CHAPTER - 4
LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

4.1 INTRODUCTION

Sedimentology is defined as 'the study of sediments' (Wadel, 1932) and embraces chemical precipitates, like salt, as well as true detrital deposits not only in liquids but also in gaseous fluids, such as eolian environments (Selly, 2000). It also involves the study of the processes and products of sedimentations (Sengupta, 2007). Sedimentology enables us to unravel the chain of events responsible for a particular succession and hence the depositional environment through facies analysis. The word facies is used in both, a descriptive and an interpretative sense and 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 segments of basin comprises the subject of facies analysis (Miall, 1984). A rock facies is a body of rock with specified characteristics that reflect the conditions under which it was formed (Reading and Levell 1996). Facies analysis involves documenting lithology, texture, sedimentary structures and fossil contents which enable us to recognize the dominant processes (Nicols, 2009). Different facies formed facies association that reflects the depositional environment (Collinson, 1969; Reading and Levell 1996).

The sedimentation in the Kachchh Basin occurred in three distinct phases (1) Pre-Rift, (2) Syn-Rift and (3) Post-Rift (Desai and Thakkar, 2016). The succession of the study area is deposited mostly during the syn-rift stage beginning with the early syn-rift deposit of Cheriya Bet Conglomerate till the late-syn-rift deposit of Gadhada Formation during Callovian-Early Oxfordian. In the present study, the lithofacies of the Jurassic succession of the Khadir, Bela and Chorar Islands were measured at different localities, each sedimentary units are identified based on their field observation (lithology, color, textures) and laboratory analysis (petrographic study) to shed light on the processes and process response of the sediments and infer the sedimentary environments.

4.2 FACIES DESCRIPTION

The Jurassic successions of Eastern Kachchh are exposed in disconnected, topographically high grounds namely, Khadir, Bela and Chorar Islands. These islands exhibit wide lateral and vertical lithofacies variation including thickness, textural and mineral composition. The lithofacies of each island are described independently as under.

4.3 KHADIR ISLAND

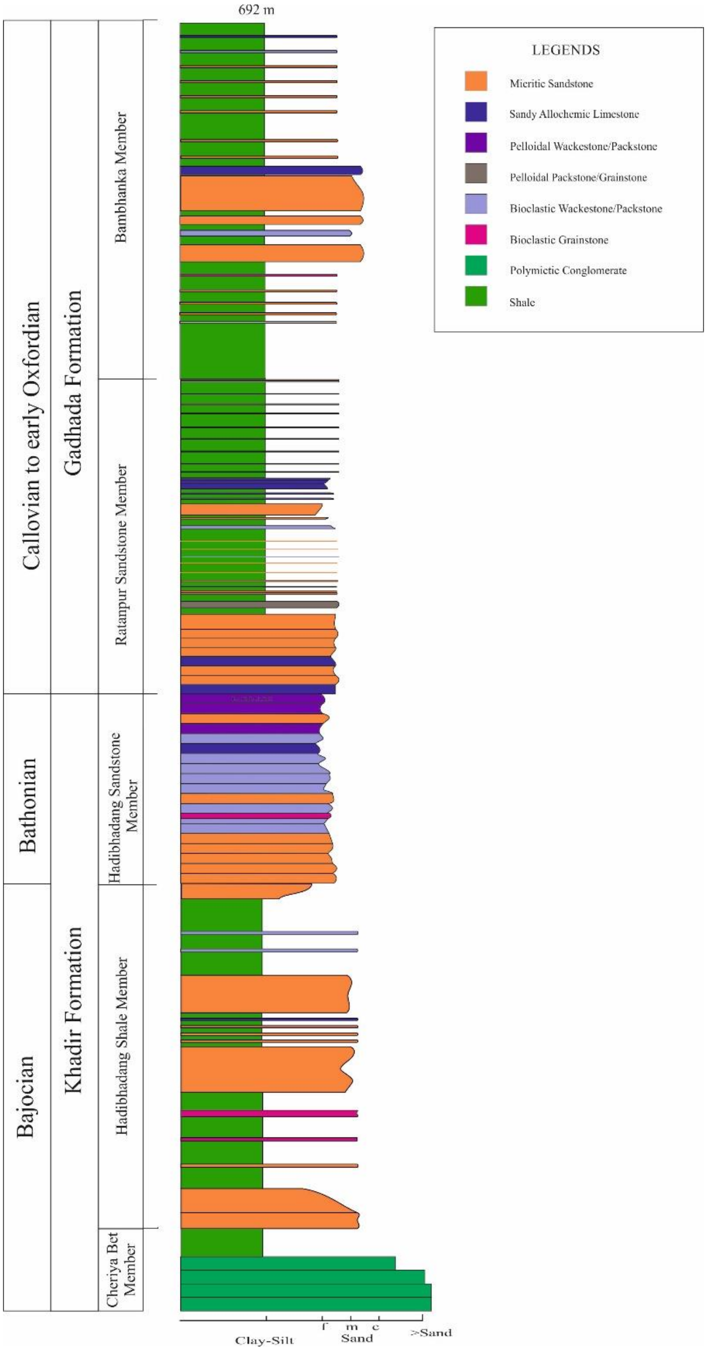

Fig. 4.1 Composite litholog of Khadir Island showing the representative lithofacies.

The Jurassic succession of Khadir Island comprises of 692 m thick clastic, non-clastic, and mixed siliciclastic-carbonate rocks exhibiting varying sedimentary structures such as cross-bedding, herringbone structure, graded bedding etc. which are broadly categorized into eight lithofacies. The Mesozoic succession in Khadir Island is characterized by mixed siliciclastic-carbonate rocks which shows wide lateral and vertical facies variation where lateral pinching out or inter-tonguing resulting from lateral facies mixing, or by sea-level changes or variation in the sediment supply (Flügel, 2010). The argillaceous content decreased towards the west where the western tip of the island is mostly arenaceous in nature. Detailed sedimentologic analysis of the Jurassic succession of Khadir Island has been carried out in light of these lateral and vertical variations. The nomenclature for the lithofacies is described based on Mount's Classification (1985) for mixed siliciclastic-carbonate rocks and Dunham's Classification (1962) for carbonate rocks. The sedimentological analysis revealed eight lithofacies which includes, bioclastic grainstone, bioclastic wakestone-packstone, peloidal wackestone-packstone, peloidal packstone-grainstone, micritic sandstone, sandy allochemic limestone, polymictic conglomerate and shales.

4.3.1 Bioclastic Grainstone

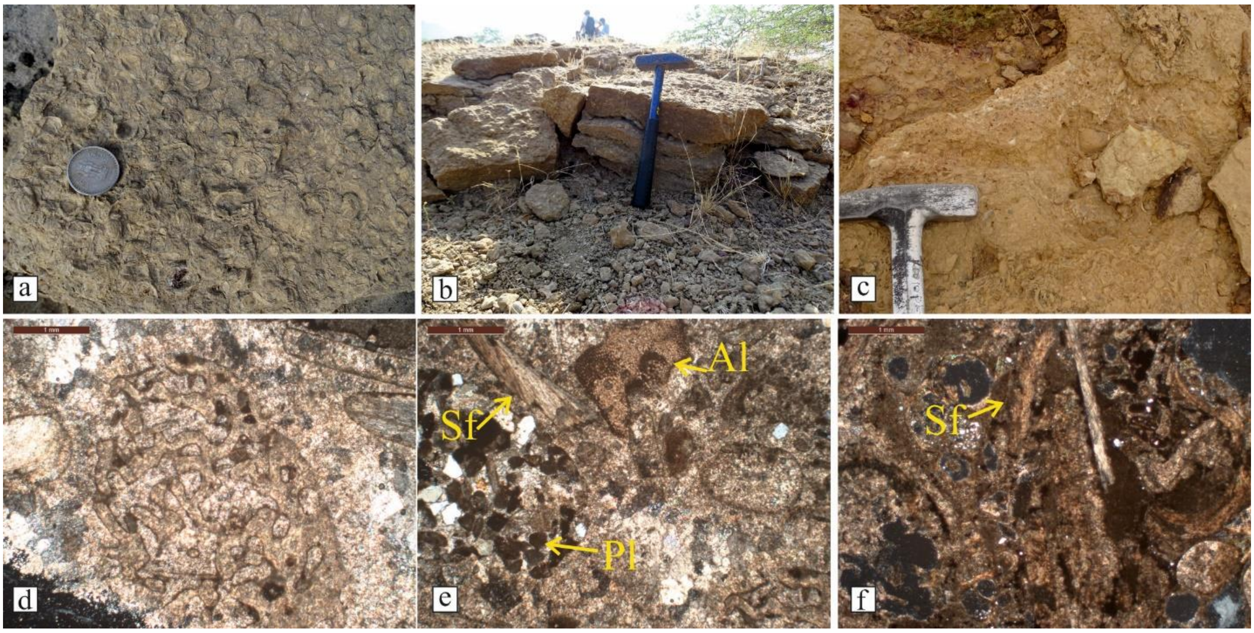

Plate 4.1 Field photographs of the bioclastic grainstone facies. (a), (b) and (c) exposed in the eastern part of Khadir Island near Umrapur village (d) Photomicrographs of bioclastic packstone grainstone facies with micritized bryozoan, (e) micritized algae (Al), bioclast/Shell fragments (Sf) and pellets (Pl) and (f) highly micritized bioclast.

Bioclastic grainstone is observed in Hadibhadang Shale and Hadibhadang Sandstone members (Plate 4.1a) of Khadir Formation. This facies is thinly bedded in nature either sandwich between shales or bioclastic packstone-wackestone suggesting a temporal change in the energy condition. This facies is also observed at the top near Amrapur village (Plate 4.1b and c). This facies is devoid of trace fossils and mainly exposed at the north facing vertical cliff of Khadir Island. The petrographic analysis shows that the facies is dominated by bioclast which include bryozoans (Plate 4.1d), pellets, shell fragments, and algae (Plate 4.1e and f) with a negligible amount of matrix (<5%). The bioclast are often sparitized with well-developed calcite crystals with a negligible amount of quartz grains.

4.3.2 Bioclastic Packstone-Wackestone Facies

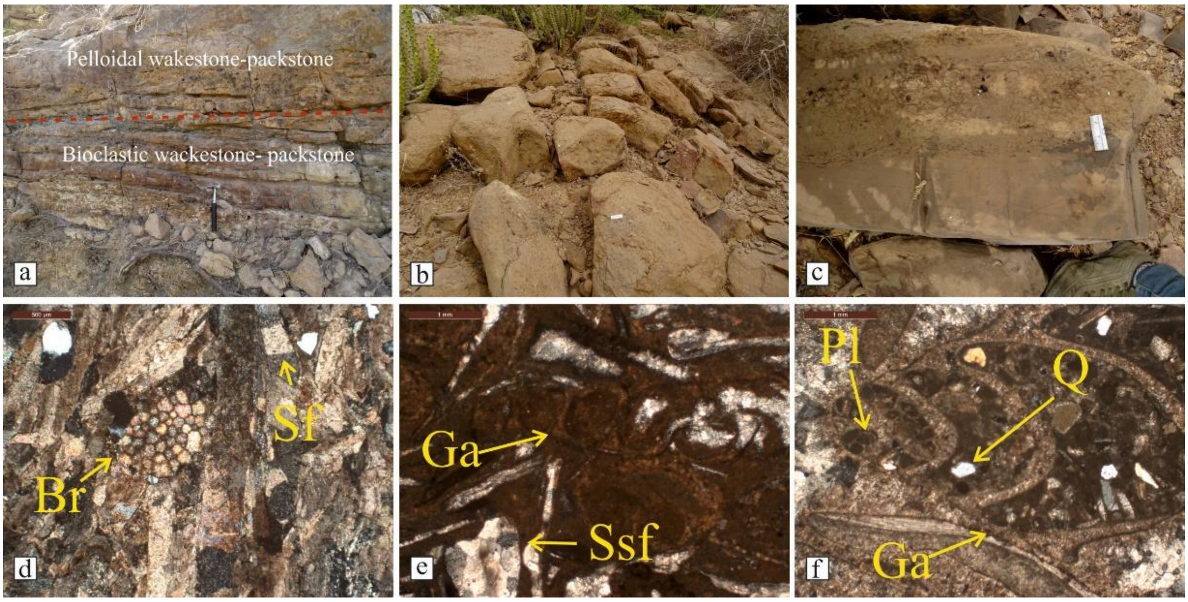

Plate 4.2(a) Bioclastic wakestone-packstone facies of Hadibhadang Sandstone Member exposed at the northern top of Khadir island, dotted line separating bioclastic wakestone-packstone and peloidal packstone-wakestone. (b) Bioclastic packstone-wackestone facies of Bambhanka Member exposed at Kakinda Bet and (c) Closed up view of event bands by the highly fossiliferous in nature. (d) Photomicrographs of bioclastic wakestone-packstone facies, bryozoans (Br) at the centre with abundant shell fragments (Sf). (e) Photomicrographs showing gastropods (Ga) and sparitised shell fragments (Ssf) in the micritic medium. (f) Photomicrographs showing highly micritized shell fragments and gastropods (Ga) where the internal cavities are filled with quartz (Q), pellets (Pl) and micrite.

Bioclastic packstone-wackestone facies is observed throughout the Jurassic succession as thin bands intercalated with shales with prominent band towards the top of Hadibhadang Sandstone Member of Khadir Formation (Plate 4.2) (a); Ratanpur Sandstone and Bambhanka members of Gadhada Formation (Plate 2.2b and c). It is characterized by yellowish thinly bedded limestone intercalated with shales in a shale-dominated sequence. It is characterized by yellowish in color and contains abundant body fossils including gastropods, bivalves, brachiopods, etc. Petrographic analysis shows abundant shell fragments in association with pellet, algae, forams, oncoids, echinoids spines, foraminifera with algae. Most of the shell fragments and algae are micritized due to digenetic processes. Bryozoan corals (Plate 2.2d) and gastropods are also observed (Plate 2.2 e and f).

4.3.3 Micritic Sandstone Facies

Micritic Sandstone facies is observed in all the members of both the Khadir and Gadhada formations (Plate 4.3a-e). This facies is highly variable in thickness from thinly bedded to thickly bedded in all the members. Thickly bedded micritic sandstones are generally friable in nature and show lenses of reworked sediments in the lower part of the Hadibhadang Shale, Hadibhadang Sandstone and Ratanpur Sandstone members. Sedimentary structures such as trough cross-bedding and planar beddings are observed within these facies. The cross-bedding in the friable micritic sandstone facies tends to be large in Hadibhadang Shale Member with a water escape structure while ferruginised and friable in Bambhanka Member.

The micritic sandstone facies is intensely bioturbated at varying intensity in different stratigraphic levels. Trace fossils such as *Arenicolites, Thalassinoides, Diplocraterion, Skolithos* and *Rhizocorallium* are observed in Hadibhadang Shale Member; *Arenicolites, Chondrites, Diplocraterion, Hillichnus, Laevicyclus, Lockeia, Monocraterion, Ophiomorpha, Planolites, Taenidium,* and *Thalassinoides* in Ratanpur Sandstone Member while *Curvolithus, Didymaulichnus, Gyrochorte, Laevicyclus, Monocraterion, Ophiomorpha, Ophiomorpha, Palaeophycus, Phycodes, Planolites, Protovirgularia, Rhizocorallium* and *Skolithos*, in Bambhanka Member of Gadhada Formation. Petrographic analysis shows siliciclastic content more than carbonate content. The siliciclastic component comprises about 80-85% quartz grains with feldspar and mica. The carbonate 15-20% component comprises mainly of micrite with occasional allochems in the form of shell fragments which are sparitized with algae (Plate 4.3g and h), pellets (Plate 4.3f) and ooids.

Plate 4.3 Micritic sandstone facies of Hadibhadang Shale Member exposed (a) at the base of the northern cliff of Khadir Island. (b) Close up view of micritic sandstone show cross-stratification and (c) containing fossil wood in Hadibhadang Shale Member of Khadir Island. (d) Highly friable micritic sandstone showing prominent cross stratification and parallel lamination in Ratanpur Sandstone Member of Khadir Island. (e) Thickly bedded ferruginous micritic sandstone of Bambhanka Member exposed at the southern slope of Kakinda Bet. (f) Photomicrographs of ferruginised micritic sandstone containing, fine, well sorted quartz grains and pellets. (g) Micritic sandstone with quartz grain with point contact and echinoid spines (Es). Photomicrographs of micritic sandstone with partially micritized algae (Al).

4.3.4 Pelloidal Wackestone-Packstone Facies

Pelloidal wackestone-packstone is observed at the top of Hadibhadang Sandstone Member of Khadir Formation (Plate 4.4a) and intercalated with shales in Ratanpur Sandstone Member of Gadhada Formation. This facies is marks the top of Hadibhadang Sandstone Member which is the facies equivalent of Raimalro limestone of the Patcham Island, sandy allochemic limestone in of the Bela Island and Coralline limestone of the Chorar Island. The carbonate grains/allochems include abundant pellets (Plate 4.4b and c) in association with forams, algae, shell fragments, and echinoids spines. The bioclast are intensely micritized making identification of bioclast cumbersome. The siliciclastic component comprises of approximately 5% quartz grains which are fine to medium, well sorted and subrounded in nature.

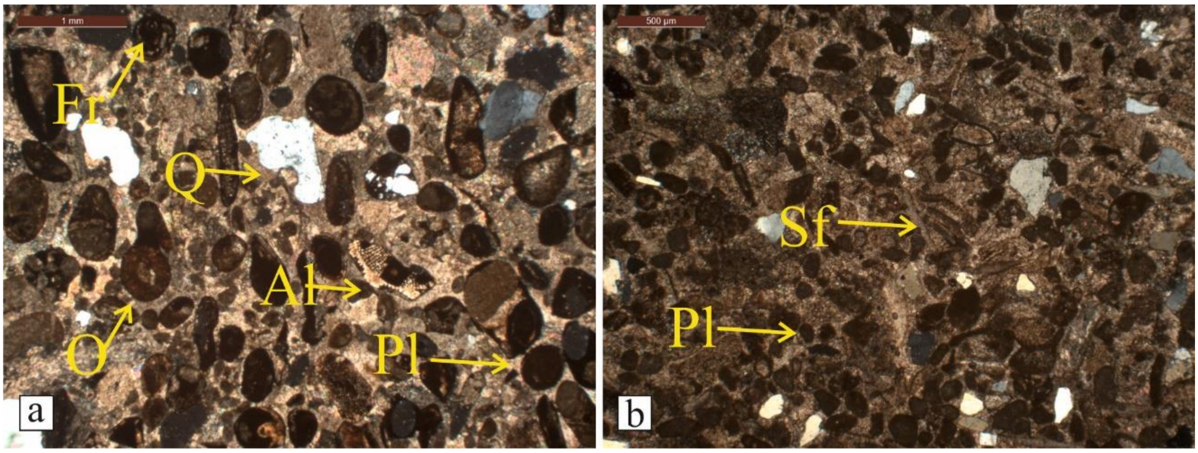

Plate 4.4(a) Photomicrographs of pelloidal wakestone-packstone containing algae (Aa), forams (Fr), onchoids (O), quartz (Q)and reworked pellets (Pl). (b) Photomicrographs of pelloidal wakestone-packstone containing abundant Pellets (Pl) and shell fragments (Sf) and algae.

4.3.5 Pelloidal Packstone-Grainstone facies

Plate 4.5(a) Field photograph of golden oolites in the form of pelloidal packstone-grainstone (b) Close up view of golden oolites observed in Ratanpur Sandstone Member on Khadir Island. (c) Photomicrographs of pelloidal packstone-grainstone with angular to subangular quartz (Q) grains with abundant pellets (Pl) and few shell fragments (Sf).

Pelloidal grainstone facies is observed in Ratanpur Sandstone Member of Gadhada Formation where they occur as thin bands in between shales as golden oolites (Plate 4.5a-b). It is characterized by bright yellow in color, thinly bedded, with parallel lamination. The petrographic analysis shows a grain-supported limestone where the carbonate components include allochems of about 75% consisting of abundant pellets with oolites, shell fragments, algae, forams, and gastropods cemented by micrite (20%). The siliciclastic component is dominantly comprising of medium grain, sub-angular and polycrystalline quartz of less than 5% (Plate 4.5c).

4.3.6 Polymictic conglomerate Facies

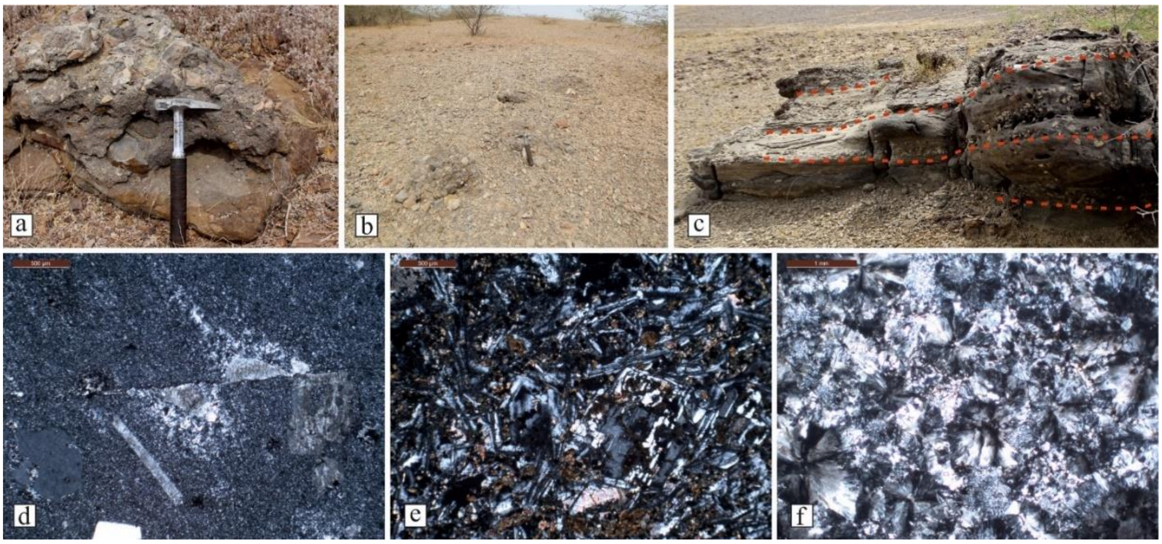

Plate 4.6(a) Close up view of matrix supported polymictic conglomerate. (b) Field photograph of the clast of weathered polymictic conglomerate exposed in Cheriya Bet. (c) Thickly bedded, showing fining upward sequence with conglomerate at the base Showing 4-5 cycles of fining upward sequence. (d) Photomicrographs of micro-faulting observed in quartz grains. (e) Photomicrographs of the clast of the conglomerate, basalt and (f) spherulite in rhyolite.

Polymictic conglomerate facies is observed in Cheriya Bet Conglomerate Member of Khadir Formation and is exposed extensively in a small islet called Cheriya Bet in the north of Khadir Island. It is also observed as pockets or lenses within the arenaceous bands of Hadibhadang shale and Hadibhadang Sandstone members of Khadir Formation. The pebbles and cobbles are matrix supported with no preferred orientation. These facies often occur as graded bedding of typical fining upwards with polymictic conglomerate at the base shows the fining upward and become sandy (Plate 4.6a and c). The conglomerate is highly faceted, multi-color clast ranging from brown, greenish, pink to black clast which includes dolerite, trachyte etc, cemented in sandy matrix (Plate 4.6b). The clast of the polymictic conglomerate comprises of syenite, chert, basalt (Plate 4.6c), and photomicrographs shows microfracture in quartz grains (Plate 4.6d), spherulite in rhyolite (Plate 4.6f).

4.3.7 Sandy allochemic Limestone Facies

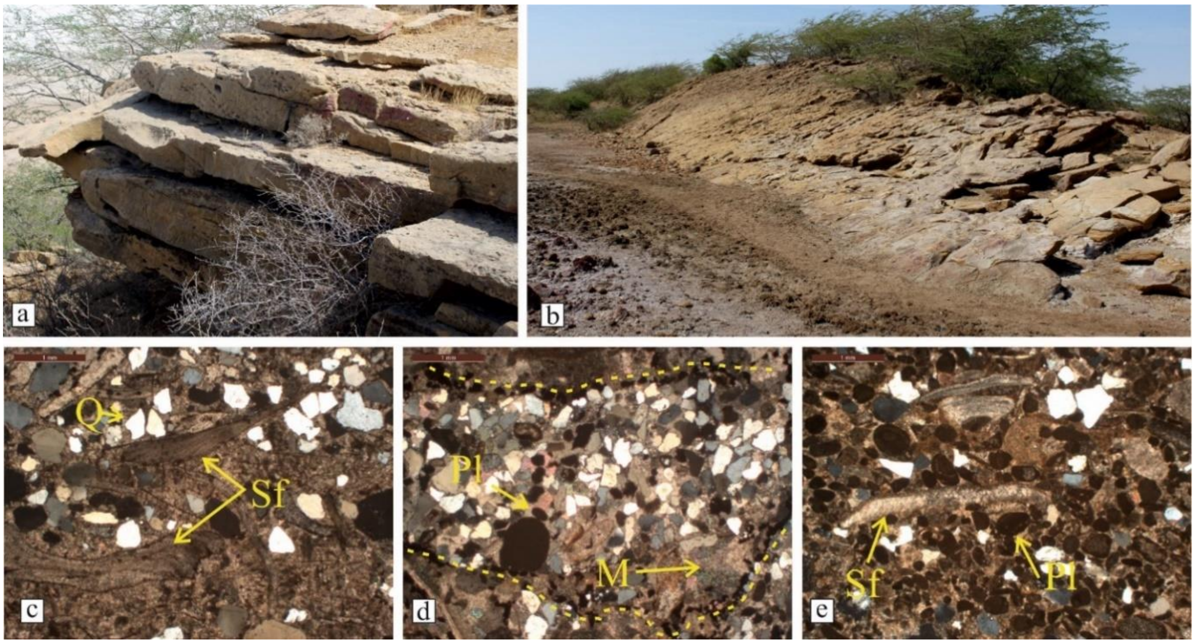

Plate 4.7 Sandy allochemic limestone facies observed in Ratanpur Sandstone Member at the top of the northern cliff of Khadir Island. (b) Field photograph of Sandy allochemic limestone of Bambhanka Member exposed at the southern tip of Khadir Island. (c) Photomicrographs of sandy allochemic limestone facies with abundant shell fragment (Sf) and angular to sub angular quartz (Q) grains. (d) Photomicrographs of sandy allochemic limestone facies showing along the transverse section of the tubes with distinct burrow fill and the host rock separated by distinct dotted burrow wall as shown in dash line; the burrow fill consists of micrite (M), quartz, and pellets (Pl). (e) Photomicrographs of sandy allochemic limestone facies with abundant pellets (Pl) and shell fragments (Sf).

Sandy allochemic limestone facies is observed as thickly bedded, highly bioturbated in Ratanpur Sandstone Member of Gadhada Formation (Plate 4.7a) while occur as thin bands in Hadibhadang Shale and Hadibhadang Sandstone members of Khadir Formation and Bambhanka Member of Gadhada (Plate 4.b) Formation. This facies is characterized by thickly to thinly bedded, greyish black to bright yellow colour containing abundant body fossils and trace fossils especially *Chondrites* in Ratanpur Sandstone Member. Other trace fossils include *Arenicolites, Chondrites, Curvolithus, Lockeia, Palaeophycus, Planolites, Ophiomorpha,* and *Thalassinoides.* The body fossils include ammonites, bivalves (*Alectryonia*), gastropods, etc. Petrographic analysis shows that the siliciclastic component is less than the carbonate component. The siliciclastic component (30-45%) comprises of very fine, well sorted, angular quartz grains having floating to point contact (Plate 4.7c). The higher siliciclastic content usually occurs in burrow fills. The carbonate component (Plate 4.7d) comprises of allochems which include echinoids spines, algae, forams, shell fragments, pellets constituting about 20-35% with up to 35% micrite (Plate 4.7e). The allochems are often highly disoriented, sparitized or micritized thereby masking the fabrics.

4.3.8 Shale Facies

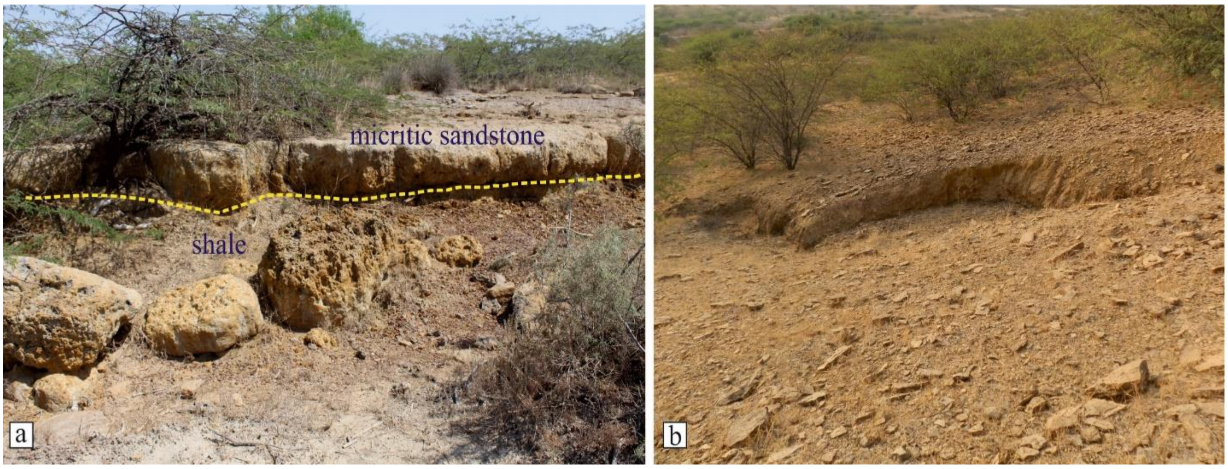

Plate 4.8 Greyish gypseous shale facies of Bambhanka Member observed at the (a) core below the hard band of highly weathered micritic sandstone and (b) the back slope of Kakinda bet

Shale facies is observed in almost all the members of Khadir and Gadhada formations. It shows variation is color, thickness and composition at both laterally and vertically. The shale tends to be silty at places and ranging in color from greyish to purple in Hadibhadang Shale Member. The ferruginous content is mainly due to igneous activity which is evident from the dolerite dyke at the base of the northern cliff of Hadibhadang Pir. Shale facies is laterally absent in Hadibhadang Sandstone Member from central to western part of the Island, while the thickness of shale facies increase in the eastern part of the Khadir Island. Shale facies of the upper part of the Ratanpur Sandstone Member contain thin bands of highly fossiliferous limestone (bioclastic packstone) with micritic sandstone containing abundant trace fossils. This facies is gypseous in nature at the base of Bambhanka Member which is exposed at the core of Kakinda bet (Plate 4.8a and b).

4.4 FACIES ASSOCIATION AND INTERPRETATION

The Mesozoic succession of Khadir Island shows unique facies characteristics with profound vertical and lateral facies variation. Lateral pinching or interfingering of argillaceous to arenaceous or non-clastic carbonates and vice versa is fairly common. These lithofacies may be grouped into lithofacies association or assemblages which are the particular characteristics of a particular depositional environment (Mial, 2000). These facies associations include alluvial fan-delta complex, and shoreface-offshore facies. The fan-delta complex facies is further divided into proximal fan-delta complex, prodelta and delta front sub-facies associations.

4.4.1 Fan-Delta Complex Facies Association

The term fan delta is introduced by Holmes, (1965) and is defined as an alluvial fan that has prograded to from adjacent highland/fault into a standing body of water, either a lake or sea. The principal criterion for the recognition of a fan-delta is the evidence of alluvial fan as the feeder system and its proximity to a highland or fault scarp is important (Nemec and Steel, 1988). The presence of angular polymictic conglomerate with polished surface/striations in Cheriya Bet Conglomerate suggest alluvial fan feeder system along a faulted scarp overlain by marine deposits of Hadibhadang Shale Member suggest alluvial fan-delta complex. The fan-delta complex facies association is further divided into three sub-facies association which include distal fan-delta complex, tide dominated prodelta and delta front sub-facies associations.

4.4.1.1 Distal Fan-Delta Complex

The polymictic conglomerate facies observed in Cheriya Bet Member of Khadir Formation, characterized by basement derived clast which includes syenite, basalt, etc. (Plate 4.6a-c) marks the beginning of sedimentation within the sub-basin. It is characterized by pebbles, wood fossils, cross-bedded sandstone and thinly laminated sandstone with cycles of fining upwards sequence (Plate 4.8c). The pebbles-boulders constituting the polymictic conglomerate facies often containing polished surface/striations suggesting a faulted zone. The poorly sorted, faceted pebble-boulder polymictic conglomerates with cycles of fining upward sequence suggest a short distance transport that dumped the detritus material. The poorly sorted with abundant gravel-size detritus suggest the progading fan-delta complex formed by short distance transport by short-lived feeder channels along the fault scarp.

4.4.1.2 Tide-Dominated Delta Front Facies Association

Fan delta front subfacies are the underwater part of alluvial fan delta complex, with extensive distribution, which often constitutes the main part of fan (Zhao et al., 2018). The Pale yellow to greyish thickly bedded, cross-bedded micritic sandstone with large wood fossils is envisaged to be deposited in delta front environment. This facies association is observed in Hadibhadang Shale in the western part of Khadir Island and Hadibhadang Sandstone members of Khadir Formation as well as the lower part of Ratanpur Sandstone Member Gadhada Formation. The linkage between pro-delta to delta front is observed at the foothills of Hadibhadang Pir as a coarsening upward transition of shale to micritic sandstone at the base of Hadibhadang Sandstone Member. This facies association forms the majority of the northern cliff section, the back slope as well as the western tip of Khadir Island. The thick micritic sandstone facies is characterized by well-sorted fine to medium quartz grains having point to floating contact and sedimentary structures such as planar cross-stratification and cross-bedding are observed. The micritic sandstone with lenses of polymictic conglomerate and abundant reworked materials suggests a to abundant sediment supply forming a prograding pro-delta-delta front environment.

The base of Ratanpur Sandstone Member of Gadhada Formation that overlain the top of Hadibhadang Sandstone Member is characterized by thin bands of sandy allochemic limestone and thick cross-bedded micritic sandstone marking the rejuvenation of sediments influx within the basin and are often bioturbated and ferruginised. The thickly bedded often contain lenses of polymictic conglomerate suggesting reworking of sediments. The presence of sedimentary structures such as ripple marks, cross-bedding, and herringbone structure indicates tide influences the delta front environment.

4.4.1.3 Tide-Dominated Prodelta Facies Association

The shale-dominated succession intercalated with thin bands of highly fossiliferous centimeters thick micritic sandstone, bioclastic wackestone/packstone and bioclastic grainstone suggest pro delta environment. These shale facies are often truncated by friable, cross-bedded, and thickly bedded micritic sandstone. The thick shale succession shows a greyish to brown color, containing abundant gastropods. The variation in the color of shale is due to the doleritic dyke passing through the shale. The greyish thickly bedded micritic sandstone sandwich between these shale facies of a pro-delta environment is envisaged to be bar deposits. These facies are characterized by moderately sorted fine to coarse grain with abundant polycrystalline clast and abundant rock fragments of the basement. It also contains sedimentary structures such as large cross-beddings and water escape structures. This facies association is observed in Hadibhadang Shale Member of Khadir Formation. Hadibhadang Shale Member of prodelta environment that overlain the distal fan-delta complex deposit of Cheriya Bet Conglomerate marks the initiation of marine sedimentation vis-à-vis marine encroachment into the sub-basin thus forming a prograding fan-delta complex (Holmes 1965; McPherson's et al. 1987; Nemec and Steel, 1988) setting.

4.4.2 Offshore-Shoreface Facies Association

The thick micritic sandstone of Hadibhadang Sandstone Member is suddenly overlain by non-clastic thinly bedded bioclastic wackestone/packstone and grainstone facies interrupted by thin bands of sandy allochemic limestone and micritic sandstone facies. Deposition of non-clastic sediments suggests the sediment supply ceased or starved sedimentation and initiation of precipitation of non-clastic carbonates during Bathonian transgression. The top of Hadibhadang Sandstone Member is characterized by oolitic-pelloidal packstone facies which is the facies variation of Raimalro Limestone. The reduction in the siliciclastic component and deposition of carbonate sediments on top of the delta front deposits suggest deepening of the sea level to offshore condition.

A thick succession of gypseous shale intercalated with thinly bedded pale yellow to reddish-brown micritic sandstone, bioclastic packstone/wackestone, and sandy allochemic limestone facies are envisaged to be deposited in a shoreface environment. This facies association is observed in the upper part of Ratanpur sandstone and Bambhanka members of Gadhada Formation. This facies association is a shale-dominated succession. The presence of gypsum within thick shale succession suggests a restricted, low-energy shallow marine environment. The bedded sandy allochemic limestone facies contain abundant body fossils like bivalve, *Alectryonia*, belemnites and ammonites. The thinly bedded bioclastic grainstone and bioclastic wackestone/packstone sandwich between the shale represents an event band suggesting a temporal change in energy condition.

4.5 BELA ISLAND

The Jurassic succession of Bela Island comprises 263m thick succession characterized by clastic, nonclastic, and mixed siliciclastic-carbonate rocks. The succession is best exposed along the north-flowing nonperennial river in the middle of Bela Island. The succession comprises of six lithofacies which include, micritic sandstone, allochemic sandstone, bioclastic packstone, sandy allochemic limestone, mudstone, and shale facies. The detailed description of each facies is given below.

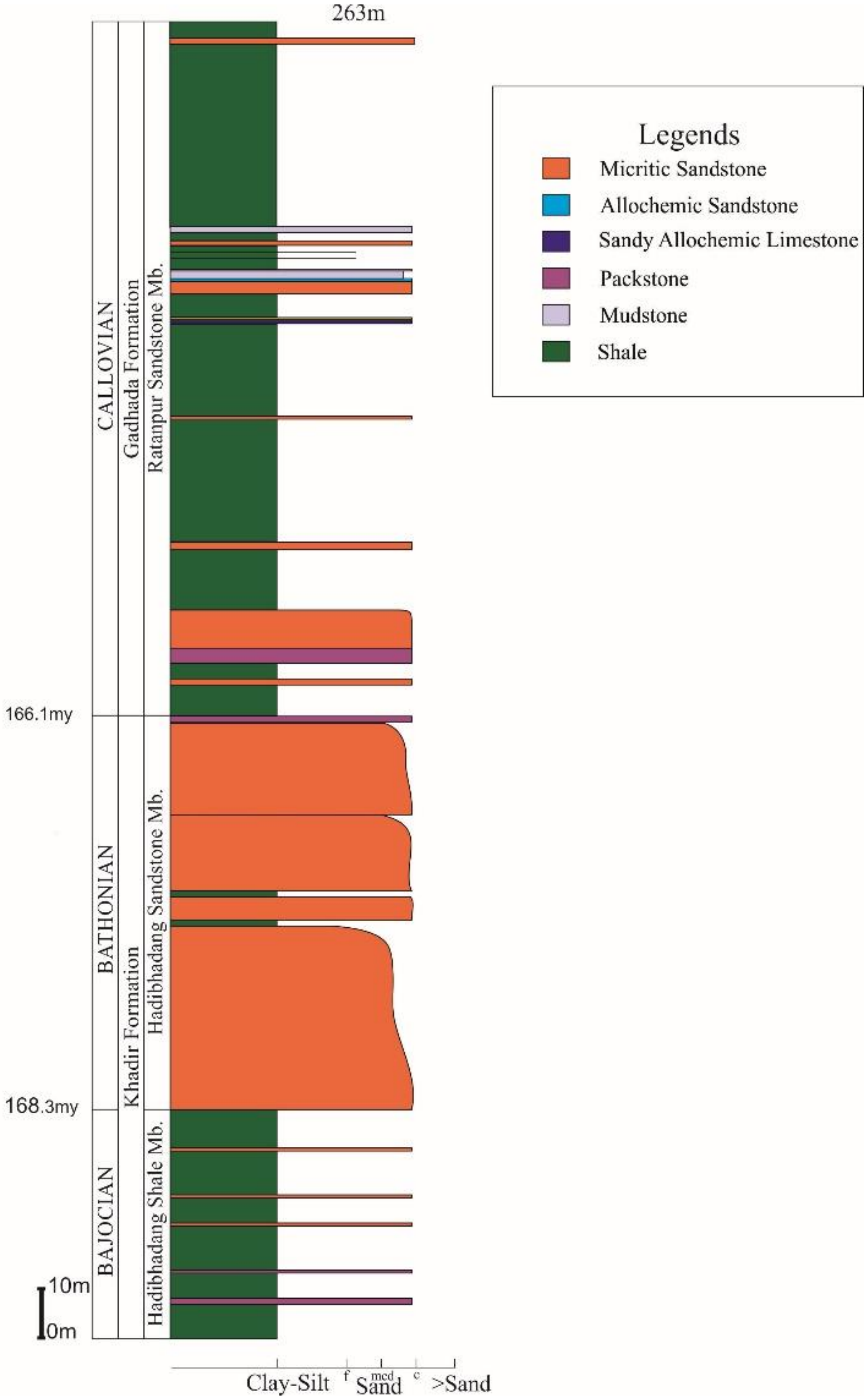

Fig. 4.2 Composite lithology of Bela Island showing the representative lithofacies

4.5.1 Allochemic Sandstone Facies

Allochemic sandstone facies is characterized by dirty yellow, brownish-colored, thickly bedded and is observed in Ratanpur Sandstone Member of Gadhada Formation exposed near Neelagar river in Kadir Island (Plate 4.10a) and eastern back slope of the Bela Island (Plate 4.9b). Petrographic studies show that siliciclastic components are more than carbonate components. The siliciclastic components (55-70%) is characterized as dominant by quartz grains which are sub-angular, very fine to medium-grained, and well sorted. Carbonate components (30-45%) include allochems such as bioclasts, algae, forams and pellets cemented by micrite (Plate 4.9c and d).

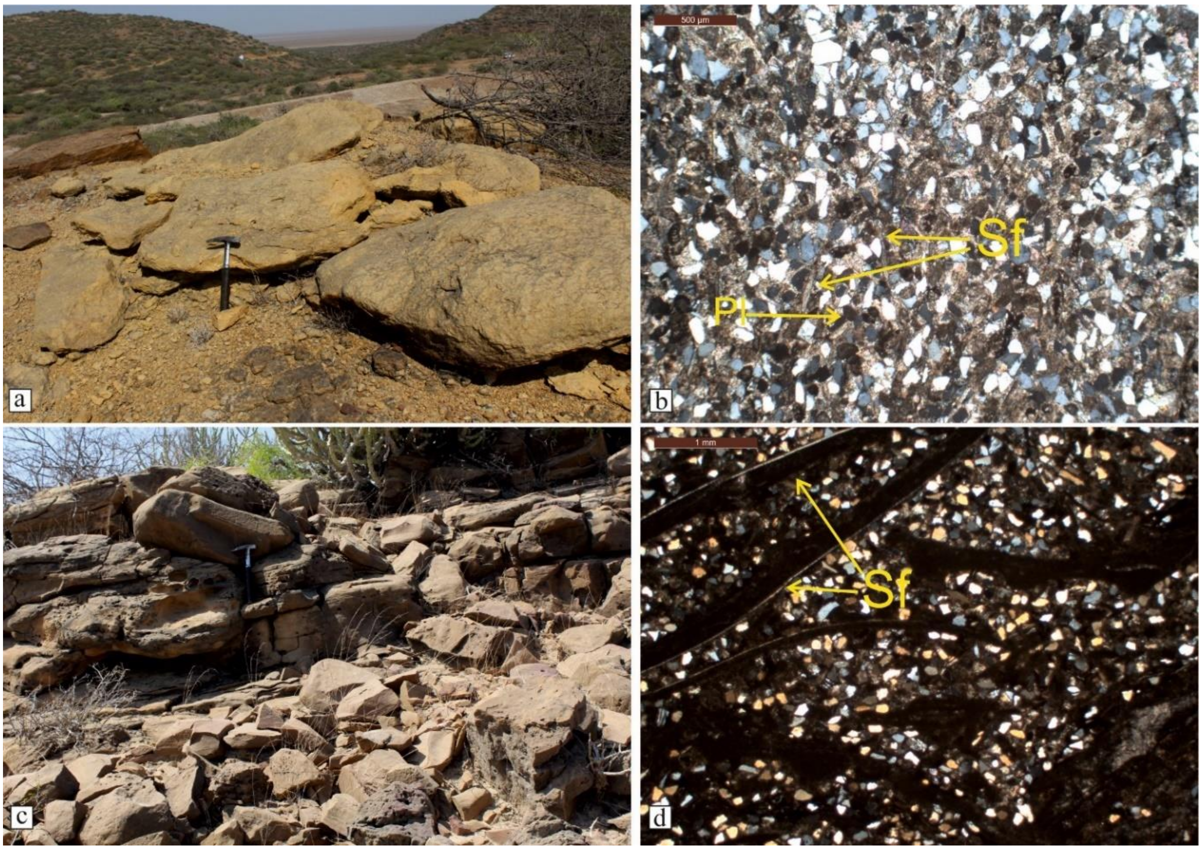

Plate 4.9(a) Allochemic sandstone facies of Ratanpur Sandstone Member exposed near Neelagar river b) Photomicrograph of allochemic sandstone showing pellets (Pl) with few shell fragments (Sf). (c) Thickly bedded allochemic sandstone facies of Ratanpur Sandstone Member exposed on the eastern back slope of the Bela Island and its photomicrograph showing (d) with well sorted, fine grained quartz grains and abundant shell fragments (Sf).

4.5.2 Bioclastic Packstone Facies

Packstone facies is observed in Hadibhadang Sandstone Member of Khadir Formation as well as in the Ratanpur Sandstone Member of Gadhada Formation. It is characterized by pale yellow to dark brown colour, highly fossiliferous thinly to thickly bedded. The thickness of bioclastic packstone at the top of Hadibhadang Sandstone Member increases towards the eastern side of Bela Island (Plate 4.10a and b) and is extensively exposed at the top of the western side of the Muwana Dome. Petrographic studies indicate that carbonate dominates in allochem (80-90%) such as shell fragments dominantly along with pellets, algae, intraclasts, bryozoans; ooids which are cemented by sparry calcite (Plate 4.10c and d) as well as it contains some amount of dolomite. The clasts are often sparitized and rounded due to diagenesis and transportation respectively.

Plate 4.10 Bioclastic packstone facies exposed at the top of eastern Bela Island at the top of Hadibhadang Sandstone Member. (b) Close up view of (a) showing abundant bivalve fossils. (c) Abundant well rounded bioclastic grains. (d) Photomicrograph shows highly sparitized shell fragment (Ssf) with micritized shell fragments boundaries.

4.5.3 Micritic Sandstone Facies

Micritic sandstone facies is observed in the Hadibhadang Sandstone Member of Khadir Formation and Ratanpur Sandstone Member of Gadhada Formation. It forms majority of the succession of Hadibhadang Sandstone Formation. It is characterized by pale yellow to grayish colors which are generally friable in nature and show sedimentary structures such as

Plate 4.11 Field photograph of micritic sandstone facies Ratanpur Sandstone Member exposed near Bela village showing plannar laminated sandstone sandwich between bedded micritic sandstone. (b) Field photograph of thickly bedded micritic sandstone of Hadibhadang Sandstone Member exposed in the north facing scarp of Bela Island. (c) Field photograph highly friable, trough cross-stratified micritic sandstone facies exposed in the north facing scarp of Bela Island. (d) Photomicrograph of micitic sandstone containing polycrystalline quartz (Pq) with sub-angular quartz grains floating in micrite (M).

parallel lamination (Plate 4.11a), cross-bedding (Plate 4.11b), trough cross stratification (Plate 4.11c) with soft sediment deformational structures. This facies shows wide variation in thickness where it is thickly bedded (Plate 4.11b) in Hadibhadang Sandstone Member while thickness decrease in upward, in Ratanpur Sandstone Member. Body fossils observed with these facies mainly comprise of bivalves in association with trace fossils such as

Diplocraterion, Helicolithus, Monocraterion, Ophiomorpha, Planolites, Rhizocorallium, Skolithos and *Thalassinoides.* Petrographic analysis shows siliciclastic components are more than carbonate components. It shows wide variation in a composition consisting of 55-85% quartz grains which are poorly sorted to well-sorted, very fine to coarse grain, and floating to point contact (Plate 4.11d). Feldspar comprises of up to 5%. The carbonate component constitutes up to 45% of the bulk volume characterized by allochems (5-10%) consisting of algae, pellets, shell fragments, forams etc. which are mostly micritized and sparitized at places. The allochems are cemented by micrite (20-35%).

4.5.4 Mudstone Facies

Mudstone facies is characterized by thinly bedded greyish white to a yellowish-white colour, intercalated with shale (Plate 4.12a) and is observed in the Ratanpur Sandstone Member of Gadhada Formation. This facies is exposed at the top of the back slop along Nilagar. It is also observed as thinly bedded, intercalated with shales along the road cut section between Dhabda and Bela village. It is also observed as thickly bedded dark grey in the back slope of eastern Bela Island (Plate 4.12b). Petrographic studies show that it is dominant by carbonate mud micrite with occasional sparite and negligible silicious content (Plate 4.12c-d).

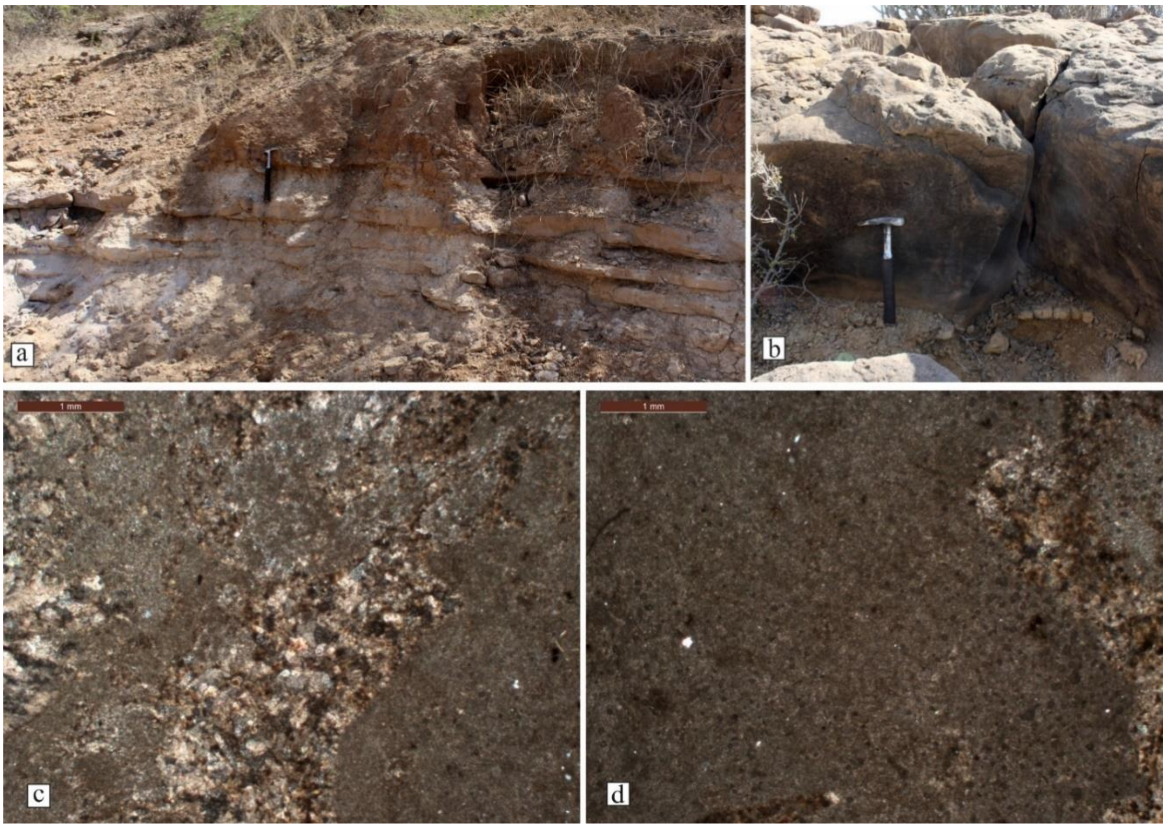

Plate 4.12(a) Thinly bedded mudstone facies intercalated with shale of Ratanpur Sandstone Member exposed near Dhabda village, East of Bela. (b) Thickly bedded mudstone of Ratanpur Sandstone Member exposed on the back slope of Eastern Bela. (c) Photomicrograph of well-developed sparite in mudstone facies. (d) Photomicrograph of mudstone with negligible siliceous content.

4.5.5 Sandy Allochemic Limestone Facies

Plate 4.13 (a) Field photograph of sandy allochemic limestone exposed on the back slope of Bela Island showing ripple marks, (b) Highly bioturbated sandy allochemic limestone including *Diplocraterion* (Di), *Skolithos* (Sk) and *Taenidium* (Ta) (c) Photomicrograph of sandy allochemic limestone with abundant pallets (Pl), shell fragments (Sf) and algae (Al). (d)) Photomicrograph of sandy allochemic limestone with abundant pallets, shell fragments (Sf) and well developed elliptical ooids (O) with distinct growth rings.

Sandy allochemic limestone facies is observed in Hadibhadang Sandstone Member and Ratanpur Sandstone Member of Khadir and Gadhada formations respectively. It is characterized by yellowish to dark red in color, shows varying thickness, straight crested or catenary ripple marks observed over the top (Plate 4.13a). It contains shell fragments of bivalve as body fossil and is preferentially bioturbated including ichnogenera such as *Arenicolites, Chondrites, Didymaulichnus, Diplocraterion, Hillichnus, Lockiea, Monocraterion, Ophiomorpha, Palaeophycus, Phycodes, Planolites, Protovirgularia, Rhizocorallium, Skolithos* and *Taenidium* (Plate 4.13b). Petrographic studies show that the carbonate components range 80-90% with dominant allochems (70%) such as pellets, shell fragments, forams, algae, (Plate 4.13c), ooids (Plate 4.13d), and brachiopod shell fragments. The shell fragments are highly micritized and sparitized and often show dolomitization. The siliciclastic components comprise dominantly of quartz which are poorly sorted, very fine to medium grained, sub-angular to sub-rounded.

4.5.6 Shale Facies

Shale facies is observed throughout the Bela Island succession, the lower part of the succession, i.e. Hadibhadang Shale Member is dominated by thick beds of shale (Plate 4.14a-b) intercalated with thin bands of micritic sandstone. Hadibhadang Sandstone Member comprises relatively thin bands of shale which are intercalated with packstone and micritic sandstone in lower and upper part of the sequence respectively, where sandstone dyke as well as baking effect due to intrusion is also observed. The thickness of this facies increased in Ratanpur Sandstone Member where it is intercalated with thin bands of allochemic sandstone, sandy allochemic limestone, micritic sandstone, mudstone and packstone facies.

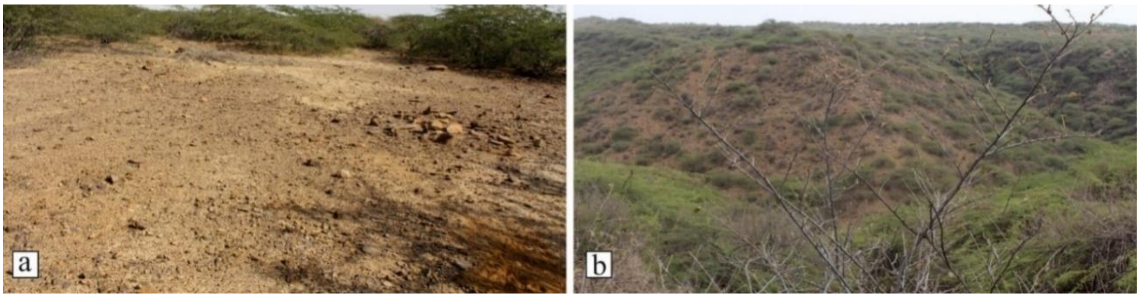

Plate 4.14 (a) Panoramic view of the north facing scarp of Bela Island (b) Shale facies of Hadibhadang Shale Member exposed at the base, showing flat topography of the north facing scarp of Bela Island

4.6 FACIES ASSOCIATION AND INTERPRETATION

4.6.1 Prodelta Lithofacies Association

The vertical succession of Hadibhadang Shale and Hadibhadang Sandstone members shows typical coarsening upward sequence of a deltaic deposits. The Hadibhadang Shale Member

(46m), characterized by thick shale with thin bands (~1 cm) of packstone and micritic sandstone exposed at the base of the northern escarpment of Bela Island. The thick shale facies represent a continuous rise in base level and the occurrence of cm thick packstone and micritic sandstone represents negligible sediment influx in low energy in pro-delta conditions.

4.6.2 Delta Front Lithofacies Association.

Hadibhadang Sandstone Member (78 m) of Bathonian age is comprised predominantly of thick-bedded micritic sandstone with thin shales. The thick-bedded micritic sandstone is characterized by pale yellow to grayish colors which are generally friable in nature and show sedimentary structures such as cross-bedding, parallel lamination with soft sediment deformational structures. Micritic sandstone is monodominant occasionally contains conglomeratic horizons and shows gradation with an initial coarsening upward then followed by fining upward sequence. The coarsening upward, thinly to thick-bedded micritic sandstone facies with negligible shale succession suggest active delta formation with abundant sediment supply in delta front setting. The upper fining upwards succession with the occurrences of thin layers of shale in between micritic sandstone represent wanning of delta front during Bathonian transgression.

4.6.3 Shoreface-Offshore Lithofacies Association

The bioclastic packstone facies characterized by abundant carbonate shell fragments, ooids, and intraclasts and dolomite grains at the top of micritic sandstone facies of delta front setting suggest a sudden increase in the sea level, The occurrence of well-developed bioclastic packstone with negligible clastic influx suggest shoreface-offshore conditions (Fürsich et al. 2001). The thick argillaceous succession intercalated with thin bands of micritic sandstone, packstone, sandy allochemic limestone, allochemic sandstone, and mudstone succession suggest low energy condition which allow settling of fine sediments interrupted by moderate energy condition. The occurrence of trough cross-bedded micritic sandstone and mega ripple structure suggests a sudden temporal increase in energy condition/storm condition. Thus, the shale-dominated succession suggests continuous sedimentation while the intercalated with thin bands of micritic sandstone packstone, sandy allochemic limestone, allochemic sandstone and mudstone suggest shoreface environment with temporal change in the sediment supply and energy condition of depositing medium.

4.6 CHORAR ISLAND

The Jurassic succession of Chorar Island is characterized by 109 m thick clastic, non-clastic and mixed siliciclastic carbonate sediments exhibiting both vertical and lateral variations in bed geometry, texture, structures and mineral compositions. The succession is well exposed in the core facing scarp of an elliptical dome near Aaval and is characterized by recurring micritic sandstone, allochemic sandstone, sandy allochemic limestone, sandy micrite, cross-bedded white sandstone, ferruginous sandstone, coralline limestone, mudstone and shales facies. The above lithofacies are briefly described below along with their field observation, petrographic characters and their stratigraphic position.

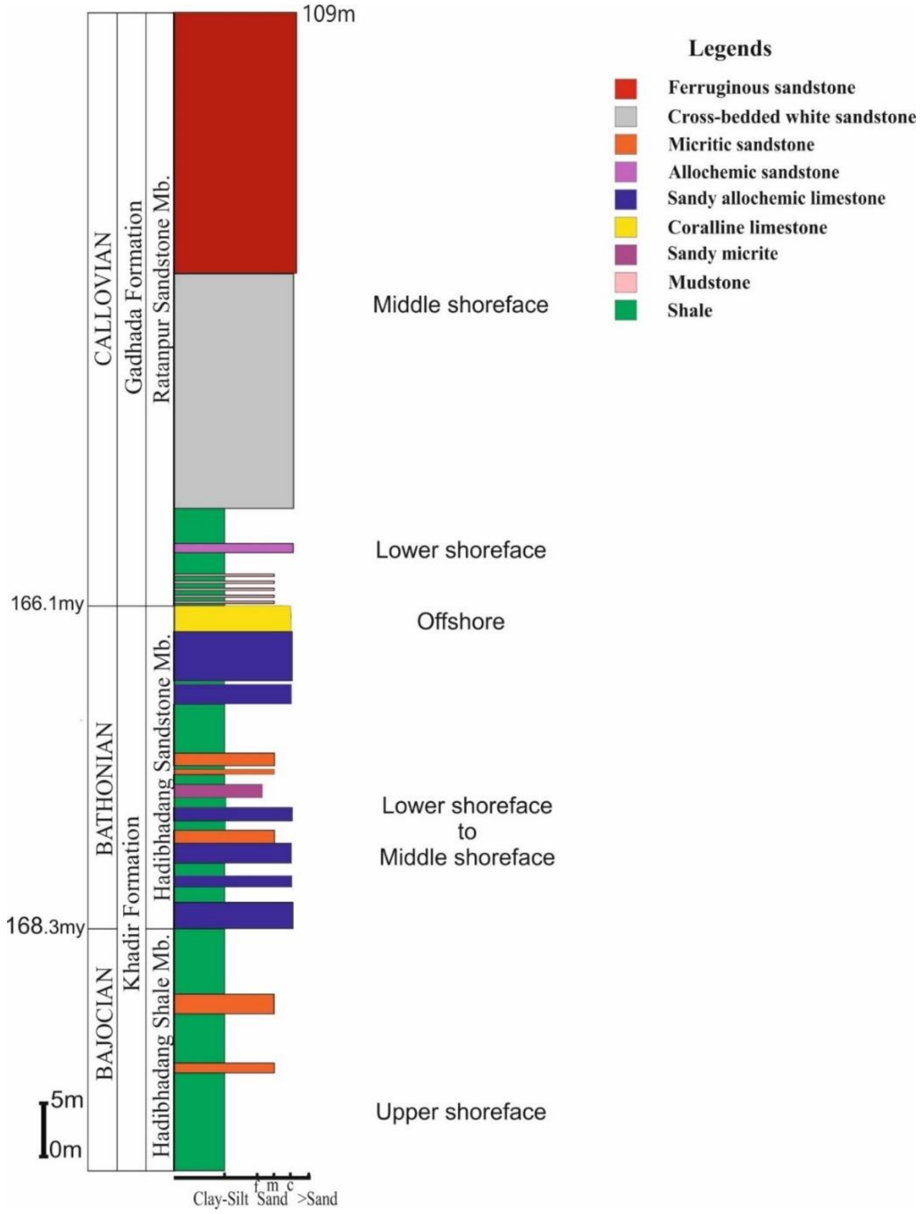

Fig. 4.3 Composite lithology of Chorar Island showing the representative lithofacies

4.6.1 Allochemic Sandstone Facies

Allochemic sandstone facies is characterized by thinly bedded, dirty yellow to brown color and intercalated with shales. It is highly fossiliferous in nature and contains abundant shells of *Trigonia* with fossils fragments which gradually grades into sandy allochemic limestone. Allochemic sandstone is observed in Hadibhadang Sandstone Member of Khadir Formation (Plate 4.15a) as well as in Ratanpur Sandstone Member of the Gadhada Formation (Plate 4.15c). Petrographic analysis of this allochemic sandstone shows that the siliciclastic component exceeds the carbonate component. The siliciclastic component comprises of 60% fine to medium quartz grains. The carbonate components comprise of allochems such as shell fragments, abundant pelloids and few foraminiferal tests, constituting about 30%; and 10% of micrite (Plate 4. 15b and c).

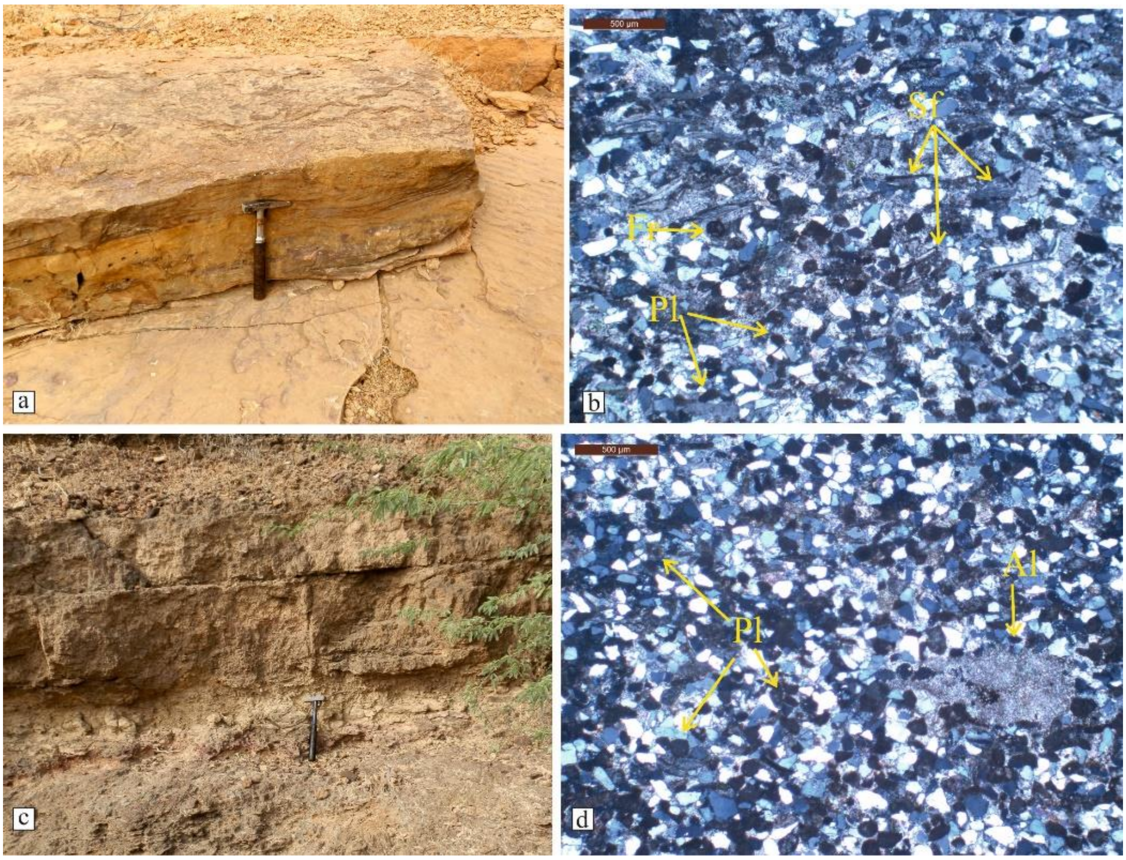

Plate 4.15 Allochemic Sandstone facies (a) Field photograph of thickly bedded allochemic limestone of Hadibhadang Sandstone Member. (b) Photomicrograph of allochemic sandstone containing abundant pellets (Pl), and shell fragments (Sf) with micrite (M) observed in Ratanpur Sandstone Member (c) Field photograph of allochemic sandstone of Ratanpur Sandstone Member intercalated with shales and its corresponding photomicrograph (d) containing algae (Al), abundant pellets (Pl) and micrite.

4.6.2 Coralline Limestone Facies

Coralline limestone is well cemented, dirty yellow color, well developed on a southern flank of the western side of Chorar Island. It attains a thickness of about 2.7 m and marks the upper limit of the Hadibhadang Sandstone Member of the Khadir Formation. It is highly fossiliferous containing abundant circular or mushroom-shaped corals (Plate 4.16 a-c) with bivalve shells. Corals are of large size and attain a diameter of more than one meter. The majority of the corals are diagenetically modified forming the large size of calcite as well as dolomite crystals (Plate 4.16f). Petrographically, coralline limestone shows about 5-10% of quartz grains which are generally fine grain, angular and poorly sorted. Allochems include algae, a few shells fragments and corals which had been completely sparitized, lost their internal structures, and obscured the skeletal-matrix boundary (Plate 4.16d). The carbonate (sparite and micrite) constitutes about 85-90%.

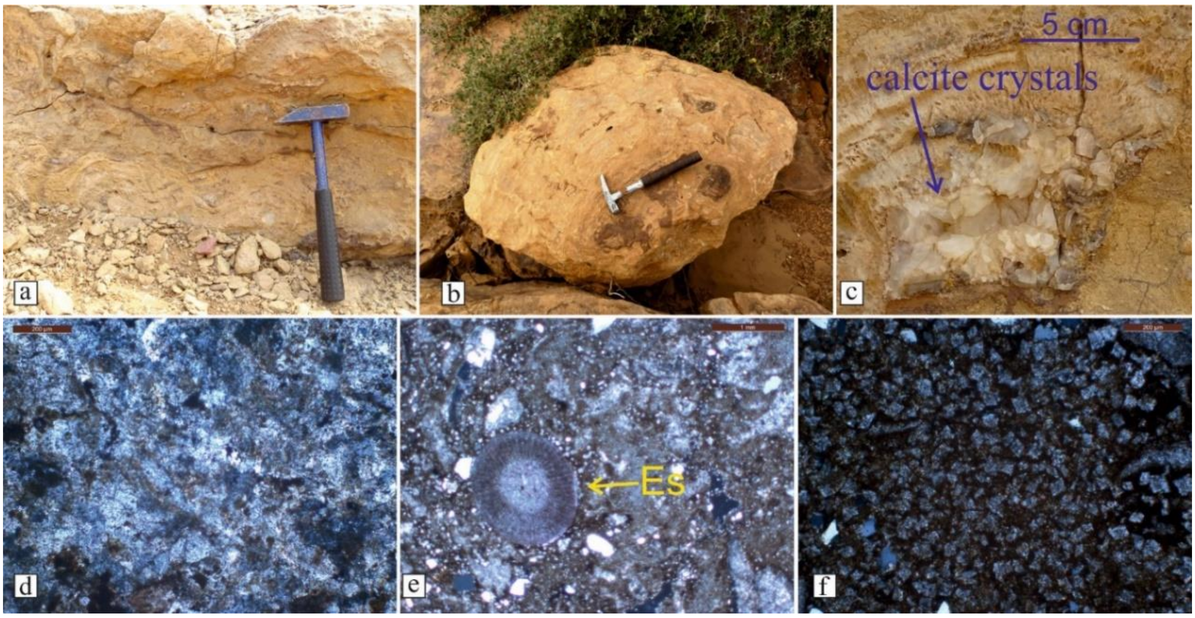

Plate 4.16 Coralline limestone facies(a) Vertical section of a recrystallized corals embedded in the host rock. (b) Semi-circular broken boulder of corals. (c) Vertical section of a highly recrystallized corals embedded in the host rock. (d) Photomicrograph of cross section of the corals. The internal structures are not preserved due to diagenetic effect of recrystallization. (e) Photomicrograph of the host rock containing abundant dolomite and well-preserved echinoids spine (Es). (f) Close up view of well-developed dolomite crystal.

4.6.3 Cross-bedded White Sandstone Facies

Cross-bedded white sandstone facies is characterized by white, dirty yellow to red-colored, soft, 22-25 m thick highly friable sandstone. It is horizontally stratified and shows faint planar-trough- cross-stratification which are often obscured due to its friable nature, diagenetic changes and weathering (Plate 4.17a). The cross-bedded white sandstone facies is often highly bioturbated by predominant *Skolithos* with few burrows of *Thalassinoides* and *Planolites.*

Plate 4.17 Cross-bedded white sandstone and ferruginous sandstone facies. (a) Thickly cross-bedded white sandstone facies of Ratanpur Sandstone Member expose on the south western margin of the Chorar Dome, showing faint mega trough cross-stratification. (b) Photomicrograph shows fine to medium grain, subrounded to rounded quartz in ferruginous matrix.

Petrographically, it shows mineralogically sub mature to immature and contains 50% to 70% quartz grains which are fine to coarse-grained, subrounded to rounded, moderately sorted (Plate 4.17b). The feldspars are completely weathered and altered to kaolin which had lost the bonding of grains and made sandstone friable. It contains high proportion of matrix being of more than 30%. Cross-bedded white sandstone is observed in Ratanpur Sandstone Member of Gadhada Formation and is extensively exposed in the southwestern margin of the Chorar Dome.

4.6.4 Ferruginous Sandstone Facies

Ferruginous sandstone facies characterized dark red to blackish/rusty brown in color showing sedimentary structures like cross-bedding, ripple marks and concretionary structures. It is coarse-grained containing abundant wood fossils with body fossils such as bivalve and gastropods, with few occurrences of trace fossils such as *Arenicolites, Diplocraterion,* *Planolites* and *Skolithos.* The high concentration of ferrous material form iron concretion and often obscured the primary sedimentary structures (4.18a).

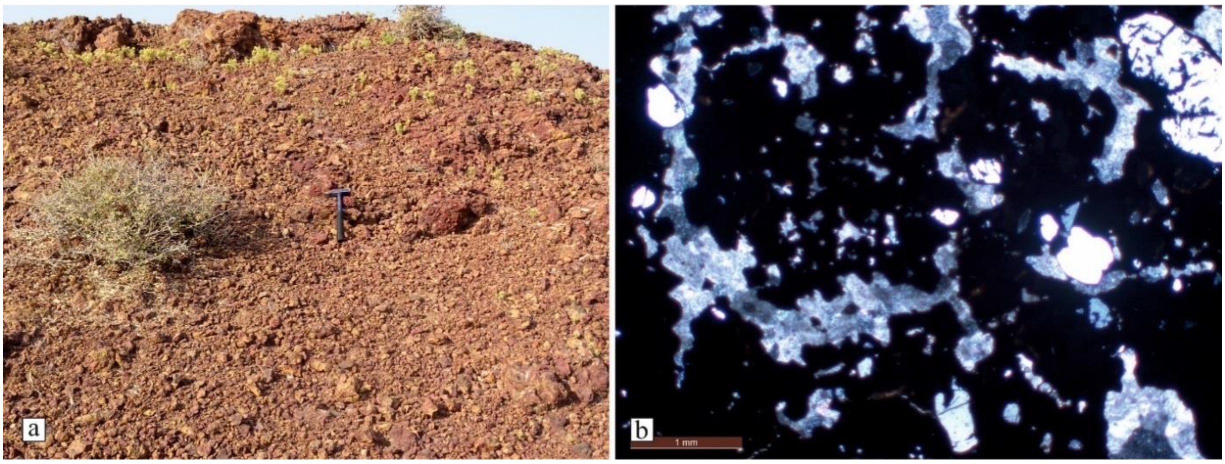

Plate 4.18 (a) Field photograph of ferruginous sandstone facies showing concretionary structures. (b) Photomicrograph of ferruginous sandstone facies where the clasts are masked by ferruginous matrix

Petrographic analysis shows a few patches of sparite cementing the quartz grains. However, due to the high concentration of ferruginous content, all the fabrics are masked (Plate 4.18b). This facies is observed in Ratanpur Sandstone Member of Gadhada Formation and is well exposed extensively along the periphery of the Chorar Dome and also form the youngest beds of the Jurassic sequence. The thickness of these facies is highly variable, 4-5 m thick in the western side and increases in the north, south; and eastern part of the Chorar Island where it comprises of three thick bands and attained a thickness of about 25 m.

4.6.5 Micritic Sandstone Facies

Micritic sandstone facies is observed Hadibhadang Shale and Hadibhadang Sandstone members of Khadir Formation and Ratanpur Sandstone Member of Gadhada Formation. Micritic sandstone facies is characterized by thickly to thinly bedded dirty yellow to dark brown color containing sedimentary structures such as cross-bedding (Plate 4.19a) often alternating with planar lamination, symmetrical (Plate 4.19c), asymmetrical, linguoid and micro ripples. It is unfossiliferous in Hadibhadang Shale Member but contains body fossils such as gastropods and broken fragments of bivalves and a few trace fossils in Hadibhadang Sandstone Member along with trace fossils such as *Palaeophycus, Thalassinoides*, *Halopoa* and *Skolithos.* Micritic Sandstone facies is observed Hadibhadang Shale and Hadibhadang

Sandstone members of Khadir Formation is the facies variant of the cross-bedded white sandstone of Ratanpur Sandstone Member of Gadhada Formation exposed in the south.

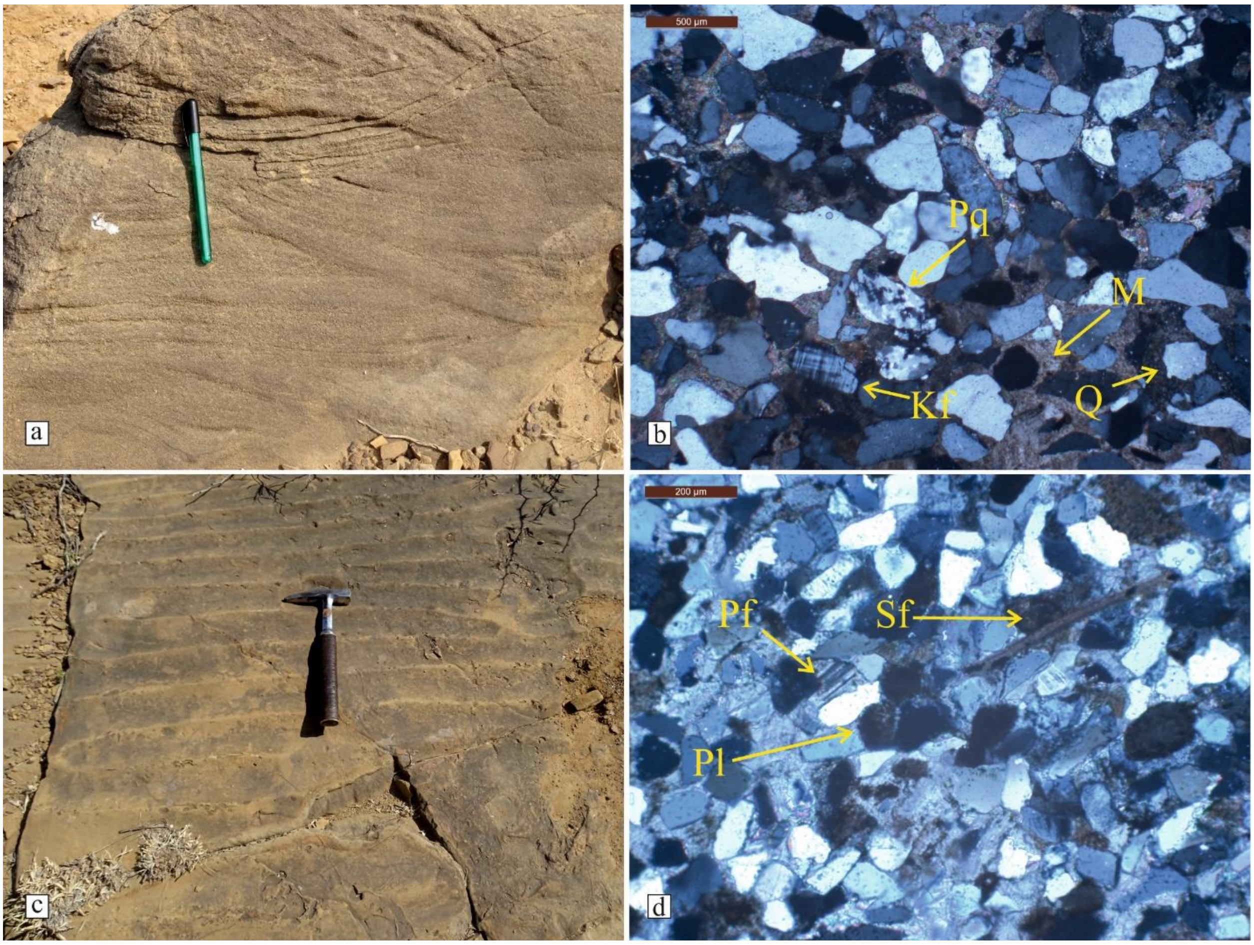

Plate 4.19 (a) Micritic sandstone facies of Hadibhadang Shale Member exposed at the base of Chorar Dome showing cross-stratification. (b) Photomicrograph of micritic sandstone with polycrystalline quartz (Pq), microcline (Kf) and sub rounded quartz (Q) grains. (c) Symmetrical ripples observed in micritic sandstone facies of Hadibhadang Sandstone Member. (d) Petrographic photograph of micritic sandstone with shell fragments (Sf), plagioclast feldspar (Pf) and with few occurrences of pellets (Pl).

Petrographic analyses of these facies show that siliciclastic proportion is more than the carbonate proportion. The siliciclastic component comprises of fine to coarse-grained which are angular, poorly sorted and a few grains of quartz are polycrystalline in nature. These clastic components are chiefly quartz (75%), feldspar (3%) and rock fragments (2%) (Plate 4.19b-d). The carbonate component consists of mostly micrite and allochem such as algae and few shell fragments (Plate 4.19d) which are now micritized. The carbonate as a whole constitutes about

20%. The siliciclastic component is cemented by calcareous cement which is replaced by ferruginous material at places.

4.6.6 Mudstone Facies

Mudstone is well cemented greyish to yellowish-brown in color, very fine-grained, and thinly bedded with fine lamination intercalated with shale (Plate 4.20a). This intercalation has overlain the coralline limestone and is exposed along the west-flowing, non-perennial fluvial channel of Chorar Dome near Aaval. It contains a few body fossils of bivalves. Petrographically, mudstone show micrite (lime mud) with micritized shell fragments of less than 5% (Plate 4.20b). This facies is observed only in Ratanpur Sandstone Member of Gadhada Formation.

Plate 4.20 Mudstone and sandy micrite facies. (a) Field photograph of mudstone facies of Ratanpur Sandstone Member occurring as thinly bedded hard band within shales. (b) Photomicrograph shows domination of the micritic material.

4.6.7 Sandy Micrite Facies

Sandy Micrite Facies is characterized by 2-3 m thick a dark-colored fine grain rock thickly bedded often devoid of sedimentary structures (Plate 4.21a). It lacks body and trace fossils. This facies is observed in Hadibhadang Sandstone Member of Khadir Formation. Petrographic analysis of sandy micrite shows that the siliciclastic proportion is less than that of carbonate proportion. The siliciclastic component comprises of 30-40% medium grain, poorly sorted, angular quartz grains floating in micrite cement (Plate 4.21b). The carbonate component (60-70%) comprises of allochems (10-20%), consisting of fragments of shells (gastropods, brachiopods), algae, pelloids, ooids; and micrite (40-50%) (Plate 4.21b).

Plate 4.21 (a) Field photograph of thickly bedded sandy micrite in Hadibhadang Sandstone Member of Khadir Formation exposed in the core of Chorar Dome (b) Photomicrograph of sandy micrite with sub-rounded to well-rounded quartz grain floating in micritic matrix.

4.6.8 Sandy Allochemic Limestone Facies

Sandy allochemic limestone facies is well developed in the Khadir Formation of the Chorar Island. It recurs throughout the succession and attain a maximum thickness of about 2.7 m. It is characterized by light yellow or dark brown in color, hard and massive, intercalated with thin calcareous shale and micritic sandstone (Plate 4.22a-c). It often consists of densely packed fossilized layer with soft sediment deformational structure (Plate 4.22b-c) and even grades to allochemic limestone. Sandy allochemic limestone facies is highly fossiliferous and contain abundant bivalves (*Alectryonia, Gervilla, Trigonia*), gastropods, echinoid spines and fragment of shells. It is often highly bioturbated. Petrographically, this facies shows that the carbonate components are more than the siliciclastic components. The carbonate components include both, allochems (40-60%) and micrite (15-20%). The allochems consist of shell fragments, calcareous algae (Plate 4.22d), peloids and ooids, echinoids spines, foraminiferal test and brachiopods. At some places, the micrites and shell fragments are diagenetically modified and form sparite to large size cleavable calcite crystals. Micrite is often replaced by ferruginous material at some places. The siliciclastic component (20-30%) comprises of fine to medium grains quartz which are angular, moderately sorted, along with muscovite (<1%) and some rock fragments. Sandy allochemic limestone facies is well developed in the Hadibhadang Sandstone Member of Khadir Formation.

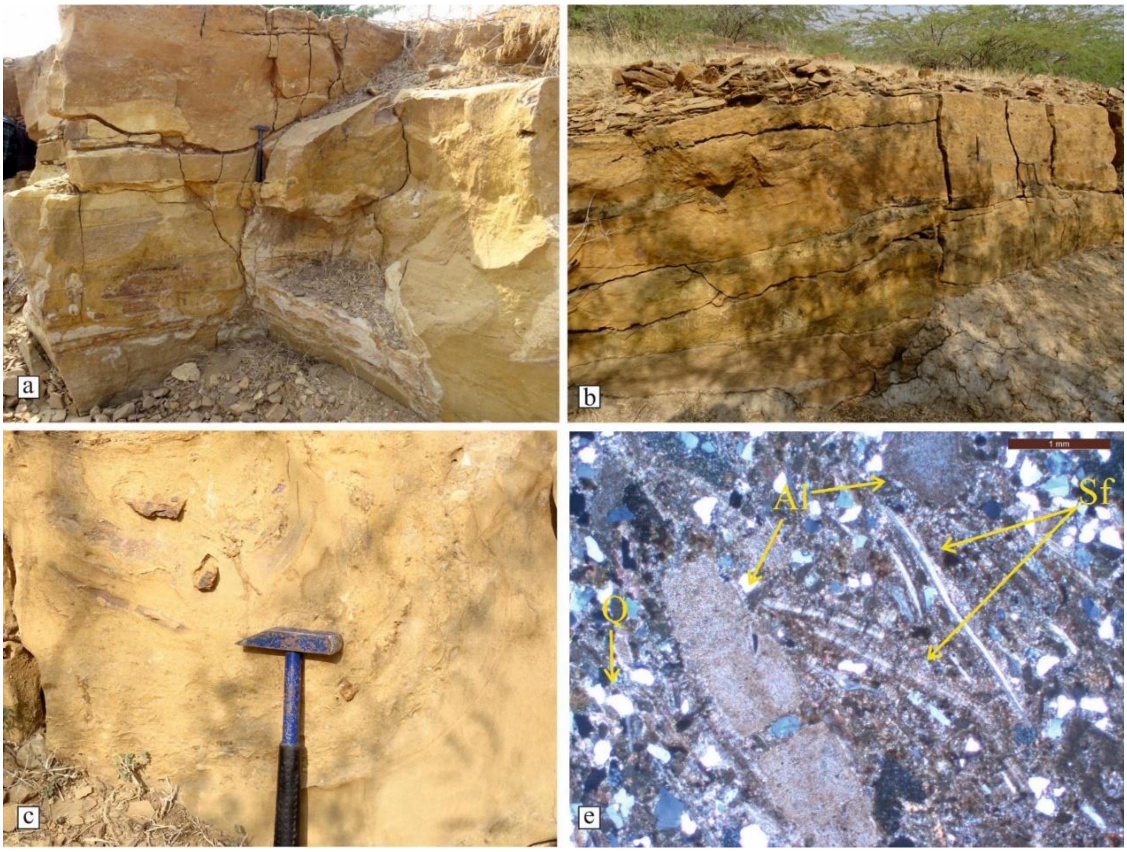

Plate 4.22 Sandy allochemic limestone (a) Field photograph of thickly bedded sandy allochemic limestone of Hadibhdang Sandstone Member exposed along the eastern side of Chorar Dome. (b) Thickly bedded sandy allochemic limestone with layers of sudden increase in chaotic fossil content representing sudden change in energy condition. (c) Close up view of liquefaction within the fossiliferous horizon. (d) Photomicrograph of sandy allochemic limestone showing abundant shell fragments (Sf) and well-developed algae (Al) with well sorted quartz (Q) grains.

4.6.9 Shale Facies

This facies is observed all through the succession and is best developed in the lower part of the succession along the core of an elliptical dome; it is characterized by thick, fissile variegated shales and often contains gypsum. The lower part of the succession is light grey, containing gypsum crystals and argillaceous material in Hadibhadang Shale Member where it attains maximum thickness. The shale becomes calcareous in nature, light to dirty yellow in color, moderately fissile and hard where it is associated with mixed siliciclastic-carbonate and coralline limestone of Hadibhadang Sandstone Member. Few ferruginous bands are seen where the argillaceous content is high (Plate 4.23). It can be distinguished from the upper argillaceous shales of Ratanpur sandstone Member based on fissility and hardness. This facies is observed in Hadibhadang Shale and Hadibhadang Sandstone members of Khadir Formation and Ratanpur Member of Gadhada Formation.

Plate 4.23 Field photograph of thick gypseous shale at the core of Chorar Dome.

4.7 FACIES ASSOCIATION AND INTERPRETATION

4.7.1 Shorface Lithofacies Association

The intercalated succession of shale, micritic sandstone, sandy allochemic limestone, mudstone, cross-bedded white sandstone, ferruginous sandstone and sandy micrite associated with sedimentary structures such as cross-bedding alternating with planar lamination symmetrical, asymmetrical, linguoid and micro ripples represent calm to agitated shoreface environment. The shale-dominated succession intercalated very thinly bedded micritic siltstone in Hadibhadang Shale Member represents calm energy condition. The sandy Allochemic limestone dominated succession intercalated with shale, micritic sandstone and sandy micrite along with sedimentary structures such as micro and macro ripples, cross-bedding with planar cross-stratification suggest fluctuating energy and sediment influx of middle to lower shoreface environment. Such facies association is observed in Hadibhadang Sandstone Member (Darngawn et al., 2019). The presence of allochems such as allochems like ooids, echinoid spines, foraminifera and brachiopods represent higher energy agitated conditions while the presence of highly disoriented and abundant shell fragments in the sandy allochemic limestone represents a storm condition in the middle shoreface environment. The intercalated succession of shale with thinly bedded mudstone overlain by allochemic sandstone suggests low energy condition lower shoreface environment interrupted by the sudden change in sediment influx and energy condition. The fine to coarse-grained sediments and presence of cross-bedding in cross-bedded white sandstone facies suggests high wave energy in middle shoreface environments. The highly ferruginous sandstone facies that overlain the cross-bedded white sandstone facies characterized by, fine to medium grain, angular, poorly sorted quartz grains with bivalves, gastropods wood fossils indicate further shallowing of the sea level in the middle shoreface environment (Patel et al., 2018).

4.7.2 Offshore Lithofacies Association

The dirty yellow, highly fossiliferous (bivalve shells), hard, thickly bedded coralline limestone facies containing large size corals is envisaged to be developed in offshore condition. The occurrences of well-developed large corals, and negligible siliciclastic components suggest calm conditions below storm weather wave base in offshore conditions (Patel et al., 2018).