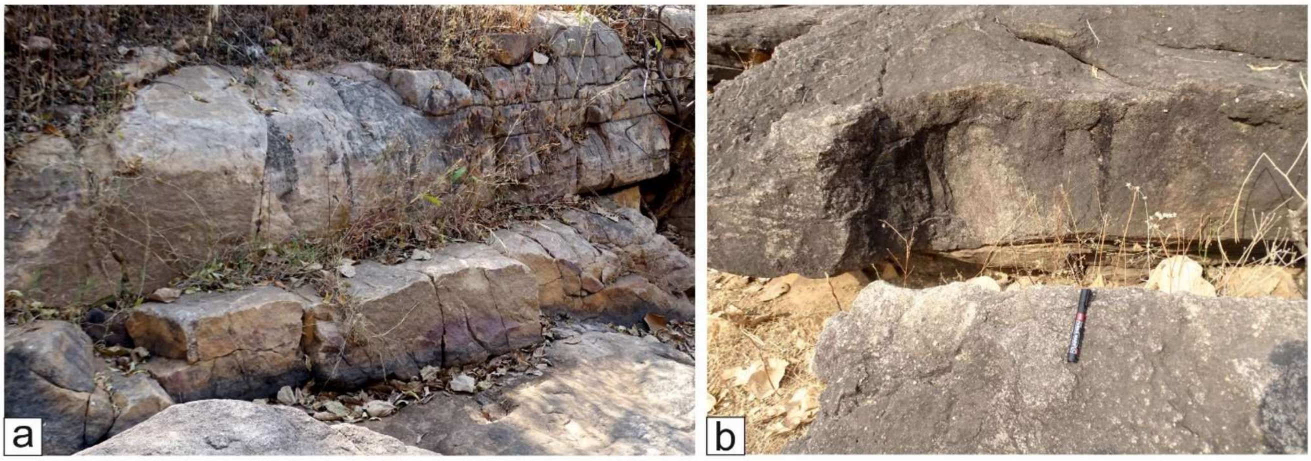


Plate 5.6 Field photographs of massive sandstone facies (Sm). a and b. fine to coarse-grained sandstone, Songir Formation, Mohanfort section.

***Interpretation*:** The massive sandstone is observed in the upper and middle part of the Songir Formation and is associated with the alluvial fan facies. This facies is usually structureless, thick sand beds, but laterally comprises of faint developed horizontal and cross-stratification, which led to confusion in the interpretation of the actual processes. These are formed by certain sedimentary gravity flows that lack a mechanism to produce primary structures (Lindholm, 1987) or on the scoured base deposition occurs rapidly from suspension with reduced turbulence which inhibits the formation of bedforms (Bouma, 1962).

5.2.2 MARINE-MARGINAL TO MARINE FACIES

With the progress of rifting during the Late Cretaceous, more accommodation space, was created which was concomitant with the transgression over the Narmada Basin due to eustatic sea-level rise. As a result, the basin got filled with marine deposits and covered the Early Cretaceous fluvial deposits. Thus, the Late Cretaceous of the Narmada Basin is characterized by thick, siliciclastic, mixed siliciclastic-carbonate, and carbonate sediments.

Plate 5.7 Field photographs of the bedded-quartz arenite facies. a. Massive thickly-bedded sandstones intercalated with shale facies; Vajepur Formation, Vajepur section. b. Trough cross-stratified sandstone; Vajepur Formation, Mohanfort section. c. Herringbone cross-stratification; Narmada Sandstone Member; Navagam section.

These rocks are well-studied in the field and laboratory, and ten different lithofacies are identified, includes bedded quartz arenite facies, Shale facies, calcareous sandstone facies, micritic sandstone facies, fine-grained sandstone- siltstone facies, sandy/silty allochemic limestone facies (SAL), fossiliferous limestone facies (FL), sandy/silty micrite facies and mudstone facies.

5.2.2.1 Bedded Quartz Arenite Facies

Description: The rocks of the facies are yellow to red, thinly to thickly bedded. The sandstones are thickly-bedded in the Vajepur Formation are intercalated with the purple shale facies (Plate 5.7a). They are primarily massive in the Mathwad Nala section but show the presence of trough cross-stratification in the Kara River section (Plate 5.7b). It is also observed in the Narmada Sandstone Member and shows the presence of herringbone cross-stratification (Plate 5.7c, 5.8a). Texturally it is very immature and comprises a wide range of grain sizes, up to fine gravels. Petrographically, it consists of fine to medium-grained, poorly sorted quartz grains (>90%) with occasional granules, polycrystalline quartz (Plate 5.8c), and mica grains (Plate 5.8b) bounded by argillaceous matrix. The quartz grains show evidence of pressure solution and overgrowth (Plate 5.8d).

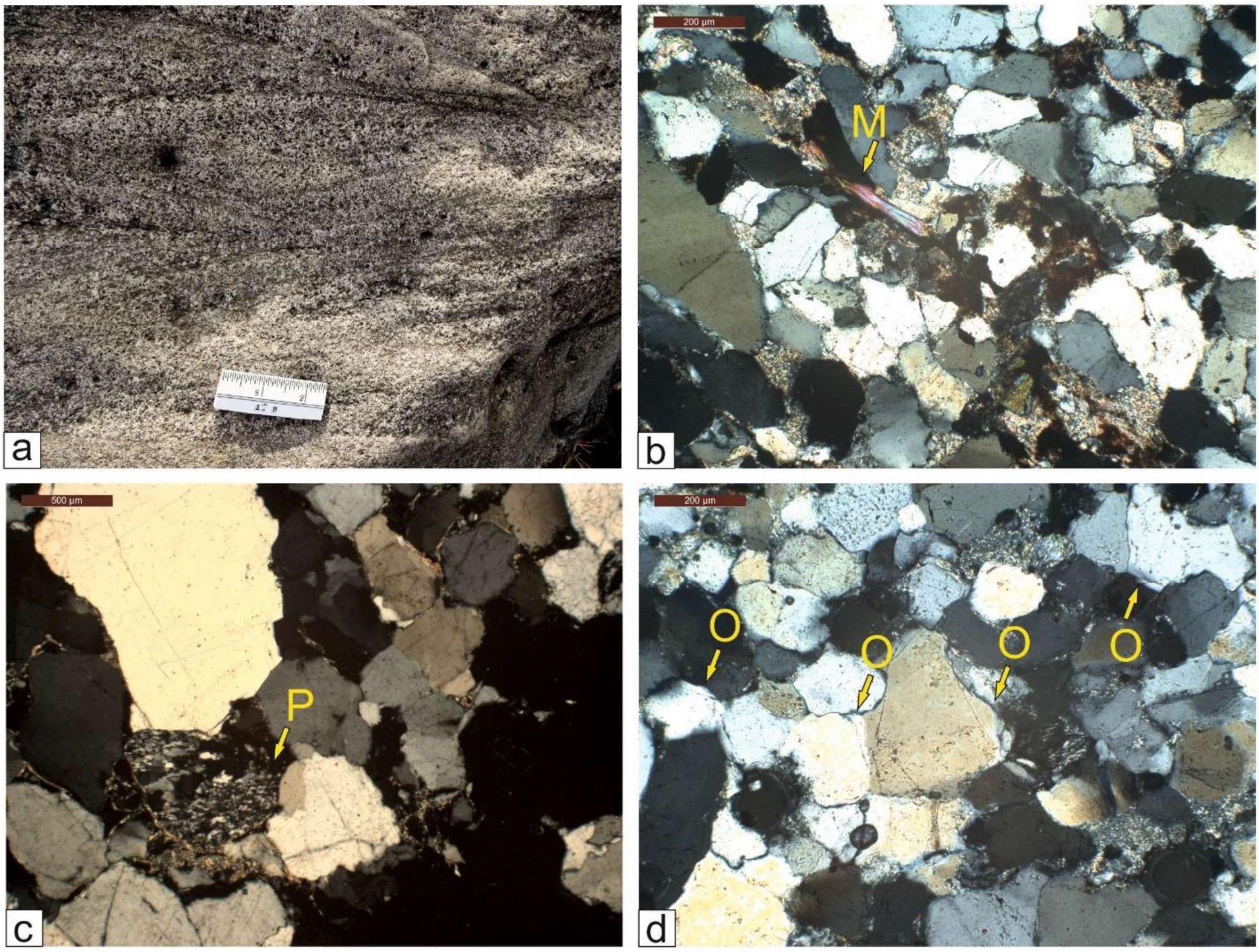


Plate 5.8 Field and photomicrographs of the bedded-quartz arenite facies. a. Herringbone cross-stratification; Narmada Sandstone Member; Navagam section. b. Fine to medium-grained quartz grains with argillaceous cement and Muscovite (M) in the herringbone cross-stratified sandstone; Narmada Sandstone Member; Navagam section. c. Poorly sorted polycrystalline (P) and monocrystalline quartz grains; Vajepur Formation, Vajepur section. d. Subangular to subrounded quartz grains showing overgrowth (O); Vajepur Formation, Kara River section.

Interpretation: Bed geometry of the Kara River of Vajepur Formation display pinching arenitic sandstone intercalated with purple shales, typically developed in the ridge-runnel system, where fine-grained sediments are characteristics of runnels. The sandstone is characterized by trough cross-stratification suggests upper shoreface to foreshore environment/ tide-influenced beach. The sequence laid down above the fluvial sandstones of the Songir Formation marked the initial phase of transgression. The well-bedded, arenitic sandstone of Navagam sections of Narmada Sandstone Member (Uchad Formation) are thickly-bedded, and display herringbone cross-stratification of upper shoreface-foreshore environments, indicate shallowing of the basin. The arenitic sandstone of the WLNV marked the initial transgression and late phase of regression.

5.2.2.2 Shale facies

Description: This facies is well-developed in Bilthana Formation and Vajepur Formation and best exposed in the Bilthana-Sultanpura (Plate 5.9a), Uchad (Plate 5.9b), Vajepur, Mohanfort (Plate 5.9c), Devaliya (Plate 5.9d), Bhekhadiya, Navagam, and Karvi area. It is frequently intercalated with the oyster beds in the Bilthana Formation and the cross-stratified sandstone, calcareous sandstone, and bedded quartz arenite facies of the Vajepur Formation with sharp contact.

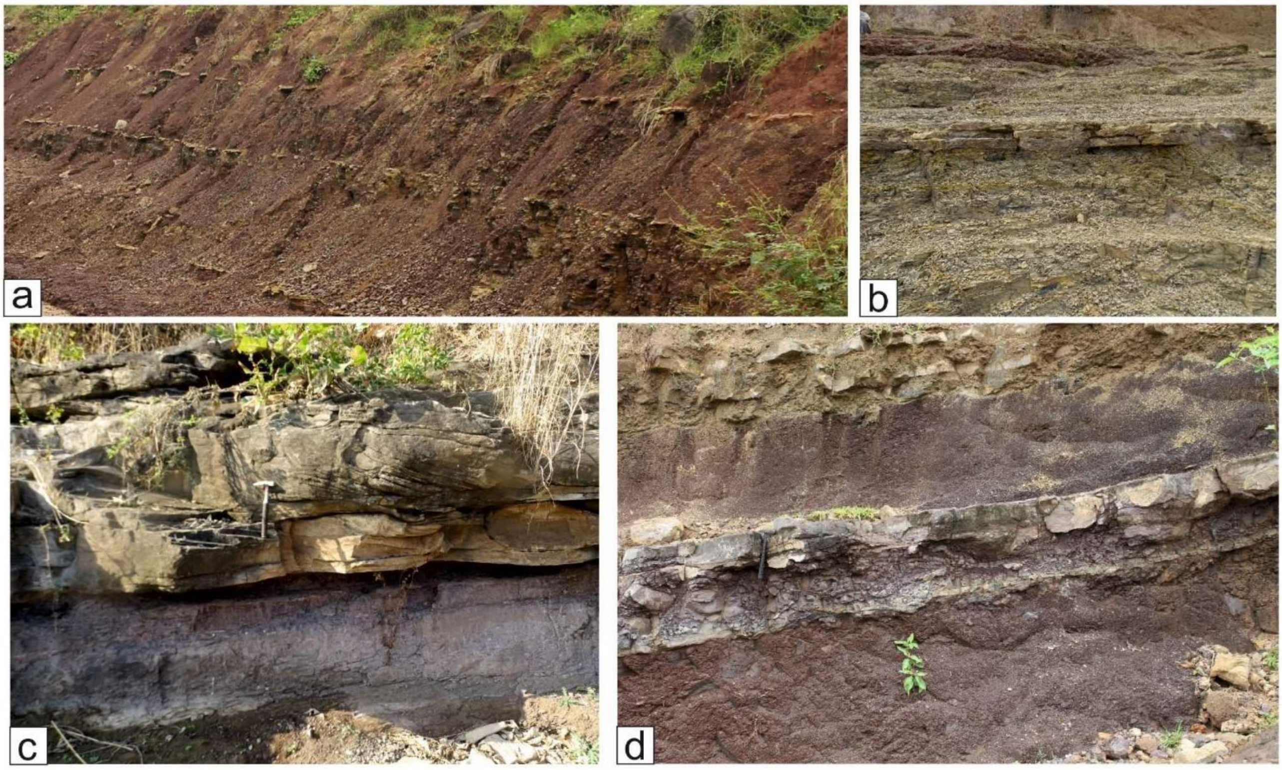


Plate 5.9 Field photographs of the shale facies. a. Reddish shale intercalated with oyster beds, Bilthana Formation, Sultanpura-Bilthana section. b. Greenish-yellow shale intercalated with oyster beds; Bilthana Formation, Uchad section. c. Purple shale underlying cross-stratified sandstone; Vajepur Formation, Kara River section. d. Purple shale intercalated with massive sandstone facies; Vajepur Formation, Devaliya section.

The shale facies in the Navagam section are intercalated with the bedded quartz arenite facies in its lower part and calcareous sandstone facies in its upper part and carbonaceous in nature. It is buff, purple, violet, black and reddish in color. The nature of the shale is splintery, and well-developed fissility is observed in the Bilthana Formation, while it is moderately developed in Vajepur Formation. Shale beds show highly variable thickness laterally and vertically, maximum 10 m thickness of carbonaceous shale observed at Navagam. Most of the beds range from 5 to 150 cm thick observed in the Bilthana Formation exposed at Uchad, and Sultanpura villages and Vajepur Formation exposed in Kara River and Men River valleys. The facies is fossiliferous and contains abundant microfossils (Keller et al., 2021) in the Bilthana Formation.

Interpretation: This facies comprises fine-grained sediments and generally good sorting in Bilthana Formation and carbonaceous shale of the Vajepur Formation, while purple shale of the Vajepur Formation shows relatively coarse in nature. The cyclic repetition of the shale facies suggests periodic fluctuations in the energy conditions. The fissile shale suggests deposition in a low-energy environment due to the suspension settling. The shale of the Bilthana Formation indicates calm to slightly agitated conditions, with a slow rate of sedimentation, probably during inter-storm phases represented by oyster limestone bands (Shitole et al., 2021). Further, the sharp contact between shale and oyster limestone bands where the trace fossils occur is marked by the erosional surface, indicating a change in the rate and pattern of sedimentation in increasing energy conditions. These cycles of thin oyster limestone bands intercalated with the shale indicate a shallow but basinal marine environment. The carbonaceous shale observed in the lower part of the Vajepur Formation in the Navagam section is suggestive of deposition in anoxic conditions and it is corroborated with the Cenomanian-Turonian ocean anoxic event. The purple shale of the Vajepur Formation exposed in the Kara River, and Men Reiver valleys is intercalated with calcareous sandstone, cross-bedded sandstone, and bedded quartz arenite, which pinch-out on either side. The bed geometry of the shale facies is a result of the ridge-runnel complex of the foreshore and upper shorefore zone, where suspended sediments were deposited in slow-moving waters or standing conditions in runnels.

5.2.2.3 Calcareous Sandstone facies

Description: This facies is extensively developed in Vajepur Formation and well exposed around Mathsar, Uchad, Sultanpura, Bilthana, Bhekhadiya, Develiya, Karvi, Navagam, and Vajepur villages. It also occurs in the middle part of the Narmada Sandstone Member exposed at Navagam and Uchad villages. The sandstone is massive (Plate 5.10a) or cross-bedded (Plate 5.10b). While the upper part is extensively developed and comprises thinly-bedded rippled sandstone.

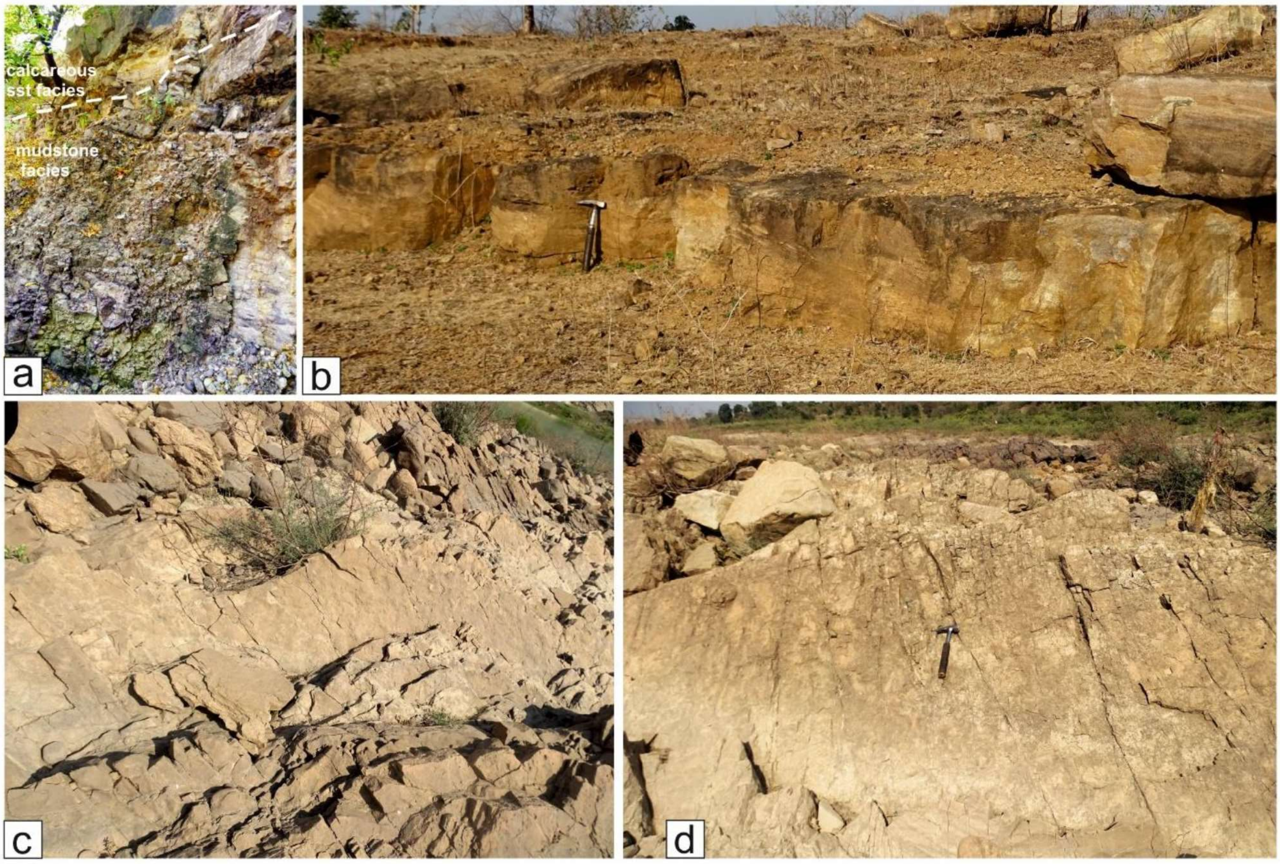


Plate 5.10 Field photographs of the calcareous sandstone facies. a. Thickly-bedded sandstone; Narmada Sandstone Member, Bilthana section. b. Thickly-bedded, cross-stratified sandstones; Vajepur Formation, Vajepur section. c. Thinly-bedded, rippled calcareous sandstones and d. Gently inclined bed surface of the calcareous sandstones; Vajepur Formation, Navagam section.

Each locality comprises of tens of thin beds of calcareous sandstone, which are topped by small, straight-crusted, linguoid, sinous, bifurcated, and symmetrical wave ripples (Plate 5.10c-d, 5.11a, c-d). The rippled calcareous sandstone is white and occasionally greenish in color and occasionally consists of load cast. The rocks are bioturbated to various degrees and consist of abundant trace fossils at their top.

It consists of trace fossils like *Archaeonassa fossulata, Archaeonassa* isp., *Didymaulichnus cf. lyelli, Lockeia cuncator*, *L. siliquaria, Planolites montanus, Skolithos linearis, Taenidium barretti, T. serpentinum, Thalassinoides horizontalis,* and undetermined meandering burrows. At the Navagam section, bioturbation has obliterated the sedimentary structure in the Narmada Sandstone Member (Plate 5.11b). The facies in the Vajepur Formation of Navagam section shows the presence of wavy and lenticular bedding. It shows the presence of trough cross-stratification in the lower part of the Vajepur Formation at the Sultanpura-Bilthana section (Plate 5.11e-f). The facies show typical fining-upward cycles at its contact with the sandy allochemic limestone facies in the Uchad section.

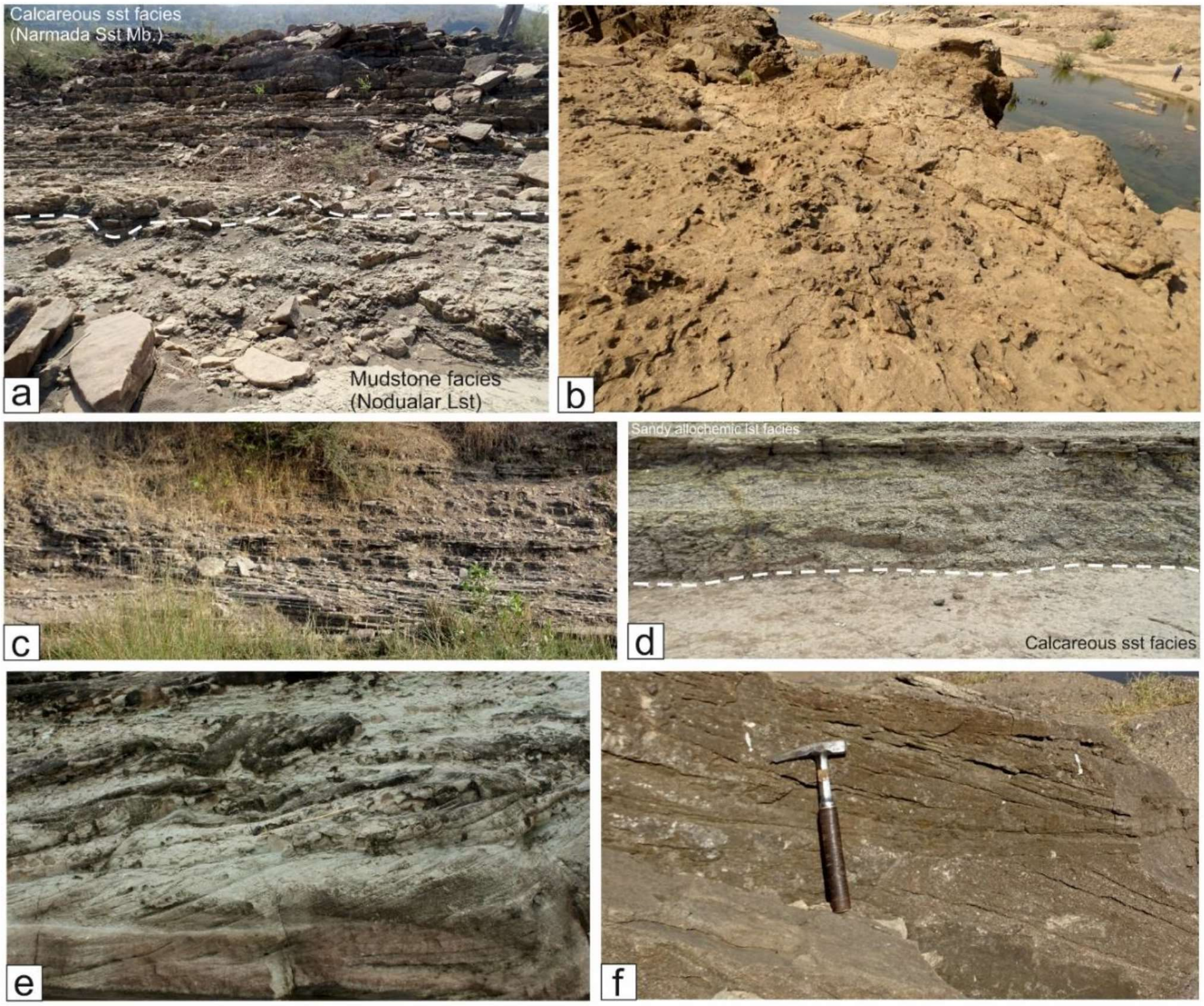


Plate 5.11 Field photographs of the calcareous sandstone facies. a. Conformable contact of mudstone facies (Nodular Limestone) with overlying thinly bedded, calcareous sandstone facies (Narmada Sandstone Member), Navagam section. b. Bioturbated calcareous sandstones; Narmada Sandstone Member, Navagam section. c. Thinly-bedded rippled sandstones; Vajepur Formation, Sultanpura section. d. Thinly-bedded rippled sandstones; Vajepur Formation underlying the sandy allochemic limestone facies, Uchad section. e-f. Trough cross-stratified sandstones; Vajepur Formation, Sultanpura-Bilthana section.

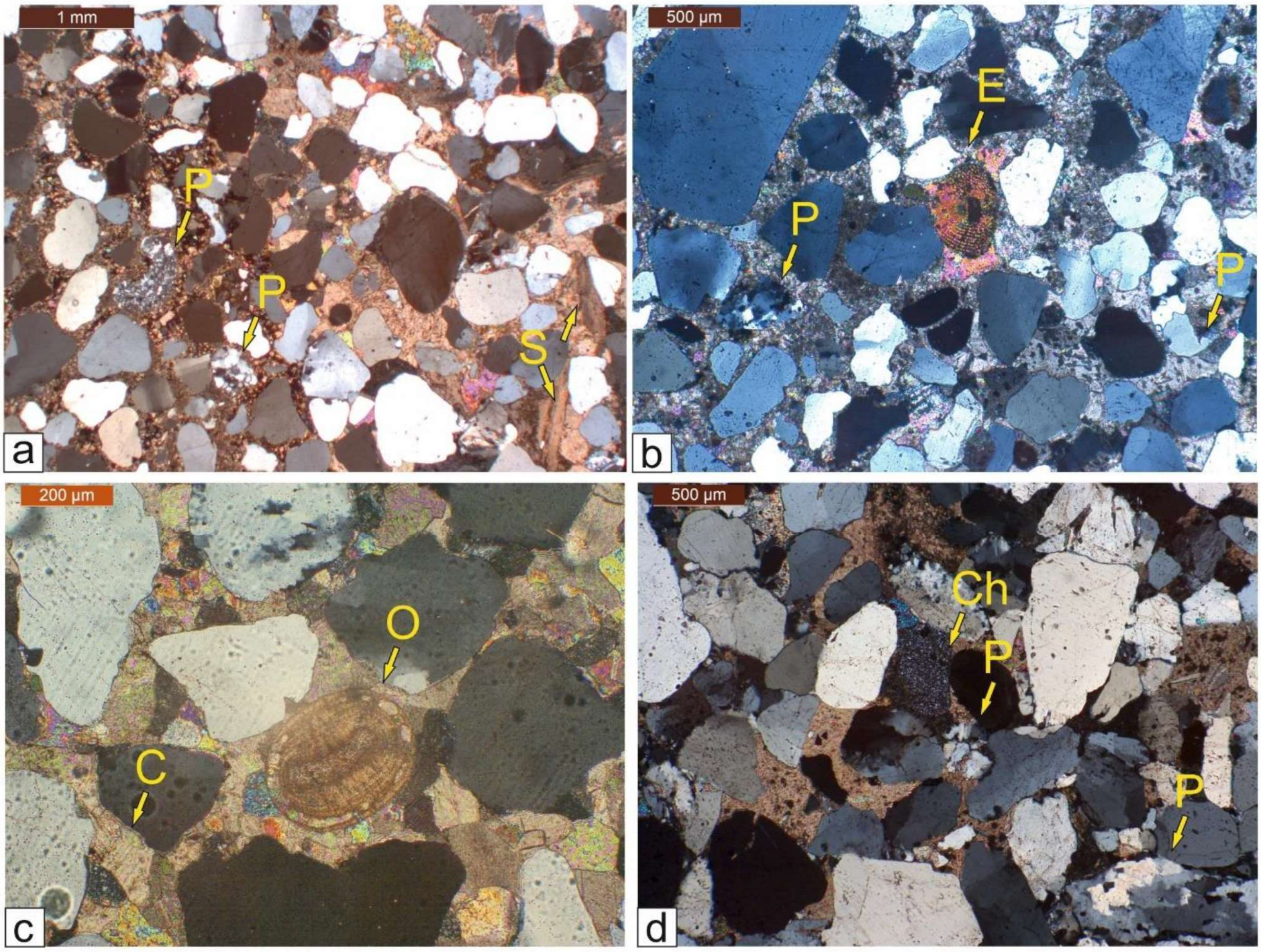


Plate 5.12 Photomicrographs of calcareous sandstone facies showing textural and compositional variations. a. Subangular to subrounded quartz grains, polycrystalline (P) quartz grains, and shell fragments are bounded by calcareous cement; Vajepur Formation, Sultanpura section. b. Poorly sorted quartz grains, polycrystalline (P) quartz grains, and echinoderm (E); Vajepur Formation, Sultanpura section. c. Oolite (O) with well-developed radial structure and center possibly of shell fragment, calcite spars (C) has filled the remaining pore spaces; Vajepur Formation, Sultanpura section. d. Fractured quartz grains, chert (Ch) and polycrystalline (P) quartz grains; Narmada Sandstone Member, Sultanpura-Bilthana section.

Petrographically, it consists of fine to coarse-grained, well to poorly-sorted subangular to subrounded quartz grains bonded by a calcareous cement. It consists of quartz grains (70-90%) with occasional overgrowth (Plate 5.13c), less than 1% polycrystalline quartz grains (Plate 5.12a-b, d), less than 1% plagioclase feldspar (Plate 5.13a), 2-5% shell fragments (Plate 5.12a-b), occasionally oolites (Plate 5.12c), up to 2% muscovite (Plate 5.13d) and burrows (Plate 5.13b).

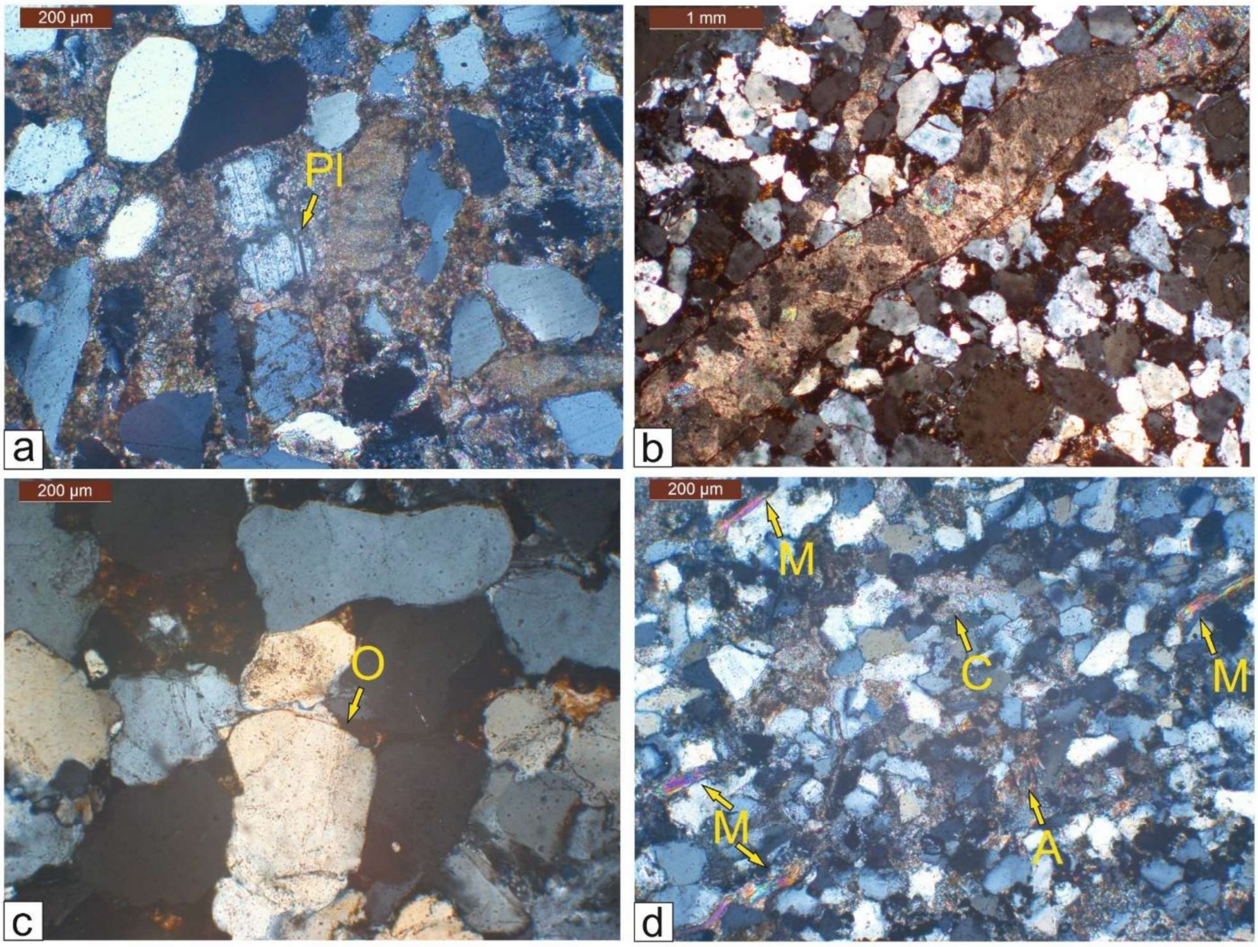


Plate 5.13 Photomicrographs of calcareous sandstone facies. a. Plagioclase feldspar (Pl) surrounded by patches of argillaceous cement; Narmada Sandstone Member, Sultanpura-Bilthana section. b. Microburrow filled with sparry calcite; Vajepur Formation, Vajepur section. c. Overgrowth (O) cementation on the detrital quartz grain in its optical continuity; Vajepur Formation, Vajepur section. d. Fine-grained quartz grains with undeformed and deformed muscovite flake with calcareous (C) and argillaceous cement (A); Vajepur Formation, Navagam section.

Interpretation: This facies is thickly bedded in the lower part of the Vajepur Formation while it is thinly bedded in the upper part of the Vajepur Formation and Narmada Sandstone Member. It is characterized by trough cross-stratification and various types of ripples developed in the subaqueous dune of shoreface environment. The lower thick calcareous sandstone is typically characterized by the fine to coarse-grained sediments with trough cross-stratification suggest migration of subaqueous dune in shoreface environment and amalgamation of the dune gave rise thick stacked unit. The sandstone beds occasionally show reversal of foresets suggestive of tidal influence. Progressively, this facies is characterized by thinly bedded rippled sandstone, suggesting extensively developed subaqueous dunes in the transgressive sea. The lack of shale deposits and the presence of ripple marks on each bed suggests the base-level is affected by the fair-weather wave base and is indicative of the upper-middle shoreface environment (Buatois and Mángano, 2011; Santos et al., 2015). The texture, structures, mineral composition, bed geometry, and associated trace fossils suggest the facies is initially deposited in the shoreface environment and progressively the change in sea level and development of clastic shore gave rise to thinly bedded sandstone of the lower-middle shoreface of the subaqueous sand dunes.

5.2.2.4 Micritic Sandstone Facies

Description: This facies is observed in the upper part of the Vajepur Formation and Narmada Sandstone Member at Uchad village and Navagam sections (Plate 5.14c). Thickness of the facies is variable, 5m and 3m were observed in Navagam (Plate 5.14b) and Uchad section, respectively. It is comprising of thickly-bedded tabular sandstone body comprises of a number of stacked units, which is up to 0.75 meters in thickness. The micritic sandstone facies comprise brown to greenish-white or greenish-yellow-colored sandstone characterized by ripple marks, wavy bedding (Plate 5.14c), and occasionally shows the presence of oysters (Plate 5.14a, 5.15b, e-f). It consists of ~60-70% angular to subrounded, poorly sorted quartz grains (Plate 5.15a-f), ~1-3% polycrystalline quartz grains (Plate 5.15a-b, d, f), 1-4% allochems (Plate 5.15f) and 30-40% micrite (Plate 5.15a-f). The micritic sandstone facies in the Narmada Sandstone Member shows evidence of pressure solution, overgrowth (Plate 5.15c-d).

Interpretation: The facies is observed mainly at the transition of calcareous sandstone and limestones, which explains the occurrence of high micritic mud in the sandstones. In the Vajepur Formation at Uchad village, the facies progressively grade upward to the carbonate-dominated rocks of Bilthana Formation and is suggest an increase of carbonate content in the transgressive shallow marine environment. At Navagam and Uchad villages, the facies is observed in the Narmada Sandstone Member and overlies the mudstones of Nodular Limestone characterized by wavy bedding. Such bodies are often interpreted as offshore sand bars using the analog of modern sand ridges in the offshore environment characterized by combined-flow ripples and parallel lamination (Buatois and Mángano, 2011). However, the facies in Narmada Sandstone Member lacks these typical characteristics. The studies by Walker and Plint (1992) had interpreted them to be formed in the shoreface environment during the sea-level fall when the shoreline shifted many kilometers out of the shelf, and they rest directly upon the regressive surface of marine erosion with a sharp base. The wavy bedding is generally considered to be produced in a tidal environment, indicating a contrasting lithology of high and low energy environment (Reineck and Wunderlich, 1968) however, it may be present in a shelf environment below the fair-weather wave base affected by frequent storms (Miall, 2000). The gradual change from carbonate-dominated Nodular Limestone to mixed-siliciclastic-carbonate rocks and lack of typical characteristics of the offshore sand bar suggests its deposition in a regressive condition. Overall, the presence of a large number of quartz grains, few shell fragments (Plate 5.15e-f), ripple marks, and stratigraphic position is indicative of relatively high energy conditions in a shallow marine environment and deposition above the storm weather wave base in a lower shoreface environment.

Plate 5.14 Field photographs of the micritic sandstone facies. a. Fossiliferous micritic sandstone bed (white arrow) overlying the rippled calcareous sandstone beds (yellow arrows); Vajepur Formation, Sultanpura section. b. Micritic sandstone consisting of few scattered gravels, Narmada Sandstone Member, Navagam section. c. Wavy bedding in the micritic sandstone, Narmada Sandstone Member, Uchad section.

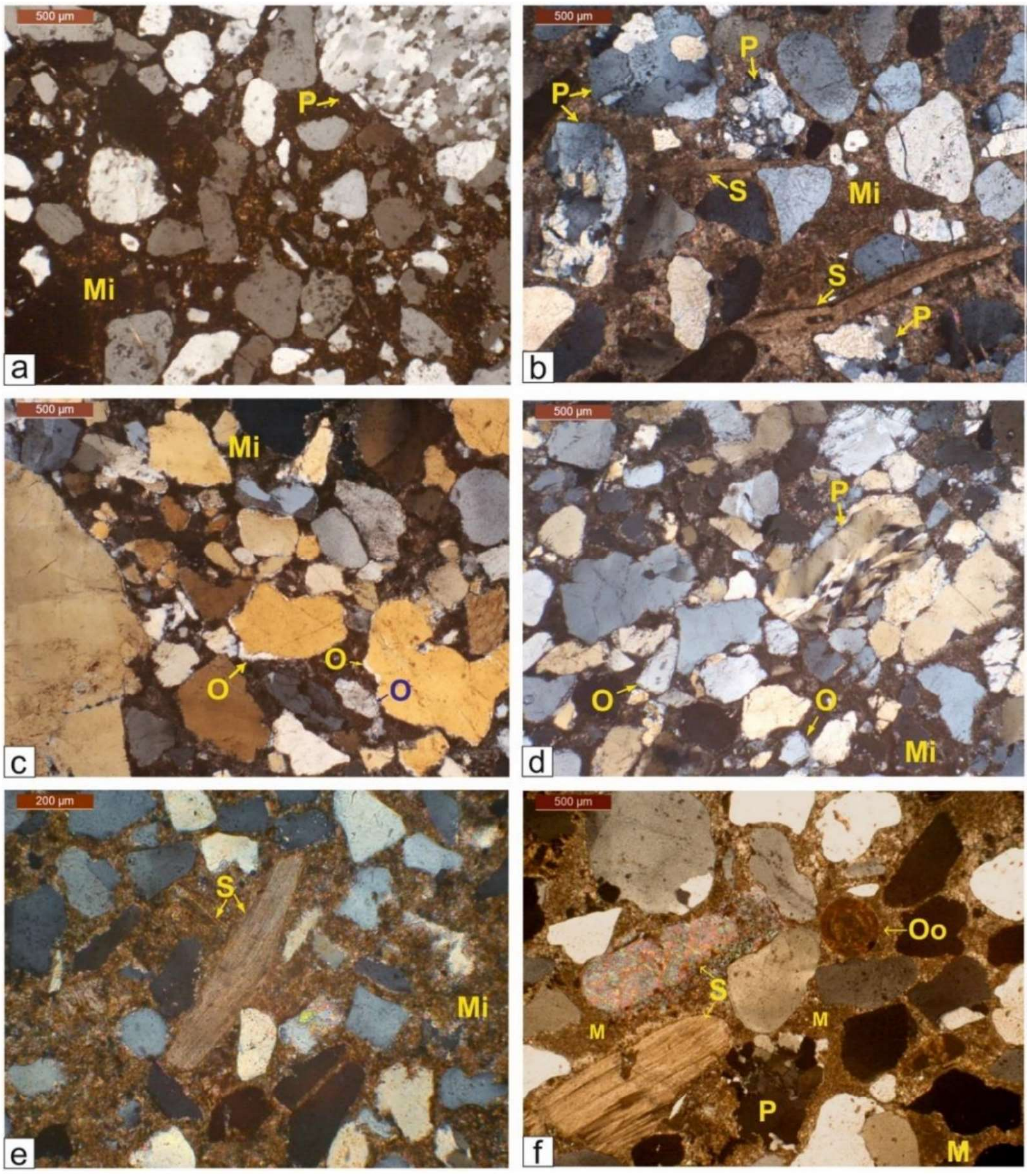


Plate 5.15 Photomicrographs of the micritic sandstone facies. a. Subangular to subrounded grains and polycrystalline (P) quartz grain in the micritic matrix (Mi); Narmada Sandstone Member, Navagam section. b. Polycrystalline (P) quartz grains, bivalve shell fragments (S), and subangular to subrounded quartz grains floating in the micritic matrix (Mi); Vajepur Formation, Sultanpura section. c. Poorly sorted quartz grains in the micritic matrix (Mi) showing overgrowth (og); Narmada Sandstone Member, Uchad section. d. Poorly sorted quartz grains, stretched polycrystalline (P) quartz grain in the micritic matrix (Mi) showing overgrowth (O); Narmada Sandstone Member, Uchad section. e. Angular to subrounded quartz grains and shell fragments with growth lines (S) in the micritic matrix (Mi), Vajepur Formation, Gulvani section. f. Sub rounded quartz grains, shell fragments (S), ooid (Oo), polycrystalline (P) quartz, and micrite *sensu* Mount (1985); Vajepur Formation, Sultanpura-Bilthana section.

5.2.2.5 Sandstone- Siltstone-Shale Facies

Description: The facies is observed in the upper part of the Vajepur Formation of the Bagh Group in transition with the overlying Bilthana Formation. It comprises of cm-scale intercalated shale-siltstone-sandstone beds and attains a maximum exposed thickness of ~20 cm observed in the Bhekhadiya village (Plate 5.16). It is also observed at Mogra, Sultanpura, Uchad, Gulvani, and Mathsar villages (Plate 5.16a-c), chiefly dominated by siltstone (Plate 5.17c). The sandstone is fine-grained and topped by small-scale low amplitude straight/sinuous crested current ripples.

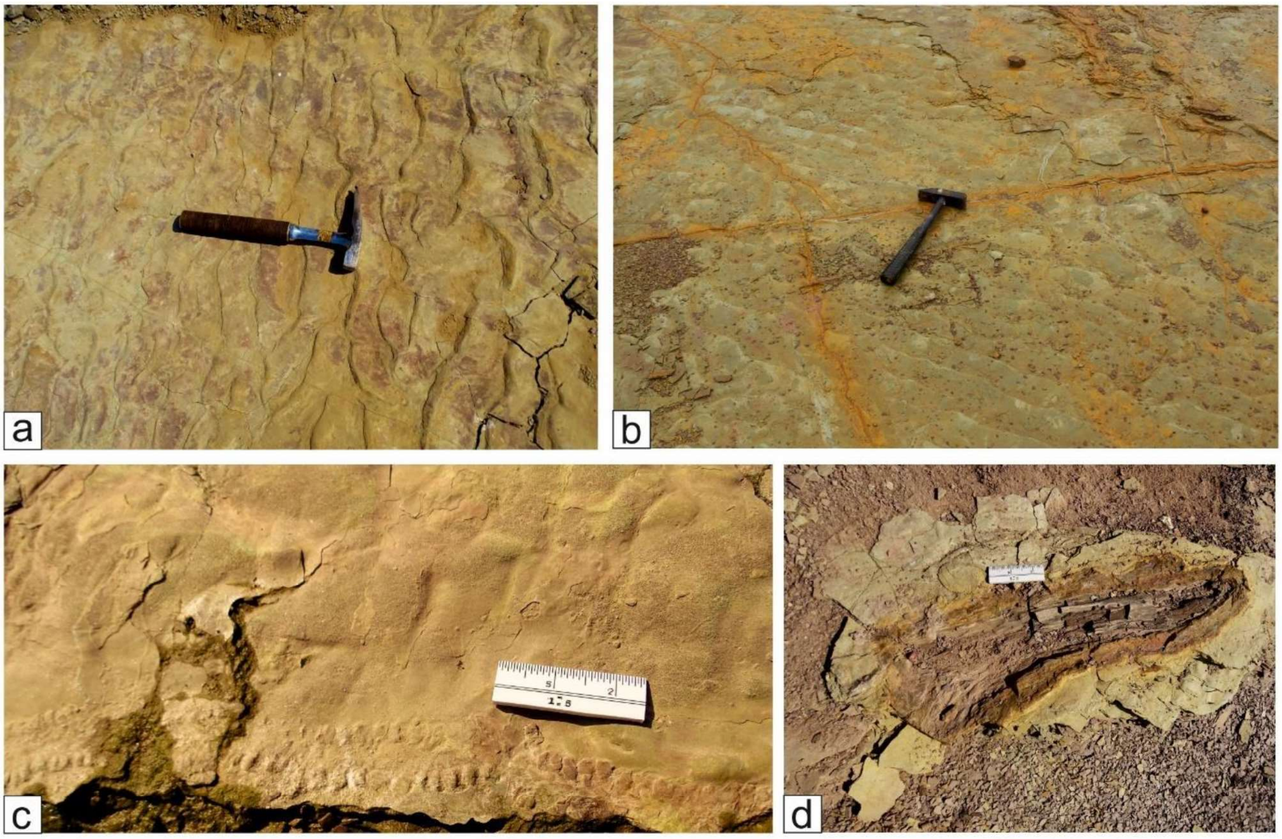


Plate 5.16 Field photographs of the sandstone-siltstone-shale facies. a. Bifurcating current ripples observed at Sultanpura section. b. Current ripples; Vajepur Formation, Bhekhadiya section. c. *Oniscoidichnus* trace fossil as epirelief on the silty micrite bed at Bhekhadiya section. d. Fossil wood in the siltstone bed at the Bhekhadiya section.

The siltstone is pale to dark brown colored and intensely bioturbated (Plate 5.16c) and can also be seen at mega and microscale (Plate 5.17d). It is either laminated (Plate 5.17a) or consists of sedimentary structures like small small-scale low amplitude straight/sinuous crested current ripples (Plate 5.16a-b) and occasionally consists of fossil wood (Plate 5.16d). It consists of trace fossils like

Conichnus conicus, Conostichus broadheadi, C. stouti (Patel et al., 2018)*, Planolites montanus, Oniscoidichnus communis* (Plate 5.16), and *Ptychoplasma vagans*. The shale is thin, laminated, fissile, brown-colored, and intercalated with sandstone or siltstone. Petrographycally, the sandstone bands of this facies are characterized by equidimensional, angular, fine-grained sand with silt-sized quartz and micas in a carbonate matrix. The facies is also characterized by well-sorted, silt-sized quartz grains in the micritic matrix or calcareous cement (Plate 5.17c) observed in Bhekhediya and Uchad villages. Replacement of the calcareous cement by the ferruginous cement is often observed in siltstone. Sandstones and siltstones consist of quartz (~60-70%), micrite and calcareous cement (~40%), mica grains (>1%), and occasional bioclasts (up to 3%).

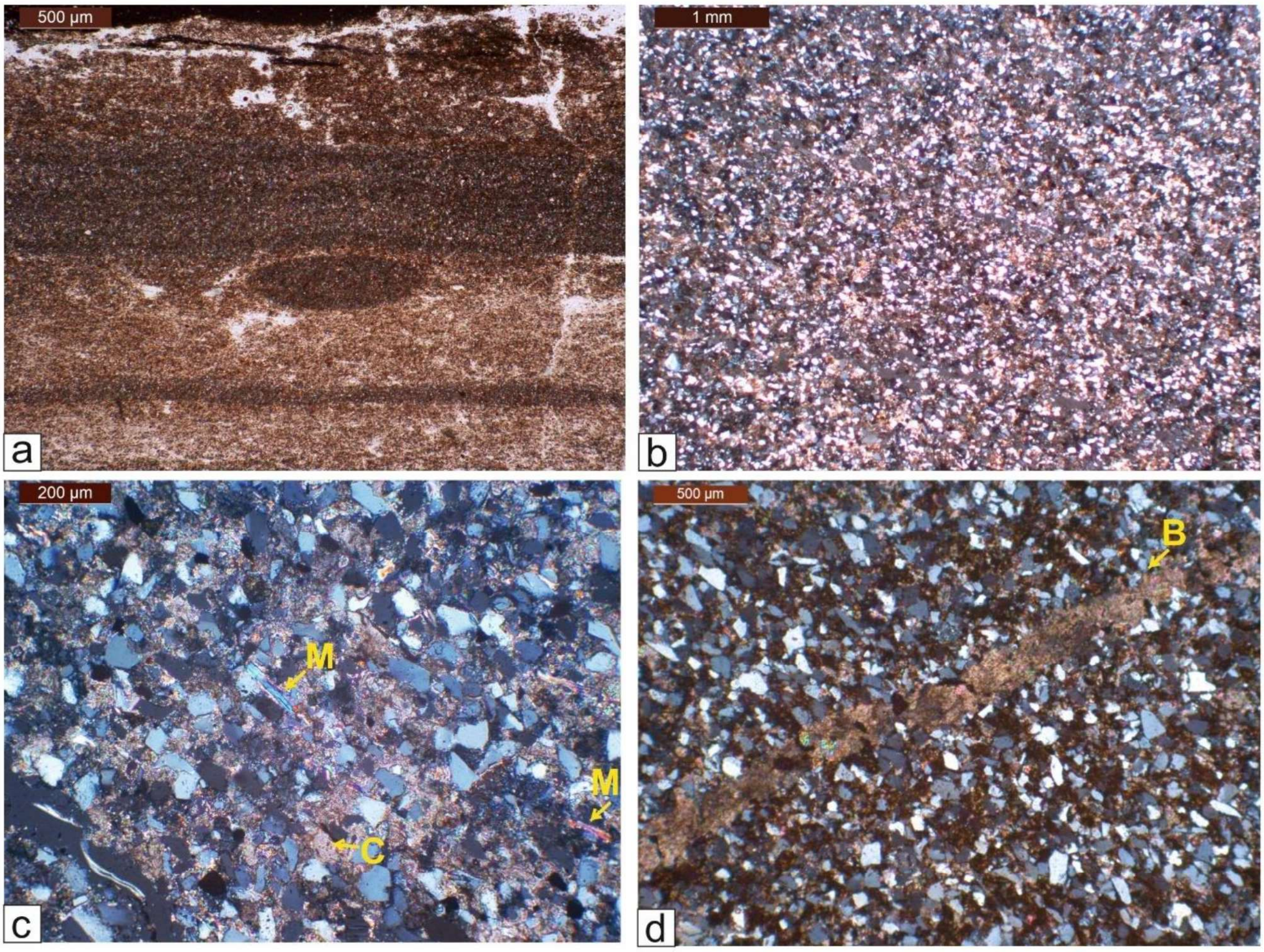


Plate 5.17 Photomicrographs of sandstone-siltstone-shale facies. a. Laminations in Vajepur Formation exposed at Bhekhadiya section. b. Predominance of silt-sized quartz grains exposed in Sultanpura section. c. Presence of angular quartz grains and undeformed mica grains (M) bounded by calcareous cement (C), Bhekhadiya section. d. Burrow (B) in the bioturbated siltstone, Vajepur section.

Interpretation: Intercalation of sandstone-siltstone-shale indicates the cyclic pattern of deposition. The sandstone and siltstone consist of small-scale straight, or sinuous crested current ripple, which indicates the agitative condition, while the intervening shale suggests the change in energy condition and sediment influx. The siltstone shows the presence of plug-shaped burrows of sea anemones (Patel et al., 2018), abundant fine grain sand and silt-sized quartz grains (Plate-h), and occasionally shell fragments floating in the calcareous cement indicate the marine environment. The dominant fine-grain size of the facies indicates low energy suspension deposition. While the presence of ripple marks suggests migration of bottom currents often encountered in the shallow marine conditions due to wave breaking. The interbedded sandstone, laminated-siltstone, and shale represent deposition due to suspension, intervened by the bottom currents, which generated ripples (Johnson, 1978). Based on the petrographic characteristics, current ripples, occurrence of laminations in the siltstone bed, and the stratigraphic position, it can be inferred that the facies was deposited in low-moderate energy of deepening shoreface environment around the fair-weather wave base. Shale-siltstone intercalations are laterally continuous and uniform in thickness, indicating the gentle gradient of the basin and wide development of facies. Abundant bioturbation along the interface of shale-siltstone intercalations indicates the prolific development and diversity of the invertebrate fauna.

5.2.2.6 Sandy/Silty Allochemic LimestoneFacies (SAL)

Description: The facies is buff-colored and individual beds are about 20 cm thick. The beds laterally pinch and merge. It is observed in the Uchad, Sultanpura, Bilthana (Plate 5.18a-b), Bhekhadiya, Gulvani, Karvi, Mathsar, Navagam, and Vajepur villages. It consists of unaltered, least abraded, disarticulated, unoriented bivalve oyster shells showing faint growth lines (Plate 5.20a, c-d) and prismatic structure (Plate 5.18c-d; 5.20a; 5.21a-b). The plan view of the bivalves shows a convex upward position, while the side view shows the dominance of straight orientated shells with few gentle inclinations. At Uchad village, the facies is characterized by intensely bioturbated limestone with abundant oysters, echinoderms (Plate 5.19 a-c; 5.20b; 5.21c-d), and bryozoans (Plate 5.19d). It consists of trace fossils like *Conichnus conicus, Conostichus stouti* and *Bergaueria hemispherica, Paleophycus tubularis, Planolites annularis, P. montanus, Thalassinoides horizontalis, T. paradoxicus, T. suevicus, T.* isp. The petrographic analysis reveals the rock is of a mixed composition comprising quartz grains and a shell fragment floating in the micritic matrix (Plate 5.18c-d; 5.19b-d).

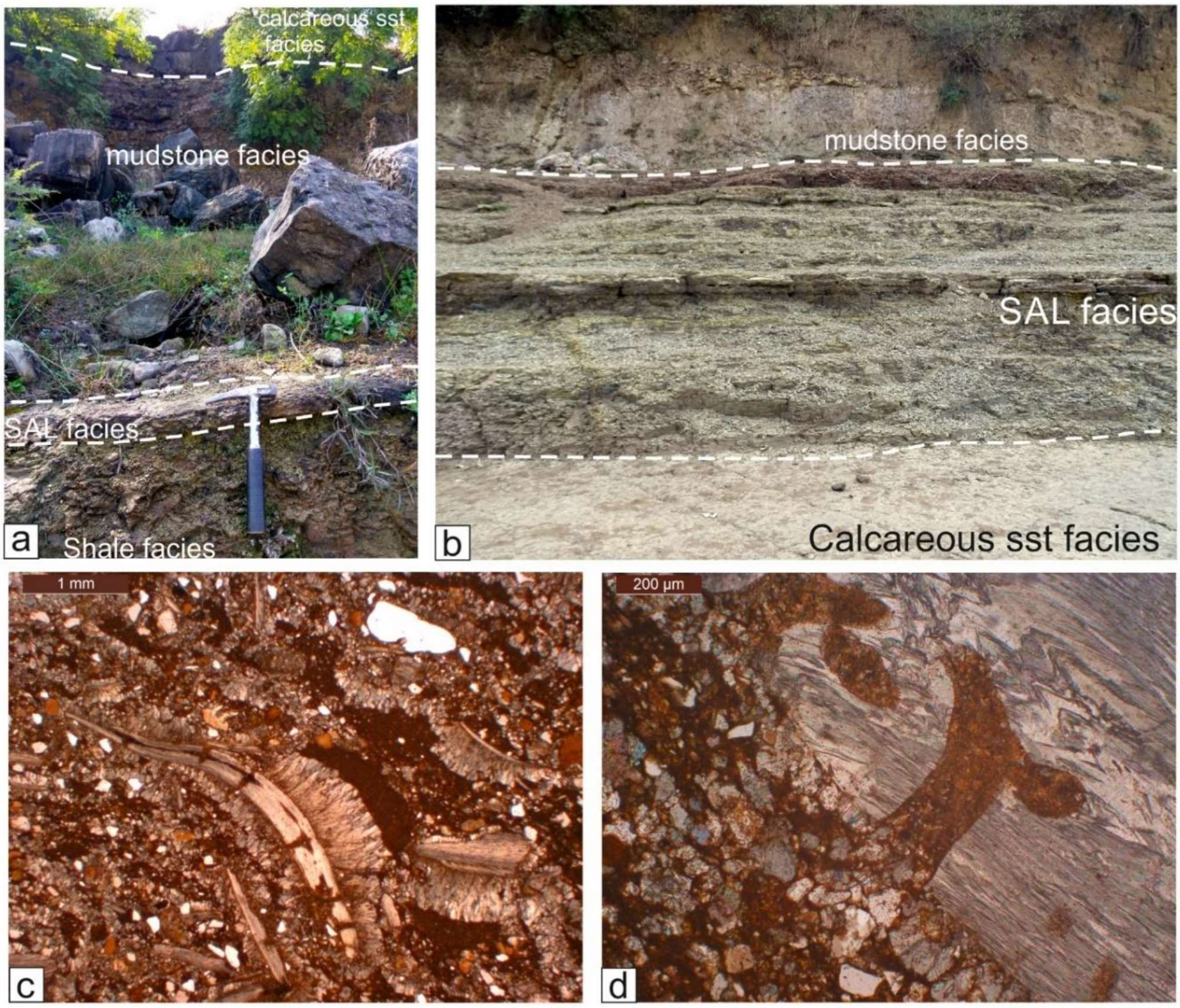


Plate 5.18 Field and photomicrographs of the sandy allochemic limestone facies showing compositional and textural variations. a. Photograph showing shale, sandy allochemic limestone (Bilthana Formation), mudstone (Nodular Limestone), and calcareous sandstone (Narmada Sandstone Member) facies, large blocks of calcareous sandstone facies have covered the part of the mudstone facies, Sultanpura-Bilthana section. b. Photograph showing calcareous sandstone (Vajepur Formation), shale, sandy allochemic limestone (Bilthana Formation), mudstone (Nodular Limestone), and calcareous sandstone (Narmada Sandstone Member) facies, Uchad section. c. fine-grained quartz, oyster shells, and micritic matrix; the shell is multilayered foliated in the center and prismatic outside; Bilthana Formation, Sultanpura-Bilthana section. d. Oyster shell cut by boring possibly sponge, the borings are filled with micrite also note the foliated structure of oyster shell consisting of randomly oriented bundles of calcitic lamellae; Bilthana Formation, Sultanpura-Bilthana section.

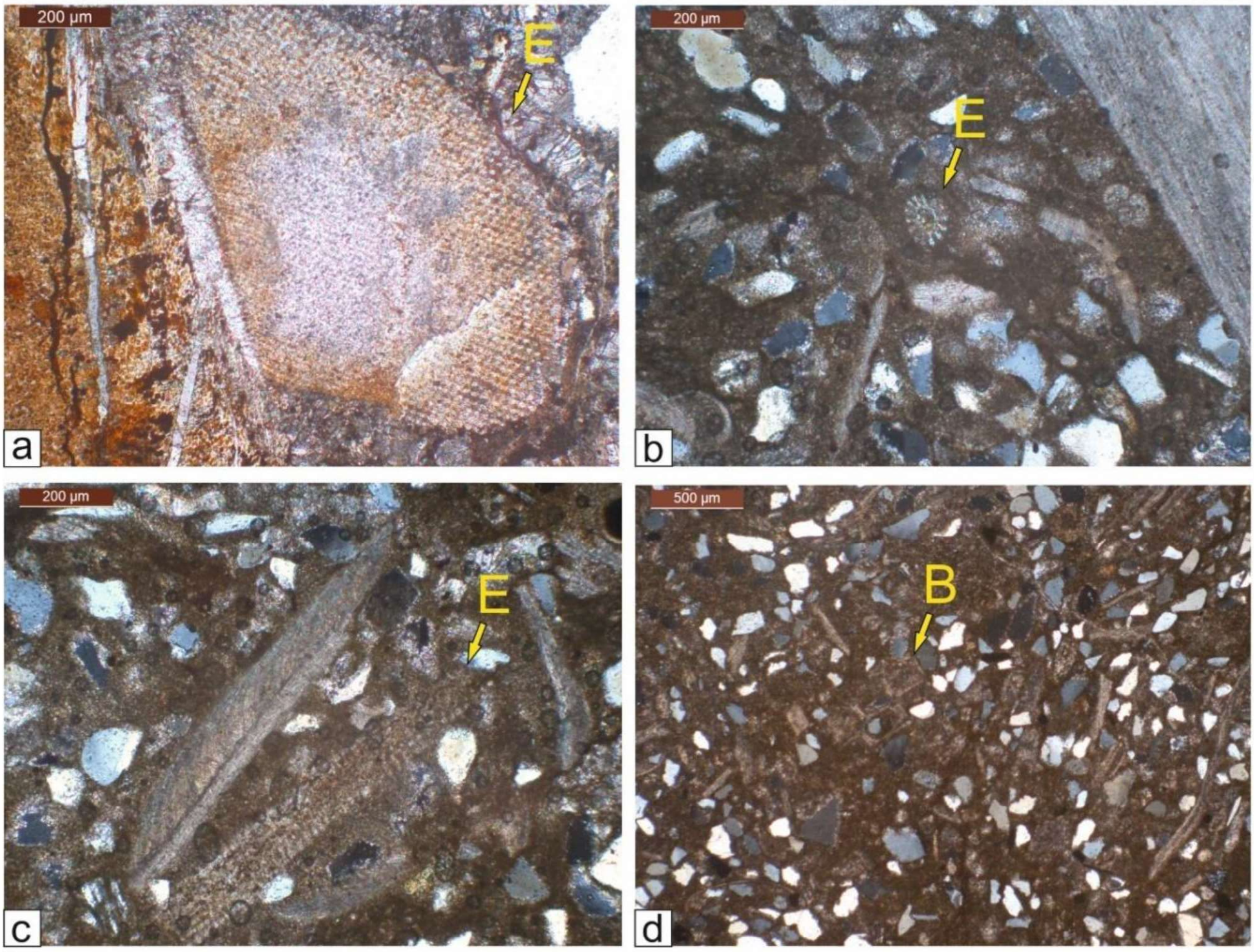


Plate 5.19 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation. a. Echinoderm recognized by a regular pattern of internal pores and singly crystal extinction, Bhekhadiya section. b. Oyster shells and echinoderm (E) in the micritic matrix; Uchad section. c. Angular quartz grains, echinoid spine (E), and foliated oyster shell in the center of photograph; Uchad section. d. Angular quartz grains, bryozoan fragment (B) in the center of the photograph, and oyster fragments in the micritic matrix; Uchad section.

Interpretation: The facies show the presence of abundant oyster shells with sand size quartz grains in the lower part of the Bilthana Formation. The oyster shells are disarticulated but lack the breakage convex up position, and horizontal (side view) orientation indicates deposition due to traction currents (Fürsich and Oschmann, 1993). The random orientation of the bivalves also indicates a rapid deposition, episodic toppling, and reworking of the sediments (Sanders et al., 2007). Therefore, the overall taphonomy of the shell beds indicates a final deposition caused by short-term high-energy

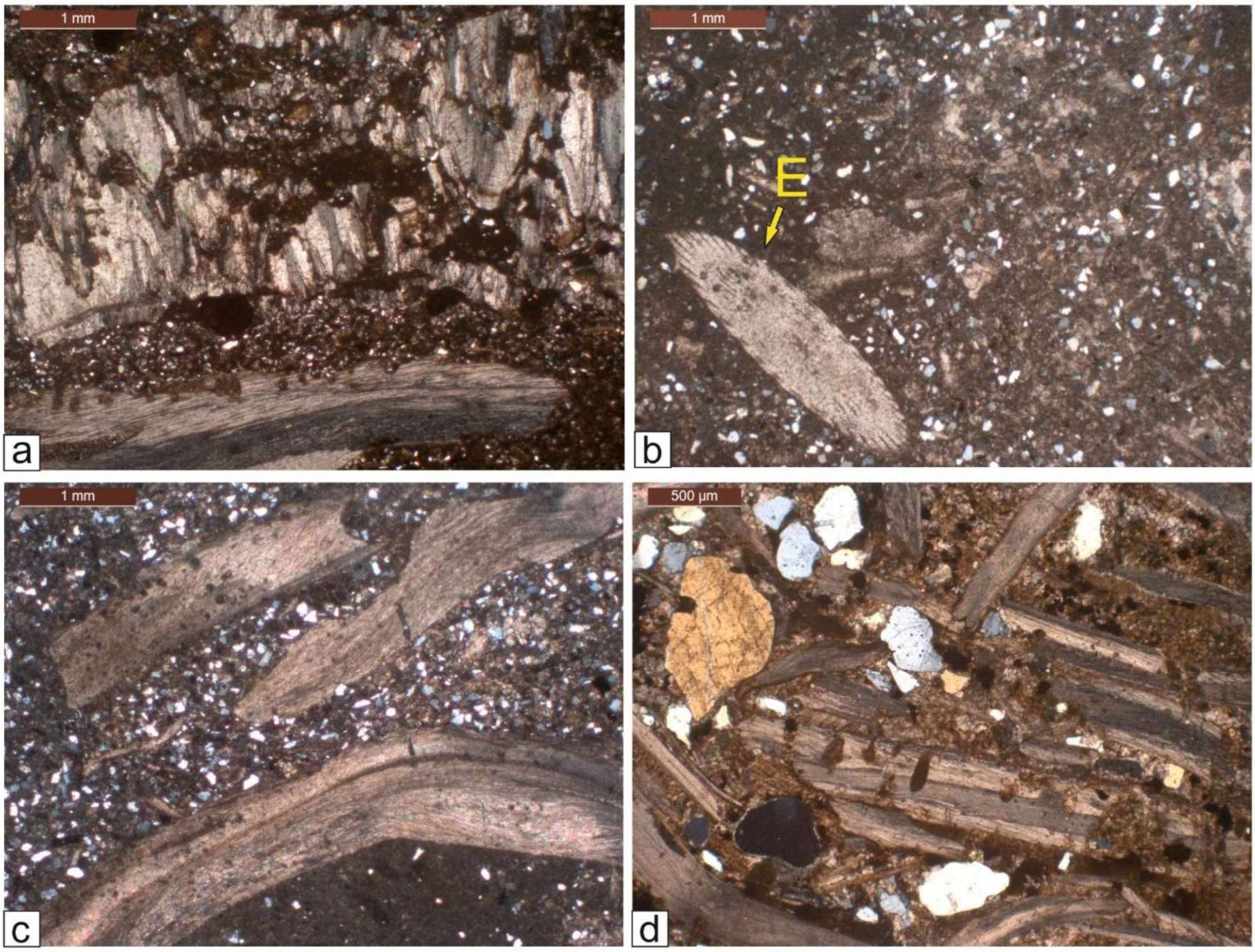


Plate 5.20 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation showing compositional and textural variations. a. Silt-sized quartz grains, foliated and bored oyster at the bottom and prismatic in the center in the top band of oyster; Uchad section. b. Silt-sized quartz grains, micritized echinoderm (E), and other shell fragments in the micritic matrix; Vajepur section. Note the prismatic shell fragment is broken and appears as calcitic prisms in the matrix. c. Abundant quartz grains and shell fragments in the micritic matrix; Vajepur section. d. Fine to coarse-grained quartz with foliated and bored shell fragments in the micritic matrix; Uchad section.

event such as a storm flow. The storm-dominated shallow marine settings are highly reported in the lower shoreface environments (Pemberton et al., 2012). The storm events mixed the mud with the silt-sized quartz grains, brought the filter feeders, and played a role in surface exhumation, but bioturbation also played a role in mixing the sediments. This is supported by the occurrence and sudden disappearance of resting/dwelling traces of sea anemones (*Conichnus* and *Conostichus*) in the facies.

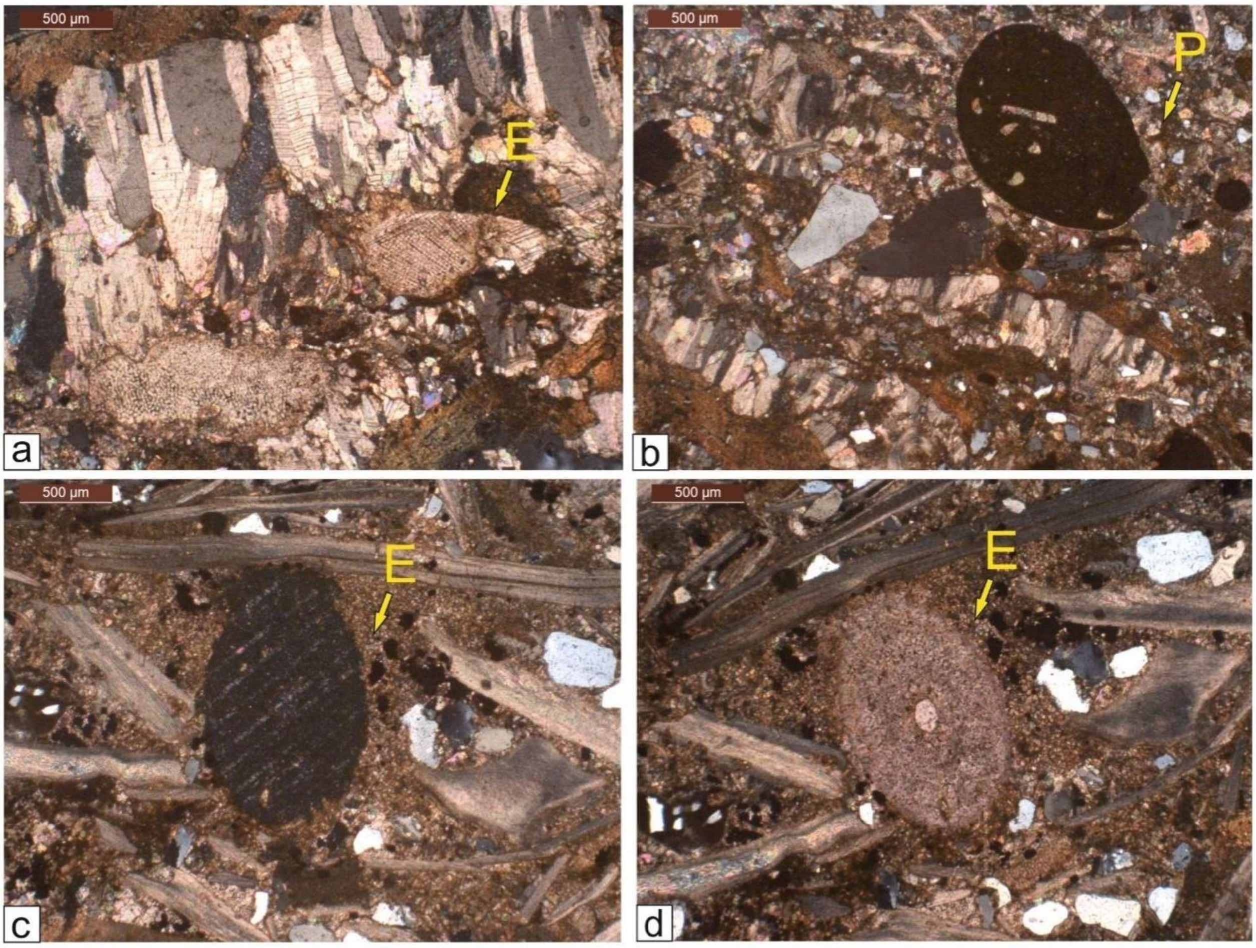


Plate 5.21 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation, Uchad section. a. Recrystallized (calcitic) prismatic oyster shells and echinoderm fragments (E). b. Disintegrated prismatic shell fragment, which forms the matrix and pellet? (P) in the top right corner. c-d. Calcitised echinoderm (E) in the center of the photograph and d. its rotated view.

5.2.2.7 Fossiliferous Limestone facies (FL)

Description: The rocks of these facies occur in the Bilthana Formation, and the Narmada Sandstone Member of Uchad Formation exposed at Uchad, Sultanpura-Bilthana, Bhekhadiya, Navagam, Gulvani, Mathsar, Karvi, Chikhli, and Vajepur sections. The facies consist of wackestone, packstones, and grainstones characterized by a variable proportion of mud to grains. It occurs mainly towards the top of the Bilthana Formation with shale (Plate 5.22a, c-d) in Uchad, Bilthana, Karvi, and Mathsar sections and at the top of Nodular limestone (Plate 5.23d) in the Navagam section.

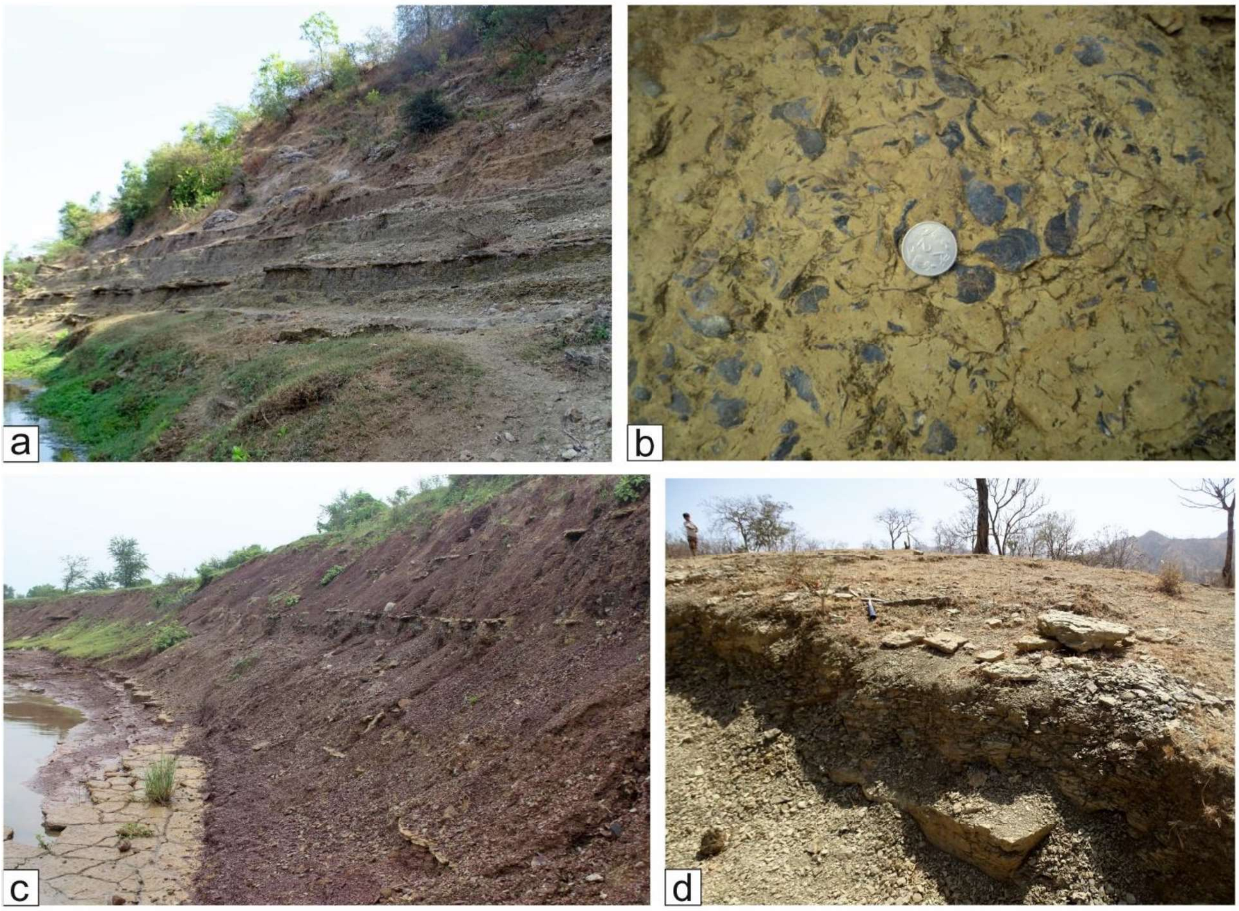


Plate 5.22 Field photographs of fossiliferous limestone facies of Bilthana Formation. a. Panoramic view of the oyster beds intercalated with yellow shale; Uchad section. b. Close-up of the oyster bed; note the disarticulated oysters in convex-up and -down positions; Uchad section (diameter of coin = 23 mm). c. Panoramic view of the oyster beds intercalated with red shale, Sultanpura-Bilthana section. d. Fragmented fossiliferous oyster slabs, Mathsar section.

The taphonomy of oysters and sudden truncation of plug-shaped burrows suggest event bed sedimentation. The frequent high-energy storm events or strong tidal currents resulted in the deposition of the sandy allochemic limestone. The presence of fossils like oysters, echinoderms with angular sand-silt size quartz suggests a storm-dominated lower shoreface environment. The thickness of an individual bed varies from 6 cm to 20 cm. Around ten bands of oyster bearing limestone are observed at the Uchad section, which are either laterally merged or pinched out at a short distance. The facies show presence of crowded oysters (Plate 5.23a-c) in a convex-up position, unoriented with growth lines (Plate 5.22b, 5.23c, 5.26a-d), recrystallized (Plate 5.25c), or prismatic structure (Plate 5.26d) on the surface of beds. Petrographically, the facies show presence of fossils like bivalves (Plate 5.24-5.26), bryozoans (Plate 5.24c; 5.25d), and echinoids (Plate 5.24d, 5.26a-c; 5.27a). The oyster shells are heavily bored at places (Plate 5.24a-b; 5.25a).

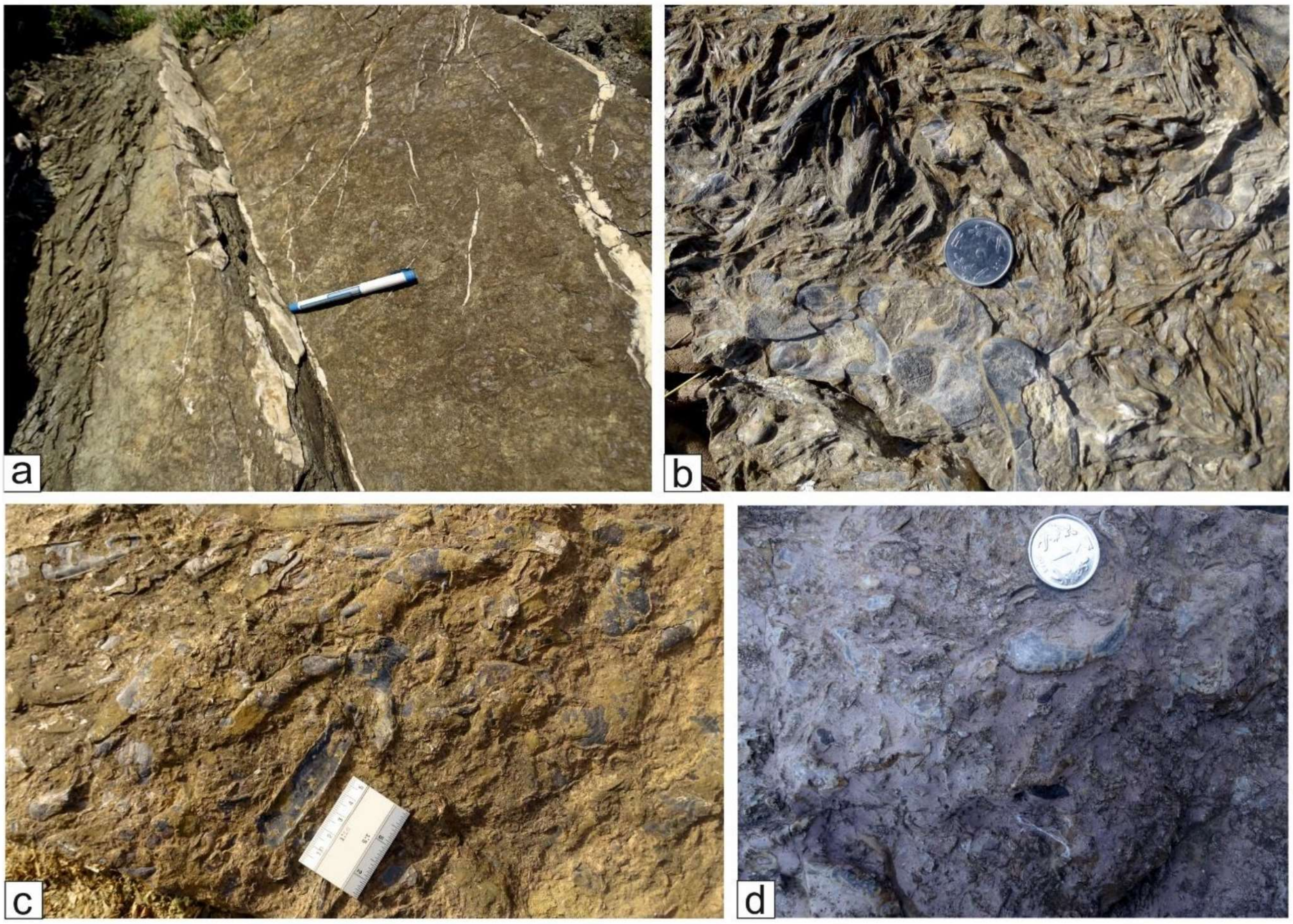


Plate 5.23 Field photographs of fossiliferous limestone facies. a. Oyster slab of the Bilthana Formation, Navagam section. b. Close-up view of the crowded oysters in the fossiliferous slab of Bilthana Formation, Karvi section (diameter of coin = 23 mm). c. Close-up view of the broken oyster slab of the Bilthana Formation, Gulvani section. d. Close-up view of the oysters of Nodular Limestone, Navagam section (diameter of coin = 25mm).

Intraclasts (Plate 5.26a) are observed, which are the angular lumps of fine-grained carbonates or mud partly lithified. The facies is devoid of primary sedimentary structure but consists of trace fossils like *Skolithos linearis* and *Thalassinoides* isp. Abundant microborings (differentiated from macroboring based on their size <1 μm to 100 μm) are observed (Plate 5.27b, d). The fossiliferous limestone facies include packstone, Wackestone, and Grainstone, which are further subdivided into two microfacies, namely bioclastic grainstone and bioclastic packstone-wackestone.

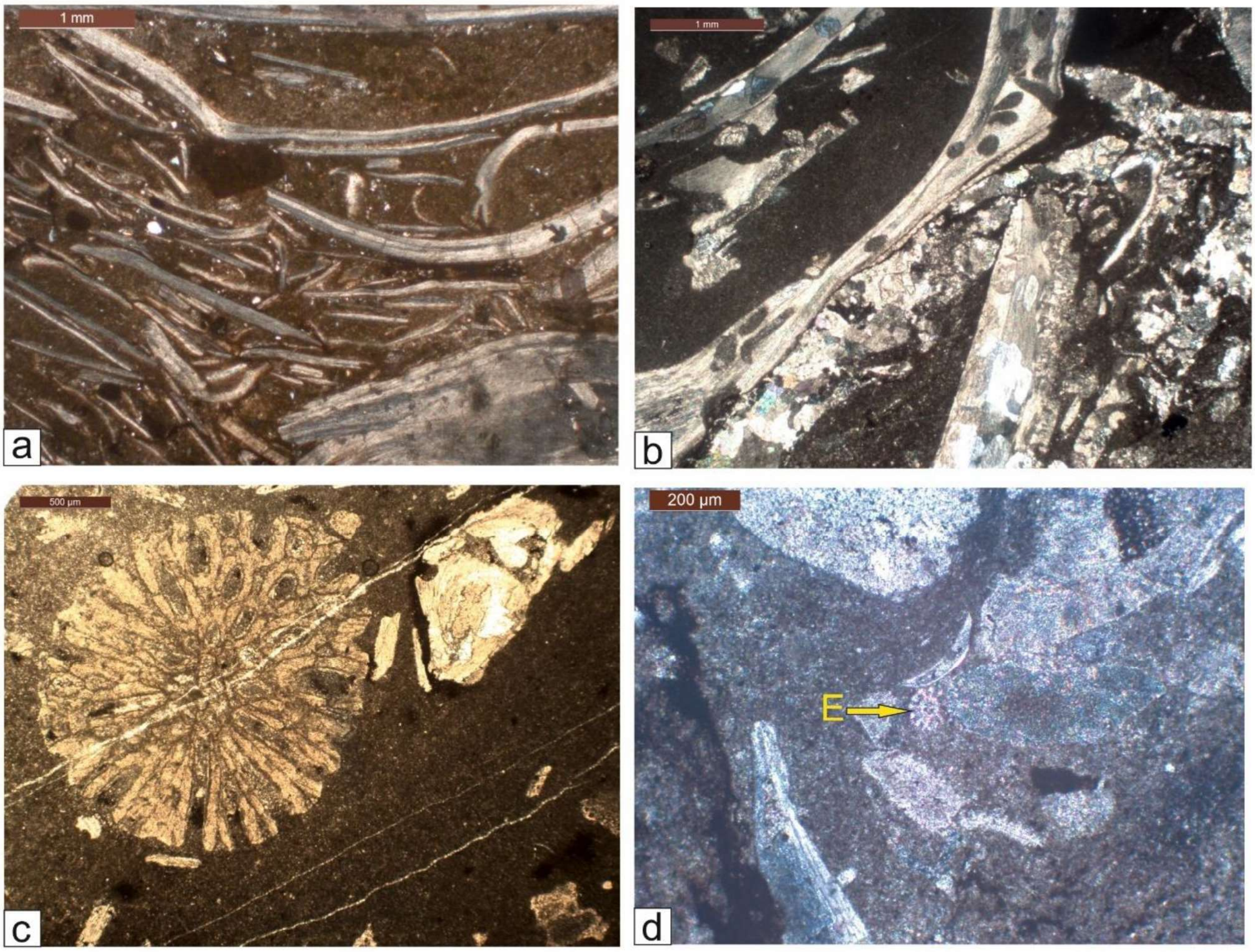


Plate 5.24 Photomicrographs of the fossiliferous limestone facies showing textural and compositional variations. a. Abundant oyster fragments showing growth lines cemented in the micritic matrix; Bilthana Formation, Gulvani section. b. Bored and partly dolomitized oyster shells in micritic matrix suggesting diagenesis (compaction); note the zoned dolomitized crystals in the shell; Nodular Limestone, Navagam section. c. Transverse section of bryozoan, note the zoned dolomitized crystals in the shell at the right corner; Nodular Limestone, Navagam section. d. Echinoderm (E) and micritized shell fragments; Nodular Limestone, Navagam section.

5.2.2.7. 1 Bioclastic Grainstone microfacies (BGm)

The bioclastic grainstone microfacies are observed in the Men River Valley, Gulvani, and the Karvi sections of WLNV. It shows the presence of trace fossils like *Thalassinoides*. Petrographically, it consists of more than 95% carbonate constituents. It consists of allochems like bioclasts (more than 70%), intraclasts (Plate 5.25a) in micritic cement. The bioclasts constitute oysters, bryozoan (Plate 5.25d), and echinoderms (Plate 5.26a-c); siliciclastics (Plate 5.26b) are also observed up to 5%. It also shows the presence of calcareous worm tubes (Plate 5.27c) and borings in oyster shells.

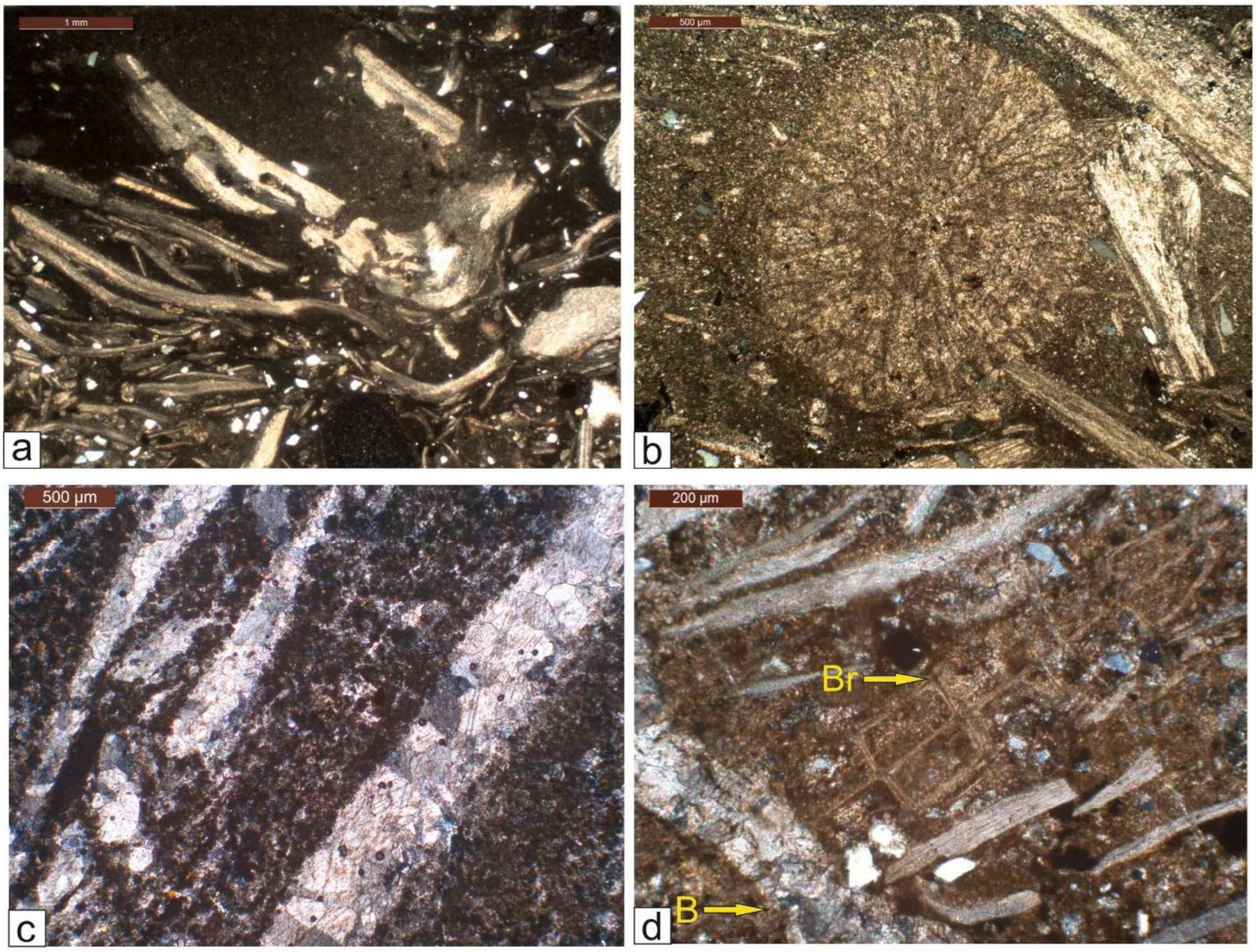


Plate 5.25 Photomicrographs of the fossiliferous limestone facies of the Bithana Formation. a. Heavily bored oyster shells with growth lines and few silt-sized quartz grains in the micritic matrix; Navagam section. b. Micritised shell fragments of echinoderm? and oyster in the micritic matrix; Navagam section. c. The oyster shells are recrystallized to form cleavable calcite; Navagam section. d. Grainstone composed of oyster shell fragments with growth lines, bryozoan (Br), and burrow (B) filled with sparry calcite; Mathsar section.

5.2.2.7.2 Bioclastic Packstone-wackestone microfacies (BPm)

The microfacies are observed in Men River valley, Navagam, Mogra, and Mathsar sections. It shows the presence of trace fossils like *Thalassinoides*. Petrographically, it consists of more than 70% carbonate constituents. The carbonate constituents are comprised of allochems. The bioclasts constitute oysters, echinoderms (Plate 5.26a-c), and bryozoans. Few fine-grained and silt-sized quartz grains are also observed. The oysters show borings (Plate 5.25a, 5.26b, 5.27b, d) and are micritized (Plate 5.25b), dolomitized (Plate 5.26b), or metamorphosed to calcite (Plate 5.25c). The primary dolomite is distinguished from the secondary dolomites based on its grain size (less than 0.02 mm).

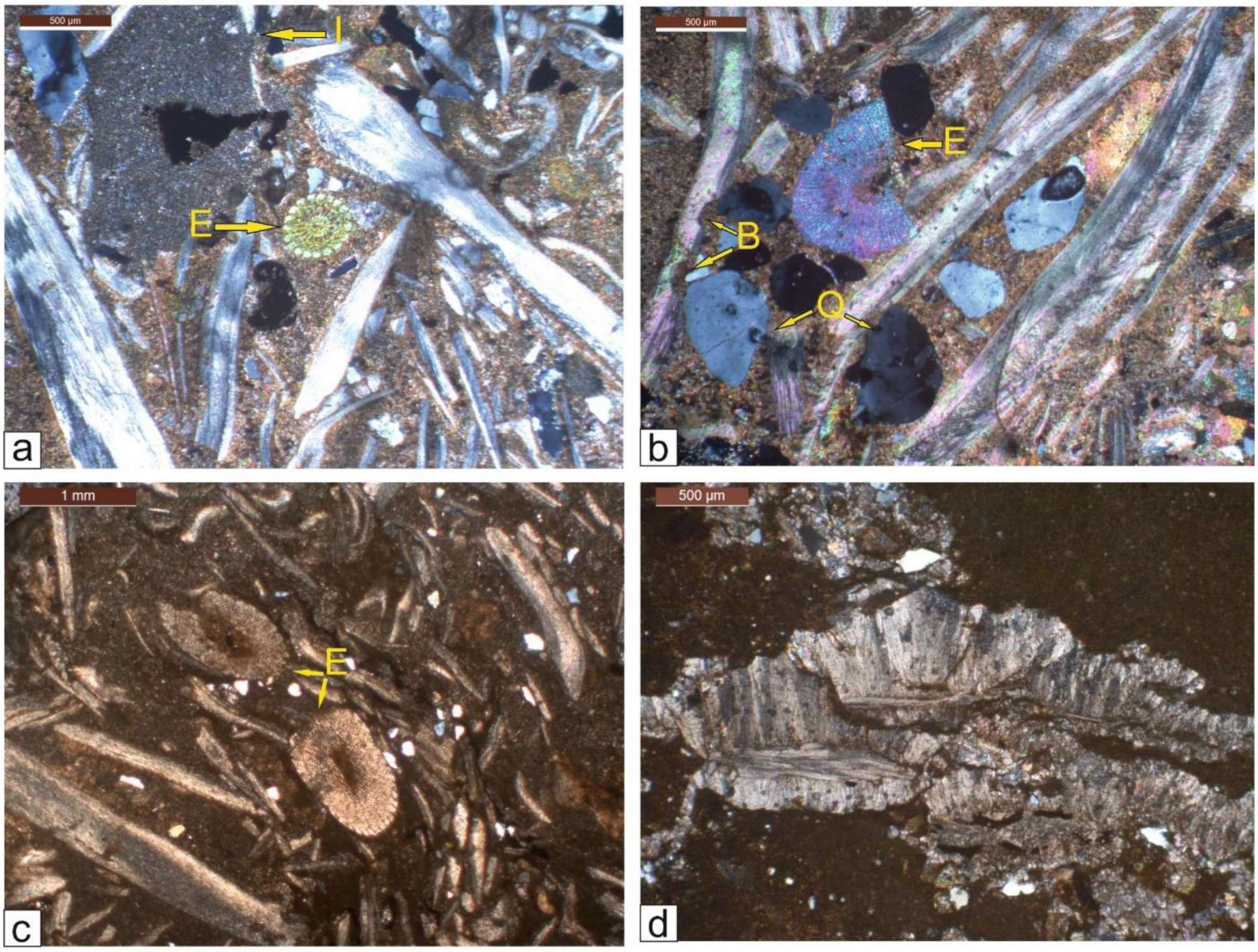


Plate 5.26 Photomicrographs of fossiliferous limestone facies of Bilthana Formation showing textural and compositional variations. a. Grainstone consisting of oyster fragments showing growth lines, transverse section of echinoderm spine (E), intraclasts (I), and scattered silt-sized quartz grains in the micritic matrix; Bhekhadiya section. b. Grainstone consisting of oyster fragments showing growth lines, transverse section of fragmented echinoderm spine (E), fine-medium quartz grains (Q), and bored oyster shells (B); Bhekhadiya section. c. Grainstone consisting of unoriented oyster fragments showing growth lines, transverse section of fragmented echinoderm spines (E), and fine quartz grains (Q); Uchad section. d. Prismatic microstructure in oysters showing the alignment of closely spaced calcite crystals; Uchad section.

Interpretation: The fossiliferous limestone facies mostly occur intercalated with the shale facies in the Bilthana Formation, which suggest deposition below the fair-weather wave base in the lower shoreface/offshore transition environment. The deposition of shale was interrupted by high energy events like storm or long-term currents, which deposited the oyster beds. The taphonomy of the oyster beds suggests deposition due to high energy storm events or long-term currents (Shitole et al., 2019), as indicated by the presence of unaltered, least abraded, disarticulated, unoriented, bored oyster shells with faint growth lines. The presence of echinoderm fragments suggests an open marine setting. Moreover, the storm-dominated shallow marine settings are widely reported in the lower

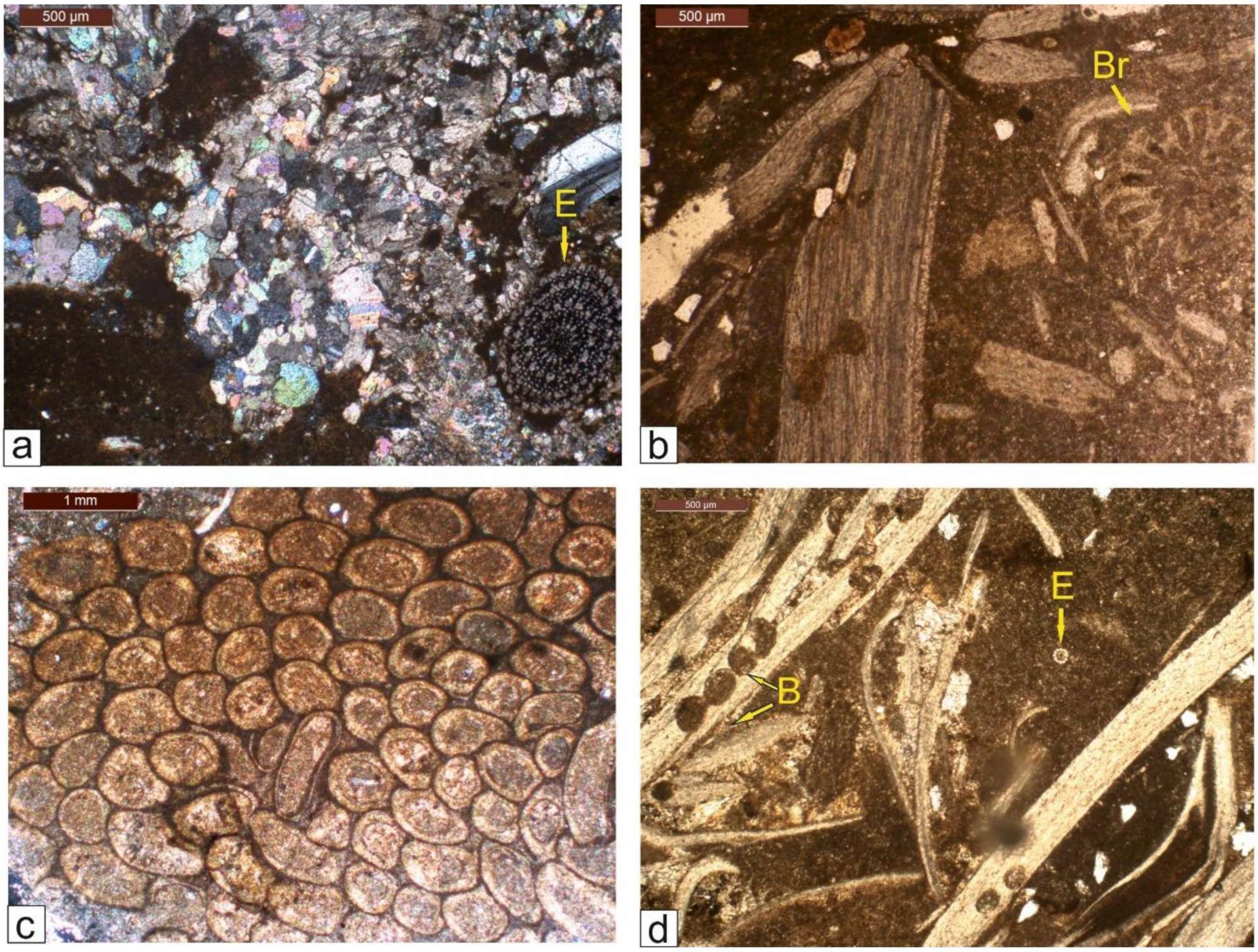


Plate 5.27 Photomicrographs of fossiliferous limestone facies of the Bilthana Formation. a. Recrystallized bivalves shell fragments formed cleavable calcite crystals and transverse section of echinoderm spine (E) in the micritic matrix (black); Uchad section. b. Bored oyster shell with bryozoan (Br); Uchad section. c. Calcareous worm tubes; Uchad section. d. Packestone consisting abundantly bored (B) oyster shells with a transverse section of echinoderm spine (E) and scattered quartz grains in the micritic matrix; Mogra section.

shoreface environment. The microborings observed in the fossiliferous limestone facies are made by algae, fungi, and bacteria, which are found in a wide range of environments, but most microborers occur in shallow marine subtidal and intertidal environments (Flügel, 2010). The facies is interpreted to represent a storm-dominated lower shoreface environment. The presence of dwelling burrows at the contact of oyster limestone bands (sandy allochemic limestone, grainstone, packstone) with the shale facies suggests low energy periods with a low rate of sedimentation interrupted with high energy events. The depth of FWWB on shoreface is about 10-15m (Boggs, 1987). The lower shoreface deposits in the study area are best observed in the Men River Valley near the Uchad section in the Bilthana Formation. The facies overlie the sandy allochemic limestone facies, indicative of an increase in the carbonate content and a deepening shoreface. The presence of abundant marine invertebrate fossils (echinoderms, oysters, bryozoan) with quartz grains and taphonomy of oysters suggests a lower shoreface of normal salinity with high energy events.

5.2.2.8 Sandy/silty micrite facies

Description: The sandy micrite facies is pale red to grey colored sandstones. It is observed in the Narmada Sandstone Member in Navagam (Plate 5.28a-b) and Nodular Limestone in the Uchad section (Plate 5.29a). The maximum thickness observed is ~3 m at the Uchad section. The facies grades laterally into micritic siltstone facies in the Uchad section.

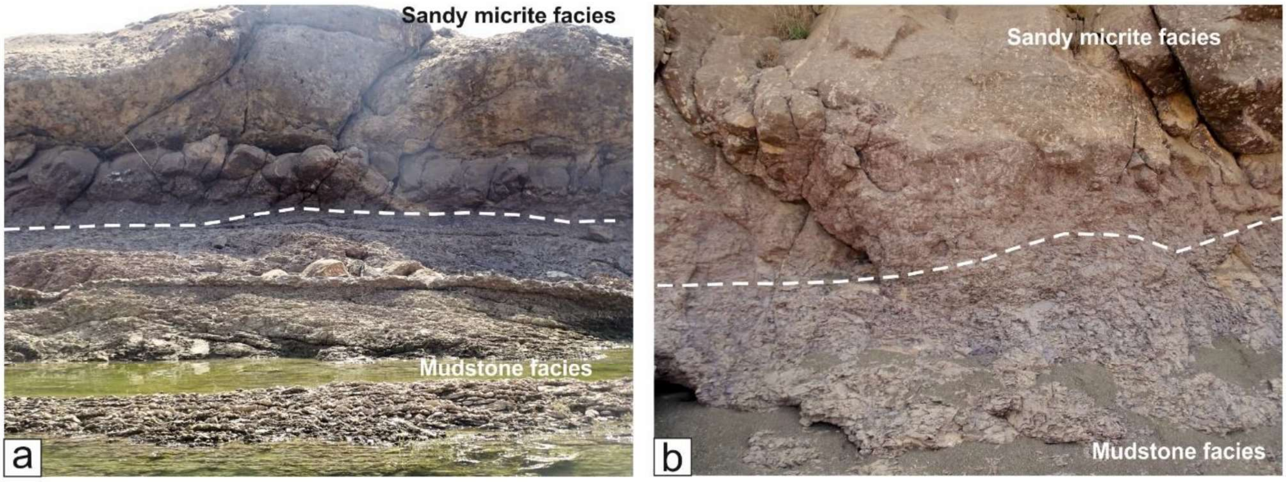


Plate 5.28 Field photographs of the sandy micrite facies. a. Thickly-bedded sandy micrite facies of Narmada Sandstone Member overlying the mudstone facies of the Nodular Limestone, Navagam section. b. Close-up view of a. note the gradational contact between the two lithostratigraphic units.

It is devoid of body fossils and trace fossils. Petrographically, it consists of ~40 % angular, poorly sorted, and fine to coarse-grained quartz and less than 1% polycrystalline quartz grains (Plate 5.29c) in ~ 60% of the micritic matrix (Plate 5.29b-d) representing sandy micrite of Mount (1985). At the Uchad section, it is well sorted.

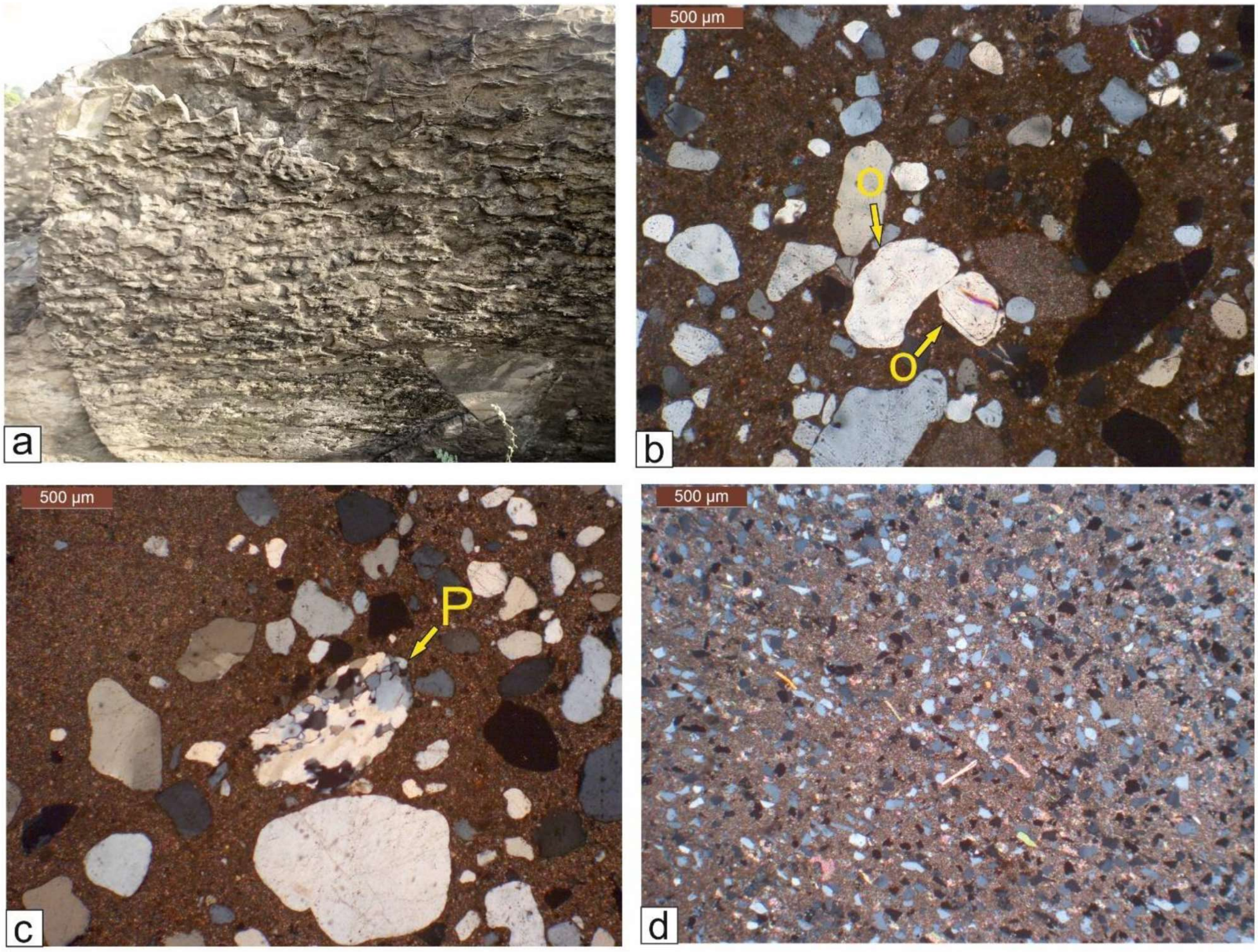


Plate 5.29 Field photographs and photomicrographs of the sandy/silty micrite facies. a. Silty micrite facies; Nodular Limestone, Uchad section. b. Subangular to subrounded, poorly sorted quartz grains in the micritic matrix; quartz grains showing the presence of overgrowth (O); Narmada Sandstone Member, Navagam section. c. Poorly sorted quartz grains and polycrystalline quartz (P); Narmada Sandstone Member, Navagam section. d. Silty micrite facies showing the presence of abundant silt-sized angular quartz grains in the micritic matrix; Nodular Limestone, Uchad section.

Interpretation: Based on stratigraphic position and poorly sorted coarse-grained quartz and the presence of polycrystalline quartz which is supposed to be derived from the basement. The facies represent a relatively high-energy regressive shoreface environment in the Navagam section, which were deposited above the transgressive mudstone facies of the Nodular Limestone. The well-sorted silt-sized quartz grains of the Uchad section suggest its deposition in the low-moderate energy offshore transition environment.

5.2.2.9 Mudstone facies

Description: The mudstone facies is whitish-grey, thin-medium bedded to nodular limestone. Bedding contacts are parallel in thin-medium bedded units (Plate 5.31b). Individual bed thickness varies from mm to cm, but packages are several meters thick. It is around 76 m thick in the Navagam section and 6 m thick in the Uchad section. Macrofauna is typically absent except for some poorly preserved ammonites and oysters. The unit is laminated (Plate 5.30c-d) to thinly bedded (Plate 5.30a-b, 5.31c-d) and is exposed at Navagam, Uchad, Bilthana, Bhadarwa, Sultanpura, Karvi, Mathsar, Mogra, and Gulvani sections. The individual beds show a nodular appearance towards the top at a few localities (Plate 5.30a-b, d, 5.31c). Bioturbation is generally absent but seen only at the middle

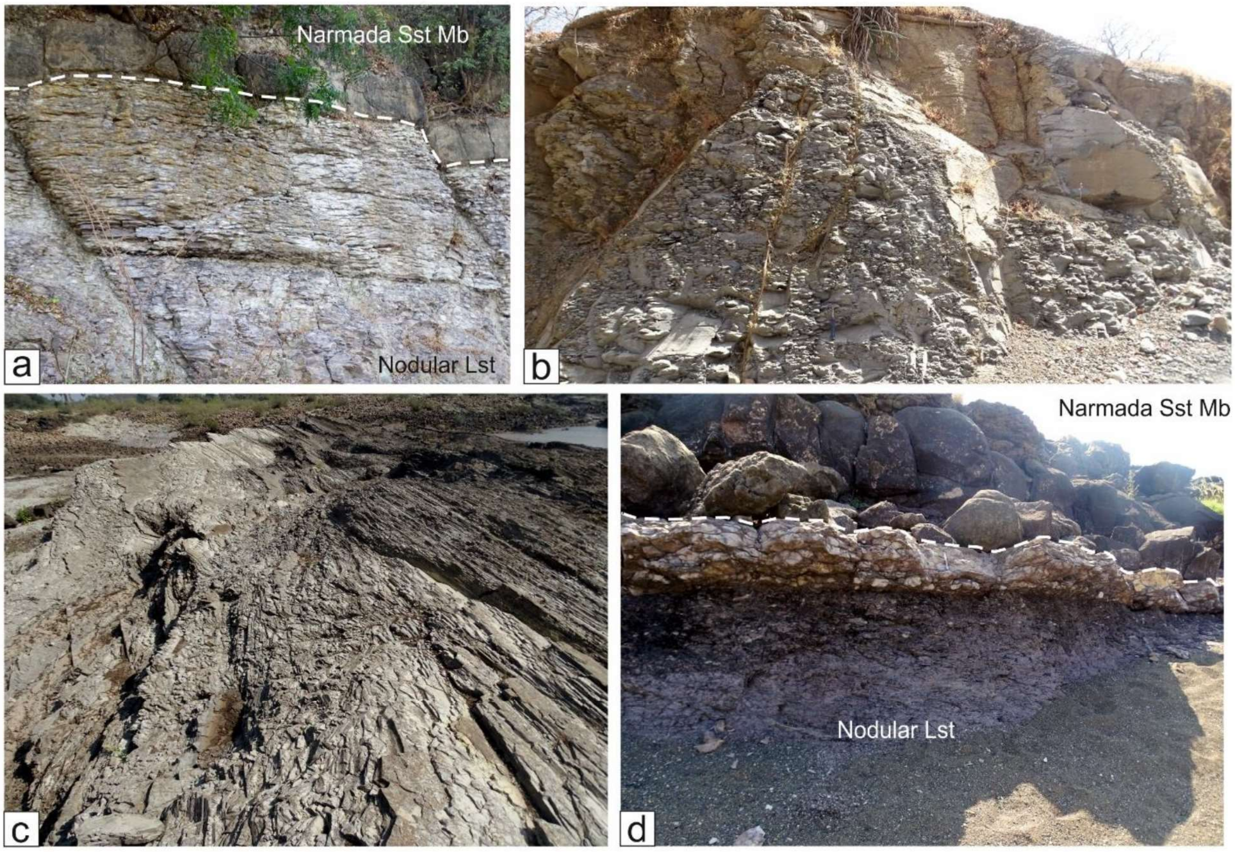


Plate 5.30 Field photographs of mudstone facies. a. Mudstone of Nodular Limestone showing bedded appearance in contact with the overlying Narmada Sandstone Member; Uchad section. b. Mudstone exhibiting nodular appearance; Nodular Limestone, around Mathsar village. c. Extensively fractured thinly-bedded mudstone; Nodular Limestone, Navagam section. d. Mudstone with the textural variations at Uchad typical nodular appearance of the Nodular Limestone in contact with the overlying Narmada Sandstone Member; Navagam section.

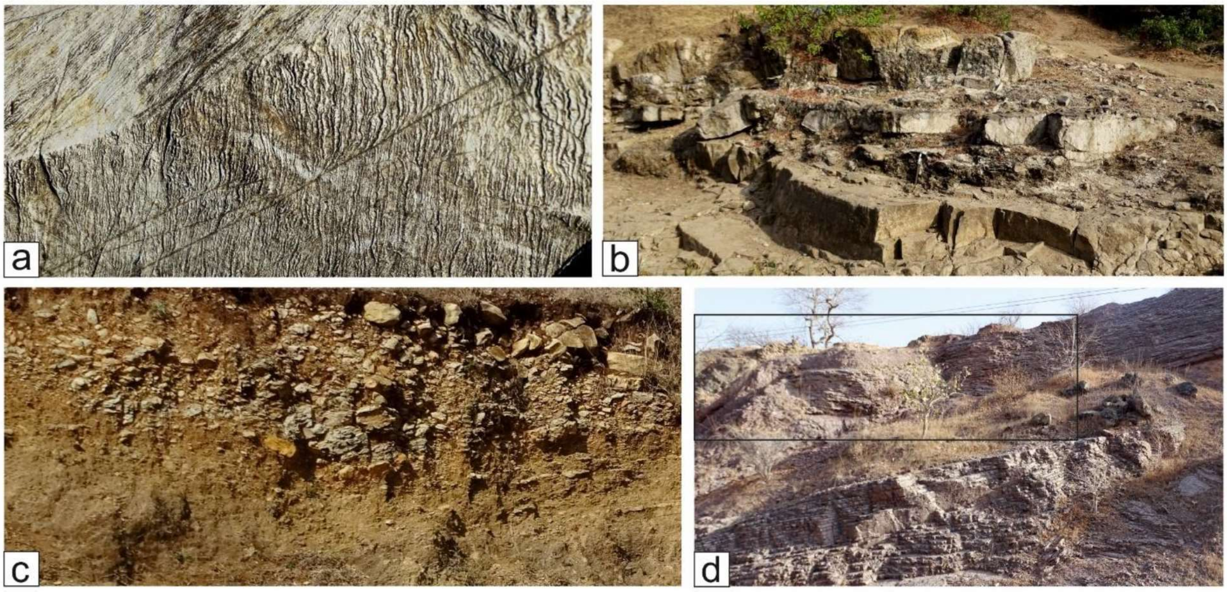


Plate 5.31 Field photographs of the mudstone facies. a. Intense chemical weathering marks on the limestone surface; Nodular Limestone, Navagam section. b. Thickly-bedded mudstone of the Men Nadi Limestone Member, Uchad Formation; Uchad section. c. Mudstone exhibiting nodular appearance; Nodular Limestone; Karvi section. d. Thinly-bedded and locally folded mudstone beds; Nodular Limestone, Navagam village.

level and shows the presence of trace fossils like *Arenicolites* isp. and *Thalassinoides paradoxicus*. Petrographically, the facies show presence of delicate fragments of molluscan shell, calcitised foraminifers, echinoid (Plate 5.33d) and ostracods? (Plate 5.33c), few pyrites (Plate 5.33a) and silt-sized quartz grains (less than 5%) are also observed and is dominated by micrite (Plate 5.32a-d, 5.33a-d).

Interpretation: The limestone consists of very low clastic content and suggests deposition away from littoral zone. Based on the presence of micrite and microfossils, the facies is interpreted to reflect deposition in the offshore environment (distal) below the storm wave base due to suspension settling on a low energy seafloor (quiet water sedimentation), but occasional siliciclastic input is observed as lateral facies variation due to change in current energy. The presence of micrite and ammonites suggests deposition in a neritic sublittoral environment. The facies consist of straight, sharp calcitic veins and fractures, which occur singly or as fracture sets crossing each other; they are important in imparting porosity and permeability to the rocks and are formed possibly due to diagenesis (dewatering during compacting) or due to tectonic fracturing.

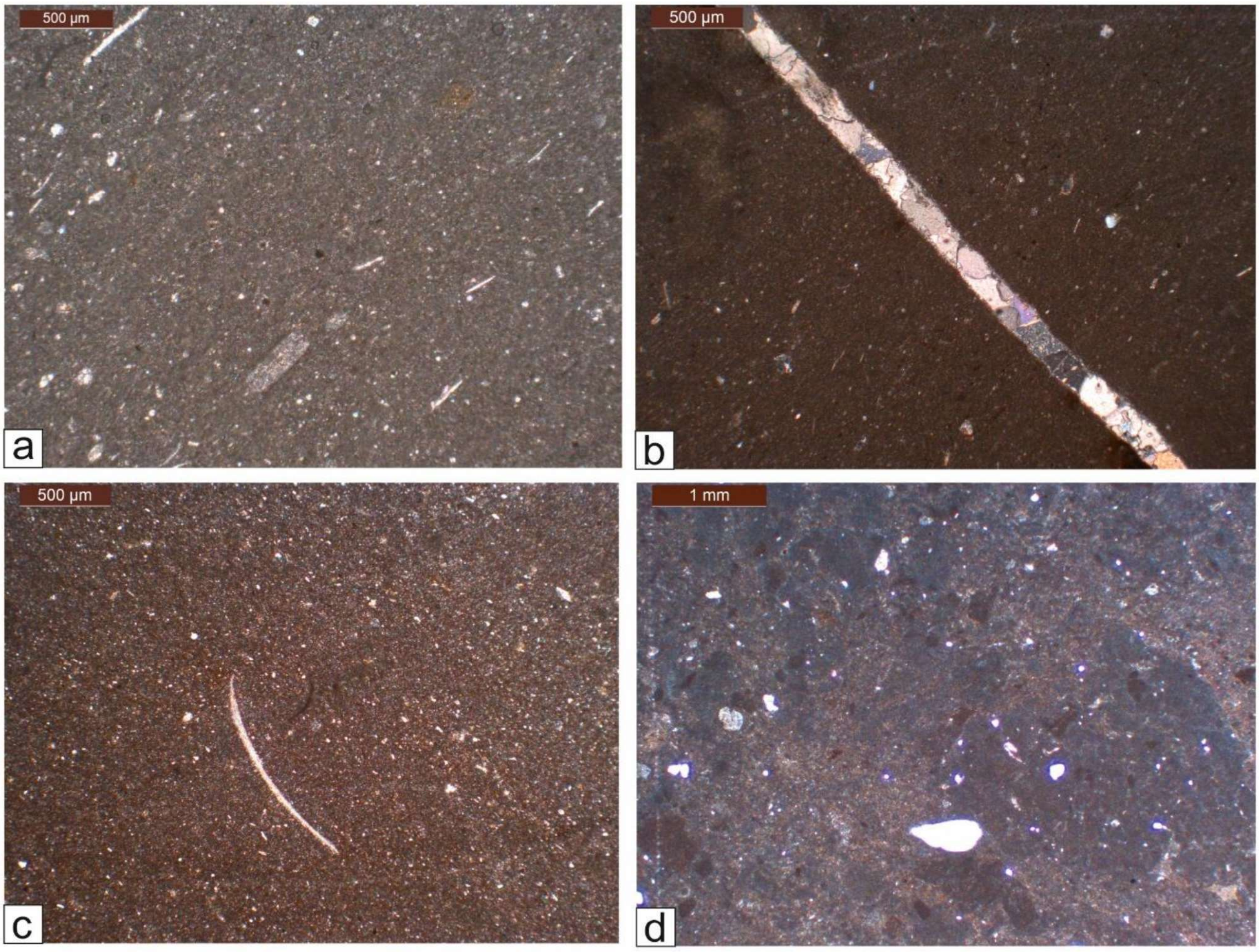


Plate 5.32 Photomicrographs of mudstone facies showing compositional and textural variations at the Uchad section. a. Mudstone consisting of delicate shell fragments with scattered fine quartz grains; Nodular Limestone. b. A calcitic vein in mudstone possibly due to fracturing during burial process; Nodular Limestone. c. Delicate bivalve shell fragment with very fine quartz grains; Nodular Limestone. d. Mudstone with silt to medium-sized quartz grains disseminated in the micritic matrix; Narmada Sandstone Member.

5.2.2.10 Muddy micrite facies (MM)

Description: The facies is whitish colored limestone and has nodular appearance or bedded structure (Plate 5.34a-b), observed in the Uchad and Vajepur sections. It is characterized by silt to medium-sized quartz grains embedded in a micritic matrix. The facies show presence of occasional shell fragments in Uchad section and is devoid of trace fossils. Petrographically, the muddy micrite shows carbonate proportion more than the siliciclastic proportion and consists of silt to medium-sized quartz grains

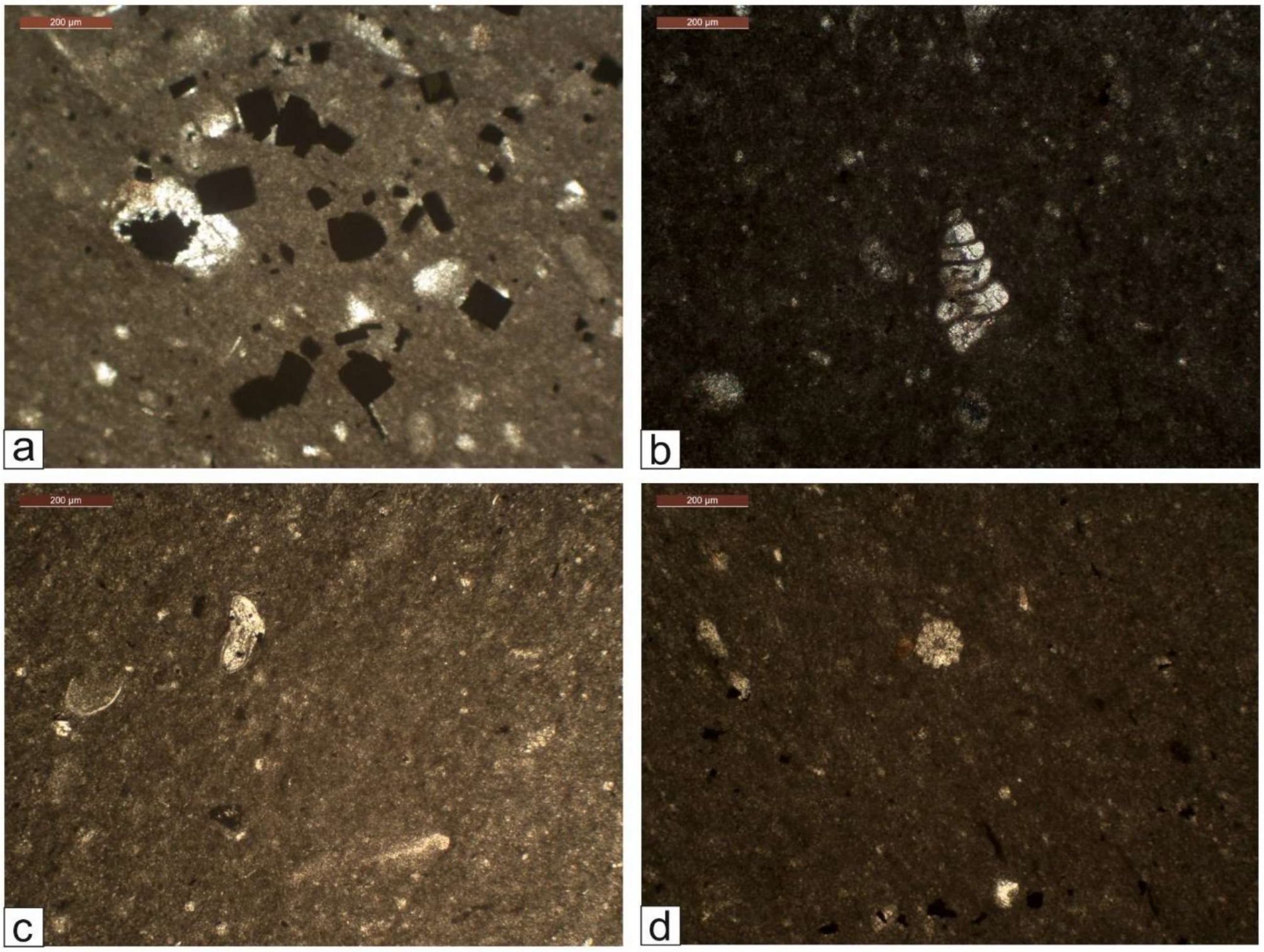


Plate 5.33 Photomicrographs of the mudstone facies; Nodular Limestone. a. euhedral, isotropic, pyrite grains in micritic matrix. b. Calcitised helicoid gastropod in micritic cement. c. Ostracod carapace? in the micritic matrix. d. Transverse section of echinoid spine and fecal pellets? in the micritic matrix; Nodular Limestone, Vajepur section.

Plate 5.34 Field photographs of the muddy micrite facies. a. Bedded muddy micrite occurring with thin shales, underlying the mudstone facies; Men Nadi Limestone Member, Uchad section (scale bar = 1m). b. Nodular appearance of the beds; Nodular Limestone; Vajepur section (hammer length = 32 cm).

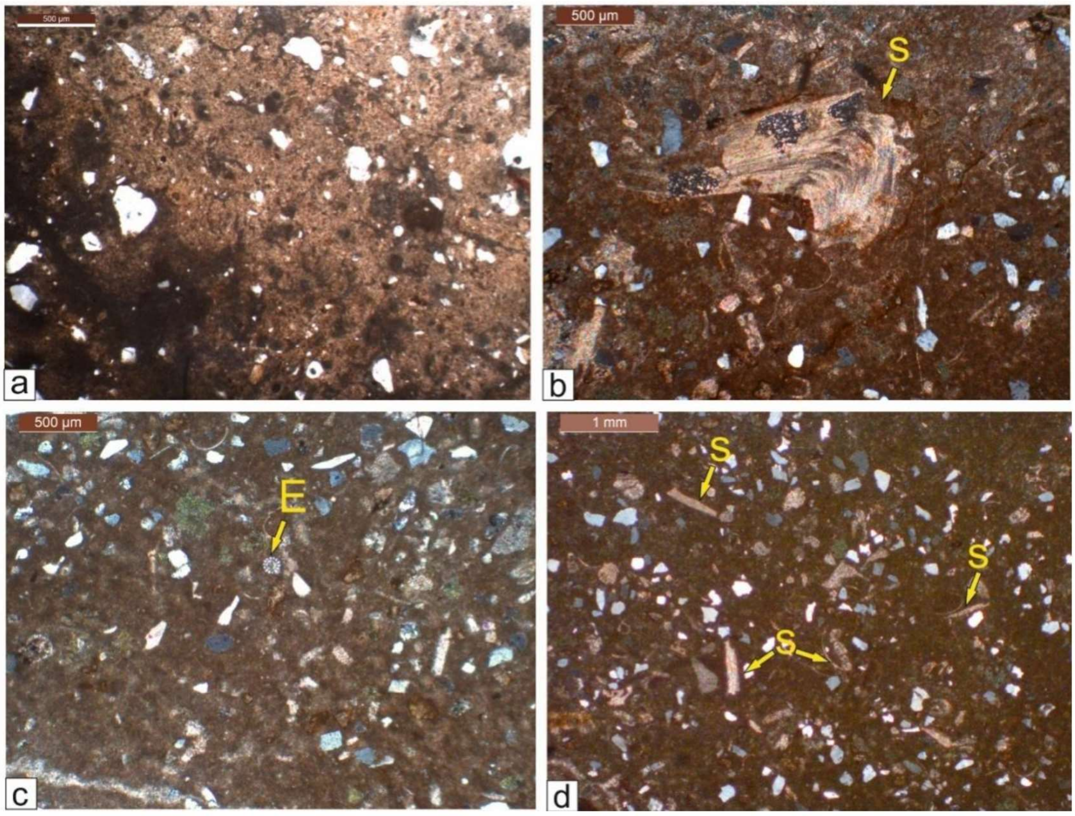


Plate 5.35 Photomicrographs of the muddy micrite facies. a. Subangular to subrounded silt to medium-sized quartz grains floating in the micritic matrix; Men Nadi Limestone Member, Uchad section. b. Silt-fine grained quartz grains and fecal pellets? in the micritic matrix and shell fragment showing growth lines (S), c. Echinoderms (E), quartz grains, and d. Abundant quartz grains, shell fragments, and fecal pellets? in the micritic matrix in the Nodular Limestone, Vajepur section.

(~30-40), and micrite (60-70%) (Plate 5.35a), allochems constitute less than 1% echinoderms (Plate 5.35c), and bivalve shell fragments (Plate 5.35b, d). It is developed at mainly at the transition of carbonates and siliciclastics and consists of broken shell fragments which explains phases of high energy events and the source of siliciclastics in the offshore shallow marine environment.

Interpretation: The facies is developed in the carbonate-dominated Nodular Limestone and in the Men Nadi Limestone Member, suggesting a relatively moderate-high energy environment in a shallow marine environment. The deposits are relatively siliciclastic starved and show the presence of bioclasts like oysters and echinoderms, which suggests its deposition in a lower shoreface environment. Poorly sorted and well-sorted quartz grains observed in the Men Nadi Limestone Member and the Nodular Limestone, respectively. This suggests deposition under low to moderate energy conditions. Storm events were common, which mixed the mud with the silt and fine-grained quartz grains.