SEQUENCE STRATIGRAPHY OF THE MIDDLE JURASSIC ROCKS OF PATCHAM ISLAND, KACHCHH, WESTERN INDIA: A SEDIMENTOLOGICAL AND ICHNOLOGICAL APPROACH

A THESIS SUBMITTED TO
THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

(GEOLOGY)

BY
JAQUILIN K. JOSEPH

DEPARTMENT OF GEOLOGY
FACULTY OF SCIENCE
THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA
VADODARA

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2013

Dedicated to My Maternal Uncle

Late Lalaji Kovilakam

CERTIFICATE

This is to certify that the following thesis entitled "Sequence stratigraphy of the Middle Jurassic rocks of Patcham Island, Kachchh, western India: a sedimentological and ichnological approach" which is submitted by me for the award of Ph.D comprises of the original research work carried out at the Department of Geology of the Maharaja Sayajirao University of Baroda.

This is also to certify that the content of the thesis have not been submitted for any other degree or diploma to any institute or university.

SATISH J. PATEL (GUIDE)

JAQUILIN K. JOSEPH (CANDIDATE)

PLACE: VADODARA

DATE:

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JAQUILIN K. JOSEPH

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CHAPTER-1
INTRODUCTION

1.1 STRATIGRAPHY AND STRATIGRAPHIC DISCIPLINES

"Stratigraphy" is the scientific discipline that deals with the layered rocks (strata) which obey Steno's Law of Superposition. It includes recognizing and interpreting the physical, biological and chemical property of the strata. It also defines a variety of stratigraphic surfaces and units on the basis of the vertical changes in these properties.

Over the past 50 years, apart from the "Lithostratigraphy" (changes in lithology) and "Biostratigraphy" (changes in fossil content), other properties of strata have been used to define new stratigraphic disciplines like "magnetostratigraphy" (changes in magnetic properties), "chemostratigraphy" (changes in chemical properties), "allostratigraphy" (based on discontinuities), "seismic stratigraphy" (change in seismic reflections) and "sequence stratigraphy" (changes in depositional trend). The vertical changes in the specific property of the strata recognize and delineate the stratigraphic surfaces within that discipline. Stratigraphy is useful to determine the time relationships of a stratigraphic succession by evaluating the stratigraphic boundaries in terms of their relationship to time. Each stratigraphic surface has a degree of diachroneity over its extent as it represents an episode of change over a discrete interval of time but those that have low diachroneity are the closest approximation to time surfaces and have the most utility for the construction of stratigraphic cross sections and time frameworks (Embry, 2009).

As already discussed the sequence stratigraphy, a branch of stratigraphy, is based on the changes in the depositional trends. The strength of the sequence stratigraphic method depends on the basic observations that include; the type of facies (lithofacies, biofacies, chemofacies); the nature of stratigraphic contacts (conformable, unconformable); the pattern of vertical stacking of facies (depositional trends); stratal terminations (lapouts); and stratal geometries (Fig. 1.1). Based on such observations, the delineation of the sequence stratigraphic surfaces and the identification of the stratigraphic system tracts are done in order to define the stratigraphic sequences (Catuneanu et al, 2009).

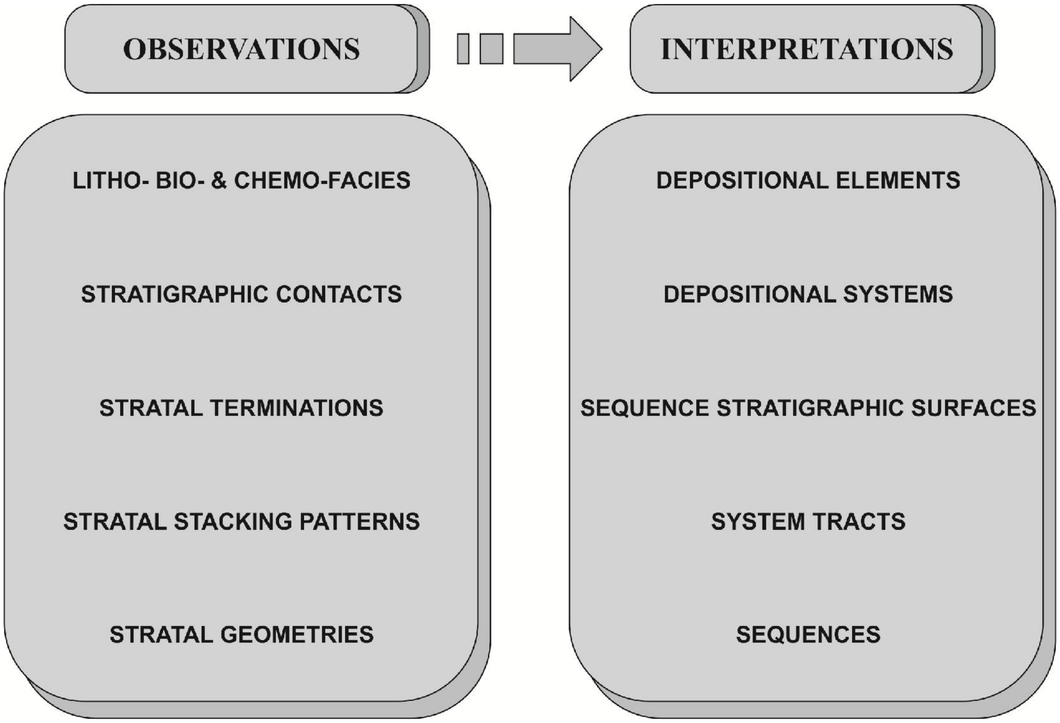


Figure-1.1 Basic observations and interpretations involved in the sequence stratigraphic methodology (Catuneanu et al, 2009).

1.1.1 HISTORICAL DEVELOPMENT OF SEQUENCE STRATIGRAPHY:

Sequence stratigraphy has been slowly evolving ever since the late 1700's when James Hutton (1726-1797), Father of Modern Geology, first described unconformity at Siccar Point in northern Scotland. Hutton (1785) recognized the importance of unconformities and the stratigraphic nature of the igneous rocks. William Smith observed the rock layers and realized that they were arranged in a predictable pattern and that the various strata could always be found in the same relative positions. Moreover, he noticed an easterly dip of the beds of rock small near the surface than after the Triassic rocks which gave Smith a testable hypothesis which he termed as "The Principle of Faunal Succession". He also measured and described the outcrop stratigraphy during an excavation in England. Charles Lyell (1830-1833) advocated the concept of "uniformitarian" which was later dubbed by William Whewell (1837) who coined the term in order to convey Hutton's sense of order and regularity in the operation of nature and Lyell's sense that there was a uniformity of rates of geological processes.

In 1892, Johannes Walther proposed a law known as "Walther's Law of Facies Succession" which states that the "facies adjacent to one another in a continuous vertical sequence also accumulates adjacent to one another laterally". Eliot Blackwelder (1909) published use of unconformities as the time markers and introduced concept of time represented by surfaces generated by erosional removal and sedimentary hiatus. In 1940, Amadeus Grabau proposed the "Pulsation Theory" which attributed the distribution of the Principal Stratigraphic Units to great rhythmic advances and regressions of the seas, which were in turn dependent on the restriction and expansion of the capacities of the ocean basin: eustatic control. He gave distinctive names to his pulsation systems, such as Taconian, Cambrian, Cambrovician, Skiddavian, Ordovician, Silurian and Siluronian and placed fourteen of these cycles in Paleozoic era, five in the Mesozoic era and two in the Cenozoic era. He thought that each pulsation had duration of about 30 million years and contraction of the seas at the close of each period leading to mark changes in the organisms. He related the distribution of lands and seas to pulsing transgressions and regressions and based on historical accidents rather than any natural principles, suggested it to be further controlled by the provincial warping movements accentuating or reversing the effects of the eustatic movements. His contribution brought about a three-dimensional attitude towards the sedimentary rock distribution, rather than emphasizing the faunal correlation of exposed rock sections. In 1917, Joseph Barrell interpreted the irregularities in the strata and stated that the geological processes are halting and discontinuous. He also stated the time-space distribution of the deposition and non-deposition i.e. the alternating rise and fall of the base-level.

Sequence stratigraphy began as a specific stratigraphic discipline almost 64 years ago when Sloss et al (1949) coined the term "sequence" for a stratigraphic unit bounded by large magnitude, regional unconformities which spanned most of North America. Rich (1951) termed the shape of the depositional surface at the scale of the entire continental margin as "Clinoform". Currently, the term "clinoform" denotes the strata packages with oblique internal layering, best imaged on seismic reflection profiles, where three geometric elements are recognized: (1) "topset," the most shallow and low-angle area, (2) "foreset," the central and steepest area, and (3) "bottomset," the flat area farther basinward (Mitchum et al., 1977). Sloss et al. (1949) gave the concept of a sequence and Wheeler (1958) has generated a chronostratigraphic chart introducing the time stratigraphy in the lineage of the stratigraphic development. Wheeler and Murray (1957) and Wheeler (1958, 1959, 1964a, 1964b) have published a series of papers which provided real world examples of unconformity-bounded sequence and used theoretical deduction to provide a foundation for the development of unconformities and consequent sequences. Thus, by the mid 1960’s the sequence stratigraphy was characterized by two separate approaches, one of data-driven empiricism (Sloss, 1963) and other of theoretical deduction (Wheeler, 1958), which ultimately suggested a sequence being a unit bounded by subaerial unconformities generated by base level fall (tectonic uplift or eustatic fall).

Suess (1906) was the first to propose that sea level changes could be global. Later Peter Vail and his colleagues from Exxon, in 1977, used regional seismic lines as their primary data base and demonstrated that the sedimentary record consists of a series of units that are bound mainly by unconformities. In addition to providing a new methodology and definition for sequence delineation, Vail et al (1977) also interpreted that the multitude of sequence boundaries on the seismic data from many parts of the world were generated primarily by eustatic sea level changes instead of tectonics as suggested earlier by Sloss (1963). Although Vail et al.'s classical study on seismic stratigraphy was published in 1977; the general geological community did not embrace it until the 1980's, especially after 1985 when Van Wagoner's classical abstract was released by Exxon for the mid-year SEPM meeting in Denver. Since the mid-1980's sequence stratigraphy revolutionized the study of sedimentary deposits. This approach predicts the distribution of facies based on the response of depositional environments to changes in base level. In the early 1990’s the emphasis from the sea level changes, changed to the relative sea level changes (Hunt and Tucker, 1992; Christie-Blick and Driscoll, 1995) that marked as the major turnaround in the sequence stratigraphy. This led to relate the key surfaces and the strata units between them to neutral curve of relative sea level changes that can accommodate any balance between the allogenic controls on accommodation (Catuneanu, 2006).

1.2 SEQUENCE STRATIGRAPHY

Sequence stratigraphy is the study of rock relationships with a time stratigraphic framework of repetitive, genetically related strata bounded by surface of erosion or non-deposition, or their correlative conformities (Posamentier et al, 1988; Van Wagoner, 1995). It places a strong emphasis on (i) facies analysis and (ii) contacts that represent the event-significant bounding surfaces marking the changes in sedimentation regimes. These contacts separate the packages of strata; characterized by specific depositional trends that include progradation, retrogradation, aggradation and downcutting; and are important for the regional correlation and for understanding the facies relationships within specific depositional systems. The depositional systems are the three-dimensional assemblages of process-related facies that record major palaeogeomorphic elements (Galloway 1989) and the linkage of the contemporaneous depositional systems form the subdivision of the sequence called as the system tracts (Brown and Fisher, 1977). These system tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces. The timing of system tracts is inferred relative to a curve that describes the base-level fluctuations at the shoreline.

However, there is diversification of approaches which resulted into several types of sequence, namely; (i) "Depositional Sequences", bounded by subaerial unconformities and their marine correlative conformities (e.g., Posamentier et al, 1988; Van Wagoner et al., 1988, 1990; Hunt and Tucker, 1992); (ii) "Genetic Stratigraphic Sequences", bounded by maximum flooding surfaces (Galloway, 1989); and (iii) "Transgressive-Regressive (T-R) Sequences", also referred to as T-R cycles, bounded by maximum regressive surfaces (Johnson and Murphy, 1984; Johnson et al, 1985). Embry and Johannessen (1992) recently redefined the T-R sequence as a unit bounded by composite surfaces that include the subaerial unconformity and the marine portion of the maximum regressive surface. The nomenclature of the system tracts and the timing of the sequence boundaries in relation to the base level change for each of these approaches are shown in Fig.1.2

Sequence stratigraphic application to a specific depositional system thus reveals the process of facies formation, facies relationships and facies cyclicity in response to the base level changes while at larger scales, the lateral correlation of the coeval depositional systems help in facies predictability based on the basin-wide nature of the allogenic controls on sedimentation (Catuneanu, 2006). In short, sequence stratigraphy is a methodology that employs stratal stacking patterns and key bounding surfaces to erect a framework in which the depositional facies of sedimentary environments can be mapped and interpreted in the context of palaeogeography (MacEachern et al, 2012). The sequence stratigraphic method therefore blends both autogenic (i.e. from within the system) and allogenic (i.e. from outside the system) processes into a unified model to explain the evolution and stratigraphic architecture of the sedimentary basins (Miall, 1995).

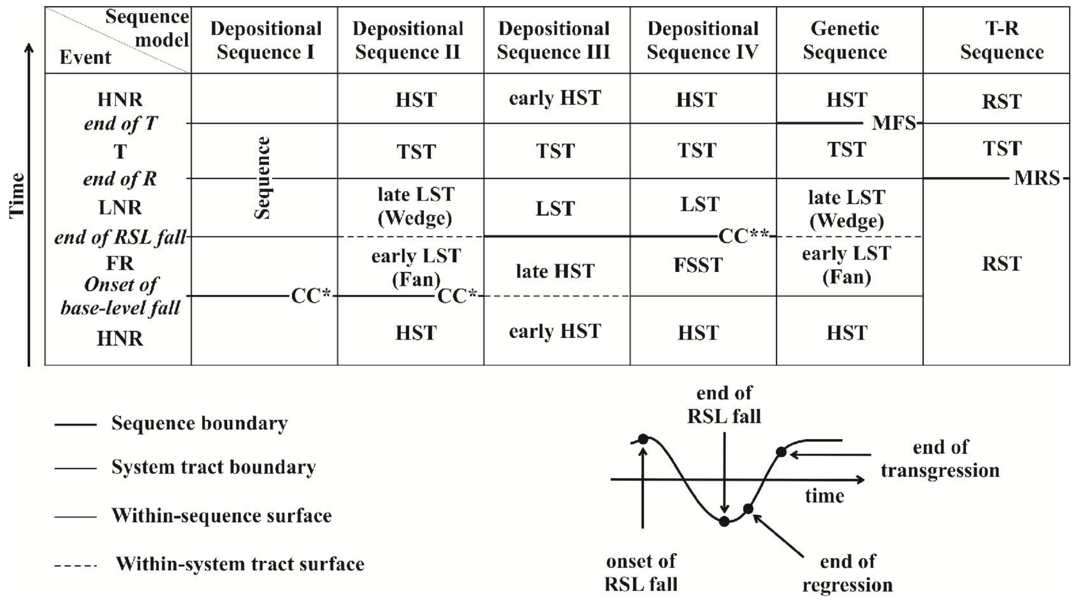


Figure-1.2 Nomenclature of system tracts, and timing of sequence boundaries for various stratigraphic approaches. HST-Highstand System Tract, TST-Transgressive System Tract, LST-Lowstand System Tract, FSST-Falling-stage system tract; CC*- Correlative conformity in the sense of Posamentier and Allen (1999); CC**- Correlative conformity in the sense of Hunt and Tucker (1992); MFS-Maximum flooding surface; MRS- Maximum regressive surface (Catuneanu et al, 2010).

1.2.1 ICHNOLOGY AND ITS APPLICATION TO SEQUENCE STRATIGRAPHY:

Ichnology is a branch of paleontology in geology that deals with the biogenic structures like burrows, borings, tracks and trails. There are two divisions of ichnology: *Paleoichnology*; that deals with the trace fossils and *Neoichnology*; that deals with the study of modern traces. Parallels between the modern traces and trace fossils help to decode the possible behaviour and anatomy of the trace maker.

Trace fossils represent both sedimentologic and palaeontologic entities and also represents a unique blending of potential environmental indicators in the rock record (Savrda, 1991; Pemberton et al, 2004). The trace fossil approach can also used as a proxy for benthic oxygenation for better understanding of palaeo-oceanographic conditions in ancient basins and the hydrocarbon-source potential of marine mudrocks deposited therein (Savrda, 2007). The characteristics that make trace fossils valuable in sedimentology and palaeoecology limit their usefulness in biostratigraphy. However, the trace fossil biostratigraphy can help to calibrate and test more traditional biostratigraphic methods when other biostratigraphic data are sparsely available (MacNaughton, 2007). The marine trace fossils are not generally considered to be useful as climatic indicators, because of their usually long stratigraphic ranges and similar ichnotaxa formed by a variety of different animals. However, recent analysis of a number of Tertiary and Pleistocene occurrence of echinoids and crustacean burrows, together with modern examples suggested a general model of climatic control for this geological interval; wherein three latitudinal zones in modern coastal and shoreface settings were recognized (Goldring et al, 2007).

Since early 1970s, the ichnology has become increasingly relevant to a variety of related disciplines including the palaeontology, sedimentology, palaeoecology, archaeology, geochemistry, diagenesis, sequence stratigraphy, petroleum reservoir characterization and petroleum explorations. In sequence stratigraphy, ichnology may be employed effectively (i) to aid in recognition of various types of discontinuities, (ii) to assist in their genetic interpretation, and (iii) to resolve surfaces of sequence stratigraphic significance through the recognition of substrate-controlled ichnofacies and through careful analysis of vertical ichnological successions (Pemberton and MacEachern, 1995). The substrate-controlled ichnofacies represents the time gaps between the original deposition of a unit and later superimposition of a post-depositional trace fossil assemblage while the vertical ichnological successions are analogous to facies successions. This ichnological procedure integrated with the sedimentologic and stratigraphic analyses result as a new and powerful approach to recognize and interpret the genetical sequence stratigraphic surfaces and their associated system tracts.

1.3 TECHNIQUES IN ICHNOLOGY

There are various techniques employed in ichnology that aid in recognizing various behavioural characteristics of organisms. An appropriate programme of sampling, description and analysis of an environment is planned according to the particular environmental conditions. In subaqueous environments, diving equipments and underwater cameras or televisions are required for the observing and recording of traces (Collinson & Thompson, 1982). Accordingly, the sampling, scaled photographic evidence, orientational data, preparing scaled diagrams and samples collecting and curetting are done. Other useful techniques includes box coring, vertical and horizontal peeling using the lacquer, polyester and expoxy resin, and the casting of burrows both subaerially and underwater. The experimental and neoichnological studies of modern sediments of both intertidal and subtidal settings include many classical studies using box-coring and serial sectioning or X-ray analysis (e.g. Reineck 1958; Howard & Reineck 1972). These techniques require improvements to closely relate to the depositional events in modern settings to facilitate more informed interpretation of ancient environments. Tomography of serial sections (e.g. Fu et al. 1994; Sutton et al. 2001), X-rays and NMR imaging techniques help in visualizing such data. The ecological studies of trace fossils of many environments are well established and ideal for incorporating in models of ancient depositional environments (e.g. Reed 2002; Mcllroy 2004). A new and the most exciting technology for ichnologists, developed by the petroleum industry, is the downhole imaging (FMI) that include the potential in recovery of image data down the full length of the well, which ultimately helped the sedimentologist/ichnologist to get rid of studying exclusively on the cored interval.

Many of these techniques are inappropriate while observing and recording the trace fossils on the outcrops. The techniques used in the outcrop studies include logging, drawing of scaled diagram, staining, and photographing. The burrows may be accentuated by wetting the rock surface or smearing it with small quantity of ink. Staining of fine grained carbonate and clay mineral rich rocks is done by organic dyes such as alizarin red, methylene blue, or Indian ink. The delicate scratches and fine detail should be whitened with powdered chalk or ammonium chloride and photographed in strong oblique light. The acetate peels are made by polishing a cut surface and etching it with the acid and then applying acetone and covering it with the acetate sheet which could be peeled off. The trace fossil blocks of ~1 cm thick can be subjected to X-radiography or infrared and ultraviolet photography. In the present study the graphic logs of the section including data on occurrence and distribution of the trace fossils are done. The observation and recording of trace fossils (as discussed in next section) along with the scaled diagram and photography is done. X-radiography of sample is also done which helped to identify the synaeresis cracks resembling trace fossils (Patel, 2013).

1.4 OBSERVATION AND RECORDING OF TRACE FOSSILS

Collinson and Thompson (1982) suggested three complementary ways to observe, describe, measure, and record the trace fossils effectively. These three ways include description of the morphology of preservation, the mode of preservation, and the position and process of preservation.

1.4.1 MORPHOLOGY OF PRESERVATION:

Accordingly, the identifiable trace of the organisms are categorized into eight shapes, i.e. (a) a single shape (e.g. a print or track made during locomotion); (b) several similar shapes repeated to form a pattern (e.g. a track made during locomotion); (c) a trail (i.e. a continuous groove made during locomotion); (d) a radially symmetrical shape developed in a horizontal plane (e.g. by the resting of a star fish); (e) a tunnel or shaft caused by a burrower seeking food and/or refuge; (f) a series of spreiten, which are U-shaped, closely related, concentric laminae caused by an animal shifting the location of its burrow as it grows or moves upwards, downwards, forwards and backwards by excavating and backfilling; (g) a pouch shape, for example caused by the resting of bivalves; (h) a network pattern.

1.4.2 MODE OF PRESERVATION:

The mode of preservation of the trace fossils are identified either as cast or mould. The fill of the burrow may be active (e.g. backfilling action of a burrower) or passive (i.e. by normal sedimentation). Moreover, whether the trace fossils are preserved as diagenetic concretions should also be noted. Trace fossils like *Chondrites, Rhizocorallium, Thalassinoides* and *Ophiomorpha* are often preserved as the calcite and siderite nodules in shale or limonite nodules in sand while the small diameter burrows like crustaceans are often preserved in pyrite which oxidizes to red-brown goethite, in flint or chert (Collinson and Thompson, 1982).

1.4.3 POSITION AND PROCESS OF PRESERVATION:

The Mode of occurrence of the trace fossils is usually defined according to the position of the structure on or within the stratum, or relative to the position of the structure (Buatois and Mángano, 2011). It is preserved as epichnial, hypichnial, exichnial or Endichnial (Martinson, 1970) or can be derived (i.e. preserved by burial following erosion). In order to understand the process of preservation in epichnial traces (on top of the casting medium), the composition of the trace and the marks (if any on the top or bottom of the trace) are noted. If a hypichnial trace (on bottom of the casting medium) is preserved then it is observed whether it shows any evidence of sediment-water interface or is only the deformed sub-interface laminae. Whether the trace is preserved at sediment-sediment interface (at a concealed junction); what the overlying and underlying composition is; and whether the laminae of the overlying or underlying beds are deformed, should be observed carefully. In an exichnial trace (outside the main body of the casting medium) the lithology of the trace is observed as isolated in a different lithology; a sharp upward termination of such traces may be indicative of the connection of the burrow fill to a bed removed by the erosion at present. While in the endichnial trace (internal position with the main body of the casting medium), whether the trace show bioturbated texture (very densely distributed and interpenetrating burrow) or are mottled burrow (common but distinct burrows) are noted. Along with these, the relief (e.g. full-relief); composition (with respect to the body of the cast); lining (layers of mucus and/or faecal pellets made of mud); and internal structures (e.g. spreiten) has to be well observed and recorded.

The derived trace fossils are those that after burrowing are eroded and winnowed leaving the mucus-bound burrow linings as sediment-filled gloves which are covered later by possibly different sediments. Alternatively currents may also scour out the burrows formed in mud and fill them with sand later. Bored pebbles and pieces of bored wood may be reworked as clasts into younger sediment.

1.5 TRACE FOSSILS IN CLASTIC VERSUS NON-CLASTIC SEDIMENTS

Body fossil are well preserved and recorded from the non-clastic (i.e. carbonate) rocks while they are poorly preserved in the clastic rocks, owing to higher porosity. However, the trace fossils are best preserved in the clastics and are inconspicuous and difficult to study in non-clastic sediments. The grain size and the depositional facies of the siliciclastic sediments contribute for the favourable preservation of the trace fossils in the siliciclasts. Even at greater depths the siliciclasts experience negligible overburden pressure, lesser reduction in intergranular space during compaction, and retain their original volume (especially textural property) with less altered size and shape.

Whereas, in carbonate rocks, the preservation of the trace fossils is largely dependable on the following conditions: (a) substrate mineralogy and mean grain size of sediments; (b) Depositional mode (continuous or discontinuous); (c) Carbonate susceptibility to early and late diagenetic modifications; (d) subjection to wide variety of microfacies and several sub-environmental geochemical features; (e) volume reduction or compaction of carbonates during burial process; (f) solution activity (fabric or non-fabric selective solutions altering or destroying the trace). Therefore, trace fossil studies in carbonate sediments are restricted to few in numbers compared to the siliciclasts.

1.6 STUDY AREA

The Kachchh basin is situated at the western margin of the Indian plate (Biswas 1982) opening into the so-called Malagassy gulf, southern extension of the Tethyan Ocean (Fürsich et al 2004), wherein the sedimentation started in the Bajocian or possibly Alenian time (Pandey and Dave, 1993) during the Jurassic period. These early sediments are well exposed at the islands bordering the south of the Great Rann of Kachchh (Biswas, 1977). The study area, Patcham Island is the westernmost island in the Kachchh island belt region of Gujarat, western India (Fig. 1.3.). It is situated at 60 km north of Bhuj city, between 23° 43' 43" to 24° 0' 22" N latitudes and 69° 40' 00" to 69° 58' 40" E longitudes and covers approximately ~550 sq. km. The study area also included Kuar bet, a small islet that situated 2 km northwest of Patcham Island, lies between 23^0 58′ 30″ to 24^0 03′ 30″ N latitudes and 69^0 42′ 00″ to 69^0 45′ 30″ E longitudes. The present study is carried out through different traverses in following twelve localities: (1) Kuar bet, (2) Chhappar Bet, (3) Dingy hill, (4) Kuran village, (5) Babia cliff, (6) Raimalro hill (7) Dhorawar village, (8) Paiya village, (9) Tuga village, (10) Juna village, (11) Sadhara dome, and (12) Modar Hill (Fig.1.3).

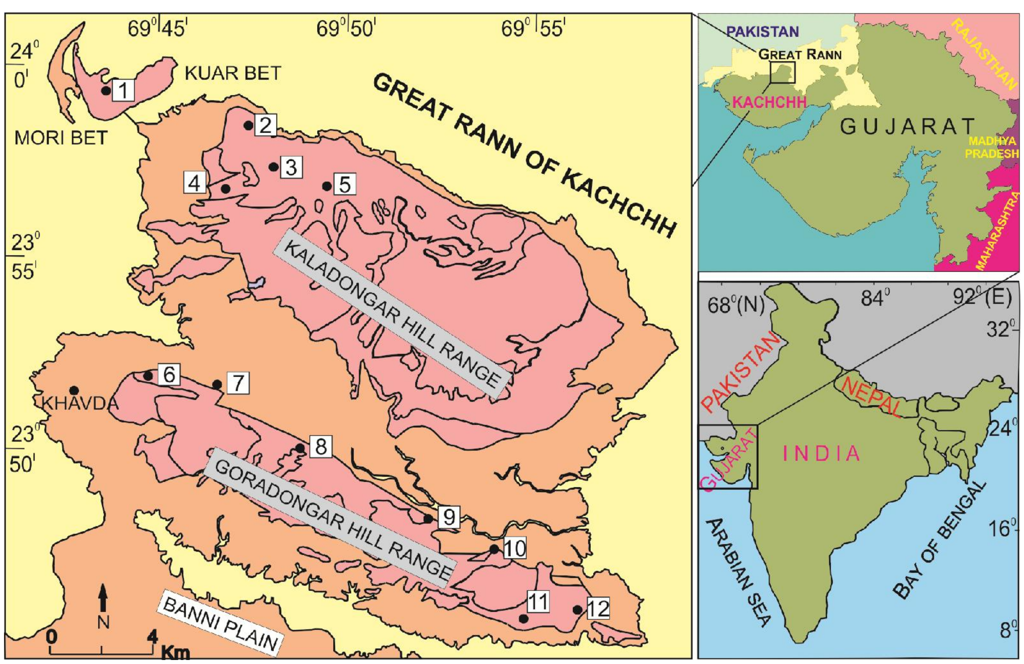


Figure- 1.3 Location map of the study area, Patcham Island, Kachchh.

1.7 AIMS AND OBJECTIVES

The purpose of the study was to integrate the sedimentological and ichnological entities in order to analyse the sequence stratigraphy of the Middle Jurassic sediments of the Patcham Island. The main objectives of this investigation therefore included:

(i) To understand sedimentary facies variation of the exposed sequence;
(ii) To document the trace fossils and analyse them for the palaeoenvironment and palaeoecological parameters in the light of the modern conceptual terms such as ichnoassemblages and ichnofacies;
(iii) To comment on the use of trace fossils in recognizing and interpreting the significant stratigraphic surfaces;
(iv) To use both physical and biogenic sedimentary structures for identification of the stratal stacking patterns, sequence boundaries, and system tracts; and
(v) To construct the sequence stratigraphic model in order to evaluate the stratigraphic architecture of the basin and the influence of the regional as well as global factors.

1.8 METHODOLOGY

The Middle Jurassic rocks of Patcham Island, ranging in age from Bajocian to Callovian, comprises of two Formations namely, Kaladongar and Goradongar. The present study is carried out in different localities exposing Kaladongar and Goradongar ranges. The litholog along with the physical and biogenic structures were observed, and scaled litho-sections were prepared for each location and traverse. The lateral and vertical continuity of each sedimentary bed was observed and a composite litholog was prepared. Bed-wise samples were collected from each location and thin sections were prepared for mineralogical and textural studies. The sedimentary facies were identified and distinguished based on the field characteristics and petrographic analysis. The trace fossils were observed, recorded (abundance and diversity), photographed, collected (wherever it's possible), and identified at ichnospecies level. Preservational aspects were studied with reference to casting medium; and recurrence patterns were observed and further analysed for ichnoassemblages and ichnofacies for palaeoecological interpretation. Sedimentological and ichnological data were integrated for sequence stratigraphic analysis; depositional stacking patterns were analysed based on facies associations and ichnoassemblages/ichnofacies which led to identification of the stratigraphic system tracts. These stratigraphic system tracts are then analysed for major as well as minor T-R sequences. A sequence stratigraphic model is then reconstructed for the Bajocian to Callovian sequence of the Patcham Island, Kachchh, Western India. A brief illustration of the method of analysis and their analytical product is shown in Fig.1.4.

1.9 SCOPE OF WORK

The present study emphasizes on the sequence stratigraphic analysis of the Bajocian-Callovian sediments of Patcham Island with a sedimentological and ichnological approach. The facies association and trace fossil association (ichnoassemblage) would help to understand the environmental conditions at the time of deposition. The integrated study may also enhance the understanding of major and minor sea level fluctuations that affected the sub-basin during the early sedimentation in the rift. Further this study would help to reconstruct a sequence stratigraphic model for a rift basin similar to the one proposed by the Martins-Neto and Catuneanu (2010) with or without amendments. Apart from the present study, the data could be useful in interpreting and analysing the reservoir prospectus of this Kachchh basin window.

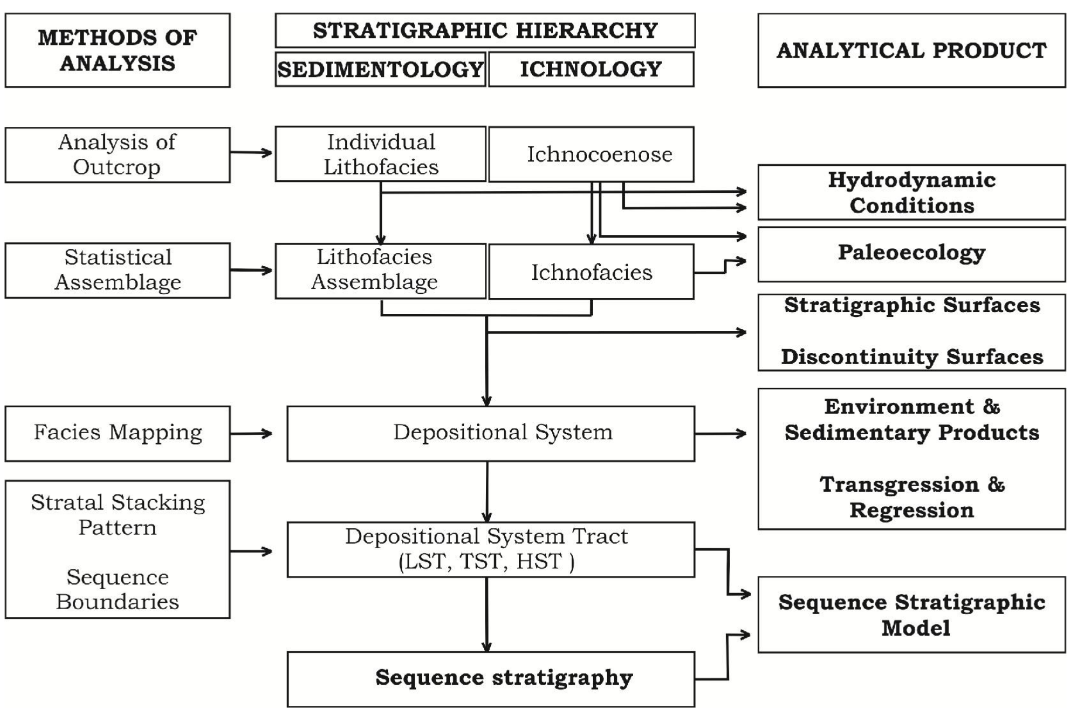


Figure-1.4 Work flow for the sequence stratigraphy of the Patcham Island, Kachchh.

CHAPTER-2
THE REGION OF KACHCHH

2.1 PHYSIOGRAPHY

Kachchh is the western-most district of Gujarat state covering approximately 44,200 sq. km. of area and lies between N 22^0 44’ and 24^0 41’ latitude and E 68° 09’ to 71° 31’ longitude. It is a semi-desert region; bordered by Banaskantha district to the east, Kathiawar peninsula and Gulf of Kachchh to the south, Arabian Sea to west and south-west, and Pakistan to northwest and north and Thar Desert to north. It has a long coastline of ~352 km, representing Arabian Sea extending from Lakhpat to Mandvi coast and Gulf of Kachchh extending from Mandvi to Shikarpur coast. The shallow Gulf of Kachchh separates the peninsulas of Kachchh and Kathiawar. The physical features of Kachchh are characterised by the contrasting occurrence of extensive plains and highlands with lofty hills (Biswas, 1977). The highlands are the Mainland of Kachchh, Wagad, Patcham, Khadir, Bela and Chorar (Banaskantha district) while the extensive plains are manifested by the Great Rann of Kachchh on the north, the Little Rann of Kachchh on the east (connecting the Great Rann of Kachchh and the Gulf of Kachchh) and the Banni plains (Fig.2.1).

2.1.1 HIGHLANDS OF KACHCHH:

2.1.1.1 The Mainland

The Mainland of Kachchh is the biggest among the five highlands of Kachchh. It is surrounded by the Great Rann and Banni of Kachchh to the north, the Little Rann to the east, Gulf of Kachchh to the south and Arabian Sea to the west and southwest. The mainland consists of two main east-west running hill ranges: (i) the northern range that occur along its northern margin with the Great Rann and Banni, and (ii) the Charwar Range which occur in the middle of the Mainland.

The northern range of mainland is the longest range in Kachchh running about 193 km from Ghuneri on the west to Bhachau on the east. Jhurio Hill is the highest among the hills in this range and is in the middle of the range. The high hills in this range include Kas

Hills, Habo, Keera, Kaya Dongar, Jumara and Jaramara from east to west. Dhinodhar, Arara, Varar and Bhujia hills, formed of igneous intrusions, occur singularly on the plain, in south of the range. Charwar range (Chaduva hills) runs for about 64 km from Satapur on the east to Waramseda on the west. Another hilly terrain formed of Deccan trap hills, known as Dhola Hills, occurs at the south of Charwar range with a stretch of a narrow sandy plain in between them. These two hill range forms the central plateau of the Mainland Kachchh. Beyond Mata-nu-madh, the Chaduva hills merge with the large triangular area of Garda Hills. A 16 km wide sandy plain called as Nakhatrana-Bhuj lowland occurs between the Northern range and Garda-Chaduva-Charwar line of hills while Naliya-Kothara lowland lies between Garda Hills and the Western portion of Dhola Hills. The Mainland is bordered to the west and south by a wide belt of coastal plain. The western coast is made up of mud flats of several large creeks while the south coast forms a gentle, sandy beach bordering the deep blue sea.

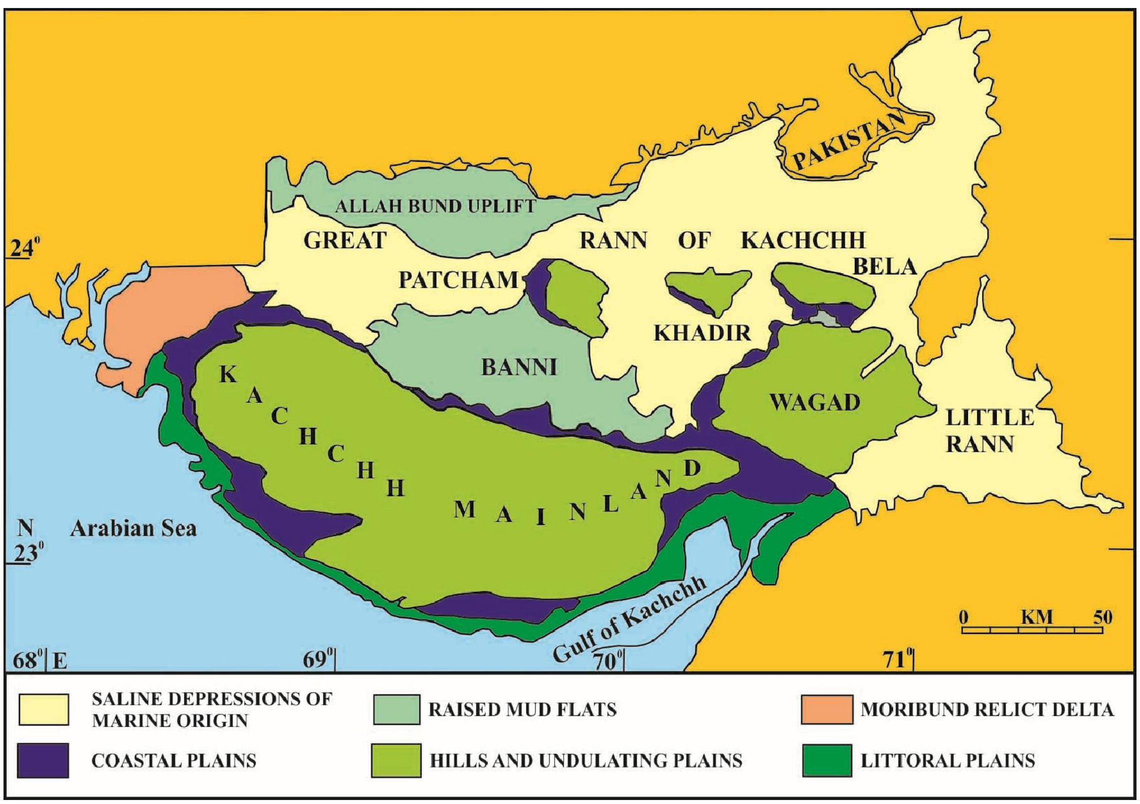


Figure-2.1 Morphogenetic regions of Kachchh district (Kar, 2011)

2.1.1.2 Patcham (Pachchham) Island

Patcham Island shows physical features similar to the Kachchh Mainland and consists of two east to west running hill ranges, namely, Kaladongar (Black hills) range and Goradongar (White hills) range separated by central valley. The Kaladongar range runs along the northern margin of the island with an escarpment facing to the north and high plateau sloping gently to the south into the Central valley. Two small hills, Dingy hill and Flamingo hill, occur to the north of the escarpment near the Rann. The Goradongar range runs along the southern margin of the island throughout its length with an escarpment facing the central valley to the north and a slope to the south into the Banni plain. A rocky terrain with small hills form the islet of Kuar bet in the north-west and Mori bet covered by sand dunes, in the north-west of Patcham Island.

2.1.1.3 Khadir Island

The Khadir Island is featured by a hill range along its northern margin which forms a prominent escarpment facing the Great Rann. The entire island is formed of the gentle southern slope of this hill range. The top of the range is fairly level which drops gradually in height at both the sides from the central peak. The important hills of this range are Hadibhadang, Modi bet and Chocha hills.

2.1.1.4 Bela Island

A high hill with prominent escarpment on the north, facing the Rann, runs along the entire length of the island. The height of the hill range does not drop much to the east and end up to the prominent hill called as Mouwana. This hill range known as Bela hills and the Mouwana hill is separated by a wide saddle in between.

2.1.1.5 Chorar Hill (part of Banaskantha District)

Chorar hills form a low ridge at the north-western fringe of Gujarat Plains close to the Little Rann which runs in an arcuate trend from Eval on the west to Phangli on the east. The ridge comprises of cuesta with peaks facing the rann in the north and gently sloping to the south. The highest hill is near the Eval in the west of the ridge.

2.1.1.6 Wagad Highland

It is characterised by a central hilly terrain known as Wagad (Vagad) hills, and a long narrow hill range along the southern margin of Wagad, running from Wamka on the west, through Adhoi, to Gon at the eastern tip of the area. The Wagad Hills and the Southern Range are separated by a valley. In the middle of the low Banni type plain that separates Bela and Wagad hills, another small range of hills extend form Maiya Wandh on the west to Fatehgadh on the east through Desalpur known as Desalpur-Fatehgadh range. These hill ranges divides the lowland into two; the southern Rav Lowland and the northern Balasar Lowland.

2.1.2 THE PLAINS OF KACHCHH:

2.1.2.1 The Ranns

The Great Rann of Kachchh is a vast partially dry mud flat extending from the north of Mainland of Kachchh in India to the sand dunes of Thar Parkar in Pakistan. The Little Rann is the head of the Gulf of Kachchh, formed by the regression, and is connected with the Great Rann by a stretch of dry mud flats extending between the eastern Wagad and the Gujarat Plains to the east. Local undulations forms uplands of small heights in the Rann known as Bets and smaller features called as dhois or birs. Some of the important islets are Chhad Bet, Bear Bet, Kuar Bet, Kakindia Bet, Cheriya Bet, Tangari Bet, Gangta Bet, Vongara Bet, Kara Bir, Gora Bir and Chirak Dhoi. The low-lying portions of the Rann remain permanently wet with salt encrustation. According to the works of Merh and his associates (Roy and Merh, 1977; Merh and Patel, 1988), the region is geomorphologically divisible into five units: (i) Northern Bet Zone (NBZ), north of Allah Bund, (ii) Linear Trench Zone (LTZ), between Kori Creek and Kuar Bet, (iii) Banni Grassland Plains (BGL), between Great Rann and Mainland Kachchh, (iv) Great Barren Zone (GBZ), western part of the Great Rann, (v) Little Rann of Kachchh (LRK), separated from the Great Barren zone by a narrow rise Adesar-Piparala.

The Northern Bet Zone (NBZ) lies to the north of the line joining the Kuar Bet and Bedia. It forms a slightly uplifted area in the north and is made up of a complex network of bets and interlet channels. This uplift is limited by the Allah Bund in the south and by the sand ridges of Sindh (Pakistan) in the north. The Bet zone unit represents the abandoned mouth of a river, consisting of the main stream course and its distributaries pointing to a wetter past. It is above the tidal range and its inundation is entirely due to the accumulation of rain water that flows down from the north through various shallow seasonal channels.

The Linear Trench Zone (LTZ) is a depression extending from the Kori Creek eastwards upto Kuar Bet which gets inundated by tidal waters of the Arabian Sea through the Kori Creek. The tidal current and the strong winds are the main factors that control the flooding of this zone.

The Banni Grassland (BGL) comprises a transitional land between the rocky Mainland of Kachchh and the Great Rann and form an alluvial tableland rising 3 to 10 m above the level of the Great Rann. An intervening stretch of salty waste separates the Banni from the Mainland in the south. The entire area in this unit is more or less flat and almost gradientless covering about 3000 sq km of saline grass-lands. The nature of the sediment in the Banni points their strong affinity to the material brought by the rivers from the north and the east; characteristically similar to the sediments of the bet zone. The Great Rann encroaches from the north during the stormy monsoon while the mainland river water flows over the Banni during the heavy rainfall period.

The Great Barren Zone (GBZ) is lies in the easternmost part and is free from the sea water inundation which forms an extensive barren area, topographically comprising a vast shallow saucer-shaped depression limited by the sand dunes of Thar desert (Pakistan) in north, Kachchh Mainland in south and alluvial plains of Banaskantha in east. This zone gets inundated due to direct monsoonal precipitation as well as by the discharge of water from the Luni river and other streams flowing down from the rocky Kachchh Mainland.

The Little Rann of Kachchh (LRK) represents the former extension of the Gulf of Kachchh during the high sea level conditions of last Holocene transgression. It forms a featureless marshy ground, 4 m high above the high water line at its northern point. Earlier the rivers like Banas, Saraswati, and Rupen extended and flowed into the Gulf of Kachchh. The inundation of LRK is caused both by the tidal waters from the SW and the rain waters brought by the various inland rivers.

2.1.2.2 The Banni Plain

Banni are the higher portion of the Rann which are covered with vegetation and are made of alluvial and aeolian sediments deposited on the Rann between the Highlands and along their peripheries. Besides from this main Banni Plain, another small Banni Plain occurs between the Bela and Wagad (Biswas, 1993). The Banni areas normally remain dry but become wet during heavy monsoon seasons.

2.2 GEOMORPHOLOGY

The islands and highlands are the zones of principal uplifts and the hill ranges are the uplifts of second order within them. The highlands that represent principal uplifts are tilted fault blocks with the hill ranges formed on the faulted up side of these blocks. The low lying plains are the residual depressions whereas the central valley of the Patcham and the lowlands occupy the structural lows where the back slope of one fault block meets the scarp of the other. There is direct relationship between the structural complexity and the ruggedness of the terrain, e.g. in Patcham Island, the Goradongar Range represents a rugged terrain than the Kaladongar Range. When viewed from Rann side, the typical features of a fault-line scarp like wine-glass valleys, triangular fault-facets, and steeply inclined alluvial fans containing rock fragments of various sizes and fanglomerates resting at the foot of the escarpments.

The dome hills of the Northern Range of Mainland show various stages of erosion due to differential uplift during the latest period of rejuvenation (Biswas, 1977). Along the western domes, the Jara and Jumara domes are dissected and are in its late youth stage while the Jhurio and Habo Hills are in its early youth and mature stages of erosion respectively. These highland areas which bear the evidences of the several erosional cycles in different geological times compose the polycyclic landscape of Kachchh. There is a buried ridge known as the Median Ridge (or High), which runs across the Kachchh Basin in a roughly north-south direction and subsequently influences the geomorphology of the area to a great extent**.** The central highland of Charwar Range, the highest Jhurio Hill in the middle of Northern Range, and the Kaladongar and Goradongar hill range of Patcham Island are the manifestation of this ridge. The Banni, which is an elevated region in the plain of the Great Rann of Kachchh is also the superficial expression of this high. The matured topography of the highland areas and the development of regular drainage patterns with sizeable valleys suggest the present desert geomorphic cycle to be superimposed on a fluvial one. Roy and Merh (1977, 1982) carried out a detailed geomorphic study of the Great Rann, classified the Great Rann and also described the pattern and causes of its annual inundation. Gupta (1977) described the layered sequence of Little Rann sediments while Ghosh (1979, 1982) described the Little Rann and also envisaged the existence of a palaeo-river bed beneath the Rann sediments suggesting transgression of sea over an earlier fluvial channel network during a marine incursion around 7000 years B.P. (Middle Holocene).

2.3 GENERAL GEOLOGY

The western continental margin of India can be classified as an Atlantic-type passive margin (Biswas, 1982) wherein Kachchh basin has the longest and the most complete record of the Mesozoic in western India (Biswas, 1981; 1987) with ~3000 m thick accumulations of Late Triassic to Lower Cretaceous sediments (Biswas, 1987). These sediments were deposited in a sheltered gulf in sublittoral to deltaic environments in two major cycles: a Middle Jurassic transgressive cycle and a Late Jurassic-Early Cretaceous regressive cycle (Biswas, 1981). These sediments were laid down on a Precambrian granitic basement which is exposed only in the Nagar Parkar Hills in Pakistan, bordering the northern flank of the graben. The Mesozoic sediments were uplifted, folded, intruded and covered by the Late Cretaceous-Early Paleocene Deccan trap. The terrestrial volcano-clastic sediments represented the Paleocene sediments while the Early Eocene transgression and subsequent Tertiary deposits filled the peripheral lows bordering the Mesozoic highs as well as the lows between them.

2.3.1 PREVIOUS WORK:

Kachchh Basin is well famous for its abundant fossil content. In early nineteen's, Grant (1837) firstly attempted to write a comprehensive account of the geology of Kachchh, but a much satisfactory account was recorded by Blanford (1867). Wynne and Fedden (1868-1872) systematically mapped and investigated the geology of Kachchh in detail and later on, the same was published by A. B. Wynne in a memoir (Vol. IX, 1872) of Geological Survey of India which provided the base and only reference for all subsequent work in Kachchh. He divided the Mesozoic sequence into two subdivisions lower (marine) and upper (non-marine) Jurassic. Thereafter, Stoliczka suggested a four-fold classification which includes Pachham, Chari, Katrol and Umia groups (in chronological order), based on the mineralogical and palaeontological characters.

Waagen (1871, 1873-1876) studied ammonites of Kachchh and was first to correlate four-fold classification of Stolickza with European Zones on the basis of the identified ammonite assemblage zones. This was the first chronostratigraphic classification that came into existence and has been used and modified according to the palaeontological observations thereon. Accordingly, the Pachham, Chari, Katrol and lower part of Umia correspond to the 'Lower Series" and the upper part of Umia with the Upper Series of Wynne (1872). Many authors such as Kitchen (1900), Cox (1940) and Gregory (1906) studied brachiopods, bivalves, echinoids and corals, and they gave more emphasis on taxonomy rather than the biostratigraphy. In 1932, Rajnath established a succession on the basis of the ammonites, bivalves, and plant fossils. He restricted the term Umia to the lower Umia of Waagen and divided the stratigraphy of the Mainland into five units including the Upper Umia made of non-marine beds named as Bhuj Series of Middle Cretaceous.

O.N.G.C. India has carried out extensive geological field mapping, deep drillings and geophysical surveys on land and offshore (1956-1967). These published results contributed extensively in understanding depositional and tectonic history of Mesozoic rocks of Kachchh. Tiwari (1948) and Arkell (1956) worked to assign and modify the age of the Jurassic rocks while Agrawal (1957) modified the stratigraphic nomenclature of Habo Series for Chari Series and Mebha oolites for Dhosa oolites. Pascoe (1959) compiled Spath (1927-33) classification and described more systematic classification with the proper usage of stratigraphic terms like series, stages and zones on the basis of lithological and palaeontological characteristics. Poddar (1964) later modified Rajnath (1932) chronostratigraphic classification considering Ukra Beds as Formation and changing the rank term suffix "Formation" in place of "Series" (Table. 2.1).

A significant work on the stratigraphy of Kachchh was initiated by Biswas (1971, 1977) who proposed lithostratigraphy of Mesozoic of Kachchh based on International stratigraphic standards and also suggested corresponding nomenclatures. The facies variations in different part of the basin detached by fault-bound outcrop areas separated by covered plains stand as a difficulty for lateral continuity and therefore, he restricted the use of uniform rock unit sequence throughout the basin and recognized independent classification for the three main lithological provinces within the basin (Table. 2.2).

FORMATION	AGE	SUB-DIVISION	LEADING FOSSILS
Bhuj Stage	Post-Aptian	Bhuj-beds (Umia plant beds) Sandstones/Shale	*Palmoxylan in upper beds ptylophyllum Flora*
Ukra beds	Aptian	Ukra beds-Marine Calcareous Shales	*Australiceras, Colombiceras, Cheloniceras, etc.*
Umia (1000 m)	U. Neocomian	Umia beds - Barren Sandstones and shales	*Unfossiliferous*
	Valaginian	Trigonia beds Barren sandstones	*Trigonia* *Unfossiliferous*
	U.Tithonian	Umia ammonite bed	*Virgatosphinctes, Umiatites, Micracathoceras, etc.*
Katrol (300m)	M. Tithonian	U.Katrol shales	*Hildoqlochiceras, Dorsoplnites, Haploceras*
	M. Tithonian	Gajansar beds	*Belembopsis, Streblites, Phylloceras, Hildoglochiceras*
	L. Tithonian	U. Katrol (Barren) sandstones	*Autocosphinctoides, Virgatosphinctes*
	M. Kimmeridgian	M. Katrol (Redsandstones)	*Waagenian, Katroliceras, Panchysphinctes, Aspidoceras*
	M. Kimmeridgian	L. Katrol (sandstones, shales, marls)	*Torquastisphinctes, Aspidoceras, Ptychophylloceras*
	U. Oxfordian	Kanthkot sandstone (Bimammatum zone)	*Epimayaites, Prograyiceras, Ataxioceras, Bipilices, Trigonia*
Chari (360m)	U. to L. Oxfordian	Dhosa oolites (green and brown oolites)	*Tramerlliceras, Discosphinctes, Perisphinctes,* *Mayaites, Epimayaites, Paracenoceras*
	U. Callovian	Athleta beds (marls & gypseous shales)	*Peltoceras, Orionodes*
	M. Callovian	Rehmanni beds (yellow Lst)	*Perisphinctes, Indosphinctes, Reineckiea, Kinkeliniceras* *Reineckiea, Sivajiceras, Idiacycloceras, Kellawayssites*
	M. Callovian	Macrocephalus beds (shales with calc. bands, with golden oolites-diadematus zone- in the up. Part)	*Macrocephalites, Dolichocephalites, Indocephalites, Kamptocephalites, Pleurocephalites, Belemites*
Pachham (300 m)	L. Callovian	Pachham coral beds	*Macrocephalites, Sivajiceras, Proceraites, Stylina, Montivaltia*
	L. Callovian to Bathonian	Pachham shells limestone Pachham basal beds (Kuar bet beds)	*Macrocephalites, Trigonia, Corbula* *Corbula, Eomiodon, Trigonia, etc.*

Table-2.1 Chronostratigraphic division of Mesozoic of Kachchh (Rajnath, 1932; Poddar, 1964).

Biswas and Deshpande (1970, 1973, and 1983) published a detailed geological and structural map of Kachchh. Further, Biswas (1978, 1980, 1981, 1982, 1983, 1987, and 1991) discussed lithostratigraphy, structure, basin framework, palaeo-environment and depositional history, rift-tectonic and sedimentary evolution of Mesozoic rock sequences of Kachchh on a regional scale. He also developed the concept of monoclinal flexures and domes aligned along the margin of all the major faults of the region i.e. Nagar Parkar Fault (NPF), Island Belt Fault (IBF), Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF).

Later on, the age of lithostratigraphjc units of Biswas (1977, 1980) were revised based on subsequent biostratigraphic studies. Singh et al (1982) reported occurrence of the earliest ammonites from the Patcham Island and suggested the Bajocian age as the oldest deposits in the Basin. Krishna (1984), Krishna and Cariou (1986) and Krishna and Pathak (1991, 1993) established the Jurassic ammonite biostratigraphy in the Kachchh. Pandey and Dave (1993) also contributed towards the foraminiferal biostratigraphy of the Mesozoic basin. They made detailed foraminifera and biostratigraphic studies in the representative sections of Jhurio, Jumara, Jhuran and Bhuj Formations, based on lithostratigraphic classification of Biswas (1971, 1977). They dated the above formations and proposed Indian Jurassic and Cretaceous stages namely, Bannian, Patchamian, Badian, Charian, Dhosaian, Katrolian, Umiaian and Mundharian, based on the lithobiochronostratigraphy of the Mesozoic sediments of the basin. Morris (in Grant, 1840), Fiestmantel (1876), Seward and Sahni (1920), Bose and Kasat (1972) made valuable contributions, of well preserved, varied and diversified plant megafossil of Kachchh. Bose and Banerji (1984) also made a detailed palaeobotanical studies on the Mesozoic plant megafossils of Kachchh mainly recorded from Jhuran (Kimmeridgian-Tithonian) and Bhuj (Tithonian-Neocomian) Formations.

The palynological studies on the Mesozoic sediments of Kachchh Basin were initiated by Singh et al (1963). Later on, works mainly concentrated on the taxonomic studies of the palynofloras were recorded from different Jurassic as well as Lower Cretaceous lithounits in Kachchh basin (Mathur and Mathur, 1965; Venkatachala, 1967, 1969a, 1969b; Venkatachala and Kar, 1968a, 1968b, 1970, 1972; Venkatachala, Kar and Raza, 1969a, 1969b; Mathur et al, 1970; Maheshwari and Jana, 1987; and Koshal, 1975, 1983. Apart from taxonomy, Jain et al (1986) and Kumar (1986) dated the different lithounits of the Jurassic on the basis of dinoflagellate cysts; and Mishra et al (1995) provided palynological characterization for each formation and categorized into three palynological zones based on the detailed spore-pollen as well as dinoflagellate cyst studies in reference (type) sections of Jurassic and Lower Cretaceous.

<table>
<tr><th>AGE</th><th colspan="3">MAINLAND</th><th colspan="3">PATCHAM</th><th colspan="3">E.KUTCH (KHADIR-BELA-WAGAD)</th></tr>
<tr><th></th><th>Frm.</th><th>Member</th><th>Litho</th><th>Frm.</th><th>Member</th><th>Litho</th><th>Frm.</th><th>Member</th><th>Litho</th></tr>
<tr><td rowspan="4">NEOCOMIAN-ALBIAN</td><td rowspan="3">BHUJ (815 M.)</td><td>Upper (260m.)</td><td>X-bedded Sst., claystone</td><td colspan="3" rowspan="8"></td><td></td><td></td><td></td></tr>
<tr><td>Ukra (30m.)</td><td>Sst, Sh. Fossiliferous</td><td></td><td></td><td></td></tr>
<tr><td>Ghuneri (W) or Lower (E) (525m.)</td><td>Sst. & sh., Plant, fossils</td><td rowspan="5">WAGAD SANDSTONE (365 M.)</td><td rowspan="2">Gamdu (+165 m.)</td><td rowspan="2">Felds-Sst., Sh., red iron-stone + plant Fossil</td></tr>
<tr><td rowspan="4">JHURAN (760 M.)</td><td>Katesar (180 m.)</td><td>X-bedded Sst.</td></tr>
<tr><td rowspan="3">KIMMERIDGIAN TO TITHONIAN</td><td>Upper (300 m.)</td><td>Thin bedded calc. Sst.</td><td rowspan="3">Kanthkot (200 m.)</td><td>(Upper) Sst. & Sh.</td></tr>
<tr><td>Middle (160 m.)</td><td>Shales</td><td>(Middle) X-massive Sst</td></tr>
<tr><td>Lower (120 m.)</td><td>Shale/ sst Fossils</td><td>(Lower) Silty Shale
(?Paracon-formity)</td></tr>
<tr><td>OXFOR-DIAN</td><td rowspan="3">JUMARA (275 M.)</td><td>Dhosa Oolite (115 m.)</td><td>Shales with Oolitic-Lst bands</td><td>WASHTAWA (WAGAD)</td><td>Bambhanka Shales (160 m.)</td><td>Mainly Shale having fossils</td></tr>
<tr><td rowspan="3">CALLOVIAN</td><td>Middle (75 m.)</td><td>Sst. (E)-Lst., Golden Oolite (W)</td><td rowspan="4">GORADONGAR (154 M.)</td><td>Modar Hill (+130 m.)</td><td>Up. Sst. & Lr. Shales</td><td rowspan="6">KHADIR
KHADIR ISLAND (650 M.)</td><td>Gadhada (185 m.)</td><td>Shales and Sst.</td></tr>
<tr><td>Lower (85 m.)</td><td>Green Shales, Fossiliferous</td><td>Raimalro (9 m.)</td><td>Cherty Lst.</td><td rowspan="3">Hadibhadang (280 m.)</td><td>(Upper) Cherty Lst.</td></tr>
<tr><td rowspan="4">JHURIO (290 M.)</td><td>Upper (70 m.)</td><td>Bedded limestone</td><td>Gadaputa (6 m.)</td><td>Sandstone</td><td>(Middle) Sst.</td></tr>
<tr><td rowspan="3">BATHONIAN</td><td>Middle (85 m.)</td><td>Shale with Golden oolitic Limestone</td><td>Flagstone (8 m.)</td><td>Lst. With Golden Oolite</td><td>(Lower) Shales-fossils</td></tr>
<tr><td rowspan="2">Lower (135 m.)</td><td rowspan="2">Lst. & Shale interbedded</td><td rowspan="2">KALADONGAR (470M.)</td><td>Kala Dongar Sst. (180m.)</td><td>X-bedded Sst.</td><td rowspan="2">Cheriyabet (25 m.)</td><td rowspan="2">Petromict Granite-Cobble-Conglo. and arkose</td></tr>
<tr><td>KuarBet (290 m.)</td><td>Shale & Sst.</td></tr>
<tr><td></td><td colspan="6"></td><td></td><td>Precambrian</td><td>Granitic basement</td></tr>
</table>

Table-2.2 Mesozoic Rock-stratigraphic classification of Kachchh (Biswas, 1977).

The ichnological study commenced long back at the time of Wynne (1872) and later Howard and Singh (1985) proposed a depositional model for Jurassic-Cretaceous rocks based on the trace fossils supportive by gross lithology of Mesozoic. Shringarpure (1984 and 1986) was first to interpret trace fossils in terms of their ethology, palaeoecology, animal sediment relationship, event stratigraphy and depositional environments. Badve and Ghare (1978), Ghare and Kulkarni (1986), Kulkarni and Ghare (1989, 1991), Bhatt (1996) Fürsich (1998) and Patel (2009) added further data on the ichnology from the Kachchh region. Recently many works like Patel et al (2008a, 2008b, 2009, 2010, and 2012), Desai et al (2008), and Jaquilin et al (2012) have contributed in the field ichnology and described many ichnogenera and discussed their significance in terms of palaeoecology and palaeoenvironment of the Mesozoic sediments of the Kachchh basin.

After late 90's, many workers (Singh, 1989; Mishra, 2008;, Mishra and Biswas, 2009; Patel et al 2010, in *press*; Patel and Jaquilin, 2012;, and Bhatt et al, 2012) discussed the transgressive-regressive cycles of Mesozoic sequence in the various part of the Kachchh. Fürsich et al (1991, 1992, 1994 & 2001) discussed paleoecological and palaeoenvironmental conditions of various exposures in the Mainland Kachchh and Sadhara Dome based on the identified marker beds of Jurassic. He inferred their depositional environment and sequence stratigraphic significance. Biswas (2005) detailed review of structure and tectonics of Kachchh basin with reference to the Earthquakes.

2.3.2 STRATIGRAPHY:

Kachchh represents a complete sequence of strata ranging in age from Middle Jurassic to Holocene. The Mesozoic and Cenozoic rocks of Kachchh are separated by a period of non-deposition, followed by diastrophism, erosion and volcanism, during the close of Cretaceous period. The Mesozoic rocks consist of marine sediments from Bathonian to Tithonian (Portlandian) and non-marine sediments in Cretaceous. The earliest age of the Mesozoic rocks of the Kachchh are still controversial. Waagen (1872) suggested it to be Bathonian based on faunal data and ammonite biozonation data which was later supported by Rajnath (1932; 1942). Jaitley and Singh (1983) and Pandey and Dave (1993) reported Bajocian age for Goradongar Formation of Patcham Island based on ammonites and foraminiferal assemblages respectively (Jana and Hilton, 2007). Pandey and Dave (1993) conjectured the age of Kaladongar Formation to be Alenian based on the order of stratigraphic superposition.

Mathur (1972) disputed the age not to be older than Early Cretaceous based on palaeobotany and palynology but later the same was reinvestigated by Jana and Hilton (2007) who considered Bathonian to Callovian age for the Kuar bet, the oldest sediments of Kachchh. However, the precise position within the Middle Jurassic remains uncertain with palaeobotanical and palynological results while faunal evidence supports an early Middle Jurassic (Bajocian) age. In the present study, the age of Mesozoic rocks of Kachchh is considered to range from Bajocian to Albian with reported earlier sediments of Alenian.

2.3.2.1 Mesozoic Stratigraphy

The Mesozoic rocks of Kachchh range in age from Middle Jurassic to Lower Cretaceous and are exposed in the following six disconnected areas which form the highlands amidst the extensive plains: (a) Kachchh Mainland, (b) Pachcham Island, (c) Khadir Island, (d) Bela Island, (e) Chorar Island, and (f) Wagad. The lithofacies variation form one part of the basin to the other and the detached fault-bounded outcrop areas separated by covered plains make it difficult to trace a set of rock units, recognized in one area, strike wise to the other areas. Therefore, for a systematic description and proper representation of the stratigraphy bringing out the lithofacies relationship, the rock sequence of each outcrop has been classified separately in the lithostratigraphic classification (Biswas, 1977). Accordingly, the lithologically correlatable areas of Wagad, Bela, Khadir, and Chorar, collectively known as Eastern Kachchh; the Mainland Kachchh and Patcham Island were recognized within the basin and in each province rocks have been classified separately as already shown in Table. 2.

2.3.2.1.1 Kachchh mainland

The stratigraphic sequence of Mainland is divided into four formations namely, Jhurio (Jhura), Jumara, Jhuran, and Bhuj Formations in ascending order. The base of the Jhurio Formation is unexposed while the Bhuj Formation is disconformably overlain by the basic flows of the Deccan Trap Formation (Biswas and Deshpande, 1973) on the south.

2.3.2.1.1.1 Jhurio Formation (Bathonian to Lower Callovian)

Jhurio or Jhura Formation is named after the type section in Jhurio (Jhura) hill in the north-central Mainland. It comprises of a thick sequence of limestone and shales with bands of “golden oolites”. The Formation is exposed only as small inliers in three hills namely, Habo, Jhurio and Jumara (from east to west) which are large domal structures, along the northern margin of the Mainland. The core of the Jhurio dome is composed of this formation and also exposes the maximum thickness of the formation (+287 m) while only the upper part of the formation is exposed in Habo and Jumara domes.

This formation is particularly rich in fossils in Jumara dome where the shales and biostromes are packed with corals (Gregory, 1900), brachiopods, bivalves and ammonites (Biswas, 2002). The physical and biological aspects of the formation indicate intertidal to subtidal environment.

The upper boundary of this Formation matches with the lower *Macrocephalus* zone which indicates a Callovian age (Mitra and Ghosh, 1964; Agrawal, 1956 & 1957) while Ghosh (1969) fixed the lower limit of these rocks in Jumara as Middle Bathonian. Thus, the age of the formation ranges from Bathonian (? Middle) to Lower Callovian.

2.3.2.1.1.2 Jumara Formation (Callovian to Oxfordian)

The Jumara Formation comprises of a thick argillaceous sequence overlying the Jhurio Formation, named after its type section exposed in Jumara Hill near the Rann, north of Jumara village. This formation is exposed as inliers at the centre of the domal and anticlinal hills along the northern edge of the Mainland and in central Charwar Range in more or less circular to elliptical outcrops. This Formation is subdivided into four informal members I to IV from below on the basis of the limestone or sandstone interbeds dividing the continuous shale sequence (Biswas, 1977).

The fossiliferous oolitic limestone bands occur near the top of the member IV which is called as “Dhosa Oolite beds” by earlier workers are the main key bed in the Mainland sequence. This member is thus named as ‘Dhosa Oolite Member” based on its lithological characteristics (Biswas, 2002). This formation is richest of all in fossil content. Varieties of ammonites, belemnites, brachiopods, bivalves, corals and gastropods are found throughout the formation. From the lithologic and biological aspects it appears to have been deposited below the subtidal zone.

The boundaries of this Formation match with those of the Chari Series described by Rajnath (1932) from Jumara hill. Based on the fossil assemblages, Ghosh (1969) fixed a Callovian-Argovian age for the Chari Series of Jumara dome. The Jumara Formation is therefore assigned an age ranging between Callovian to Oxfordian (Waagen, 1873; Biswas, 1977; Pandey and Dave, 1993; Talib and Gaur, 2008).

2.3.2.1.1.3 Jhuran Formation (Kimmeridgian to Early Neocomian-Valanginian)

The Jhuran Formation comprises of a thick sequence of alternating beds of sandstone and shale, defined between the lower Dhosa oolite member and upper non-marine sandstones of Bhuj Formation. This formation is subdivided into four informal members- lower, middle (Rudramat shale), upper, and Katesar members. The type sections of Jhuran River (for lower and middle members), Mundhan anticline (for upper member) and Katesar River (for Katesar member) constitute the composite stratotype for the formation.

The formation is richly fossiliferous in the Western Mainland and becomes less and less fossiliferous towards east. Common fossils include ammonites, belemnites, bivalves, gastropods, and locally corals and echinoid. The paralic facies and the physical and biological characteristics of the sediments of different members tend to indicate that the environment shifted from sub-tidal to supra-tidal and finally into continental deposition of the overlying formation.

The ammonite faunas of the "Jhuran Belemnites Marl" (i.e., Lower member) and the "Upper Katrol Stage" (Gajansar and Nara Beds i.e., Middle member) have been assigned respectively to Lower Kimmeridgian and Portlandian by Spath (Pascoe, 1959). The green oolitic ammonite bands in the lower part of Rajnath's Umia Series (i.e., lower part of the upper member that pass eastward into the upper part of the middle member due to diachroneity) have been assigned an age of Tithonian (Rajnath, 1932) while the base of the Formation, above the Dhosa Oolite band, coincides with the Katrol series of Rajnath (1932) which is assigned an age of Kimmeridgian. The Trigonia beds of Kachchh including the Ghuneri Trigonia band near the top of this Formation is assigned an age of Tithonian-Neocomian (Cox, 1952; Sahni and Prasad, 1957). Therefore this formation is assigned an age ranging from Kimmeridgian to Valanginian age (Biswas, 1977, 1980 & 2002).

2.3.2.1.1.4 Bhuj Formation (Neocomian to Albian)

Bhuj Formation comprises of huge thickness of non-marine sandstones of uniform character, named after its type locality around Bhuj. This Formation is defined by the marine beds of Jhuran Formation below and the Deccan trap flows above. The Bhuj Formation is exposed extensively in the Mainland occupying about 3/4th of total area of the Mesozoic outcrop in two wide belts stretching from Bachau on the east to Ghuneri on the west, occupying lowlands between the hill ranges. This formation is subdivided into three informal members- Ghuneri, Ukra, and Upper members. The lithological and biological characteristics indicate deltaic deposits with distal part (delta front) towards the west and the proximal part (fluvial) to the east in the direction of the land.

2.3.2.1.2 Patcham island

The “Pachham Series” was described from the Jumara dome of the Mainland and was included in the Jhurio Formation in the old classifications. The rocks of the Patcham Island were not studied well except Wynne (1872), and later Pascoe (1959) studied and included the rocks of the Patcham island in “Pachham Series” and divided them into Upper and Lower Pachham “Stages”. Biswas (1977, 1980) divided the Jurassic rocks of the Patcham Island into two rock units- lower Kaladongar Formation and upper Goradongar Formation. The Kaladongar sandstone show granite-cobble-conglomerates which indicate the closeness of the basement which is also exposed some 80 km to the NE of Patcham Island. The increase in clastics and decrease in faunal content of the Patcham Formations as compared to the Jhura and Jumara Formations of the Mainland to which they are partly correlatable, are attributed to the proximity of the northern margin of the basin.

2.3.2.1.2.1 Kaladongar Formation

A thick sequence of sandstone and shale developed in the Kaladongar (Black Hills) Range of Patcham Island constitutes the oldest stratigraphic unit of Kachchh formally named as Kaladongar Formation. The section exposed in the lofty scrap facing the Rann, below the highest Babia Peak (456 m), and along the stream west of Narewari Wandh is designated as the type section. This formation outcrops extensively in the north-face of Kaladongar escarpment along the Rann from Kuran village in the west to Nir wandh in the east and also along the scarp face of the southern Goradongar Range. The oldest beds are exposed in "Dingy Hill" and in "Kuar Bet" islet, 1.6 km NW of Patcham, which is the last outcrop within the Indian Territory. Its lithologic, structural and fossil characteristics indicate an intertidal environment of slowly transgressing sea over a granitic terrain.

Based on the occurrence of *Corbula lyrata*, *Bakevellia waltoni*, *Gervillia* sp.etc throughout the formation, a Bathonian age was assigned to Kuar Bet beds (Cox, 1940; Arkell, 1956; Pascoe, 1959). Therefore, the age of this formation was tentatively fixed as Bathonian by Biswas (1977). However, Singh et al (1982) reported the earliest ammonite found within the basin which indicated a Late Bajocian age. The bed in which this ammonite occurred was underlain by more than 200 m of partly terrestrial and partly marginal marine sediments and thus they suggested that the earliest marine sediments may be of Early Bajocian or even Alenian in age. Therefore, the age of the Kaladongar Formation is considered to be late Bajocian to Bathonian

2.3.2.1.2.2 Goradongar Formation

A sequence of limestone, shale and sandstone above the Kaladongar Formation is grouped under this formation which is named after its type locality, Goradongar (White hills) range. The Goradongar Formation is exposed extensively in both the ranges topping the back slopes. It occurs as an outlier in Kaladongar Range. The maximum thickness of the members of the Goradongar Formation is noticed on the southern flank but maximum development of the formation observed in the eastern part of the Goradongar range. The top of this formation is not exposed, being covered by the Tertiary and Rann sediment. The lower hard beds form the ridges, cliffs and mesas while the soft sandstones in the upper part are eroded down to the plains. The fossiliferous bands of Goradongar flagstone comprise abundant bivalves and brachiopods; Gadaputa sandstone member is barren except a fossiliferous layer of bivalves; Raimalro limestone member contains brachiopods, crinoid stems, plates and occasional starfish while, Modar hill member contains abundant bivalves and ammonites. The lithological and biological association indicates offshore environment.

On the basis of the occurrence of Macrocephalus zone of ammonite assemblage in the shale beds of Modar Hill member, the age of this Formation was considered to be Callovian (Richter-Bernberg and Schott, 1963; Biswas, 1977). However, later the earliest two levels of ammonite zones were reported from the Goradongar Flagstone member correlatable with the type horizon of *P. arkelli* of Madagascar of Middle Bathonian which partly represented *Progracilis* zone of Europe (Pandey and Callomon, 1995). The oldest occurrence in the Raimalro Limestone member characterised by *Macrocephalites madagascariensis* corresponding to the *Triangularis* association of Krishna and Westermann (1987) and to the *Triangularis* zone or Lower *Macrocephalus* beds zone of Spath (1927-33). This member is thus assigned to latest Late Bathonian age (Callomon, 1993; Fürsich et al., 1994). Therefore, this formation is assigned an age of Middle Bathonian to Callovian.

2.3.2.1.3 Eastern Kachchh (Khadir, Bela, Chorar and Wagad highland)

The stratigraphy of eastern Kachchh is represented by interrelated rock-units exposed in the unconnected outcrops of Wagad, Khadir, Bela and Chorar. The Lithostratigraphic classification of these rocks is proposed by several workers (Table. 3). Biswas (1977), however, classified them into three formal Formations, namely, Khadir, Washtawa and Wagad Sandstone Formations. Accordingly, the Khadir Formation includes the oldest beds of the sequence while the Washtawa Formation which is exposed only in Wagad appears to be equivalent of the uppermost part of the former because both are conformably overlain by Wagad Sandstone Formation. The base of the Khadir Formation and the top of the Wagad Sandstone Formation are not exposed.

2.3.2.1.3.1 Khadir Formation

The rocks of the Khadir Island are named after it and are included in the Khadir Formation. This formation is exposed strikewise in Khadir, Bela and Chorar islands. The N-S cross-country section passing through Gadhada from the northern most point at Cheriya Bet to the southern tip of the island is the reference section of this formation. However, the upper part is not exposed in this island but as parts in Gangta Bet and Nagalpur of North Wagad. It is more exposed in the southern and the eastern outcrops- Kakindia Bet, Kara Bir, Gora Bir and in the series of hills between Maiya Wandh to Nagalpur on Desalpur-Fatehgadh Range between Wagad and Bela islands.

The fossiliferous bands in Hadibhadang Shales are full of bivalves, gastropods, corals and local occurrence of *Rhynchonella*. The limestone bands in Hadibhadang Sandstone member are full of crinoid stems and plates besides Rhynconellids, gastropods and bivalves. Gadhada sandstone and Bhambanka Shale members are also highly fossiliferous and also contains ammonites. Kakindia limestone band, an important fossiliferous marker band near the top of the Gangta member, is also highly fossiliferous. The sequence of lithological and biological characteristics of members of this formation indicates intertidal to sub-tidal environment suggesting deepening of the basin with the sedimentation.

Based on the occurrence of *Corbula lyrata* and *Gervillia* sp. Assemblage (Cox, 1940), the Khadir Formation is assigned an age of Bathonian to Callovian. Pascoe (1959) mentioned Argovian age for the Gangta bed and therefore the age of the formation extends at least upto Early Oxfordian. Prasad and Kanjilal (1985) reported "*athlete* assemblage zone" representing *P. athleta* which is equivalent to *Athleta* bed of Waagen (1873), lower and upper Athleta beds of Spath (1927-33) and Athleta and unnamed zone of Krishna (1984). Recently, *Semirugosus* and *Maya* subzones of "*Maya* assemblage zone"; and *Helenae* and *Kranaus* subzones of "*Helenae* Assemblage zones" were reported by Patel et al (2012) which indicate an age of Early to Middle Oxfordian for Gangta member. Therefore, the age of this Formation is assigned to be Bathonian to Middle Oxfordian.

2.3.2.1.3.2 Washtawa Formation

A lithologically distinct unit occurs below the Wagad Sandstone Formation in similar stratigraphic position as the Bhambhanka/Gangta members of Khadir Formation. This unit is named as Washtawa Formation after its designated type section in Washtawa dome, north of Washtawa. This formation is exposed as a large oblong inlier in Wagad Sandstone Formation at the centre of Wagad Highland. It is also exposed around Chitrod in southern and Narada in Northern Wagad at the cores of the dome.

The shaly facies in the western part is richly fossiliferous while the sandy facies in the east bara few calcareous bands containing bivalves and gastropods. Several red ferruginous marlstone bands, called Kanthkot ammonite bands occurring in the uppermost shale bed near Kanthkot yields a rich crop of ammonites together with belemnites, bivalves, gastropods and fossil wood.

The facies pattern, lithological association, fauna and its distribution suggest shallowing of depositional environment from sub-tidal to inter-tidal from west to east. This formation is equivalent to the Gangta member and thus was considered to be of early Oxfordian age. However, Krishna et al (1998) described Late Oxfordian ammonites form these bands and concluded that the Washtawa Formation represents a complete succession of Oxfordian in Kachchh and is conformably overlain by the Kimmeridgian beds of Kanthkot member.

2.3.2.1.3.3 Wagad Sandstone Formation

The sandstone conformably overlying the Khadir and Washtawa Formations, in northern and central Wagad respectively have been included in this formation which is named after Wagad where it is extensively and exclusively exposed. In western Wagad, the formation has two distinct components members – a lower marine and an upper non-marine, whereas ineastern Wagad, it is represented only by non-marine sandstones. The marine sandstone member named as Kanthkot member after its type section in the scarp of Kanthkot Fort Hill passes laterally into non-marine sandstone in eastern Wagad where it is indistinguishable from the upper non-marine Gamdau member which is named after the stream flowing near Gamdau village. This Formation is extensively exposed in Wagad Highland and occurs also in the eastern part of the Desalpur-Fatehgadh hills of Northern Wagad between Gedi and Mora. Isolated patches are also exposed in Mardakh, Kesmari and Venasar bets of the Little Rann, suggesting its continuity with the Dhrangadhra Sandstone of Kathiawar underneath the Rann cover.

The Wagad sandstone shows the facies of Bhuj Formation indicating a similar deltaic environment. The sedimentation of the Wagad Sandstone shows intertonguing marine and non-marine lithosomes which is an ideal example of delta front zones at the cratonic border of a marginal basin. Towards east, in the direction of the shore, the non marine facies transgress the time plane downward with the vertical shift of environment from intertidal to deltaic.

On the basis of the ammonites and faunal studies, the “Kanthkot member” is assigned an age younger than Argovian, i.e., Late Oxfordian or Kimmeridgian (Pascoe, 1959; Krishna et al, 1998; Biswas, 2002). The overlying “Gamdau member” containing Ptylophyllum and its isochrones (in Eastern Wagad) are seemingly continuous with the Dhrangadhra Sandstone of Kathiawar which suggests at least Early Cretaceous (pre-Aptian) age. Therefore, the age of this Formation ranges from Late Oxfordian to Early Cretaceous (pre-Aptian).

2.4 STRUCTURE AND TECTONICS

2.4.1 INTRODUCTION:

Kachchh Basin is a pericratonic embayment through a marginal graben between Nagar Parkar and Saurashtra uplifts, respectively to the north and south. The basin is limited on east by the Radhanpur arch and extends offshore and encompasses the Kachchh continental shelf in west. Biswas (1980, 1981, 1982, 1987, and 2002) has discussed the structure, basin architecture and its evolution. Accordingly, the regional slope of the basin is towards WSW and the depositional axis passes close to the Saurashtra uplift to the south. The Indus shelf hinge extended perpendicular to the depositional axis which formed a first order basement high, i.e. median high, across the middle of the embayment (Biswas, 1987) trending NNE-SSW. This meridional high passes transversely across both positive and negative elements of the basin so that the uplifts plunge bilaterally and the sub-basins have a central high or shallow region. The basin is deeper to the west of the high with thicker accumulation of sediments showing facies change from shallow to deeper shelf; and it is shallow to the east of the high with less thickness of sediments showing facies change from shallow marine to intertidal and fluvial.

2.4.2 UPLIFTS AND FAULTS:

The Median High that controlled the facies and thickness of sediments is a tectonised zone along the hinge line of the basin and is featured by intense faulting, folding and intrusions. Structurally, the basin is featured by residual basement ridges along the primordial faults that are parallel to the major Precambrian tectonic trends (Biswas, 1982). These ridges are foot wall uplifts with intervening half grabens that remained as the passive highs within the basin during the deposition. Later these highs were rejuvenated by the reactivation of the faults and are manifested in sub-parallel uplifts with narrow flexures along the master faults (Biswas, 1980). The vast mud and salt flats of the Great and the Little Ranns of Kachchh and Banni plains occupied the “residual depressions” that surrounded the uplifted areas. The graben/half-grabens thus formed different depositional domains, sub-basins, for rift-fill sedimentation and the domal structures, that exposed older Mesozoic strata offering the opportunity for the detailed studies, were formed by the culmination along the marginal flexures (Biswas, 2002). Moreover, the scattered uplifts show typical geometry of tilted basement blocks draped over by thin sediment cover, long gently sloping back limbs and short quasi-vertical to over turned forelimbs.

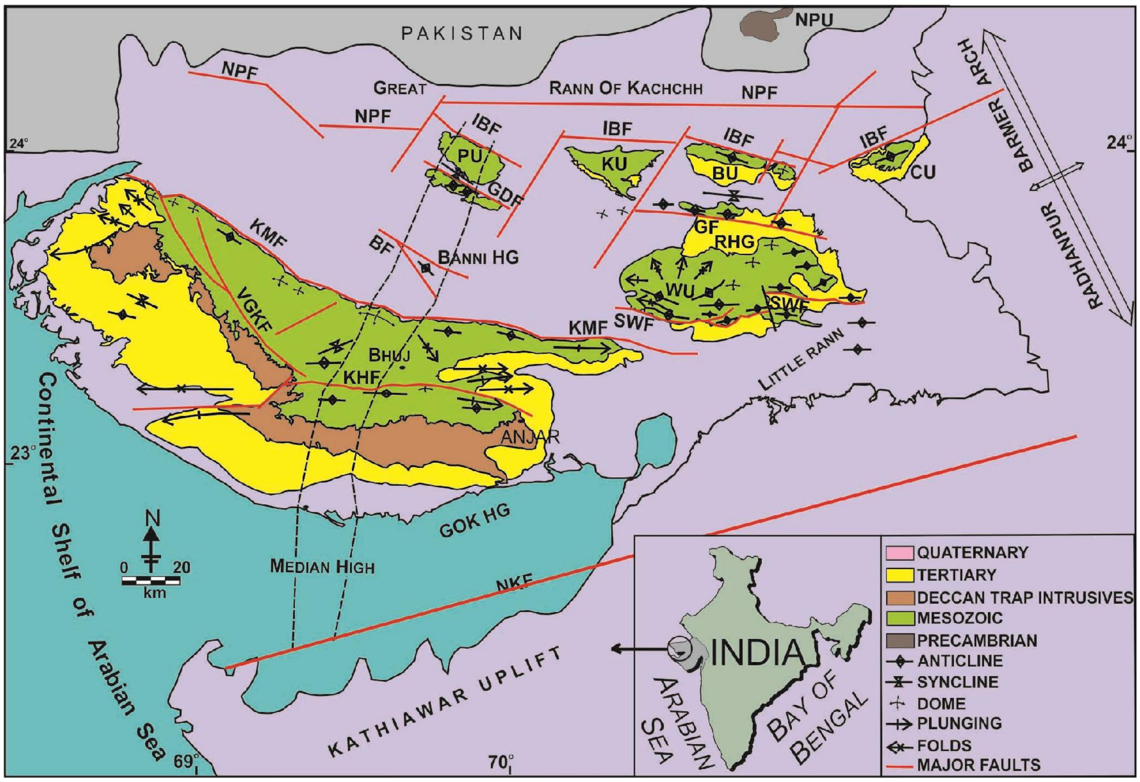


Figure-2.2 Geological and structural map of Kachchh Basin (Biswas and Deshpande, 1970 & 1973; and Biswas, 1982 & 1987).

The uplifts are oriented E-W along five parallel faults (Fig.2.2): (1) Nagar Parkar fault (NPF), (2) Island Belt fault (IBF), (3) South Wagad fault (SWF), (4) Kachchh Mainland Fault (KMF), (5) North Kathiawar fault (Biswas, 1980). Block tilting along these faults during the rift phase extension gave rise to four sub-parallel linear ridges: Nagar Parkar uplift (NPU), Island Belt uplift (IBU), Wagad uplift (WU), and Kachchh Mainland uplift (KMU). Accordingly, the IBU is broken into four individual uplifts presumably by unexposed transverse wrench faults as evidenced by relative displacements and orientations: Pachcham uplift (PU), Khadir uplift (KU), Bela uplift (BU), and Chorar uplift (CU). These uplifts appear as a chain of islands standing amidst the plains and hence collectively called as Island Belt. Several small faults related uplifts occur in line with the bigger ones (e.g., Kuar Bet - NW of PU, Kakindia, Karabir, Gorabir, and Gangta bet occur between KU and WU) which are defined by fault-bounded domes and/or faulted anticlines.

2.4.3 OUTLINE OF STRUCTURE AND TECTONIC:

The Kachchh Mainland fault (KMF) sidestepped to left with the shift of uplift form south to the north and continues eastward as South Wagad fault (SWF). This left stepping KMF/SWF seems to be the principal strike-slip fault that divided the basin into two main domains of sedimentation, the Banni half-graben (BHG) and Gulf of Kachchh half-graben (GOK HG) which acted as principle intra-rift fault along the rift axis (Biswas, 2002). The pattern of occurrence and the location of all the uplift blocks in the eastern part of the basin suggest an echelon arrangement with respect to KMU and right lateral shift along the respective faults. This suggests that the compressive inversion stage, which evolved the present structural style, had two phases of wrenching; the oblique slip with vertical component predomination in the initial stage of divergent wrenching followed by dominant horizontal stress during later stages of convergent wrenching. The absence of younger sediments in the Mainland half-graben against Katrol Hill fault (KHF) in KMU and Kaladongar half-graben against Goradongar fault tend to suggest that these faults, KHF and GDF, are late generation faults originated by thrusting during the inversion tectonic phase.

CHAPTER-3
MESOZOIC ROCK-STRATIGRAPHY OF THE STUDY AREA

3.1 INTRODUCTION

The Kachchh basin has most complete record of Mesozoic from Late Triassic (not exposed) to Early Cretaceous sediments. These sediments were deposited in a sheltered gulf and sublittoral to deltaic environments in two major cycles: a Middle Jurassic transgressive cycle and a Late Jurassic –Early Cretaceous regressive cycle (Biswas, 1981). In the Early Cretaceous time, the Kachchh Basin got filled up and the sea began to recede. The Mesozoic sediments were uplifted; folded, intruded and covered by the Deccan Trap basaltic flow in Late Cretaceous – Early Paleocene time (Biswas 1987). The structure of the basin with all the major faults controlling the basin is already discussed in chapter.2. Among these, the linear uplift along the Island Belt fault has given rise to positive elements or ridges which comprises of oldest Mesozoic sedimentary rocks (Biswas, 1987).

The Mesozoic rocks of Kachchh basin range in age from Middle Jurassic to Lower Cretaceous and are exposed in six disconnected areas which are major uplift zones that form highlands amidst extensive plain land- (a) Kachchh Mainland, (b) Patcham Island, (c) Khadir Island, (d) Bela Island, (e) Chorar Island and (f) Wagad Highland. The mainland outcrop exposes a continuous succession from Bajocian to Albian. The oldest sequence from Bajocian to Oxfordian is exposed in the northernmost "island" outcrops-Patcham, Khadir, Bela and Chorar, collectively referred as the "Island Belt". In Patcham Island, Bajocian to Callovian rocks are exposed and Bathonian to Oxfordian are exposed in Khadir, Bela and Chorar. The Wagad, placed in between the Mainland and the Island belt, exposes intermediate sequence between Late Callovian (Patel et al, 2012) to Portlandian (Biswas, 2002).

The study area, Patcham Island is characterized by the Kaladongar and the Goradongar Hill Ranges which are manifestation of the master-faults (Kaladongar and Goradongar faults of Patcham Island) along the margins, one among the principal structural lineaments of the Kachchh Basin (Biswas, 1977). This Patcham uplift is composed of (1) a north Kaladongar anticline associate with partially exposed Kaladongar fault, (2) a southern Goradongar fold zone associated with a subsidiary longitudinal fault (Goradongar fault), (3) a central syncline with its trough close to the Goradongar fault, and (4) an islet Kuar bet, 2 km north of the Patcham island separated by the island belt fault.

3.2 LITHOSTRATIGRAPHY

Biswas (1977) classified the Mesozoic rocks of Patcham Island into two: lower Kaladongar and upper Goradongar formations (Fig.1); subdivided into three and four informal members, respectively. These rocks are highly fossiliferous containing abundant body fossils of bivalves, gastropods, brachiopods, corals and echinoderms. The granite-cobble-conglomerate in Kaladongar sandstones indicates the closeness of the basement and an increase in clastics and a decrease in faunal content suggest the proximity of the northern margin of the basin.

Pandey (1983), Pandey et al (1984), Agrawal and Pandey (1985) and Fürsich et al. (1994) found that the Raimalro Limestone member of Biswas (1977) was co-relatable with the classical Patcham Formation of Jumara of Rajnath (1932) and Poddar (1964) on the Mainland. They also found resemblance in the facies and fossils of the overlying Modar Hill member of Biswas (1977) with the overlying Patcham Formation of the Mainland and thus suggested the term “Khavda Formation” for classifying all the beds below the Raimalro limestone of the Patcham Formation. They recognized the Gadaputa Sandstone member and the Goradongar Yellow Flagstone member of Biswas’ (1977) within the Khavda Formation in descending order in the Sadhara section. Moreover, due to difficulty in recognizing the boundaries between the members of Kaladongar Formation of Biswas’ (1977) in Sadhara, they subdivided this part into four informal members: the Middle Sandstone member, the Lower Yellow Flagstone member, the Eomiodon Red Sandstone member and the Sadhara Coral Limestone member, in descending order (Table.1). Fürsich et al (1994) briefly described the distribution and succession of each of these members in the Sadhara dome.

The present study however, well recognizes the boundaries between the members of Biswas (1977) and considers his rock-stratigraphic classification for the whole Patcham

Island instead of the one proposed by Fürsich et al (1994) which is based on the Sadhara dome of Goradongar Hill of Patcham Island.

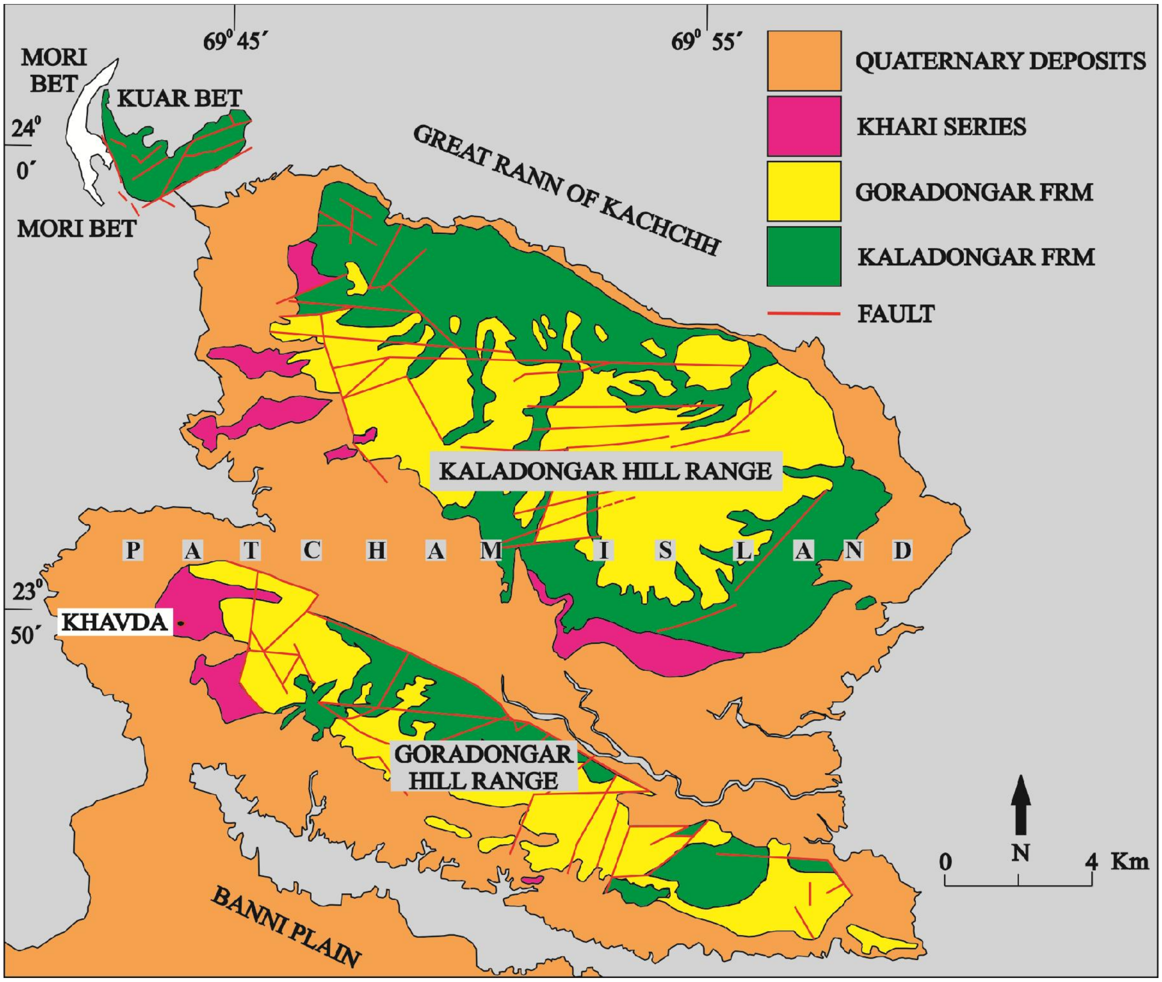


Figure-3.1 Geological and Structural map of the Study area, Patcham Island and Kuar bet (Biswas and Deshpande, 1973).

3.2.1 KALADONGAR FORMATION:

A thick sequence of conglomerate, sandstone and shale fully developed in the Kaladongar (Black Hills) Range of Patcham Island constitutes the oldest stratigraphic unit of Kachchh formally named as the Kaladongar Formation (Biswas, 2002). The type sections are designated to the section exposed in the lofty scarp facing the Rann, below the highest Babia Peak, and along the stream west of Narewari Wandh (Biswas, 1977). The sedimentary rocks of the Kaladongar Formation are exposed in the Kaladongar and Goradongar Range. The oldest beds are exposed in the Dingy hill and in Kuar bet islet, NW of Patcham Island, which is last outcrop within the Indian Territory.

MAINLAND (Waagen, 1875)		**GORA DONGAR AND KALA DONGAR** (Biswas, 1980)		**GORA DONGAR** (Pandey, 1983, Pandey et al, 1984, Agrawal and Pandey 1985)		**SADHARA** (Fürsich et al, 1994)		**AGES**
		Khari Series (Neogene)		(Tertiaries)		(Tertiaries)		
CHARI FM	Macrocephalus Beds	GORADONGAR FM	Modar Hill mb	KHAVDA FM	Kakkar mb	CHARI FM	Macrocephalus Beds	Lower Callovian
PATCHAM FM	Patcham Limestone of Jumara	GORADONGAR FM	Raimalro Limestone mb	KHAVDA FM	Taga mb	PATCHAM FM	Raimalro Limestone Mb	Upper Bathonian
PATCHAM FM		GORADONGAR FM	Gadaputa Sandstone mb	KHAVDA FM	Taga mb / Kharidongari mb	KHAVDA FM	Gadaputa Sandstone Mb	
PATCHAM FM		GORADONGAR FM	Goradongar Flagstone mb	KHAVDA FM	Kharidongari mb	KHAVDA FM	Goradongar Yellow Flagstone Mb	Middle Bathonian
PATCHAM FM		KALADONGAR FM	Babia Cliff Sandstone mb	KHAVDA FM	Pachhmaipir mb	KHAVDA FM	Middle Sandstone mb	
PATCHAM FM	Base not exposed	KALADONGAR FM	Babia Cliff Sandstone mb	KHAVDA FM	Pachhmaipir mb	KHAVDA FM	Lower Yellow Flagstone mb	
		KALADONGAR FM	Kaladongar Sandstone mb	KHAVDA FM	Pachhmaipir mb	KHAVDA FM	Eomiodon Red Sandstone mb	
		KALADONGAR FM		KHAVDA FM	Pachhmaipir mb	KHAVDA FM	[gap]	
		KALADONGAR FM	Dingy mb	KHAVDA FM	Chappar bet mb	KHAVDA FM	Sadhara Coral Limestone mb	Upper Bajocian ↓

Table-3.1 Lithostratigraphic framework of the Middle Jurassic rocks of Patcham Island.

The Kaladongar Formation comprises of ~465m thick sequence and is subdivided into three informal members; (i) Dingy Hill/Kuar Bet member, (ii) Kaladongar Sandstone member, and (iii) Babia Cliff Sandstone member (Biswas, 1977). The Dingy Hill member (Bajocian) shows intercalated sandstone-shale sequences; the Kaladongar Sandstone member (Bajocian) is chiefly consist of various types of calcareous sandstone with thin shale layers; while the Babia Cliff Sandstone (Bathonian), although resembling Kaladongar Sandstone member, can be differentiated by the presence of a thin bed of olive green bed overlain by thin grey, hard, calcareous siltstone band.

3.1.1.1 Dingy Hill Member/Kuar Bet Member:

Biswas (1977) states that this member consists of thinly bedded alternations of green and red siltstones and brown and gray, hard, calcareous sandstones in the lower part and pink to brownish, massive current bedded sandstones containing thin bands and lenses of granite-pebble-conglomerate, interbeds of shales, siltstones and thin fossiliferous calcareous sandstones. Accordingly, the rocks exposed at the Kuar bet are same in gross lithology as the Dingy Hill member but the exact correlation is not possible due to lack of marker beds.

The present study carried out in the island recognises Biswas' (1977) Dingy Hill member (DHM) exposed at Chhappar bet (+120 m), Dingy hill (+173 m), and along the traverse from Kuran village to Kaladongar hill (+184 m) and its equivalent Kuar Bet member (KBM) exposed at Kuar bet (+263 m). This member predominantly shows intercalations of sandstones and shale while the upper part of the Chhappar bet succession shows presence of siltstone-shale intercalations.

The Kuar Bet of Mesozoic is unconformably underlain by the Miocene limestone at Kuar bet (Plate 3.1a). The Kuar Bet member comprises of intercalations of poorly to moderately bioturbated sandstone and shale (Plate 3.1b) and it is highly fossiliferous towards the top of the succession. The oldest shale bed is exposed at the core and the rolled fragments of corals and large piece of wood (locally the fossilized trunk of the tree) are seen preserved towards the core part i.e. in the lower part of the Kuar bet succession. The physical sedimentary structures like climbing, asymmetrical, and interference ripples; convolute and cross-beddings; herringbone structure; planar laminations; and biogenic structures are observed at different level in the succession (Patel et al, 2010).

The Dingy Hill member exposed at Chhappar bet (Plate 3.1c) is sparsely bioturbated in the lower part of the succession, above which the succession consists of fossil wood, corals, bivalves and brachiopods. In the lower part, sandstone dykes cutting the Chhappar bet sediments are also observed (Plate 3.1d). The characteristic changes from fossiliferous and/or bioturbated to massive towards the upper part of the succession through a thin conglomeratic band in between. The upper succession shows intercalation of siltstone and shale overlain by sandstone-shale sequence. The Dingy Hill member, exposed at dingy hill (Plate 3.1e and f), consists mainly of sandstone-shale intercalation showing presence of cross beddings locally. It is highly fossiliferous and shows presence of fossil wood, corals in the upper part of the succession. The Dingy Hill member exposed at Kaladongar hill shows intercalation of sandstone-shale which is overlain by the intercalation of sandstone-siltstone sequence. The whole succession is highly bioturbated while the exposed lower sandstone beds of sandstone-shale sequence consist of fossil wood and fossil bone. Kuar bet and Dingy hill contains many bivalves (*Corbula*, *Astarte*, *Gervillia*, *Perna*, *Mytilus*) and gastropods - *Turritella* (Biswas, 1977).

The appearance of these sediments (field exposure) is similar to the sandstones, siltstones and limestones but they fall neither under the pure siliciclast (>95% clasts) sediment nor under the pure carbonates (>95% non-clastics) sediments. It display a wide compositional variations ranging in percentage between the siliciclast and the carbonate sediments and thus considered to be "mixed siliciclastic-carbonate sediments", a term profoundly used for such impure rock types (Mount, 1985; Zonneveld et al., 2001; McNeill et al., 2004; Ryan-Mishkin et al., 2009; Flugel, 2010). Patel et al (2010) and Jaquilin et al (2012b) also classified sediments of Kuar Bet member and Dingy Hill member respectively. Thus, Dingy Hill member exposes mixed siliciclastic sediments intercalated with shale and minor conglomeratic bands in Dingy hill, Chhappar bet and Kaladongar Range.

3.1.1.2 Kaladongar Sandstone Member

Biswas (1977) differentiated the dingy hill member and the overlying Kaladongar sandstone member by the top of dingy hill member marked by a fossiliferous, calcareous siltstone band (*Corbula* bed). Accordingly, he classified Kaladongar Sandstone member comprising gray to brown, massive, medium to coarse grained, quartz-arenites becoming calcareous towards the top, contains thin bands and fossiliferous calcareous sandstones at intervals and wedges of petromictic granite-cobble-conglomerate in the north-eastern part of the island. The Kaladongar Sandstone member constitutes the greater portion of the formidable northern scarp of Kaladongar Range and is also well exposed in the lower half of the Goradongar scarp. The type section of this member is exposed to the east of Kuran and on the Kaladongar scarp between Narewari wandh and Nir wandh.

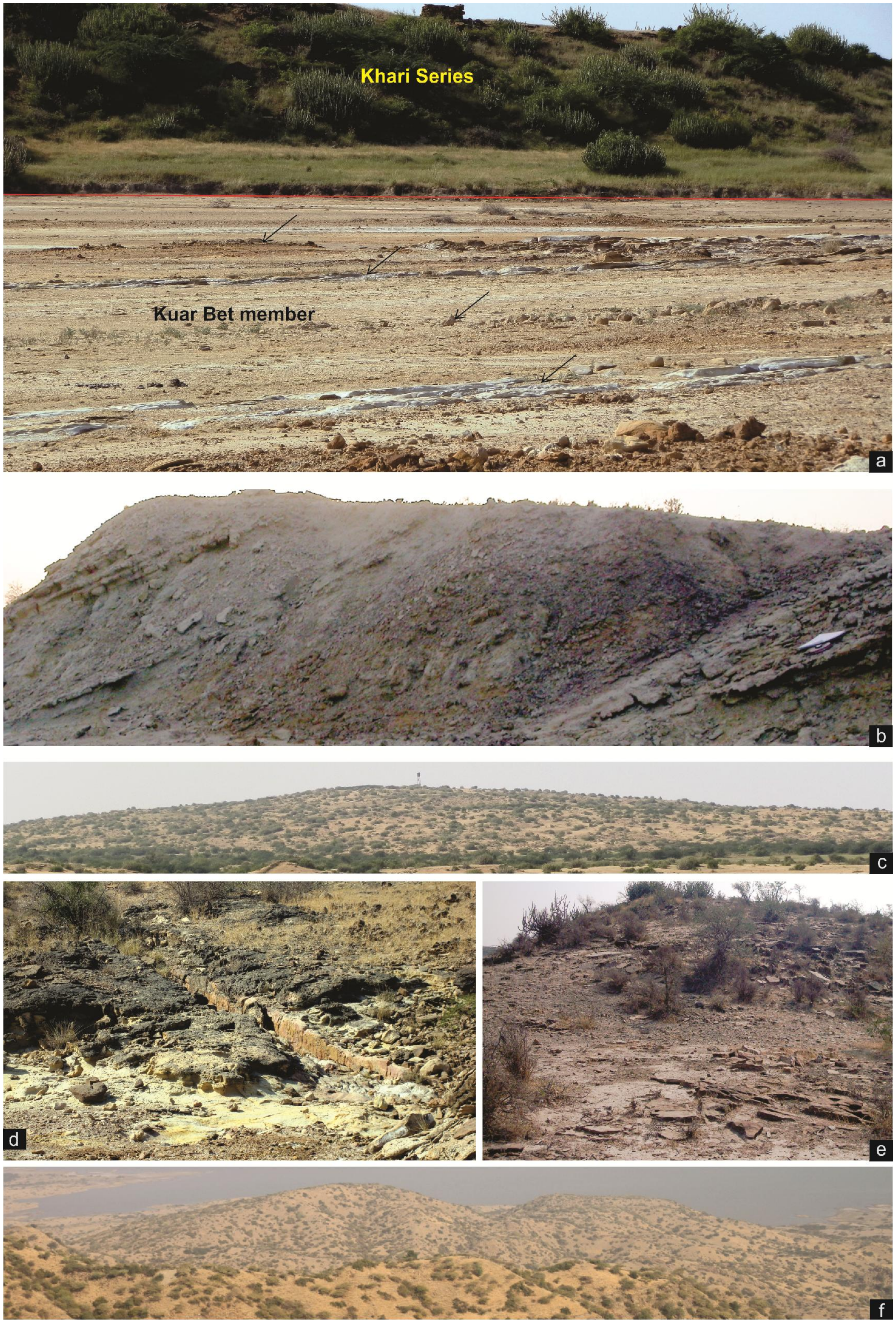

Khari Series
Kuar Bet member
a
b
c
d
e
f

Plate 3.1 Exposures of Dingy Hill/Kuar Bet members exposed at Kuar bet, Dingy Hill and Chhappar bet. **(a)** Angular Unconformable contact between the KBM (Mesozoic) rocks dipping towards south and the overlying Khari Series (Miocene) rocks at Kuar Bet, NW of Patcham Island; **(b)** Intercalated sandstone-shale sequence of KBM Kuar bet; **(c)** The Panoramic view of Chhappar bet rocks from the Dingy hill; **(d)** Intrusive (dyke) in intercalated sandstone-siltstone sequence of DHM exposed at Chhappar bet; **(e)** Sandstones exposed at Dingy hill, Patcham Island; **(f)** Panoramic view of the twin hills of Dingy, Patcham Island.

The present study identified the type section of Kaladongar Sandstone member (KSM) exposing ~ 98 m thick successions, to the east of Kuran in Kaladongar Hill (Plate 3.2a) and approx., +28.4 m at Sadhara dome in Goradongar Range. It commonly comprises non-fossiliferous and non-bioturbated massive sandstone (Plate 3.2c) and siltstone with an exception of sandstone-shale band (Plate 3.2b) that is highly bioturbated and fossiliferous (*Corbula*) calcareous units in Kaladongar Range while it is found to be highly bioturbated and fossiliferous (*Corbula*) in the Goradongar Range. The whole succession of Kaladongar Sandstone member represents impure rock units and thus falls under the mixed siliciclastic-carbonate sediments (Jaquilin et al, 2012b; Patel et al, *In press* a).

3.1.1.3 Babia Cliff Sandstone Member

Brown to mauve coloured, soft, compact, massive, well sorted, fine grained sandstones comprises the lower part of the member while brown, hard compact, massive fine to medium grained, well sorted, calcareous sandstones comprises the upper part of the member (Biswas, 1977). According to him, the Babia Cliff Sandstone member (BCSM) is well exposed below the Babia peak of the Kaladongar Range and in the upper cliffs of the Goradongar scarp. Fürsich et al (1994) studied this member in Sadhara dome but was unable to correlate with Biswas (1977) succession and divided into two members, Lower Yellow Flagstone and Middle Sandstone members.

In the present study, Babia Cliff Sandstone member exposes +71 m thick succession of siltstone overlain by thick beds of sandstone, below the Babia peak of Kaladongar Range, and ~ 9-10 m thick massive sandstones in Tuga (Plate 3.2e), Dhorawar and Sadhara dome (Plate 3.2d) of Goradongar Range. In Kaladongar range, the lower part of the succession comprises of brown to mauve coloured bioturbated sandstones showing presence of sedimentary structures like ripples, planar laminations and trough cross-bedding, and body fossils of bivalves (*Corbula*, *Trigonia*), gastropods (*Turitella*), echinoide spines and fossil wood in the lower part of the succession while calcareous rich bioturbated massive fine grained sandstone beds (Plate 3.2f), speckled with red grains of hematite in the upper part of the succession.

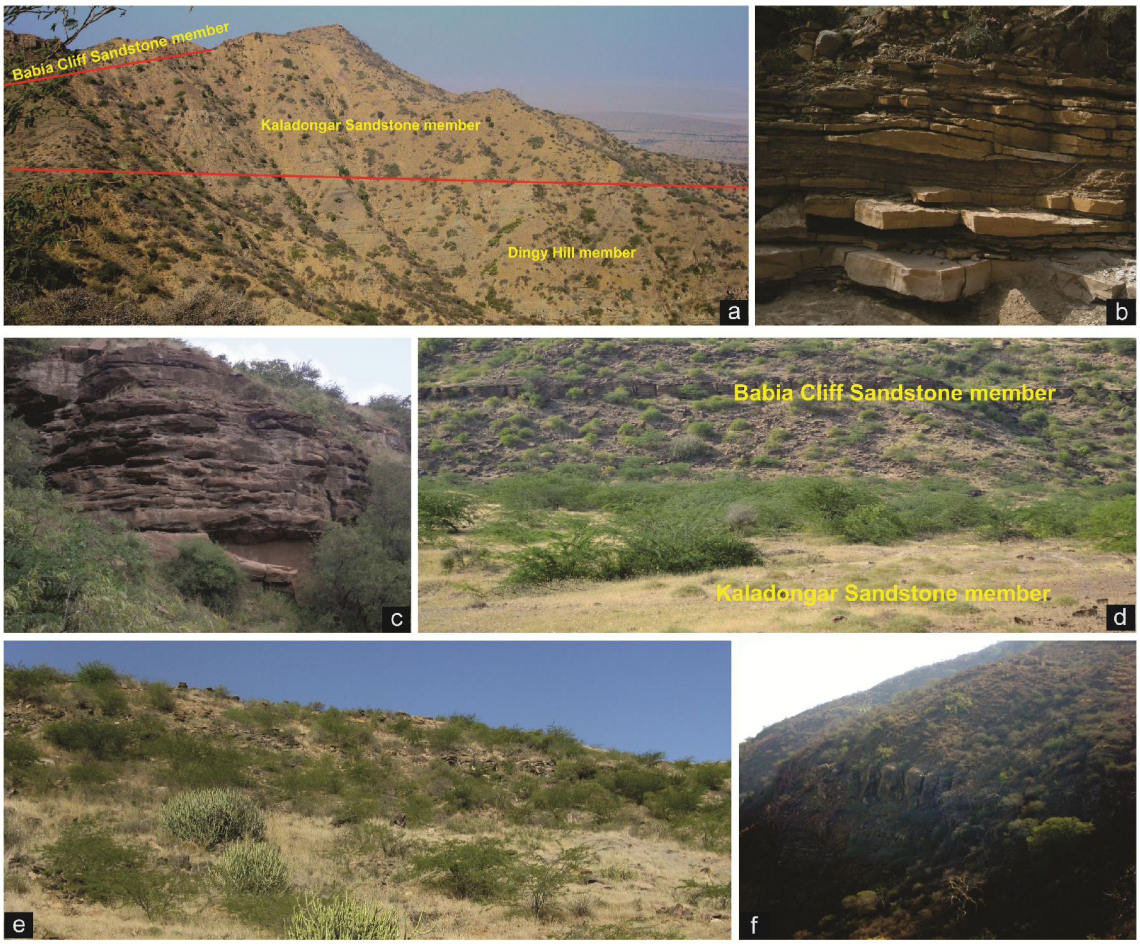


Plate 3.2 Exposures of the Kaladongar Formation exposed in Kaladongar and Goradongar Ranges. **(a)** Conformable contact between DHM, KSM, and BCSM in Kaladongar Range; **(b)** Lower sandstone beds of KSM; **(c)** The upper part of the succession of KSM, Kaladongar Range; **(d)** BCSM overlying KSM in Sadhara dome; **(e)** Upper part of BCSM exposed at Tuga Village, Goradongar Hill range; **(f)** Upper part of the succession of BCSM exposed at Kaladongar Hill Range, Patcham Island.

The upper part of the succession often shows presence of conglomeratic bands locally. In Goradongar scarp exposed near Tuga village, it comprises of buff coloured fine to medium grained thickly bedded calcareous sandstone; locally pebbly and cross-bedded in nature; while near Dhorawar village, it comprises of buff coloured medium grained feldspathic sandstone. At Sadhara dome, it comprises of massive sandstone which is locally fossiliferous containing beds of *Corbula* and Echinoide spines. These sediments comprising the Babia Cliff Sandstone member display a wide variety classifying them into impure rock unit i.e. mixed siliciclastic-carbonate sediments (Jaquilin et al, 2012b).

3.2.2 GORADONGAR FORMATION:

A sequence of limestone shale and sandstone above the Kaladongar Formation is grouped under this Formation which is named after its type locality, Goradongar (white hills) range. The complete sequence of the formation is seen in the southern flank of Goradongar Range. It is Bathonian-Callovian in age (Fürsich et al, 1994) and mainly consists of mixed siliciclastic–carbonate sediments with shales and limestone (Patel et al, *in press* a & b). This formation comprises of 152 m thick succession which is subdivided into four informal members: the Goradongar Flagstone, Gadaputa Sandstone, Raimalro Limestone and Modar Hill members (Biswas, 1977). The present study however, comprises of ~144.4 m thick succession of Goradongar Formation, distributed in the back slopes of Goradongar Range near Gadaputa, Dhorawar, Juna, Tuga and Sadhara villages, and Raimalro and Modar hills.

3.2.2.1 Goradongar Flagstone Member

The Goradongar Flagstone member is the most widespread unit of the Formation and forms a thin cap over the Kaladongar Formation (Biswas, 1977). It consists of thinly bedded to flaggy, gray and yellow limestones containing fossiliferous and golden oolitic bands which resemble “member F” of the “Jhurio Formation” (Biswas, 2002). The thinness in bedding imparts the flaggy character in the sandstone beds which is interbedded with the limestone/calcareous shales.

In the present study the sediments of the Goradongar Flagstone member (GFM) comprises 6-8 m thick succession exposed at the back slopes of Goradongar Range near Tuga, Dhorawar, Paiya (Plate 3.3a) and Sadhara villages. Near Paiya village section, the Goradongar Formation comprises of ~3 m intercalated flaggy limestone and shale sequence. In Dhorawar village, the Goradongar Flagstone member comprises of ~6.1m thick yellow, hard, flaggy fossiliferous, bioturbated limestones with thin interbeds of shale while in Tuga village, ~8 km southeast of Dhorawar, it comprises of ~6m thick yellow, flaggy, bioturbated and fossiliferous mixed siliciclastic-carbonates with a thin intercalation of golden oolitic limestone within the shale layer. Section exposed near Sadhara village shows 2-3 m thick bioturbated, fossiliferous (*Corbula*, *Gervillae*) flaggy mixed siliciclastic-carbonate sediments.

3.2.2.2 Gadaputa Sandstone Member

The Gadaputa Sandstone member comprises of pale brown to pink, massive, current bedded, medium to coarse grained quartz-arenites becoming calcareous upward (Biswas, 2002). According to Biswas (1977), the Gadaputa Sandstone member consists almost entirely of pale brown to pinkish, massive soft, poorly sorted, medium to coarse grained, felspathic sandstones. These sandstones shows an increase in calcareous content upward and towards the top they are well bedded and grade from hard calcareous sandstones to arenaceous limestones and finally to Raimalro limestone.

In the present study, the Gadaputa Sandstone member (GSM) comprises of ~10m thick succession of brownish, massive to fine grained bedded sandstone which becomes calcareous on top in Raimalro hill; and Dhorawar, Paiya, Juna, and Tuga (Plate 3.3b and c) villages. It is highly bioturbated and shows presence of cross bedding and ripple marks but has very less of fossil content. In Sadhara dome, this member shows maximum thickness of ~12.3 m and comprises of thick sequence of bioturbated sandstone-shale intercalation overlain by bioturbated limestone-shale sequence which further becomes fossiliferous on top. They consist of few dykes cutting them and also showed pyrostructures rarely. These sediments are also identified and classified under the category of mixed siliciclastic-carbonate sediments.

3.2.2.3 Raimalro Limestone Member

Raimalro Limestone member (RLM) comprises of gray and yellow fossiliferous pelsparite, thickly bedded showing a characteristic change from pebbly to nodular cherty segregation along bedding to sandy nature from lower to upper part of the succession (Biswas, 2002). According to Biswas (1977), the lower part is arenaceous and occasionally pebbly, the middle pat is coarse with much less quartz and abundant chert while the upper part is composed of bedded, yellow and gray fossiliferous pelsparites with minor quantity of coarse grained quartz. Pandey and Fürsich (1998) found the upper boundary appearing to be synchronous and therefore stated that the decrease in thickness eastward is most likely due to the lateral facies change into the sandstones of Gadaputa Sandstone member.

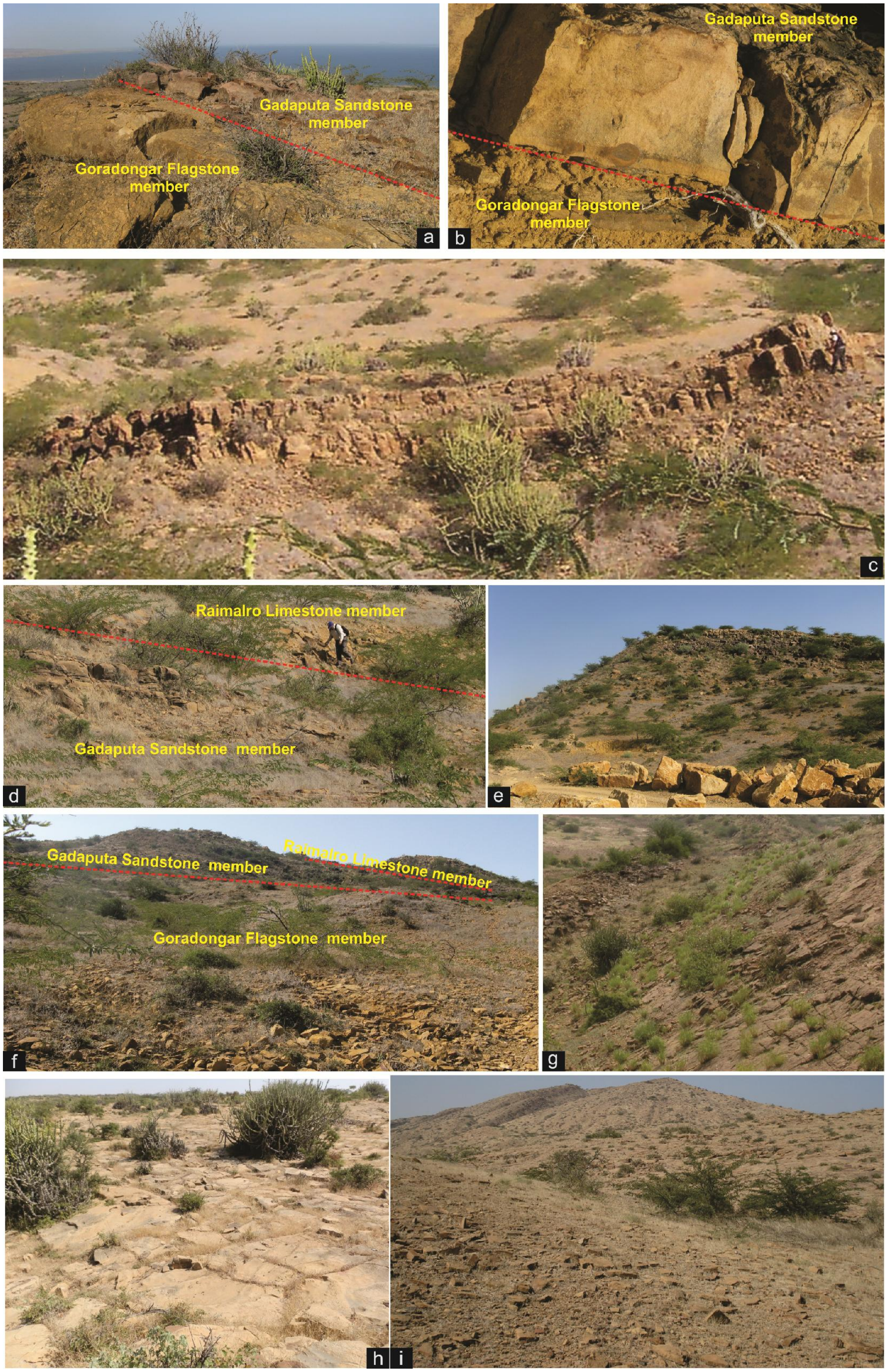

Gadaputa Sandstone member
Goradongar Flagstone member
a
Gadaputa Sandstone member
Goradongar Flagstone member
b
c
Raimalro Limestone member
Gadaputa Sandstone member
d
e
Gadaputa Sandstone member
Raimalro Limestone member
Goradongar Flagstone member
f
g
h
i

Plate 3.3 Exposures of Goradongar Formation in Goradongar Range.
(a) Fossiliferous bed of GFM in conformable contact with overlying GSM, near Paiya village; **(b)** Contact between GSM and GFM, near Tuga village; **(c)** GSM near Tuga village; **(d)** Contact between RLM and GSM, Tuga village; **(e)** Limestones of RLM, Raimalro Hill; **(f)** Contact between RLM, GSM and GFM, Paiya village; **(g)** Steeply dipping (~45%) limestone beds of RLM, exposed at Raimalro Hill; **(h)** Gently dipping (5-7%) limestone beds of RLM exposed at Sadhara dome; **(i)** Sandstone-shale intercalation of MHM, Modar Hill.

It is observed that , this member shows strong variation in thickness and comprises of grey (fresh) to yellow (weathered) coloured massive limestone with fossiliferous top (bivalves) in Dhorawar, Raimalro (Plate 3.3e) and Paiya (Plate 3.3f) villages. It shows various dips at various localities (Plate 3.3g & h). The Raimalro Limestone member exposes ~9 m thick succession of intercalated shale-limestone grading to limestone in Raimalro Hill; ~4.7 m thick bioclastic packstone bed in Paiya; ~9 m thick sequence of massive limestone with laminations, occasionally rippled and highly bioturbated in Tuga village; +2 m thick yellow massive limestone in Modar hill; +2 m thick gently inclined, yellow coloured fossiliferous limestone bed in Sadhara dome. This member shows a gradual increase in carbonate content of mixed siliciclastic-carbonate sediment upwards and forms pure limestone rock on the top; with occasional presence of abundant echinoide spines (Dhorawar and Paiya), belemnites and ammonites (Sadhara dome) and fossiliferous casts (Modar hill and Sadhara dome). It occasionally consists of few centimeters thick layers of bivalve shells arranged in concave-up and convex-up within the hard, compact massive fine grained limestone beds.

3.2.2.4 Modar Hill Member

Biswas (2002) classified "basal olive-gray fossiliferous gypseous shale with fosssiliferous flagstone and ferruginous limestone bands, overlain by gray, coarse grained, massive current bedded sandstones" into the Modar Hill member. According to Biswas (1977), the Modar Hill member starts with soft shales with limestone grading into sandstones and finally into sandstones in the upper part of the succession. Fürsich et al (2001) studied these rocks in Sadhara and proposed an informal member called as Shelly Shale member.

In the present study, the type section for the Modar Hill member (MHM) was studied in the Modar hill of Goradongar range and apart from this other exposure studied was in

Dhorawar village. It exposes ~ 92.3 m thick sequence comprising thinly bedded mixed siliciclastic-carbonate sediment layers intercalated with the shale (Plate 3.3i), grading into sandstones and overlaid by limestone-shale sequence capped by fossiliferous ferruginous sandstone, and further overlain by buff-coloured sandstone-shale intercalated beds capped by calcareous sandstones. The top of the member shows presences of bivalves and echnoid spines while the base of the member shows the presence of ammonite bivalve and gastropods. The pure sandstone beds are observed below the ammonite band, towards the base of the succession and the pure limestone occurs in the limestone-shale sequence; the rest of the succession in the sequence represents the mixed siliciclastic-carbonate sediments. Towards the top and the bottom of the succession, it is highly bioturbated and shows presence of ripple marks, cross-bedding and planar laminations. It is fossiliferous and also shows presence of clay/mud drapes at the top of the sequence.

CHAPTER 4
SEDIMENTARY FACIES

4.1 INTRODUCTION

The term "facies" is widely used in geology, especially in the study of sedimentology in which sedimentary facies refers to the sum of the characteristics of a sedimentary unit (Middleton, 1973). Amand Gressly (1838) was the first to introduce the term and concept of "facies" by systematic observation of characteristic lateral changes in Jurassic rocks of the Jura region of southern France. The facies characteristics include the dimensions, sedimentary structures, grain sizes and types, colour and biogenic content of the sedimentary record (Nichols, 2009). If the facies description is confined to the physical and chemical characteristics of a rock; or fauna and flora present; or on the trace fossils then it is respectively referred to as the "Lithofacies", "Biofacies" or "Ichnofacies" description (Miall, 1984).

The physical and chemical processes of transport and deposition of the sediments determine the lithofacies characteristics; and the biofacies and ichnofacies provide information about the palaeoecology during and after deposition. By interpreting the sediment in terms of the physical, chemical and ecological conditions at the time of deposition it becomes possible to reconstruct palaeoenvironments, i.e. environments of the past. Therefore the facies concept forms the basis for the facies analysis.

In the present study, the interpretation of the facies is objective based on the recognisation of the processes that formed the beds (Nichols, 2009). These different facies form a facies association that reflects the depositional environment (Collinson, 1969; Reading and Levell 1996).

4.2 FACIES DESCRIPTION

The Kaladongar and Goradongar Formations are exposed along the northern cliff of the Kaladongar and the Goradongar Ranges. These sequences display vertical as well as the lateral variations exhibited by sedimentary characteristics (textures and structures) and bedform geometry. The field observation and the petrographic study reveal that the sequence comprises of mixed siliciclastic-carbonate sediments intercalated with shales, sandstones, limestones and conglomerates (Fig. 4.1 and 4.2). The sandstones, carbonates and the mixed siliciclastic-carbonate sediments are classified based on Dott (1964), Folk (1959) and Mount (1985). These mixed sediments contain varying proportions of siliciclastic and carbonate materials which are categorized on the basis of four components: (1) siliciclastic sands (sand-sized quartz, feldspar, etc); (2) mud (mixture of silt and clay); (3) allochems (carbonate grains such as peloids, ooids, bioclasts and intraclasts > 20µm in size); and (4) carbonate mud or micrite (< 20µm in size) (Fig. 4.3).

A total of nine sedimentary facies were identified, including a) six mixed siliciclastic-carbonate facies namely, micritic sandstone, allochemic sandstone, sandy allochem limestone, micritic mudrock and sandy micrite; and b) pure sedimentary facies namely., ferruginous sandstone, allochemic limestone, grey shale and conglomerate facies. Each of the sedimentary facies is briefly described below along with its physical, biogenic and petrographic characters and is further interpreted briefly. The petrographical study was carried out for the textural and compositional assessment of the sediments. Although the post-depositional modification of grains were also observed but is not dealt herein because it is beyond the scope of the present work. However, the microfacies analysis within the facies is done, along with the correlation to the standard Ramp Microfacies types (RMF) of Flügel (2010).

4.2.1 ALLOCHEMIC SANDSTONE FACIES:

Allochemic sandstone facies is characterized by moderately to highly bioturbated, pale to dark brown colored sandstone. It consists of sedimentary structures like cross-bedding (Plate 4.1a), planar laminations and linguoidal (Plate 4.1b) and straight crested current ripples (Plate 4.1c) and occasionally show presence of bivalves, gastropods (Plate 4.1d), corals (Plate 4.1e-h), fossil wood (Plate 4.1g-h) and feature like load casts.

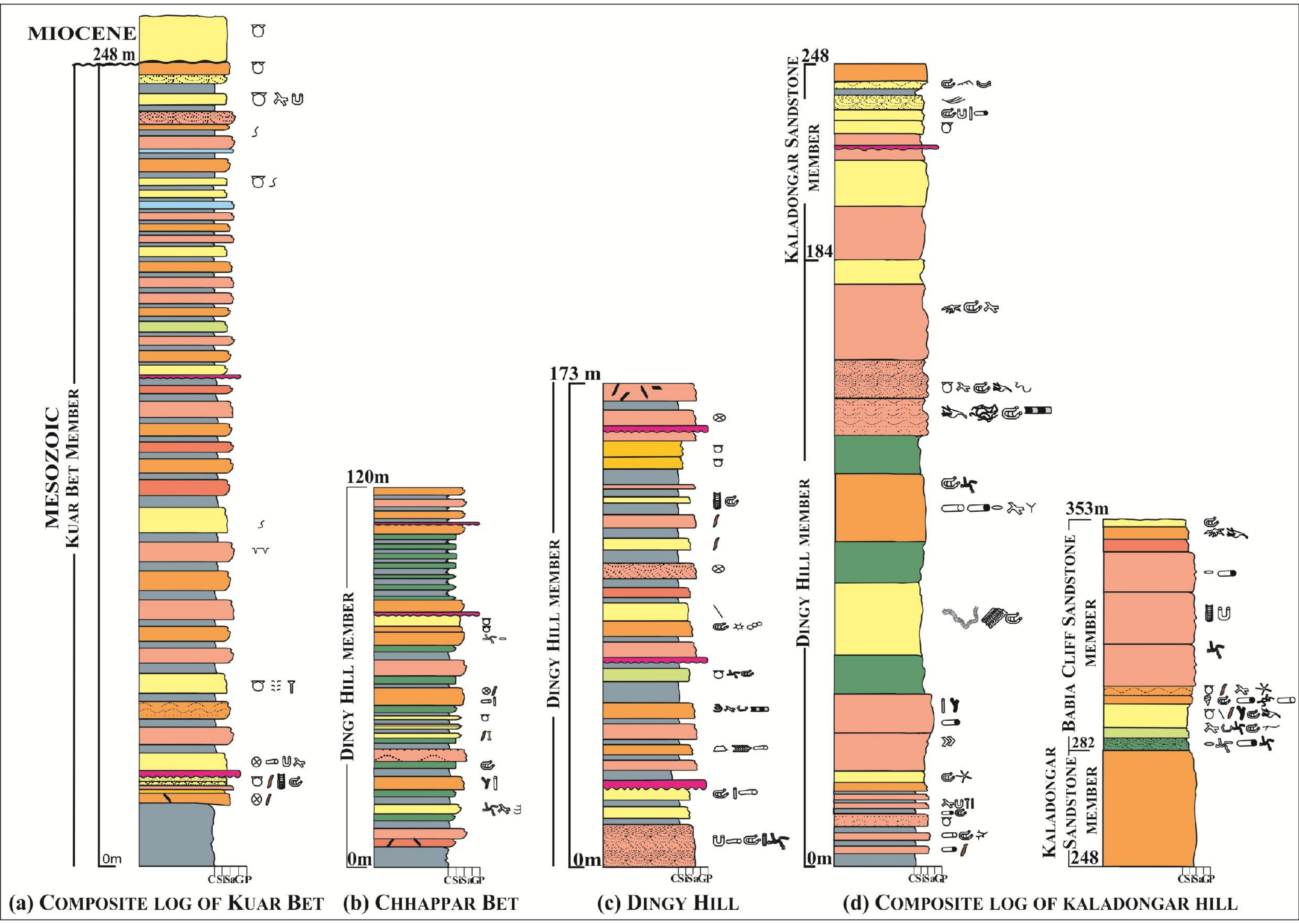
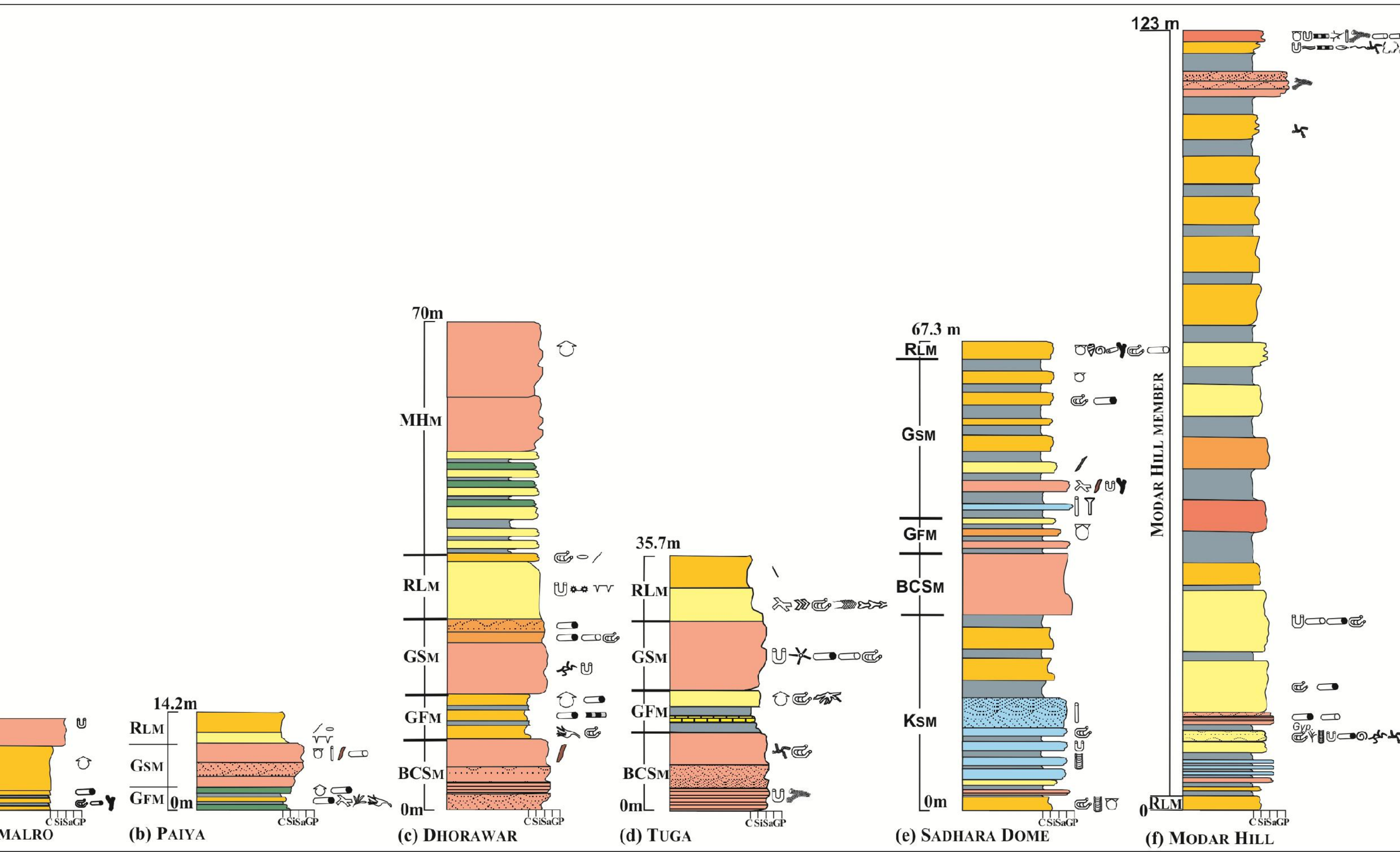
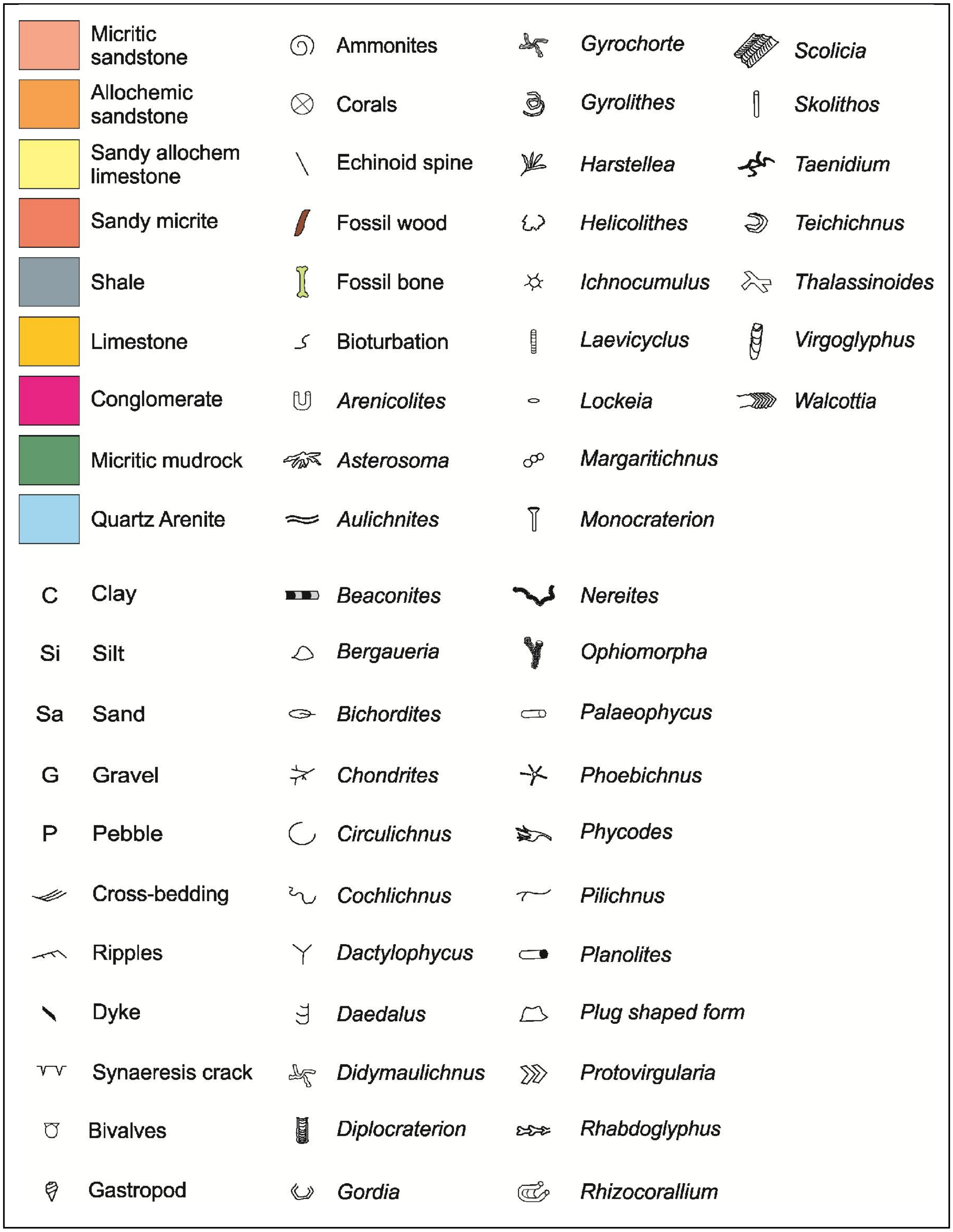


Figure-4.1 Measured lithologs of Kaladongar Formation at Kuar bet, Chhappar bet, Dingy Hill and Kaladongar range.



re-4.2 Measured lithologs of Mesozoic rocks at Paiya, Dhorawar, Tuga, and Sadhara villages; and Raimalro and Modar H
dongar Range of Patcham Island.

Legend representing the physical, biological and ichnological symbols used in present work



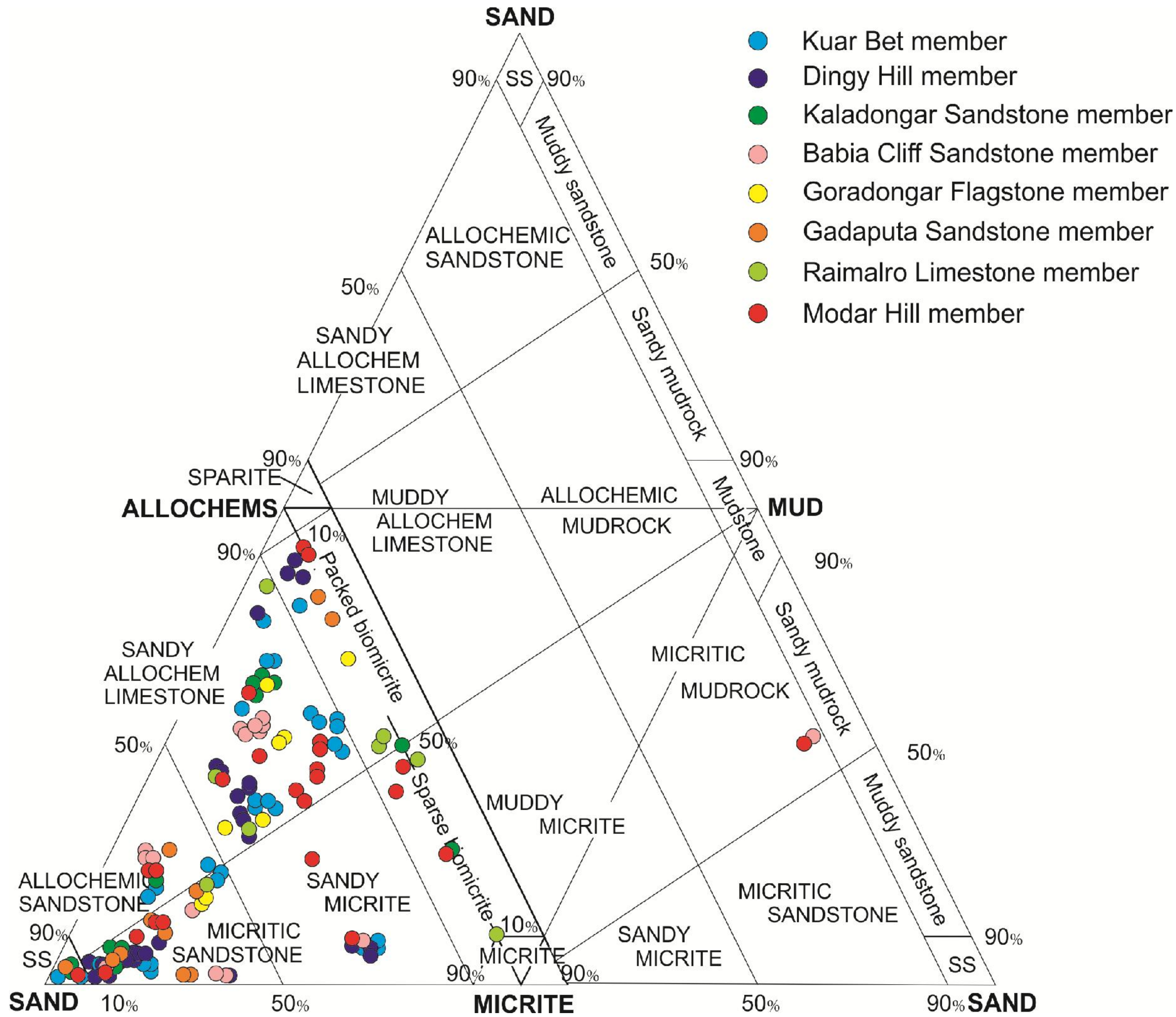


Figure-4.3 Plot diagram shows the distribution of Mesozoic mixed siliciclastic-carbonate sediments of Patcham Island in Mount's (1985) unfolded tetrahedral classification system.

It consists of trace fossils like *Arenicolites* isp., *Asterosoma radiciforme, A.ludwigae, Beaconites coronus,* ?*Bifungites* isp., *Circuliuchnus montanus*, *Cochlichnus anguineus, C.*isp., *Dactylophycus* isp., *Didymaulichnus lyelli, Diplocraterion* isp, *Gordia arcuata, Gyrochorte comosa, Gyrolithes* isp., *Hartsellea sursumramosa, Ichnocumulus radiates, Lockeia siliquaria, Margaritichnus reptilis, Ophiomorpha nodosa, Palaeophycus alternatus, P. striatus, P. tubularis, Phoebichnus trochoides, Phycodes circinnatum, P. palmatum, Phycodes cf. Palmatum, Planolites beverleyensis, Plug shaped form* cf. B*, Protovirgularia* cf. *dichotoma, P.* isp, *Rhabdoglyphus* isp, *Rhizocorallium irregular, R. jenense, R. uraliense,* *Scolicia* isp., *Taenidium serpentinum, Thalassinoides horizontalis, T. suevicus, T.* isp., and *Walcottia devilsdingli*.

This rock type is observed in Kuar Bet, Kaladongar Sandstone and Babia Cliff Sandstone members of Kaladongar Formation; and Goradongar Flagstone, Gadaputa Sandstone, and Modar Hill members of Goradongar Formation. The allochemic sandstone of maximum thickness ~34m is observed in the Kaladongar Sandstone member exposed at the Kaladongar Range while the minimum thickness ~1.87 m is observed in the Kuar Bet Member. The petrographic analysis reveals that this rock type is of mixed composition of siliciclasts and carbonates and is classified under the mixed siliciclastic-carbonate sediment.

The allochemic sandstone shows total siliciclastic (quartz, feldspar and mica) percentage greater than the carbonate sediments (calcite, allochems and micrites). It shows presence of well sorted subangular to subrounded grains of quartz (65-70%), calcite (7-10%), feldspar (2-5%), mica (0-1%), and allochems (10-15%) consisting of pellets (~5-10%), bioclast (bryozoans, fragmented bioclasts ~3-5%), corals and algae (~2%); in a micritic matrix (~10-12%).

The allochemic sandstone of the Kuar Bet member shows bioclastic to pelloidal allochemic sandstone (Plate 4.2a-b) whereas Babia Cliff Sandstone member, Goradongar Flagstone member, and Kaladongar Sandstone and Modar Hill members show bioclast dominant (Plate 4.2d), algae dominant (Plate 4.2e), and pelloid dominant (Plate 4.2c-f) allochemic sandstone.

Interpretation: The allochemic sandstone shows presence of abundant bioclast fragments, pellets/pelloids, algal fragments and few foraminifers. The relative dominance of pelloids over the bioclasts represents the lagoonal condition while the fragmented bioclasts dominance represents the high energy conditions. The dominance of allochem type observed at various stratigraphic levels of allochemic sandstone depends particularly on the geomorphic setting. This rock type represent foreshore to shoreface environment of the mixed siliciclastic inner platform/ramp settings that is dominated by high energy conditions prevalent above fair weather wave base.

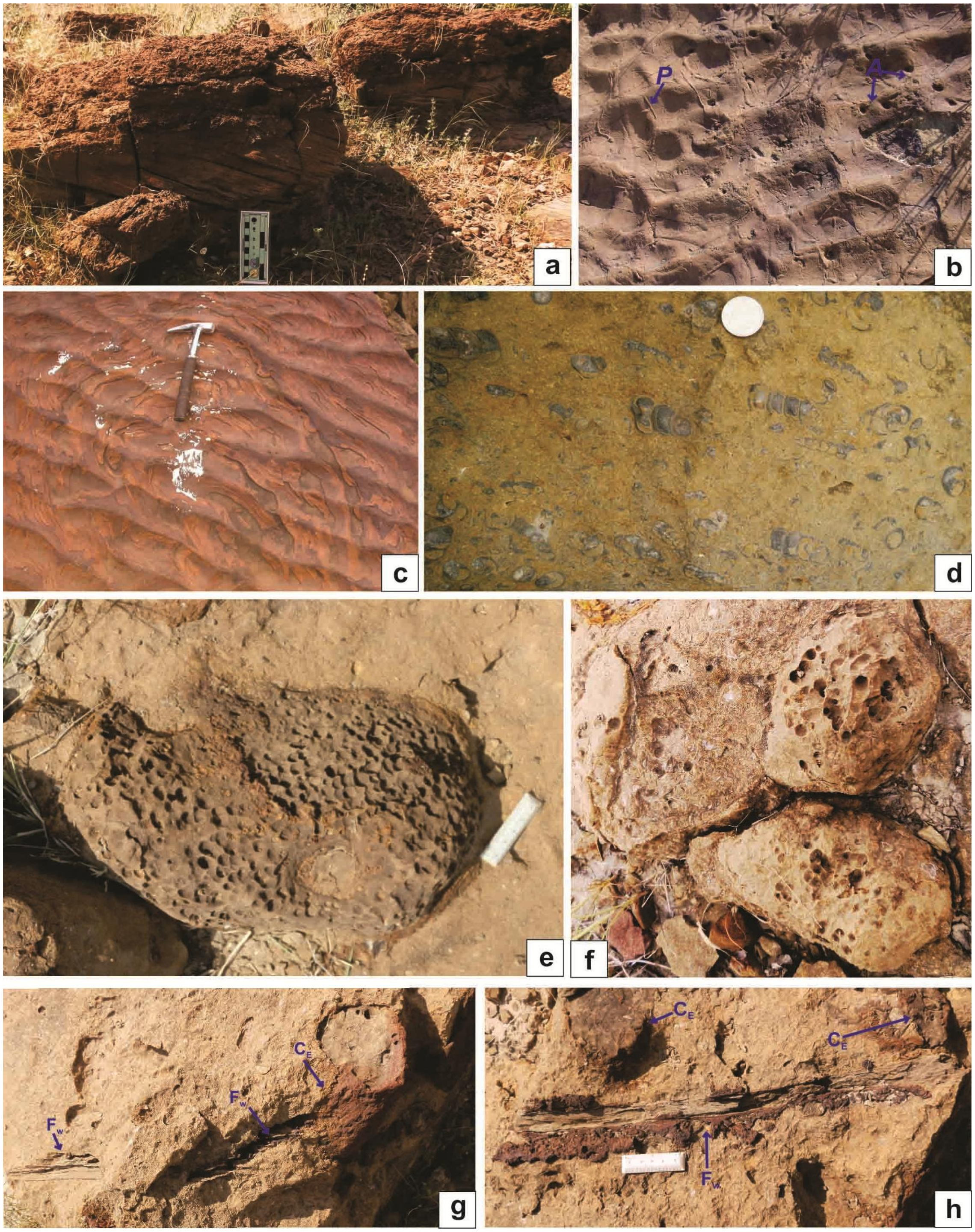


Plate 4.1 Field occurrences of allochemic sandstone facies in the Kaladongar Formation. **(a)** Cross-bedding in DHM, Dingy Hill; **(b)** *Planolites* (P) and *Arenicolites* (A) on the linguoid/lunate rippled surface of BCSM; **(c)** Straight crested current ripples of BCSM, Babia Cliff; **(d)** Transverse and longitudinal sections of gastropods observed in the BCSM; **(e)** Large coral in allochemic sandstone of DHM, Chhappar bet; **(f)** Coral colony in DHM exposed at Chhappar bet; **(g)** and **(h)** Coral fragments (CE) and fossil wood (FW) in DHM of Chhappar bet.

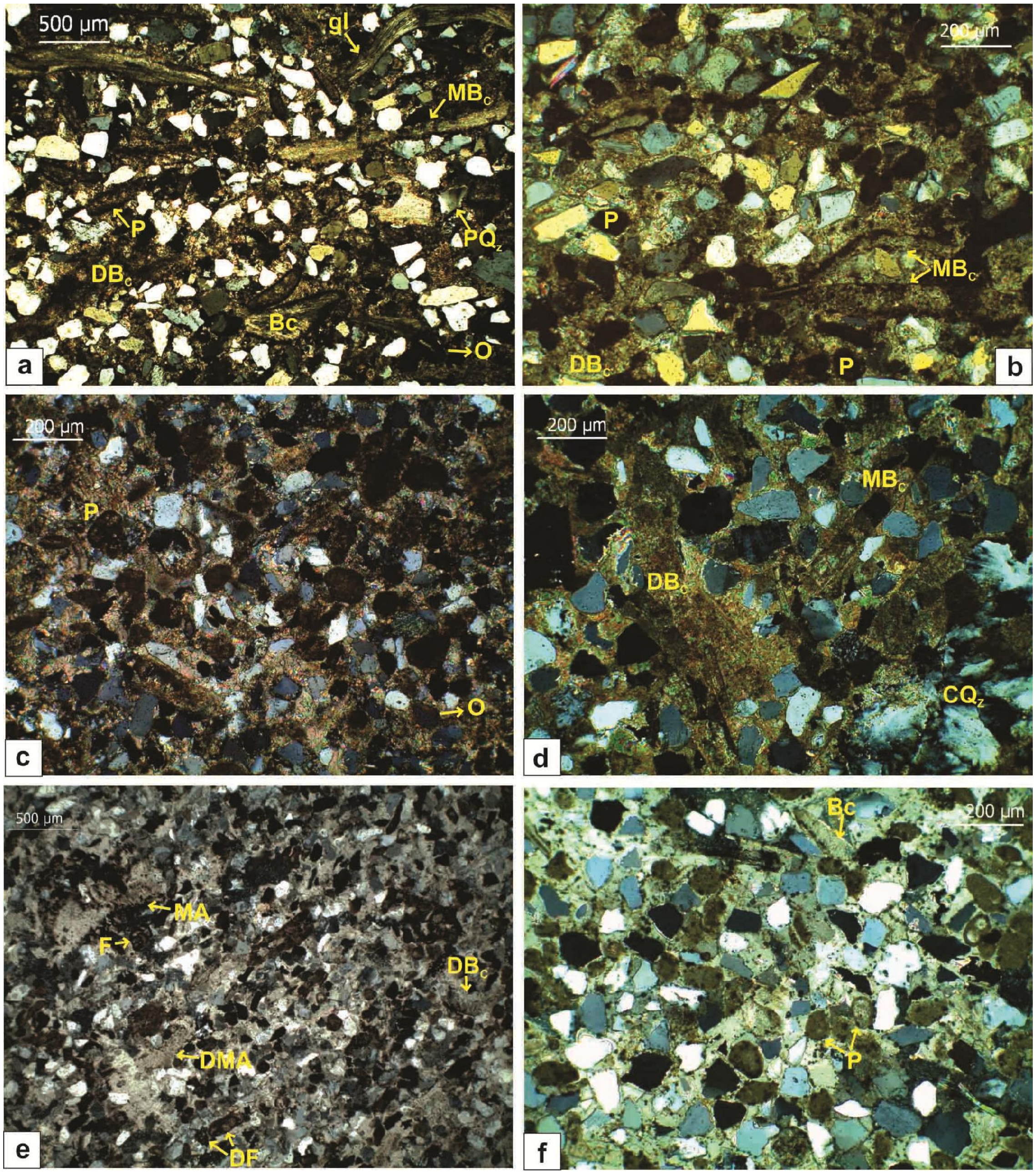


Plate 4.2 Photomicrographs of allochemic sandstone facies showing textural and compositional variations.

(a) Predominance of micritised bioclasts (MB_C) with faintly visible growth lines (gl), elongate pellets (P), quartz oolite (O) and mono- to poly-crystalline quartz (PQ_Z) in lower sequence of KBM; **(b)** Pellet (P) dominant allochemic sandstone showing micritised (MB_C) bioclast in the upper sequence of KBM; **(c)** Quartz oolite (O) in pellet (P) dominant allochemic sandstone of KSM; **(d)** Angular to subangular quartz grains with micritised bioclast (MB_C)in allochemic sandstone, upper part of BCSM; **(e)** Biserial micritised foraminifer (F) showing some visible outline, micritised bioclasts MB_C) and micritised coralline algae (MA) in GFM exposed at Sadhara Dome; **(f)** Bioclast (B_C) in Pelloid dominant allochemic sandstone of MHM, exposed at Modar Hill.

4.2.2 MICRITIC SANDSTONE FACIES:

The micritic sandstone facies comprises brown-red coloured sandstone characterized by cross beddings (Plate 4.3a), planar laminations and straight crested current ripples (Plate 4.3b) and lingoidal ripple marks (Plate 4.3c). It is commonly non-fossiliferous but occasionally shows presence of bivalves; corals (Plate 4.3d), fossil bones (Plate 4.3e) and fossil woods (Plate 4.3f). Occasionally it shows presence of synaeresis cracks in form of casts identified as the curlicue cracks of type-I and type-II showing large-sized interconnected, and small-sized either interconnected (II_{1-2}) or isolated simple forms (II_{3-4}) respectively (Plate 4.3g-h)

Few sandstone beds are highly bioturbated and consists of trace fosils such as *Arenicolites carbonarius, Bergaueria* cf. *hemispherica, Chondrites intricatus, C. targionii, Gyrochorte comosa, Laevicyclus* isp., *Lockeia amygdaloides, L. siliquaria, Monocraterion tentaculatum, Ophiomorpha nodosa, Palaeophycus annulatus, P. striatus, P. tubularis, Planolites beverleyensis, Protovirgularia dichotoma, Rhizocorallium irregular, R. jenense, Taenidium serpentinum, Thalassinoides horizontalis, T. suevicus, T.*isp., and *Walcottia devilsdingli*.

Petrographically, the micritic sandstone consists of moderately sorted, subangular to subrounded grains of quartz (~80-82%), feldspar (~3-5%), calcite (~2-5%), allochems like oolites (~0-5%), pellets (~5-10%), bioclasts (~0-5%), and micrites (~8-10%). This rock type is present throughout the Mesozoic sequence of the Patcham Island and shows variation in the proportion of the constituents with respect to its paleo-environmental conditions and settings in the basin.

It occurs in the sequence of the Kuar Bet, Dingy Hill, Kaladongar Sandstone and Babia Cliff Sandstone members of Kaladongar Formation and in Goradongar Flagstone, Gadaputa Sandstone, and Modar Hill members of Goradongar Formation. The micritic sandstone of Kuar Bet member, Dingy Hill member, and Gadaputa Sandstone member shows presence of Coralline algae (Plate 4.4a, b and f); while quartz are in abundance in Kaladongar Sandstone member (Plate 4.4c). Planar cross-beddings (Plate 4.5a) and amalgamated cross laminated (Plate 4.5b) structures are observed in micritic sandstone of Babia Cliff Sandstone member exposed at Babia cliff. Goradongar Flagstone, Babia Cliff Sandstone and Modar Hill members show dominance of bioclast (Plate 4.4e), pelloids (Plate 4.4d) and coralline-algae

(Plate 4.4h). The maximum thickness of ~ 61 m is observed in the Dingy Hill member exposed at the Kaladongar Range.

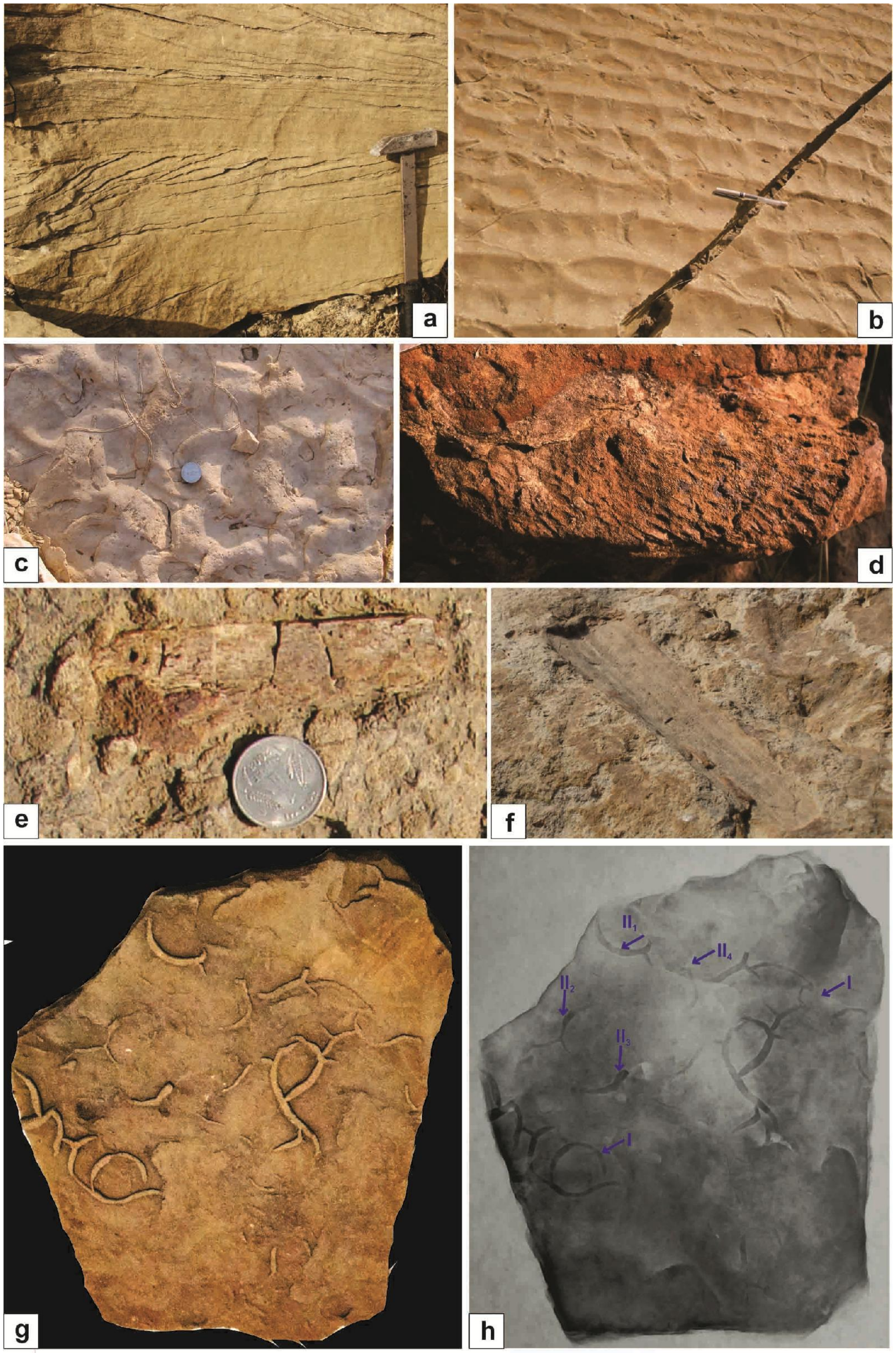


Plate 4.3 Field characteristic of micritic sandstone facies.
(a) Cross bedding in DHM exposed at Dingy Hill; **(b)** Straight-crested ripple marks in BCSM exposed at Babia Cliff of Kaladongar range; **(c)** *Gyrochorte* trials on the lingoidal ripples of DHM exposed at Chhappar bet, near to the rann; **(d)** Coral embedded in DHM exposed at Dingy Hill; **(e)** Fossil bone embedded in the micritic sandstone of the DHM exposed at Dingy Hill; **(f)** Fossil wood in the micritic sandstone of DHM; **(g)** Casts of interconnected curlicue cracks Type-I and Type-II$_{(1\text{-}2)}$ and isolated simple forms Type-II $_{(3\text{-}4)}$ in KBM in Kuar Bet; **(h)** X-ray photograph of the Type-I and Type-II of KBM.

Interpretation**:** The straight-crested current ripples and linguoid ripples suggest a unidirectional flow in lower flow regime with relatively low and high energy conditions respectively. The synaeresis cracks found in the Kuar Bet member resembled *Yakutatia* ichnogenus in appearance but the X-radiographic study of the structures revealed variable dimensions along the structures, tapering nature and sharp margin that ruled out the possibility of any biological origin (Patel et al, 2013). The different shape and size of these cracks depend upon the mode of origin. The type-I interconnected forms are suggested to be curlicue cracks formed at sediment-water interface while the smaller incomplete irregular forms of type-II representing the non-orthogonal geometry (Kidder, 1990) suggests to be substratally formed cracks (Patel et al., 2013).

The micritic sandstone of Kuar Bet, Dingy Hill, and Gadaputa Sandstone, Modar Hill members show presence of coralline-algae which suggests a restricted inner platform; while abundance of quartz in Kaladongar Sandstone member suggest relatively high energy condition while the Goradongar Flagstone and Babia Cliff Sandstone members show dominance of bioclasts and pelloids suggest shoal deposits and lagoonal condition.

4.2.3 MICRITIC MUDROCK FACIES:

It is characterized by yellow to brown coloured rock having planar laminations. It shows presence of bivalve fossils (Plate 4.5c) and trace fossils such as *Rhizocorallium irregulare, Lockeia siliquaria, Gyrochorte comosa, Didymaulichnus lyelli,* and *Planolites beverleyensis* (Plate 4.5c) are observed.

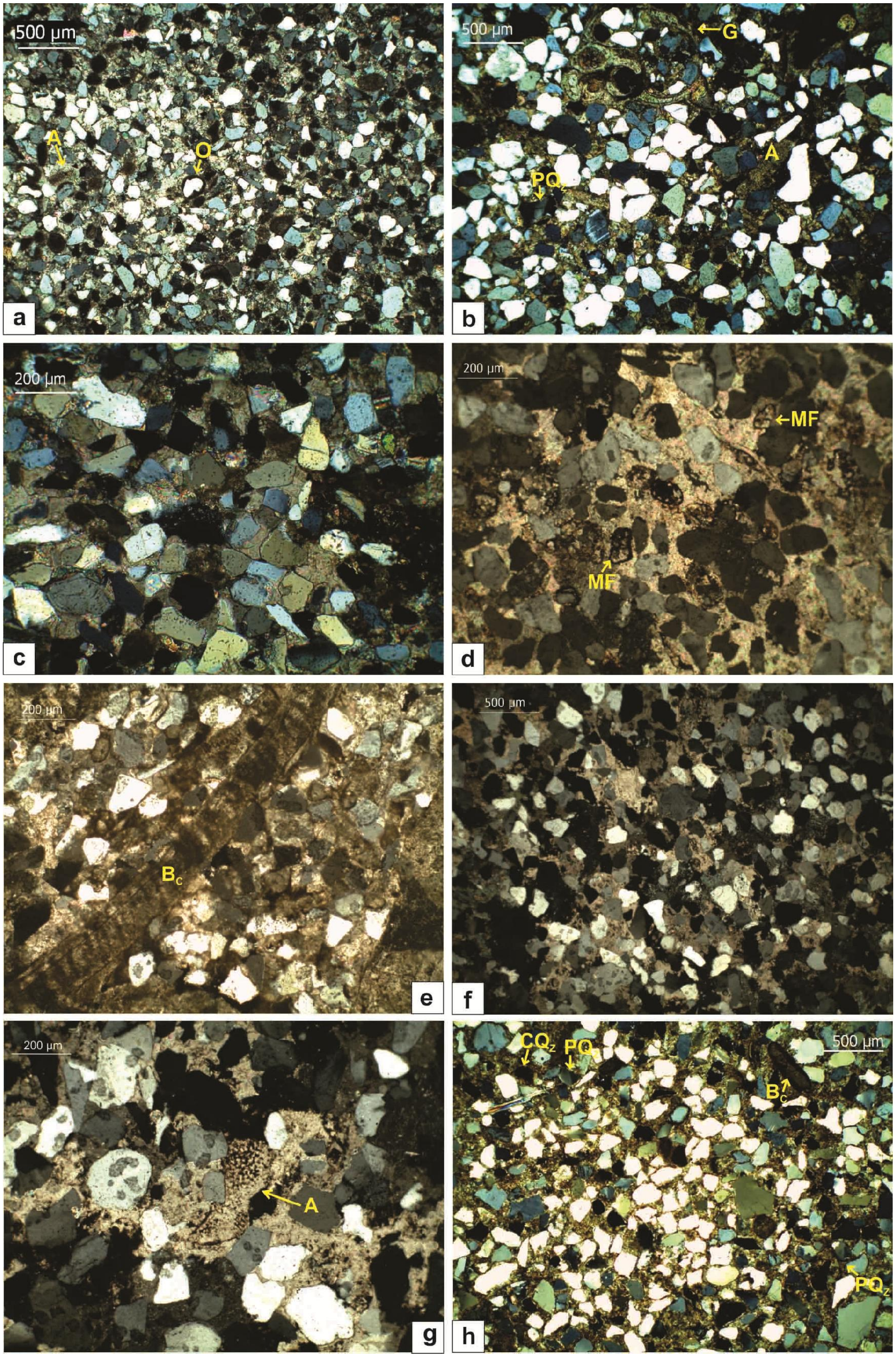

500 µm
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Plate 4.4 Photomicrographs of micritic sandstone facies is showing textural and compositional variations. **(a)** Coralline algae (A) and quartz-oolite (O) in micritic sandstone of KBM; **(b)** Longitudinal section of Gastropod (G), coralline algae (C), and polycrystalline quartz (PQ_Z) in micritic sandstone of DHM; **(c)** Quartz grains embedded in micritic matrix representing micritic sandstone of KSM; **(d)** Coarse to fine grained quartz and micritised foraminifers (MF) in micritic sandstone of BCSM; **(e)** Corroded quartz and bioclast fragment in micritic sandstone of GFM exposed at Sadhara dome; **(f)** Micritic sandstone of GSM in Sadhara dome; **(g)** Coralline algae (A) in micritic sandstone of GSM exposed at Sadhara; **(h)** Monocrystalline, polycrystalline (PQ_Z) and corroded quartz (CQ_Z) grains, bioclasts (B_C) and pelloids in micritic sandstone of MHM.

Petrographically, the micritic mudrock shows siliciclastic proportion more than the carbonate proportion but amount of sand and allochem percentage to be lesser than the mud and micrite respectively. They show presence of moderate to well sorted, sub-angular to sub-rounded grains of finer to coarser silt-sized quartz (60-65%) and calcite (2-5%) with allochems (0-5%) consisting of oolites, pellets and algae in micritic matrix (25-30%).

It is observed in the Dingy Hill and Babia Cliff Sandstone members (Plate 4.5d) of Kaladongar Formation; and in Goradongar Flagstone and Modar Hill members (Plate 4.5e-f) of Goradongar Formation. The maximum thickness observed is ~ 7 m in Dingy Hill member.

Interpretation**:** The micritic mudrock shows sedimentary structures of cross bedding and planar lamination which suggests medium flow regime and the presence of oolites, pellets and algae represents the lagoonal environment behind the shoal deposits or barriers.

4.2.4 SANDY ALLOCHEM LIMESTONE FACIES:

It comprises dark brown to black coloured sandy allochem limestone characterized by planar laminations small cross bedding (Plate 4.6a) and ripples (Plate 4.6b) and contains body fossils of bivalves (Plate 4.6c), ammonite fragment (Plate 4.6d), echinoderms (Plate 4.6e) with abundant echinoid spines (Plate 4.6f), and presence of large fossil woods (Plate 4.7a-b) and fossil bones (Plate 4.7c); It is also observed to be baked in Sadhara dome due to the dyke intrusion (Plate 4.7d). Occasionally it shows presence of casts and grooves of synaeresis cracks of the curlicue form of Type-III, which show interconnected V-shaped non-orthogonal cracks (Plate 4.7e) and few incomplete forms of cracks (Plate 4.7f) in Dhorawar and Paiya respectively.

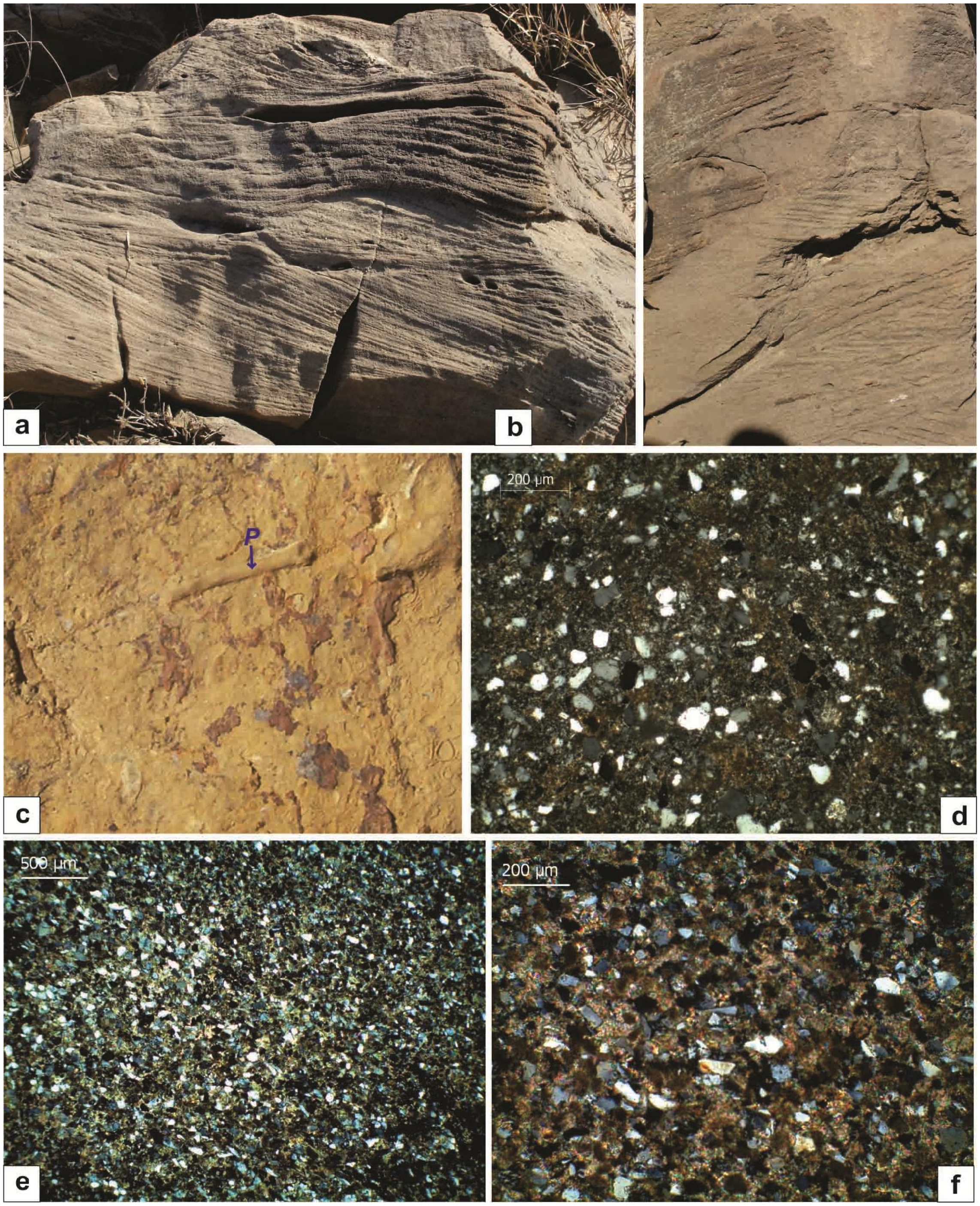


Plate 4.5 Field characteristic micritic sandstone and micritic mudrock facies and photomicrographs of micritic mudrock facies.

(a) Planar cross-beddings in micritic sandstone of BCSM; **(b)** Amalgamated cross laminated micritic sandstone of BCSM; **(c)** *Planolites* in fossiliferous micritic mudrock of GFM; **(d)** Photomicrograph of micritic mudrock of BCSM; **(e)** Silt-sized quartz in micritic matrix, micritic mudrock of MHM; **(f)** Silt-sized quartz with sutured outline in micritic mudrock of MHM.

Plate 4.6 Field characteristics of sandy allochem limestone facies of Kaladongar Formation. **(a)** Cross-bedding in KSM exposed near Kuran village; **(b)** Rippled surface in KSM; **(c)** *Trigonia* bed in BCSM; **(d)** Broken fragment of ammonite in MHM; **(e)** Echinoderms preserved in the sandy allochem limestone of BCSM, Note: attached echinoid spines; **(f)** Randomly oriented long echinoid spines in BCSM.

Sandy allochem limestone is highly bioturbated and consists of trace fossils such as *Arenicolites carbonarius, Chondrites intricatus, Daedalus* cf. *verticalis, Diplocraterion* isp, *Gordia arcuata, G.* isp., *Gyrochorte comosa, Lockeia amygdaloides, Monocraterion tentaculatum, Nereites missouriensis, Ophiomorpha nodosa, Palaeophycus tubularis, Phoebichnus trochoides, Phycodes palmatum, Pilichnus dichotomus, Planolites beverleyensis, Rhizocorallium irregulare, R. jenense, R. uraliense, Scolicia prisca,* and *Thalassinoides suevicus*.

It is observed in the sections of Kuar Bet, Dingy Hill, Kaladongar Sandstone and Babia Cliff Sandstone members of Kaladongar Formation and in Raimalro limestone and Modar hill members of Goradongar Formation. The maximum thickness ~23 m is observed in the Dingy Hill member of Kaladongar Range while the minimum thickness ~2.72 m is observed in the Kuar Bet member.

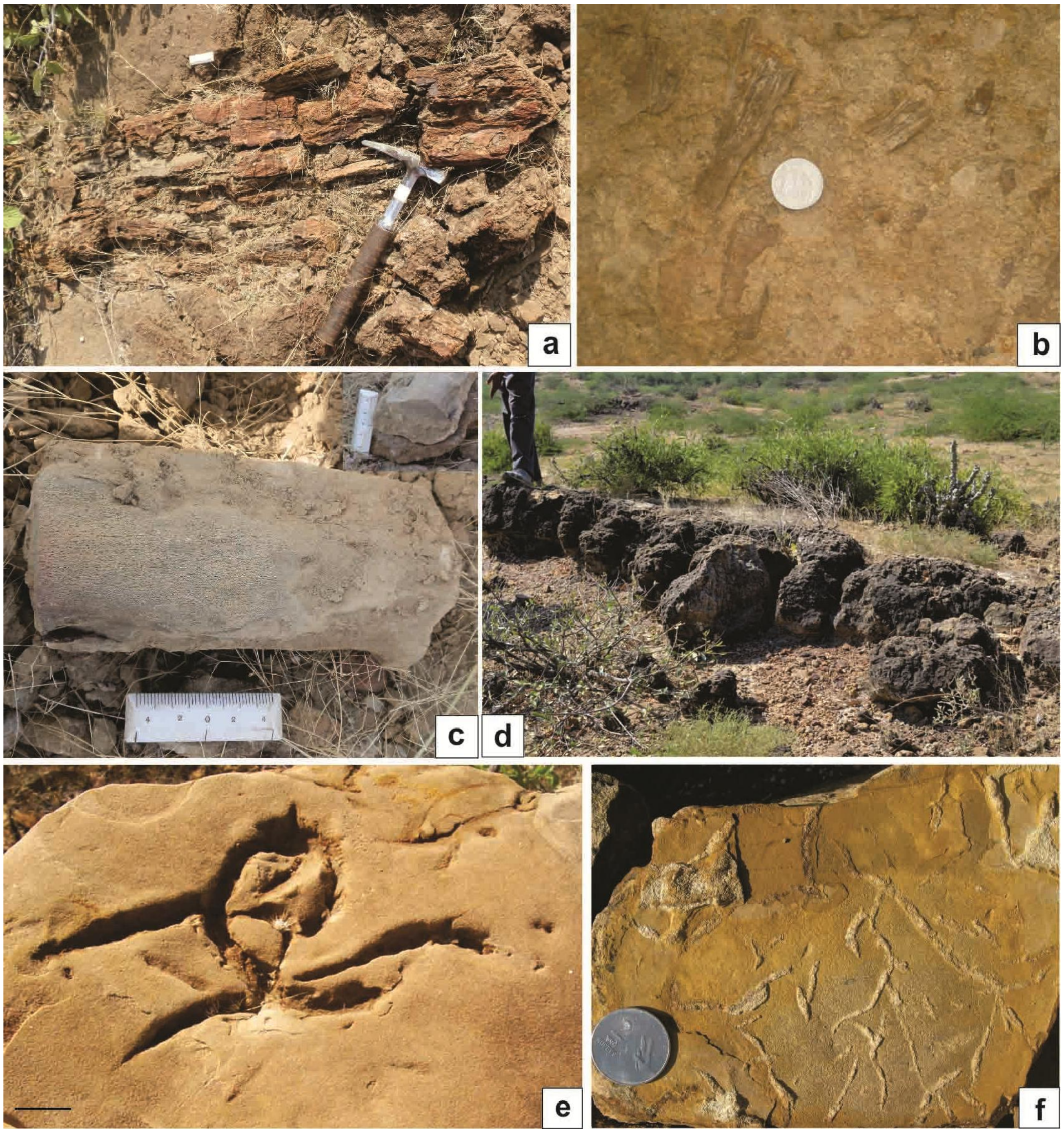
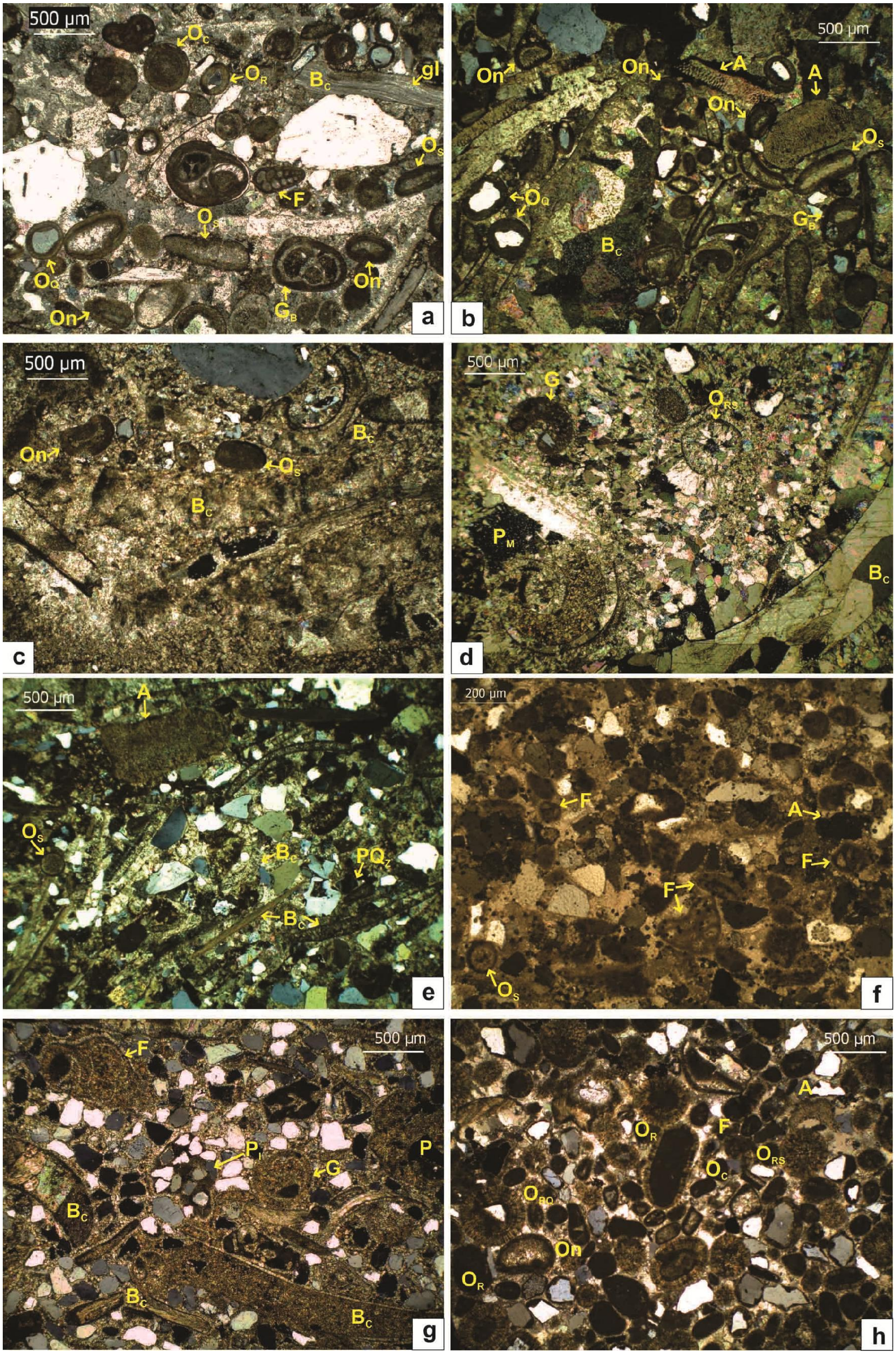


Plate 4.7 Field characteristics of sandy allochem limestone facies.
(a) Large fossil trunk (~ 90 cm long) preserved in the sandy allochem limestone of DHM; **(b)** Fossil wood pieces embedded in the sandy allochem limestone of BCSM; **(c)** ~20 cm long and 8 cm thick (inset photo) bone found in the DHM exposed in Chhappar bet; **(d)** Sandy allochem limestone bed showing baking effect by the intrusion of dyke in GSM exposed at Sadhara dome; **(e)** Groove of Type-III v-shaped curlicue crack in RLM exposed at Dhorawar village; **(f)** Incomplete cracks (casts)filled with calcites exposed at Paiya village.



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a
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A
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P_M
e
f
200 µm
PQ_Z
g
h
P_I
P
O_{RQ}

Plate 4.8 Photomicrographs of sandy allochem limestone facies of Kaladongar Formation. **(a)** Ooids of Superficial (O_S), concentric (O_C), radial-fabric (O_R) and quartz-nuclei (O_Q),, oncoliths (On), botryoidal grain (G_B), bioclasts (B_C) preserved with original growth lines (gl) and foraminifer (F) in oolitic sandy allochem limestone of KBM; **(b)** Oolitised algae (A) formed into oncoids (On), superficial ooids (O_S), and dedolomitised bioclast fragment of oolitic-bioclastic sandy allochem limestone of KBM; **(c)** Neomorphic bioclasts (B_C),with superficial ooids (O_S) and oncoliths (On) in bioclastic sandy allochem limestone of KBM; **(d)** Radial sparry calcitic ooilite (O_{RS}), oblique view of micritised Gastropod (G) and mouldic porosity (PM) in neomorphosed bioclasts (B_C) of DHM; **(e)** Bioclasts (B_C) showsoriginal structures and partly neomorphosed with superficial ooids (O_S), and mono-to poly-crystalline quartz grains (PQ_Z) in sandy allochem limestone of KSM; **(f)** Multichambered biserial to trochospiral foraminifers (F), algae (A), superficial oolite (O_S) and quartz grains in Foraminiferal sandy allochem limestone of KSM; **(g)** Micritised and neomorphosed bioclasts (B_C), gastropods (G) and foraminifera (F); grainstones; and quartz grains in the bioclastic sandy allochem limestone showing porosity (P) and intergranular porosity (P_L), BCSM; **(h)** Radial-fibrous (O_R), radial-sparite (O_{RS}), quartz-radial (O_{RQ}) oolite and oncolites in oolitic sandy allochem limestone of BCSM.

Petrographically, the sandy allochem limestone show proportion of carbonates more than siliciclast and comprises of moderately sorted, angular to sub rounded grains of quartz (25-30%), and calcite (20-25%) with allochems (30-35%) like bioclasts; oolites; pellets and foraminifers in a sparry matrix (15-20%). Kuar Bet member shows oolites (Plate 4.8a-b) and bioclast dominant (Plate 4.8c) sandy allochem limestone while its equivalent Dingy Hill member shows bioclasts and oolites (Plate 4.8d) in sandy allochem limestone.

The Kaladongar Sandstone member shows pelloidal-bioclastic (Plate 4.8e) and foraminiferal (Plate 4.8f) sandy allochem limestone and the Babia Cliff Sandstone member shows bioclastic (Plate 4.8g) and oolitic (Plate 4.8h) sandy allochem limestone. The Goradongar Flagstone member shows pelloidal sandy allochem limestone (Plate 4.9a) which also shows presence of algae and foraminifers (Plate 4.9b). Gadaputa Sandstone member shows presence of foraminifers, radiolarians, bioclasts and algae (Plate 4.9c), while it is oolitic (Plate 4.9d) in Raimalro Limestone member, and shows presence of foraminifers, bivalves, algae and oolites (Plate 4.9e-f) in Modar Hill member.

Interpretation**:** Marine ooids form by inorganic and, probably, organically induced carbonate precipitation around nuclei, and are common in environments of strong water agitation such as along shelf-margin areas and tidal-influenced shoals (IIling, 1954; Newell et al., 1960;

Purdy, 1963; Ball, 1967; Harris, 1979). Presence of sedimentary structures such as planar laminations, small cross-bedding and ripples; and body fossils such as bivalves, ammonites, echinoderms (echinoid spines) large fossil woods indicate storm-influenced platform/ramp settings or shoal deposits.

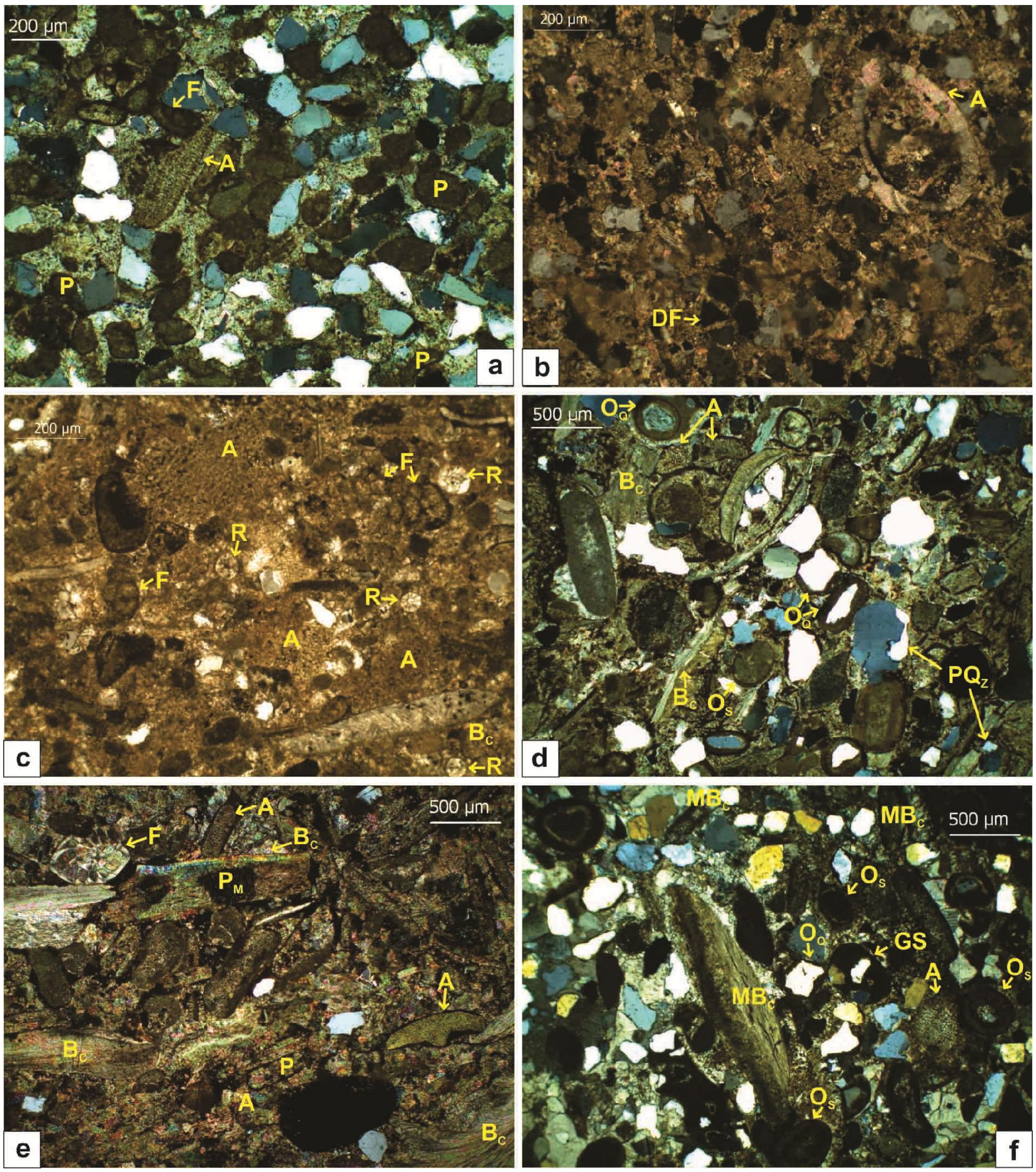

Plate 4.9 Photomicrographs of sandy allochem limestone facies shows the textural and compositional variations in Goradongar Formation.
(a) Large micritised coralline algae (A) and foraminifera (F) *Miliolid*? in pelloidal sandy allochem limestone of GFM exposed near Tuga village; **(b)** Nemorphosed *gyrogonites*, an algae (A) and completely dissolved ?foraminifer (DF) in GFM exposed at Sadhara dome; **(c)** *Globigerinina*, planktonic foraminifers (F), calcite casts of radiolarians (R), bioclast (B_C) fragments, and abundant coralline algae (A) in GSM exposed at Sadhara dome; **(d)** Quartz oolites (O_Q), superficial oolites (O_S), algae (A), bioclasts (B_C), and pellets in oolitic sandy allochem limestone of RLM exposed at Dhorawar village; **(e)** *Lenticulina sublata*? Foraminifer (F), micritised bioclast (B_C) with mouldic porosity (P_M) and preserved original texture of growth lines, algae (A) and pellets in MHM; **(f)** Superficial- (O_S) and quartz-oolites (O_Q), algae (A), bioclasts shows growth lines and partlymicritised (MB_C), and few grapstones (GS) in MHM.

4.2.5 SANDY MICRITE FACIES:

Sandy micrite facies is characterized by medium grained, brown to light brown coloured rock. It occasionally shows presence of fossiliferous layer with clay drapes (Plate 4.10a), and is also observed to be intruded by dykes (Plate 4.10b) at places.

It also consists of trace fossils such as *Arenicolites statheri*, *A.* isp., *Beaconites antarcticus, Chondrites targionii, Planolites beverleyensis Rhizocorallium irregulare, Skolithos linearis, Taenidium barrette*, and *Teichichnus rectus.* This rock type is found in the Kuar Bet, Dingy Hill, Babia Cliff Sandstone members of Kaladongar Formation; and in Modar Hill member of Goradongar Formation. The maximum thickness of ~5.08 m is observed in the Modar Hill member exposed at Modar Hill, Goradongar range.

Petrographically, the sandy micrite shows carbonate proportion more than the siliciclastic proportion and consists of medium grained quartz (35-40%) and calcite (2-5%) with 5-10% allochems consisting of pellets and bioclasts in micritic cement (50-55%). The Kuar Bet member shows presence of oolites (superficial, quartz nuclei and radial fibrous oolites) and bioclasts (Plate 4.10c) while the Dingy Hill and Babia Cliff Sandstone members show subangular to angular quartz grains and lack of allochems (Plate 4.10d-e). The Modar Hill member shows presence of allochems such as bioclasts, algae and foraminifers (Plate 4.10f).

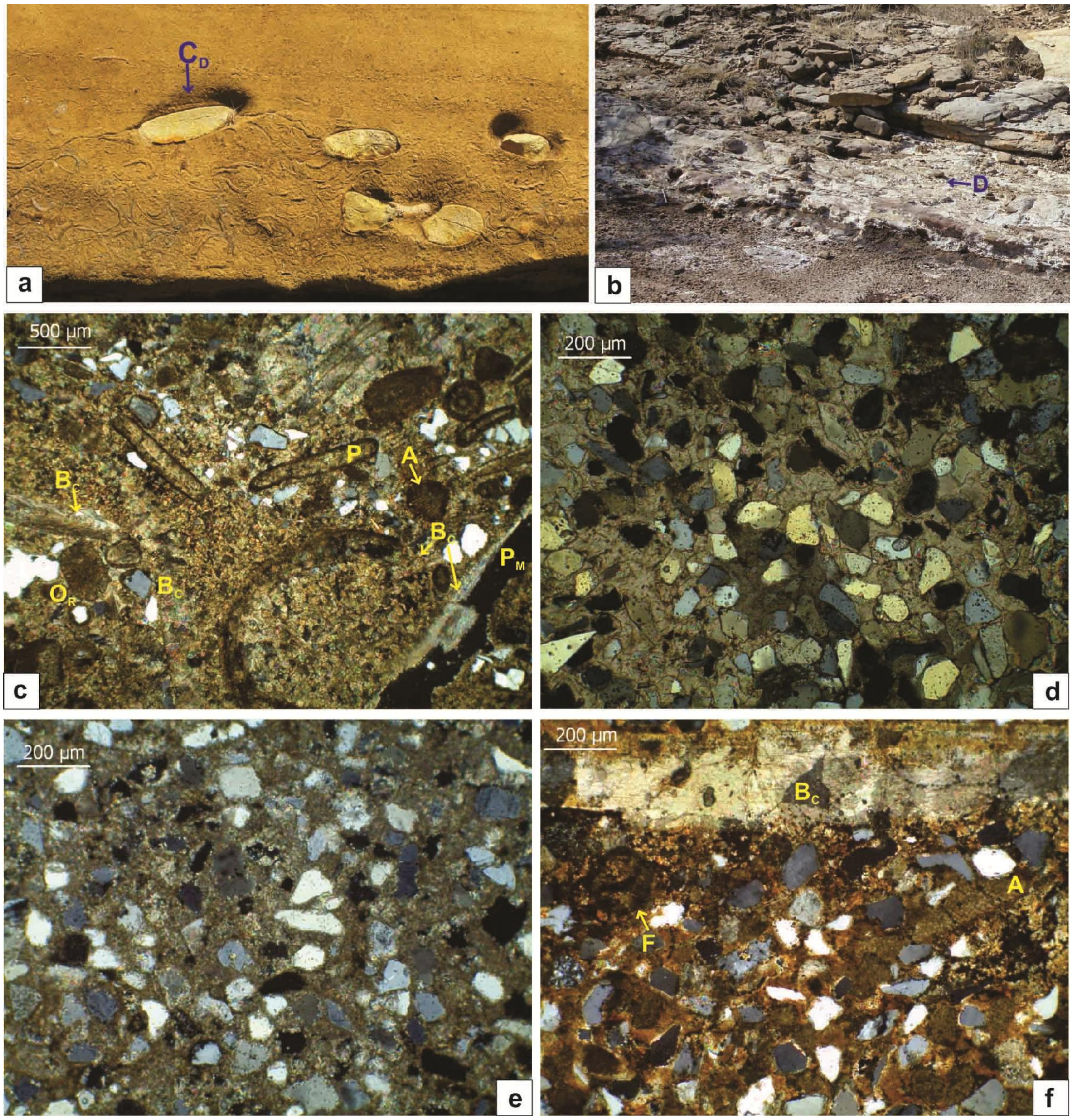

Plate 4.10 Field characteristics and photomicrographs of sandy micrite facies.
(a) Fossiliferous layers with clay drapes (C_D) in MHM; **(b)** Eroded dyke (D) in the DHM exposed at the Chhappar bet; **(c)** Bioclasts (B_C) with growth lines, and mouldic porosity (PM), Algal fragment (A), pellets (P), and superficial- and quartz-oolites with few radial fibrous oolites (O_R) in KBM; **(d)** Yellow to grey colored quartz in micritic matrix of sandy micrite of DHM; **(e)** Subangular to angular quartz grains of BCSM; **(f)** Bioclast (B_C), algae (A), foraminifer (F) and quartz grains in sandy micrite facies of MHM.

Interpretation: Sandy micrite is uncommon facies and developed at different stratigraphic levels of the Mesozoic sequence of the Patcham Island. Sandy micrite is supposed to be representing relatively high energy environment of offshore-transitional zone. The presence of fossils and clay drapes in lenticular bedforms suggests a high-energy/storm event that had reworked the basin sediments.

4.2.6 FERRUGINOUS SANDSTONE FACIES:

This facies is represented by red to brown coloured, ferruginous sandstones. It shows presence of small scale cross bedding (Plate 4.11a) and shows presence of trace fossils such as *Arenicolites* isp., *Diplocraterion* isp., *Monocraterion* isp., *Rhizocorallium irregulare,* R. *jenense* (Plate 4.11b), and *Skolithos linearis*.

Petrographically, it shows poorly sorted sub-rounded to sub-angular sand-sized quartz (90-95%) in less than 5% matrix (Plate 4.11a-f). Presence of alkali feldspar and mica grain is also present in few proportions (Plate 4.11d-e). The composition represents that of quartz arenite, which is often referred to as ultra- or super-mature sedimentary rocks. It is observed as intercalated with shale in Kuar Bet and Kaladongar Sandstone members of Kaladongar Formation, and in Gadaputa Sandstone and Modar Hill members of Goradongar Formation.

***Interpretation*:** The two primary sedimentary depositional environments that produce quartz arenite are foreshore/ upper shoreface (Blackwelder and Pilkey, 1972; Moral-Cardonna et al. 1997) and aeolian processes (Margolis and Krinsley, 1971; Biju-Duval, 2002; Chakraborty and Sensarma, 2008) due to their higher residence time, transport distance and/or energy conditions of the environment (Pettijohn, 1987).

The first cycle sands are apt to be less well rounded and to contain polycrystalline and undulatory quartz, and are more likely to retain a little feldspar (Pettijohn, 1987). The sandstones show more quartz rich and therefore a high degree of mineralogical maturity which indicates that the sands are derived from high topographic areas located long distance from the depositional areas. The ferruginous cement in the sample represents the post-diagenesis process.

Ferruginous sandstone facies intercalated with the shale in Kuar Bet and Kaladongar Sandstone members indicate the intermittently high energy conditions in shoreface environments. This facies is again developed in Gadaputa Sandstone and Modar Hill members, where comparatively proportion of micritic materials increases which indicate relatively low to moderate energy conditions in offshore to transitional environments.

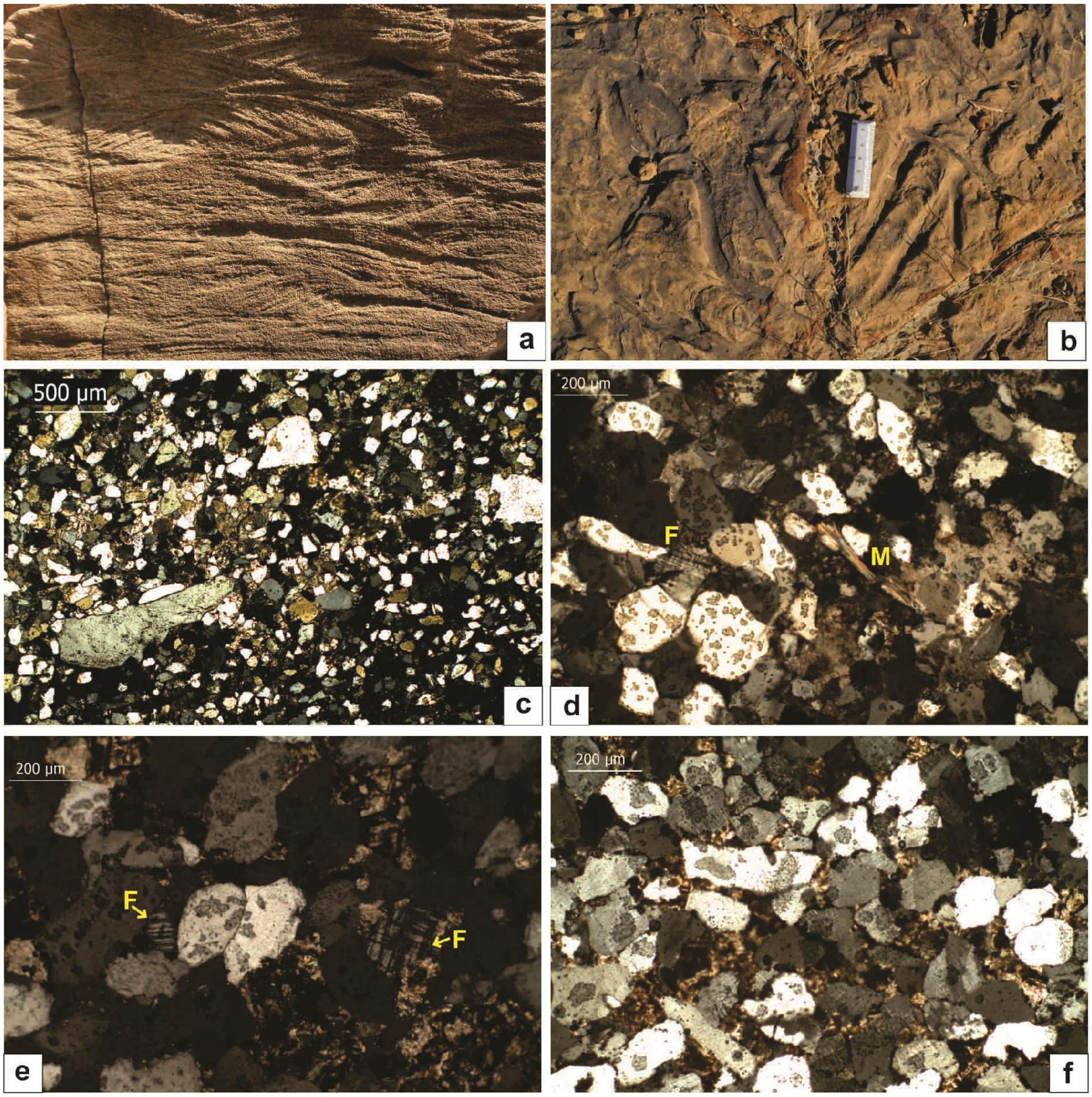

Plate 4.11 Field characteristic and photomicrographs of ferruginous sandstone facies. **(a)** Small scale cross-bedding in KSM at Sadhara dome; **(b)** *Rhizocorallium* bed in KSM at Sadhara dome; **(c)** Fine to coarse grained, subangular to angular quartz in KBM; **(d)** Quartz grains showing compact packing, with few feldspar (Fl) and mica (M) in KSM; **(e)** Coarse-grained quartz showing long contact and feldspar (Fl), in KSM exposed at Sadhara dome; **(f)** Quartz grains showing long contact and moderate packing in quartz arenites of GSM exposed at Sadhara dome.

4.2.7 ALLOCHEMIC LIMESTONE FACIES:

The allochemic limestone facies comprises yellow to dark brown coloured limestone beds. It shows layers consisting of body fossils such as bivalves (Plate 4.12a-b), gastropods (Plate 4.12a-b) and belemnites (Plate 4.12c). Occasional presence of echinoid spines (Plate

4.12d) and ammonites (Plate 4.12e-f) are also observed. This facies occur in Dingy Hill and Kaladongar sandstone members of Kaladongar Formation; and in Goradongar Flagstone, Gadaputa Sandstone, Raimalro Limestone and Modar Hill members of Goradongar Formation.

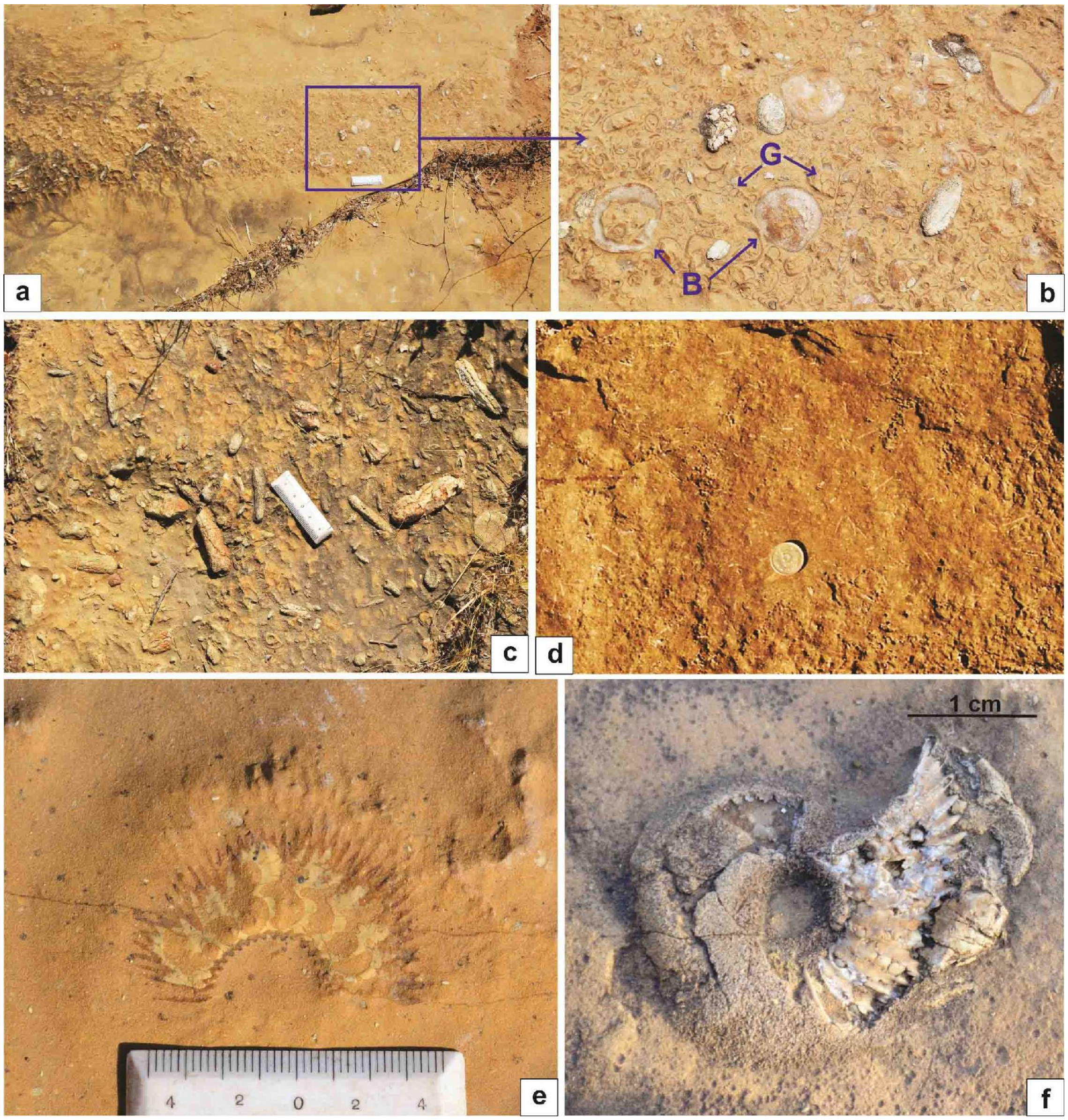

Plate 4.12 Field characteristics of allochemic limestone facies.
(a) Fossiliferous layer of bivalves and gastropod shells in allochemic limestone of RLM exposed at Sadhara dome; **(b)** Closer view of "a" showing large bivalve shells (B) and Gastropods (G); **(c)** Large reworked belemnites in RLM at Sadhara dome; **(d)** Abundant echinoid spines in RLM exposed near Dhorawar village; **(e)** and **(f)** Ammonites of ~3-8 cm diameter in RLM.

Petrographically, limestone shows moderately to poorly sorted calcite (95-98%) and quartz (2-5%) grains. The allochemic limestone facies represents “packstones” and “grainstones” that are further distinguished into five microfacies, namely, pelloidal packstone, oolitic packstone, bioclastic grainstone, pelloidal grainstone and oolitic grainstone.

4.2.7.1 Pelloidal Packstone Microfacies

The pelloidal packstone microfacies are observed in Kaladongar Sandstone, Raimalro Limestone and Modar Hill members. It shows presence of trace fossils such as *Arenicolites* isp., *Aulichnites parkerensis, Beaconites antarcticus, B. coronus, Diplocraterion* isp., *Gyrochorte comosa, Helicolithus sampelayoi, Laevicyclus* isp., *Lockeia siliquaria, Ophiomorpha nodosa, Planolites beverleyensis, Rhizocorallium irregulare, Skolithos linearis, Taenidium serpentinum,* and *Virgoglyphus modari*.

This microfacies represents two sub microfacies: foraminiferal-pelloidal packstone sub-microfacies, and algal-pelloidal packstone sub-microfacies.

4.2.7.1.1 Foraminiferal-pelloidal packstone sub-microfacies

This microfacies is observed in Kaladongar Sandstone member of Kaladongar Formation and in Raimalro Limestone and Modar Hill members of Goradongar Formation. This sub-microfacies consists of 99-100% carbonate constituents. It consists allochems such as pelloids/pellets (20-30%), foraminifer (14-20%), bioclasts (10-13%) in sparry cement (35-50%). Non-carbonate detrital grains (quartz) are also observed up to 1%.

The Kaladongar Sandstone member show foraminifers belonging to the suborder *Globigerinina* (*Pseudotextularia*) in the exposed base of the Sadhara dome (Plate 4.13a-b) while the beds of Kaladongar Sandstone member underlain by the Babia Cliff Sandstone member of Kaladongar Formation show an abundance of dissolved foraminifers belonging to suborder *Miliolina* (*Quinqueloculina*) (Plate 4.13c), *Lagenina* (*Pseudonodosaria*) and also show large gastropod shells (Plate 4.13d). The Raimalro Limestone member exposed at Sadhara dome shows presence of foraminifers belonging to *Globigerinina* (*Globuligerina*) (Plate 4.13e) while in the Modar Hill member, pellets are observed but foraminifera are very few in number; the mouldic porosity (P_M) and the recrystallization forming sparitic crystals with the edge of the bioclasts and the presence of algae (A) are observed (Plate 4.13f).

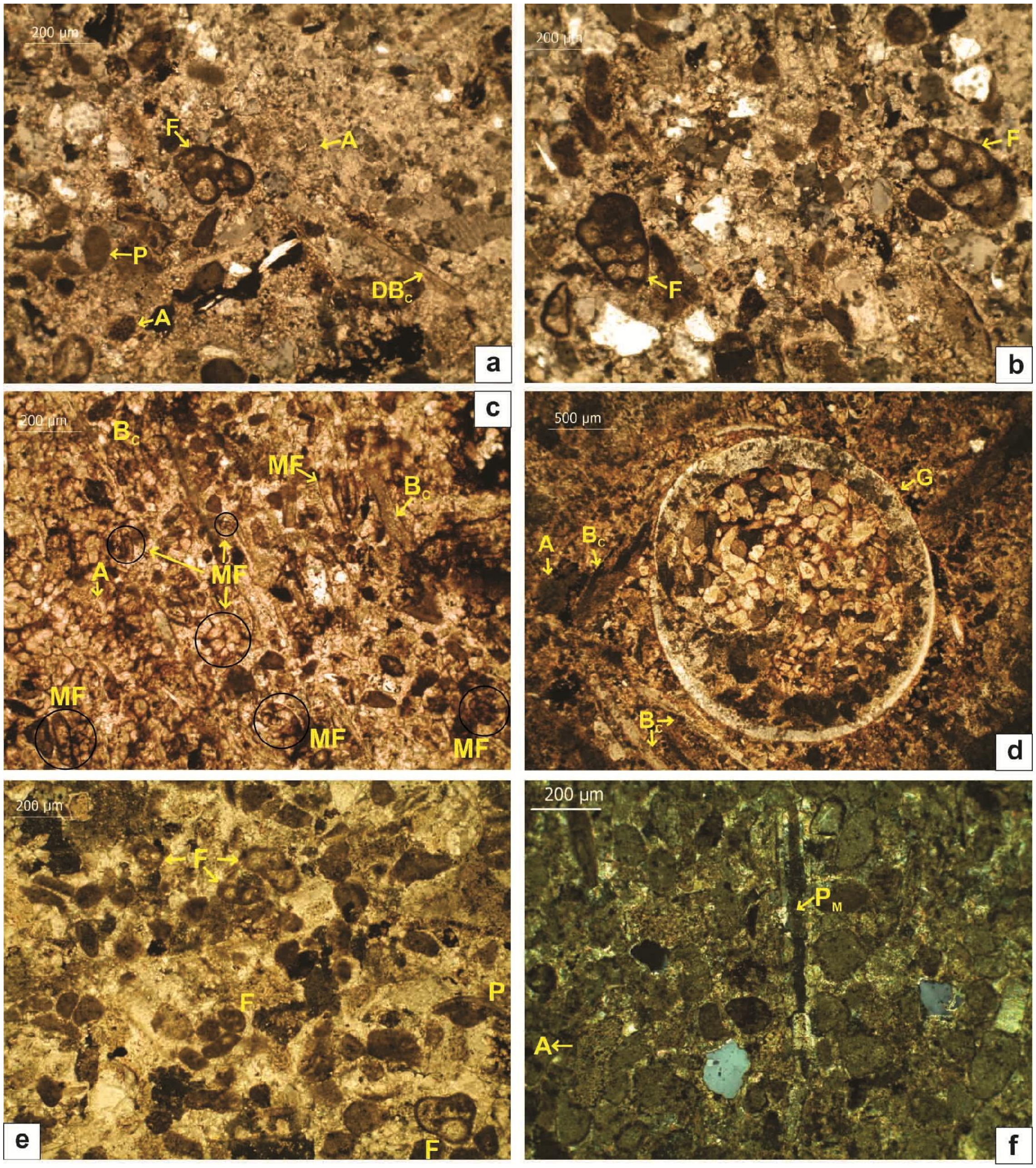

Plate 4.13 Photomicrographs of foraminiferal pelloidal packstone sub-microfacies.
(a) Fragments of algae (A), foraminifera (F), bioclasts (B_C), and pellets (P) in KSM, Sadhara dome; **(b)** Large foraminifers (F) in sparry matrix of pelloidal packstone of KSM; **(c)** Micritised foraminifers (MF), algae (A), and bioclasts (B_C) in KSM, Sadhara dome; **(d)** Gastropod (G), bioclasts (B_C) and algae (A) in KSM; **(e)** Foraminifer (F) dominated in RLM exposed at Sadhara dome; **(f)** Algae (A) and bioclast with mouldic porosity (P_M) and recrystallization in MHM exposed at Modar Hill.

4.2.7.1.2 Algal-pelloidal packstone sub-microfacies

This sub-microfacies is observed in the Raimalro Limestone and Modar Hill members of Goradongar Formation. It comprises of 99% of carbonate constituents while 1% of non-carbonate detrital grains of quartz. It consists of allochems such as pellets/pelloids (~25%), algae and algal filaments (~20%), foraminifers (~10%) and gastropod (~1%) in sparry matrix (45%); to pellets (~55%), algae (2-4%), foraminifers (~3%), bioclasts (~10%), in sparry matrix (~25%). The Raimalro Limestone member of Goradongar Formation show coralline-algal fragments and its filaments with few dissolved foraminifers belonging to *Textularina* in the Sadhara dome (Plate 4.14a-b), while presence of algae and algal filaments (Plate 4.14c) in Modar Hill. The Modar Hill member shows presence of foraminifer belonging to suborder Allogromina (*Cyclamina*), Lagenina (*Dentalina*) and Globigerinina (*Globuligerina*) (Plate 4.14d).

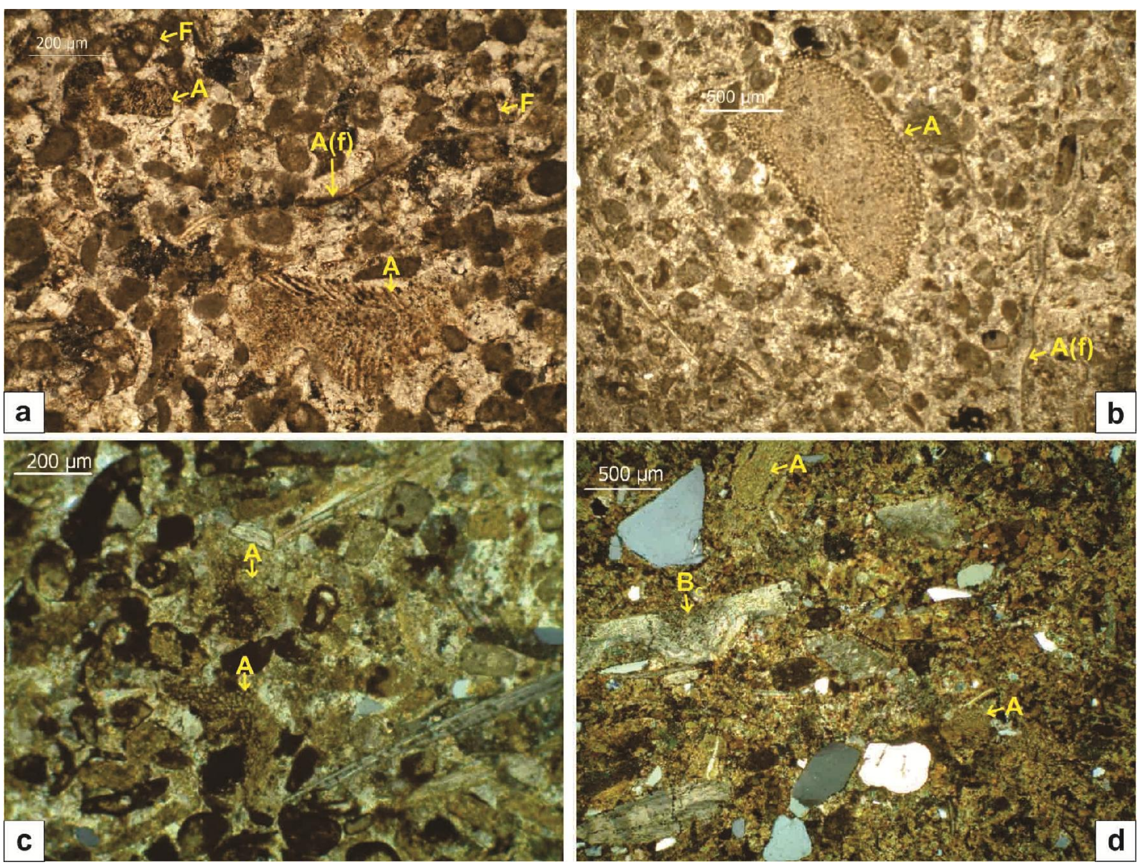

Plate 4.14 Photomicrographs of algae-dominated pelloidal packstone sub-microfacies.
(a) and **(b)** Foraminifers (F), algae and algal filaments (A(f)) in RLM, Sadhara dome; **(c)** Algae (A) in the RLM exposed at Modar Hill; **(d)** Algae (A) bioclasts (B) in the MHM, Modar Hill.

Interpretation: The peloidal nature of the framework grains suggests that the sediment was originally deposited under gentle turbulence but was modified by the intense bioturbation and mixing with the calcareous mud under low energy conditions. This may be deposited in the lee of shifting of sand flats or shoal deposits where there was a greater proportion of lime mud (Pratt et al., 2012). The pelloidal packstone microfacies is not directly co-relatable with the standard microfacies types (SMF) but it represent the storm induced current that brought the outer ramp deposits in the inner ramp.

4.2.7.2 Ooilitic Packstone Microfacies

The oolitic grainstone microfacies is observed in the Kuar Bet member of Kaladongar Formation; and in Gadaputa Sandstone and Raimalro Limestone members of Goradongar Formation. It is fossiliferous in Gadaputa Sandstone member while shows presence of echinoidspines in Tuga, Paiya and Dhorawar villages and in Raimalro Hill. It shows presence of trace fossils such as *Planolites beverleyensis*, *Rhizocorallium irregulare* and *Thalassinoides horizontalis*.

It consists of 95% of carbonate constituents and 5% of non-carbonate detrital quartz (4%) and plagioclase feldspar (1%) grains. The carbonate constituents comprised of oolites (80%) and micritic matrix (15%). The Kuar Bet member shows micritic oolite, quartz nuclei oolites, oolitization of bioclast fragments, coated pellets and foraminifer belonging to the suborder *Globigerinina* (*Pseudotextularia*) (Plate 4.15a).

The Gadaputa Sandstone member represents quartz-oolites and superficial oolites and oolitization resulting into completely dissolved fragments of algae, foraminifers, botryoidal grains, and large gastropod shells and other bioclasts (Plate 4.15b-d). The Raimalro Limestone member shows 10% of oolites and 30% of oolitized algae and foraminifers. It also shows presence of large gastropods, superficial oolites, radial fibrous oolites, foraminifers and completely dissolved bioclasts in the oolitic packstones (Plate 4.15e-f). The coated botryoidal grains and foraminifers belonging to the suborder *Miliolina* are observed.

Interpretation: The dominance of oolites indicate that storm induced current had brought the outer ramp deposits in the inner ramp and later on modified by the intense bioturbation and mixing with the calcareous mud under low energy conditions or it may be of lee of the shifting ooilitic shoal deposits of shoreface inner ramp (Pratt et al., 2012). This microfacies is correlated to Ramp Mirofacies type 30 of Flügel (2010).

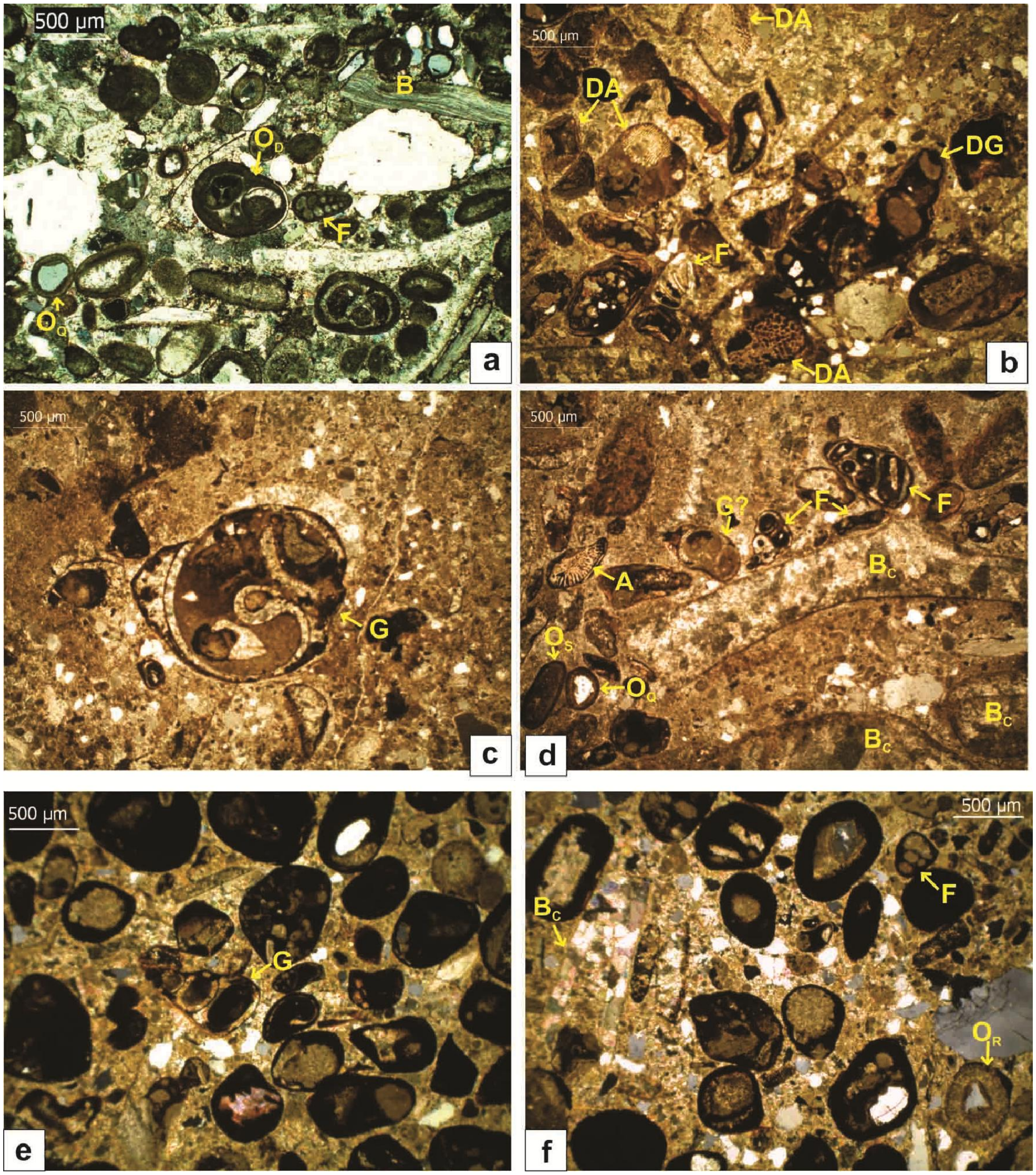

Plate 4.15 Photomicrographs of ooilitc packstone microfacies shows the compositional variations.

(a) Double-nuclei oolites (O_D), quartz oolites (O_Q), coated pellets and *Pseudotextularia* foraminifer (F) in KBM; **(b)** Oolitization resulting into dissolution of algae (DA), gastropods (D_G), and foraminifers (F) in GSM, Sadhara dome; **(c)** Large trasverse-section of Gastropod shell (G), filled with micritic mud and non-carbonate clasts in GSM; **(d)** Bioclasts (B_C), foraminifers (F), algae (A) and superficial- (O_S) & quartz-oolites (O_Q) in GSM; **(e)** and **(f)** Longitunal section of gastropod (G), bioclasts (B_C), coated foraminifers (F) and radial oolites (O_R) in RLM exposed near Tuga village.

4.2.7.3 Pelloidal Grainstone Microfacies

The Pelloidal Grainstone microfacies is observed in the Modar Hill member of Goradongar Formation exposed at Modar Hill. It shows presence of *Gyrochorte comosa*. It consists of 100% carbonate constituents and represents foraminiferal-pelloidal grainstone sub-microfacies.

The Foraminiferal-Pelloidal grainstone sub-microfacies comprises of pellets/pelloids (69-70%), foraminifers (10%), bioclasts (2-5%), coralline algae (0-2%), echinoide spines (0-1%) and sparry matrix (15%). It shows dominance of micritised pelloids and foraminifers with completely dissolved bioclasts and algae (Plate 4.16a). The textural analysis also shows porosity types of mouldic and intergranular and presence of large calcite crystals in this microfacies (Plate 4.16a-b). The dominant foraminifers in this microfacies belong to the suborder Lagenina (*Lingulina, Pseudonodosaria*) while few belonging to suborder Robertinina (*Robertina*) and Globigerinina (*globuligerina*) are also observed.

Interpretation of Peloidal grainstone microfacies: The dominance of peloids and the grainstone texture suggests an shorefore peloidal shoals on the inner ramp. This microfacies is correlated to Ramp Microfacies type- 6 of Flügel (2010).

4.2.7.4 Oolitic Grainstone Microfacies

Oolitic grainstone microfacies is observed in the Dingy Hill member of Kaladongar Formation. It consists of 95% of carbonate constituent while 5% of non-carbonate subangular detrital quartz grains. It is grain-supported and comprises of 85% of oolites. Radial oolites, micritic oolites, quartz oolites, radial fibrous oolites, and radial quartz oolites are the types of oolite structures observed in this microfacies (Plate 4.16c). Few echinoid spines are also observed. This microfacies also shows concavo-convexo contact of grains and few overgrown contacts of oolites (Plate 4.16d).

Interpretation: The dominance of oolites represents high energy conditions but the concavo-convexo contact and the overgrowth of grains suggest compactional pressure. This microfacies is correlated to Ramp Microfacies type (RMF) 30 of Flügel (2010) which represents high energy inter-and sub-tidal shoals of inner ramp.

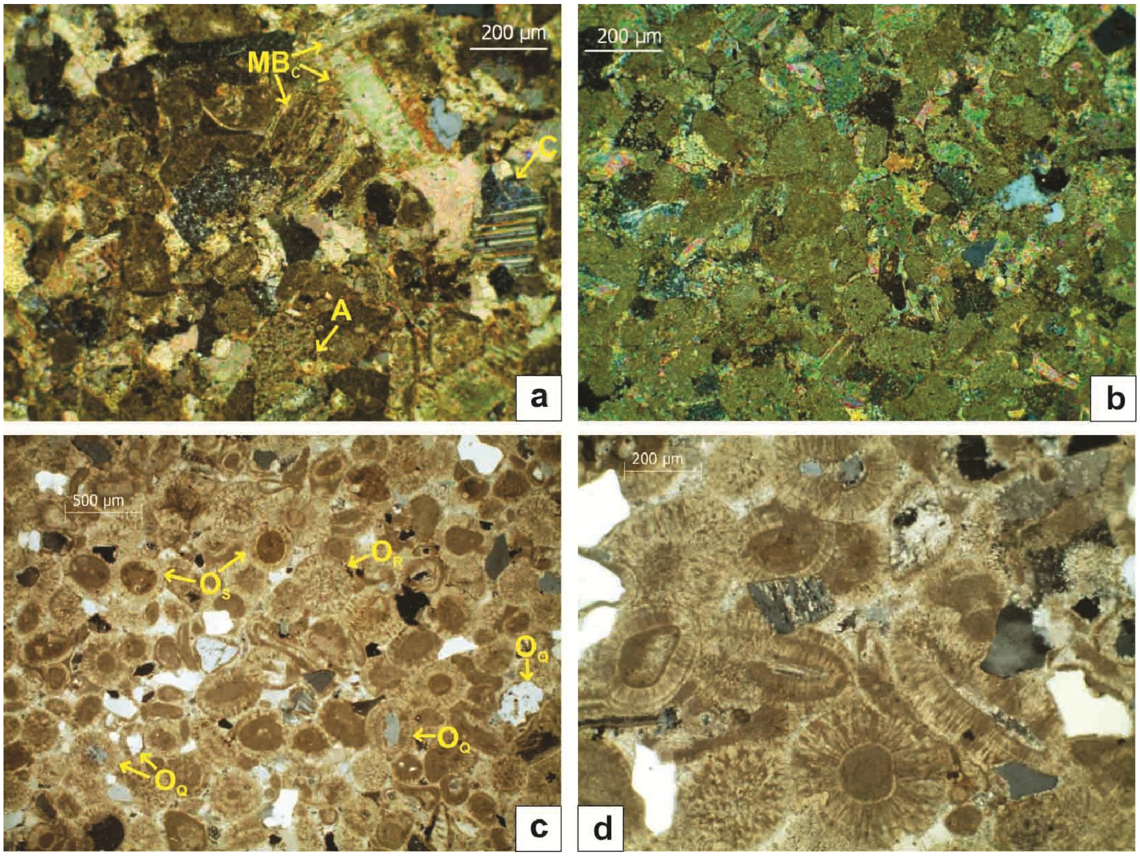

Plate 4.16 Photomicrographs of pelloidal grainstone and oolitic grainstone microfacies.
(a) Micritised pelloids, bioclasts (MB_C), algae (A), large calcite grains (C) in MHM, Modar Hill; **(b)** Closely packedmicritised pelloids in the pelloidal grainstone of MHM; **(c)** Surficial (O_S), radial (O_R), and quartz nuclei oolites (O_Q) in oolitic grainstone of DHM, Dingy Hill; **(d)** Oolitic intergrowth and micritisation in the intragranular pores in the oolitic grainstone of DHM.

4.2.7.5 Bioclastic Grainstone Microfacies

Bioclastic grainstone microfacies is observed in the Dingy Hill member of Kaladongar Formation exposed at Dingy Hill and in the Goradongar Flagstone member of Goradongar Formation exposed at Dhorawar village. It is fossiliferous in nature and shows presence of trace fossils such as *Beaconites*, *Planolites*, *Phycodes* and *Rhizocorallium*. It comprises of 97-98% of calcareous content with 2-3% of detrital quartz grains in grain-supported cement (25%). It also consists of bioclasts (65%), coralline algae (5%) and quartz-oolites (3%) and represents the algal bioclastic grainstone microfacies. The bioclasts are nemorphosed or partly dissolved; dog-tooth spars at the edges and micritised (Plate 4.17a), and also show growth lines and mouldic porosities (Plate 4.17b).

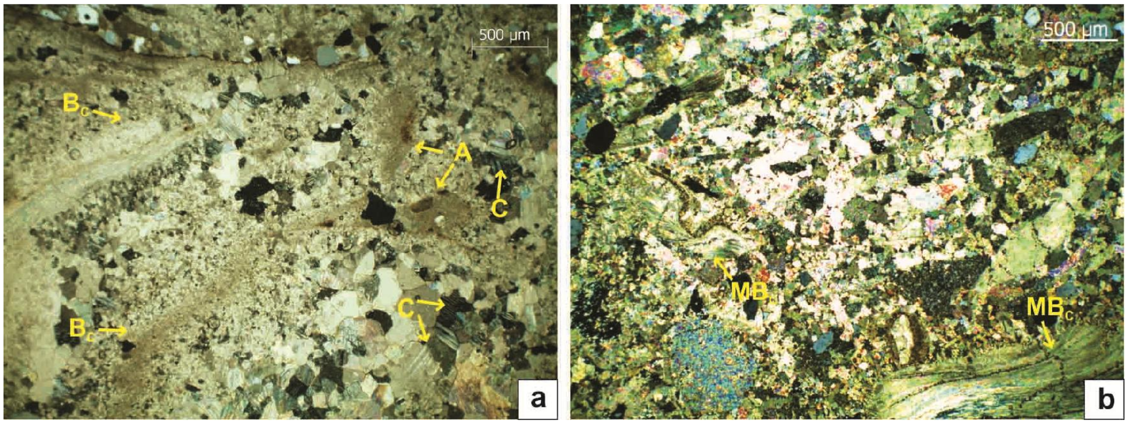

Plate 4.17 Photomicrographs of bioclastic grainstone microfacies.
a. Micritised bioclasts (B_C) with dog-tooth spars at the edges, micritised algae (A), and large recyrstallised calcite grains (C) in DHM; b. Micritised bioclasts (MB_C) with growth lines in bioclastic grainstone of GFM.

Interpretation of Bioclastic grainstone microfacies: Bivalve clast supported grainstone microfacies suggests shoreface shoal deposits on the inner ramp and is correlated to the RMF: 6 (Flügel, 2010).

Interpretation: The accumulation of ooids, skeletal grains and pelloids separately or in association, forming grainstone and packstone texture, is the characteristic of the storm-dominated ramps (Flügel, 2010). Moreover, the overall presence of oolites, bioclasts, and foraminifers in allochemic limestone facies suggests a normal to hypersaline stable inner ramp setting, may be deposited in the restricted to open water circulation having the mean water temperature of ~23^0 C and is also suggestive of low terrigeneous input (Flügel, 2010).

4.2.8 SHALE FACIES:

The shale facies is observed in both the formations and is frequently intercalated with the mixed siliciclastic-carbonate sediments, allochemic limestone and ferruginous sandstone facies. It occurs as either thin or thick layers and, argillaceous or calcareous in nature.

4.2.8.1 Argillaceous Shale Subfacies

It is characterized by dark to light greenish grey to grey colour shale. The argillaceous shale subfacies is composed of quartz grains, mica flakes and clay materials. It exhibits the phenomenon of shale wash. It is observed in Kuar Bet member/Dingy Hill member (Plate 4.18a) of Kaladongar Formation; and in Gadaputa Sandstone and the Modar Hill members of Goradongar Formation. It shows presence of gypsum crystals/layers in the shales present at the core of Kuar Bet and in the Modar Hill member.

4.2.8.2 Calcareous Shale Subfacies

It is characterized by variegated to dull yellow coloured shales; very often intergraded with mixed siliciclastic-carbonate sediments. It consists of argillaceous materials with appreciable amount of carbonate materials. It is observed in the Kuar Bet/Dingy Hill, Kaladongar Sandstone (Plate 4.18b-c) and Babia Cliff Sandstone members of Kaladongar Formation; and in Goradongar Flagstone (Plate 4.18d), Gadaputa Sandstone (Plate 4.18e), Raimalro Limestone and Modar Hill members of Goradongar Formation.

The Kaladongar Sandstone member shows presence of variegated coloured (i.e. red, yellow, brown colour) shale in the Kaladongar range while it is dull yellowish in color in Sadhara dome of Goradongar range.

Interpretation: The grey to dark grey fine grained argillaceous shale shows planar laminations of silt and clay which is consisting of carbonaceous content suggests a reducing environment in quite water conditions, e.g., a lagoon.

The dirty light- to dark-yellow coloured calcareous shale is frequently found to be intercalated with the mixed siliciclastic-carbonate sediments and showing bioturbated structures. This calcareous rich shale suggests an intermittent moderate energy conditions and normal salinity levels in the protected environments.

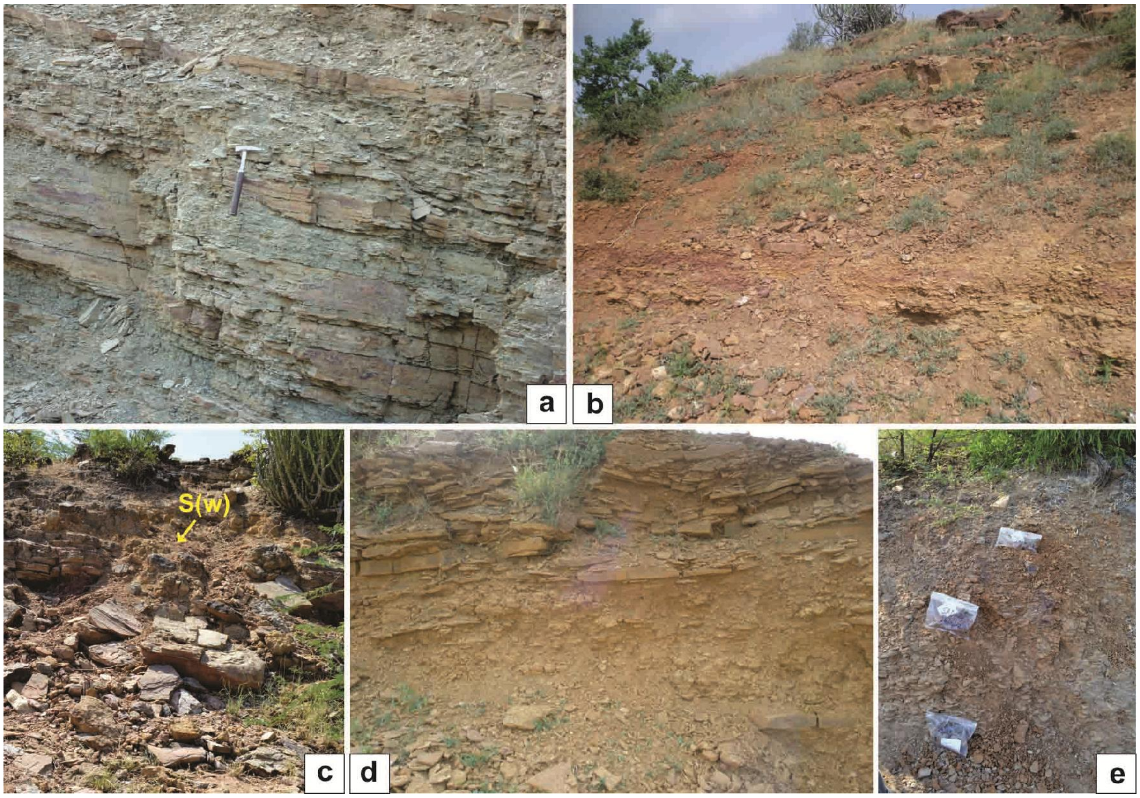

Plate 4.18 Field occurrences of shale facies in different members.
(a) Greenish-grey coloured shale intercalated with mixed siliciclastic-carbonate sediments in DHM, Narewari wandh; **(b)** Variegated shale in KSM, Kaladongar range; **(c)** Shale wash (S(w)) phenomenon in KSM, Sadhara dome; **(d)** Yellowish shale intercalated with sandy allochem limestone in GFM of Kaladongar range; **(e)** Greyish shale of GSM, Sadhara dome.

4.2.9 CONGLOMERATE FACIES:

This facies occurs at different stratigraphic levels, Kuar bet/Dingy hill (Plate 4.19a) and Kaladongar sandstone and Babia Cliff Sandstone members (Plate 4.19b) of Kaladongar Formation. The thickness of the facies vary; maximum being 50 cm. This facies comprises of conglomeratic rock consisting of different grades of sandstone, mud pebbles and gravels embedded in either calcareous or ferruginous matrix. It occasionally shows presence of few broken oyster shells and large fossil wood pieces. Petrographically, it shows many rock fragments consisting of sub-angular quartz and flat pebbles of lithoclasts (quartz and feldspar) with few broken shells.

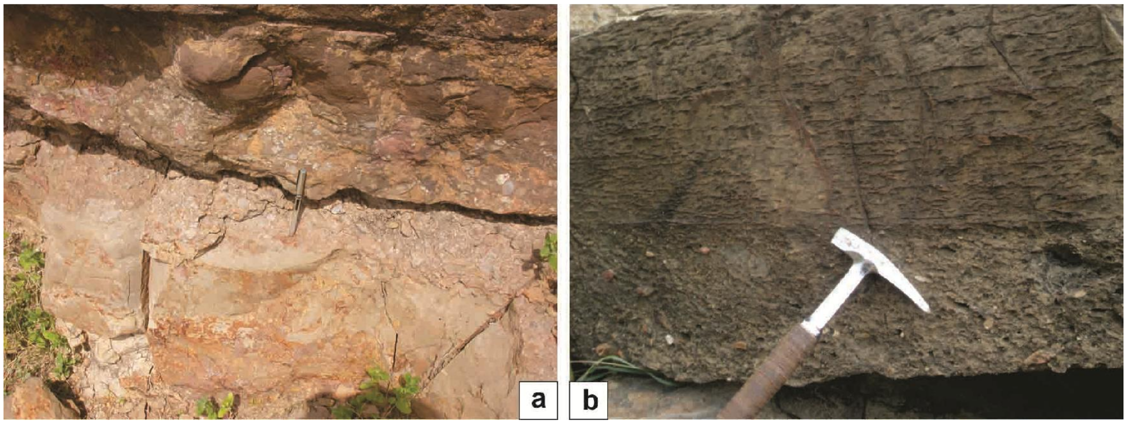

Plate 4.19 Field occurrences of conglomerate facies.
(a) Conglomerate bed in DHM, Dingy Hill; **(b)** Conglomerate bed in BCSM, Kaladongar range.

Interpretation: This facies having different grades of pebbles and gravels of older sediments (sandstone, mud and quartz), indicate local storm conditions in which the older sediments are eroded and deposited in the basin. It indicates the depositional break in the sequence and may also represent the transgressive lag deposit (Myrow et al, 2004; Yang, 2007). The presence of rolled pieces of fossil wood stranded within the conglomerates, and the broken shells of bivalves in the conglomerates show a shoreface environment of deposition.

CHAPTER-5
DESCRIPTION OF TRACE FOSSILS

5.1 INTRODUCTION

5.1.1 HISTORICAL BACKGROUND:

The work of Linnaeus (1758) invented binomial nomenclature which, among the nomenclatures yet invented, is the excellent and most practical system for the classification of organisms. However, this system was invented for the animals and not for their behavior. This statement is therefore important while classifying and naming trace fossils with the help of ICZN. Secondly, trace fossils are a reflection of behavior; they are the sedimentary structures resulting from their behavior. Trace fossils are made by organisms; they have morphology and for morphology we have classification scheme but it seemed to be nearly impossible to fit sedimentologic remains of behavior into this scheme because it was not meant for this purpose. Finally after the one and the other additional smaller fights, ichnology came under the shade of the law of the ICZN. In 1999, with the fourth edition of the ICZN, ichnology fully became integrated into the zoological system of nomenclature. Thus, although the rules of the ICZN deal only with the nomenclature, yet it is the fundament, on which ichnotaxonomy is been built. The nomenclatures used in this chapter also deals according to I.C.Z.N. rules.

The International Code of Zoological Nomenclature defined trace fossil" as the "fossilized work of an animal" which sound convincing but was insufficient. Bertling et al (2003) proposed a new definition for trace fossils but did not found general acceptance among the ichnologists and zoologists. Later the definition was emended, refined and discussed for years by several authors (Genise et al, 2004; Bertling et al, 2004) which defined trace fossils as "Morphologically recurrent structure resulting from the life activity of an individual organism (or homotypic organism) modifying the substrate". Studies depicted clearly that various morphologies may be produced by one particular animal and various different animals may produce morphologically identical structures. These facts build the foundation of the modern ichnology and as a consequence the trace fossil nomenclature and ichnotaxonomy shall be producer-independent but recognizing/identifying possible producer should affect the evaluation of ichnotaxobases.

5.1.2 CLASSIFICATIONS:

A trace fossil description should provide a clear picture of its preservational aspects. This preservational facet can be distinguished into two: (1) Toponomy and (2) Physiochemical processes of preservation and alteration (Frey and Pemberton, 1985). "Toponomy" comprises of description and classification of biogenic structures with respect to their mode of preservation and occurrence; including the mechanical processes involved in the fabrication of the structure and its alteration. (Buatois and Mángano, 2011). The fabrication of the structure is termed as the "stratinomy" and its alteration is termed as the "taphonomy".

5.1.2.1 Stratinomic Classification

The fabrication of the structures is classified through schemes proposed by Simpson (1957), Seilacher (1964) and Martinson (1970). Simpson (1957) established four preservational categories: (1) *Bed-junction preservation*, for trace fossils preserved in relief at a bed junction; (2) *Concealed bed-junction preservation*, for individual burrow that appear to be isolated within an interval of different lithology; (3) *Diagenetic preservation*, for trace fossils preserved as nodule or nodule protuberances formed during early diagenesis ; and (4) *Burial preservation*, for the filled burrows that have been subsequently exhumed by currents winnowing away the associated soft matrix.

Seilacher (1964) represented a modification of the previous classification and proposed a preservational scheme that comprised of "*descriptive*" (based on the relationship of the trace fossil to a casting medium; usually sandstone) and "*genetic*" (based on the assumed relationship of the trace fossils to the contemporary surface rather than that of the trace maker) terms (Seilacher, 1953a). The descriptive set defined two main subdivisions of structures, viz., the "*full* relief" (preserved within the stratum) and the "*semirelief*" (preserved at lithological interfaces) along with the third category, "*biodeformational*" structures. The semirelief structures are further subdivided into "epirelief" (preserved at the top) or "hyporelief" (preserved at the base) of the sandstone bed, along with the additional terms "concave" for positive and "convex" for negative relief of the trace fossil. The biodeformational structures are referred to the sediment disturbances of biological origin. The genetic terms include "*exogenic*" (surficial traces covered by sediment different from the host), "*endogenic*" (actively or passively filled structure within the host bed) and "*pseudoexogenic*" (traces formed in homogeneous medium, but subsequently uncovered by erosion and recast with sand).

Martinson (1970) also proposed a similar classification to that of Seilacher (1964b) based on the relationship of trace fossils to a casting medium. He introduced four preservational categories: (1) "*epichnial preservation*", if preserved at the upper surface of the casting strata; (2) "*hypichnial preservation*", if preserved at the lower surface of the casting strata; (3) "*endichnial preservation*", if preserved within the casting medium; and (4) "*exichnial preservation*", if preserved outside the casting medium.

Among these classifications, Simpson (1957) is not used nowadays, since it incorporates the diagnetic aspects and is thus not strictly stratinomic while the classification proposed by Seilacher (1964) and Martinson (1970) met with the most acceptance.

5.1.2.2 Ethological Classification

The ethological system of classification is based on the evidence of animal behaviour and was first proposed by Seilacher (1953a). The original system consists of five categories, viz., (1) "*Cubichnia*", the resting trace; (2) "*Repichnia*", the lomotion trace; (3) "*Pascichnia*", grazing traces; (4) "*Fodinichnia*", the feeding trace; and (5) "*Domichnia*", the dwelling traces; which are the basic building blocks of behavioural interpretations in ichnology.

Later refinements have been suggested to take account of additional behaviors and new ethological categories were added viz., "*Fugichnia*", the escape traces (Frey, 1973); "*Agrichnia*", farming traces and trap (Ekdale et al, 1984); "*Praedichnia*", predation traces (Ekdale, 1985); "*Equilibrichnia*", equilibrium traces (Bromley, 1990); "*Calichnia*", nesting traces (Genise and Bown, 1994); "*Pupichnia*", pupation chambers (Genise et al, 2007); "*Fixichnia*", fixation/anchoring traces (Gibert et al, 2004); "*Impedichnia*", bioclaustration structures (Tapanila, 2005); "*Mortichnia*", death traces (Seilacher, 2007). Apart from these categories, the others are categorized as the subdivision of the major ones (eg. "*xylichnia*" for wood boring is kept under category "*fodinichnia*").

5.2 SYSTEMATIC ICHNOLOGY

The classification scheme proposed by Książkiewicz (1977) which was further emended by Uchman (1995) and Schlirf (2000, 2005) is used to classify the trace fossils in the present study, due to its sole based on the morphological patterns. The invertebrate trace fossils are differentiated into two general categories as burrows and trails, and borings. There are five major approaches to the classification and interpretation of trace fossils: (1) the descriptive approach, in which the morphologies of traces are described in detailed; (2) the preservational approach, in which traces are categorized by their mode of preservation and host sediment; (3) the behavioral approach, in which the general activities of the trace-makers are inferred; (4) the organism approach, in which the traces are ascribed to the organisms which created them; and (5) the taxonomic approach, in which formal Latinized names are given to the traces themselves.

Ideally, all five approaches have been employed simultaneously to provide a complete description and interpretation of the trace fossil fauna from the Patcham Island. However, it is briefly studied and classified into six morphological groups (i.e. with descriptive approach) as (1) circular and elliptical structures, (2) simple structures, (3) branched structures, (4) rosette structures, (5) spreiten structures and (6) winding and meandering structures. This classification has some difficulty in assigning few traces to any of the given groups and thus they are taken as the additional information and are devoid of any taxonomical rank. The ichnotaxonomy concept based on the significant (related to distinct behavior) and accessory features (reflecting minor behavioural changes) as introduced by Fürsich (1974b) is used here. The significant features of each trace fossils are regarded for the diagnosis of the ichnogenera and the accessory features for the diagnosis of the ichnospecies.

5.2.1 BURROWS:

5.2.1.1 Circular and Elliptical Structures

5.2.1.1.1 Plug shaped forms

Ichnogenus: *Bergaueria* PRANTL, 1945

Type ichnospecies: *Bergaueria perata* Prantl, 1945

Diagnosis: Cylindrical to hemispherical vertical burrows possessing smooth, unornamented walls, circular to elliptical in cross-section, infillings essentially structureless, rounded base, with or without shallow central depression and radial ridges (Pemberton et al., 1988).

Ichnospecies: *Bergaueria* cf. *hemispherica* CRIMES, LEGG, MARCOS and ARBOLEYA 1977

(Plate 5.1a)

Diagnosis: *Bergaueria* lacking a shallow, central depression (Pemberton et al. 1988).

Description: Hypichnial mound with hemispherical smooth termination, oval in outline. The diameter of the burrow is 2.4-2.5 cm and depth is 2.3 cm, the walls of the burrow are unornamented and the fill of the burrow is essentially structureless.

Occurrence: Micritic sandstone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range.

Remarks: The general shape, the hemispherical termination, resembles to the ichnogenus *Bergaueria hemispherica* though it varies by the larger size of this specimen. *Bergaueria* is probably a cubichnial or domichnial form produced by suspension feeders (Fürsich, 1975), occurring in the shallow water deposits (Narbonne, 1984; Crimes and Anderson, 1985) and in flysch deposits (Prantl, 1945, Książkiewicz, 1977; Crimes and Crossley, 1991; Uchman, 1995). The producers of this trace are coelenterates, chiefly sea anemones (Alpert, 1973; Chamberlain, 1971).

Ichnospecies*:* *Plug shaped form* cf. *B*, UCHMAN 1995.

(no generic name assigned)

(Plate 5.1b)

Diagnosis: Convex hypichnial semi-relief, consisting of an uneven, elongate, oval cast, which is higher on one side, with steep, overturned wall at the higher side (Uchman, 1995).

Description: Oval shaped cast with one side steep, overturned higher wall, preserved as convex hypichnial semi-relief. The structure is 5cm long, 3 cm wide and 2.5 cm high.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: The name plug-shaped was introduced for peculiar resting burrows (cubichnia) preserved commonly but not exclusively as under traces (Savrda 2007; Seilacher 2007) and probably produced by suspension-feeders such as sea anemones (Pemberton et al, 1988; Uchman 1995). The present ichnospecies resembles the "plug shaped form B" of Uchman (1995) but differs in having comparatively smaller dimensions of the specimen. According to him, the trace resembles *Lockeia* JAMES or may be made by a small burrowing ray in larger dimensions making it difficult to commend on the trace maker.

5.2.1.1.2 Circles

Ichnogenus: *Laevicyclus* QUENSTEDT, 1879

Type Ichnospecies: *Cyclozoon philippi* Wurm 1912

Diagnosis: Approximatley cylindrical bodies perpendicular to the bedding planes; diameter variable in same specimen; perforated by central canal; visible on bedding planes as regular concentric circles with diameter of several cm (Häntzschel, 1962).

Discussion: Quenstedt (1879) firstly reported and named this type of fossil as *Laevicyclus* but he interpreted it as a coral and did not erect any species. Häntzschel (1962, 1965) placed genus *Cyclozoon* in synonymy with *Laevicyclus* and kept the forms of two different origins in the genus *Laevicyclus* as "Form A" (large cylindrical, vertical burrows with small central cylinder) and "Form B" (vertical burrows with concentric scrape marks on the upper bedding surface). Later, Alpert and Moore (1975) restricted "*Laevicyclus"* to Form B and named Form A as "*Dolopichnus"*. Accordingly, they placed *Laevicyclus mongraensis* Verma (1970:38, PL 1:6; Chiplonkar and Badwe 1970:9, Pl. 3:4, 4a) apparently in *Dolopichnus* and placed *Cyclozoon philippi* Wurm 1912 as the type species of *Laevicyclus* ichnogenera.

Ichnospecies: *Laevicyclus* isp.

(Plate 5.1 c and d)

Description: Endichnical, full relief, vertical cylindrical body making right angle to bedding plane and appear as regular concentric circles. The burrow shows maximum outer diameter of 2.35 cm, the central knob is large and prominent with diameter of 1.2 cm.

Occurrence: Micritic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range and pelloidal packstone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: It is regarded as the feeding burrow of trace fossil comparable with dwelling shaft and scraping circles of recent annelid *Scolecolepis squamata* (Seilacher, 1953).

Ichnogenus: *Lockeia* JAMES, 1879

Type Ichnospecies: *Lockeia siliquaria* James, 1879

Diagnosis: Bilaterally symmetrical, elongated, commonly almond-shaped, heart-shaped, club-shaped to dumbbell-like or rarely of triangular shape, with smooth margin; predominantly preserved as isolated or row-like arrangements of hypichnial mounds; single segments commonly with a distinct median crest. Vertical spreite may be present (Schlirf et al, 2001)

Ichnospecies: *Lockeia amygdaloides* SEILACHER 1953

(Plate 5.1 e and f)

Diagnosis: Stout, high-standing, almond shaped ridges with a smooth surface, tapering at both ends; sometimes showing tall vertical spreite (Schlirf, 2000).

Description: Hypichnial, small, stout, high standing, almond shaped ridges with smooth surface, tapering at both end. The trace length is 1.1-1.4 cm, width is 0.3-0.7 cm and height is 0.2-1.1 cm, and occurs in crowded form.

Occurrence: Micritic sandstone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range and in sandy allochem limestone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: This ichnospecies of the ichnogenus *Lockeia* differs from the other ichnospecies in having an almond-like stout nature. *L. amygdaloides* represents short lived resting traces of small burrowing bivalves, perhaps semi-sessile forms (Häntzschel, 1975).

Ichnospecies: *Lockeia siliquaria* JAMES 1879

(Plate 5.1g and h)

Diagnosis: Same as for ichnogenus.

Description: Convex, hypichnial, relatively small, almond shaped oblong parallel to sub parallel bodies; with tapering to sharp and obtuse points at both ends. Short, inclined or vertical endichnial shafts may also be present. They occur as isolated and their dimension varies in different burrow populations, with observed length is 1.1- 1.6 cm, width 0.4-0.6cm and height of 0.9-1.0 cm.

Occurrence: Allochemic sandstone of Dingy Hill member, and micritic sandstone and micritic mudrock of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range; and in pelloidal packstone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remark: This ichnospecies differs from the other ichnospecies of *Lockeia* by lack of a) plump nature of *L. amygdaloides* Seilacher, 1953; or *L. avalonensis* Fillion and Pickerill, 1990; b) thin and elongate as *L. elongata*, Yang, 1984; and c) asymmetrical as *L. czarnockii* Karaszewski, 1974. The ichnospecies *Lockeia siliquaria* either represents the dwelling structure of suspension feeders or the fugichnial response to changing environmental conditions, rather than short lived resting traces (Mangano et al 1998).

Ichnogenus: *Margaritichnus* BANDEL, 1973

Type Ichnospecies: *Cylindrichnus reptilis,* Bandel 1967

Diagnosis: Trail made of ball-like structures which are either unconnected or connected by ridge of same width as diameter of balls.

Ichnospecies: *Margaritichnus reptilis* BANDEL, 1973

(Plate 5.1 i)

Diagnosis: Ball-like structures of 15 to 30 mm. diameter, commonly aligned like string of pearls, rarely connected by ridge with crescentic transverse grooves; thought to be trail of large wormlike, sediment feeding animal which packed its fecal pellets in mucus.

Description: Convex, hypichnial, semirelief ball shaped structures compressed, joint together with not very visible tube forming pearl like structure. The dimension of each ball structure is approximately 1.2 cm in diameter forming the pearl like structure of about 5-6 cm long.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

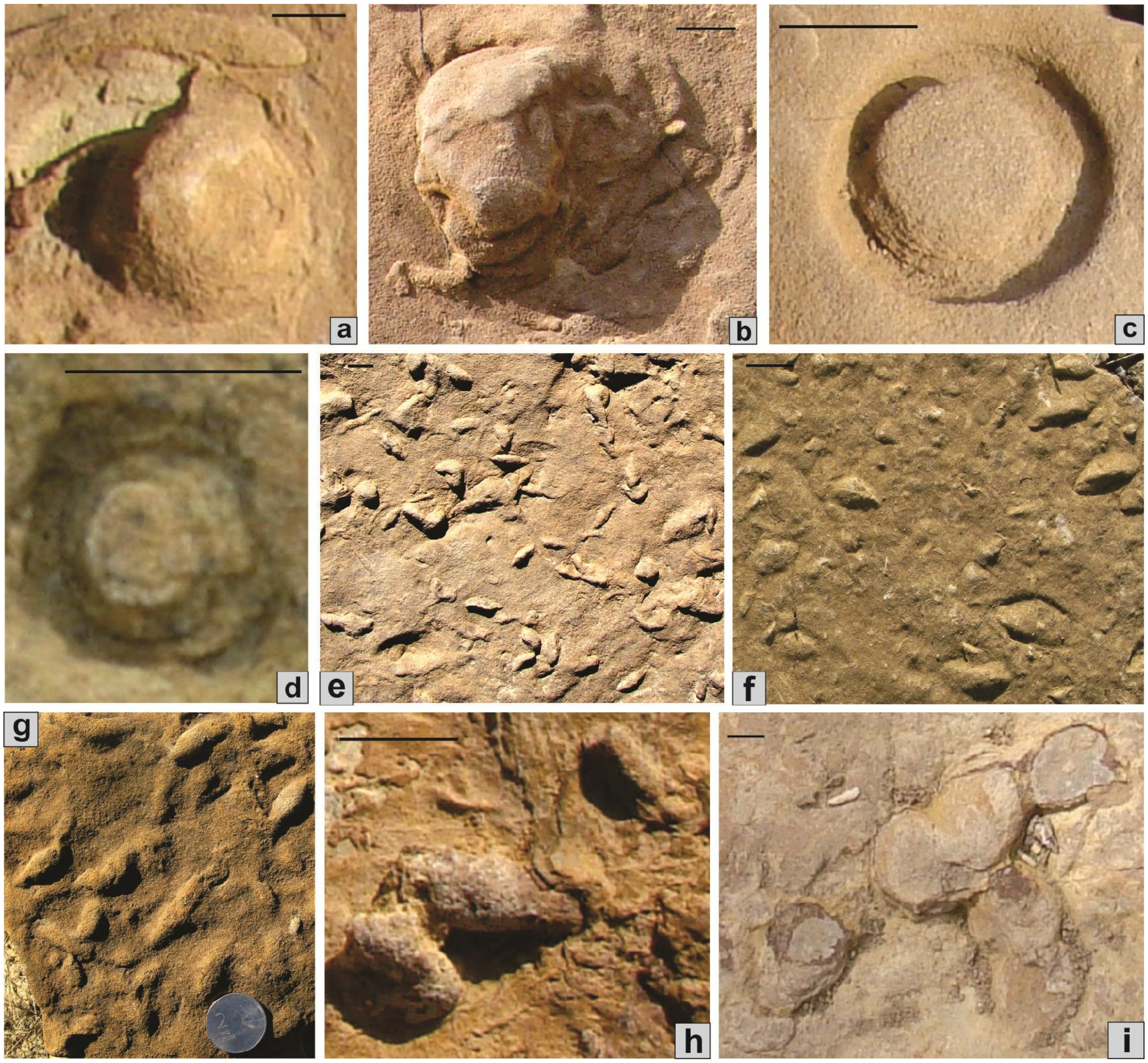

Plate 5.1 Circular and Elliptical Structures (Bar length = 1 cm)
(a) *Bergaueria* cf. *hemispherica*, smooth hemispherical mound like structure; Micritic sandstone of BCSM; **(b)** *Plug shaped form* cf. B; Hypichnial, semi relief, mound like structure; allochemic sandstone of DHM; **(c)** *Laevicyclus* isp., vertical cylindrical structure with concentric rings; micritic sandstone of DHM; **(d)** *Laevicyclus* isp., vertical cylindrical structure with concentric rings; bioclastic packstone of RLM; **(e)** *Lockeia amygdaloides*, stout almond shaped ridges with tapering ends, micritic sandstone of BCSM; **(f)** *Lockeia amygdaloides,* stout almond shaped ridges, sandy allochem limestone of RLM; **(g)** *Lockeia siliquaria*, almond shaped oblong ridges, pelloidal packstone of RLM; **(h)** *Lockeia siliquaria*, almond shaped oblong ridges, micritic sandstone of BCSM; **(i)** *Margaritichnus reptilis*, ball-shaped structure forming pearl-like form, allochemic sandstone of DHM.

Remarks: Balls are interpreted as the fecal pellets probably made by large wormlike sediment-eating animals; trails possibly formed below the sediment surface (Häntzschel, 1975).

5.2.1.2 Simple Structures

5.2.1.2.1 Vertical forms

Ichnogenus: *Monocraterion* TORELL, 1870

Type ichnospecies: *Monocraterion tentaculatum* TORELL, 1870

Diagnosis: Funnel-shaped negative epirelief with a raised knob on the floor of the funnel; this knob is continuous with a short, vertical, centrally located tubular structure. Essentially with numerous small, horizontal, slightly curving, rarely branching, occasionally lined, tubular, full-relief structures with smooth outer surface going out from the raised knob (Schlirf, 2000).

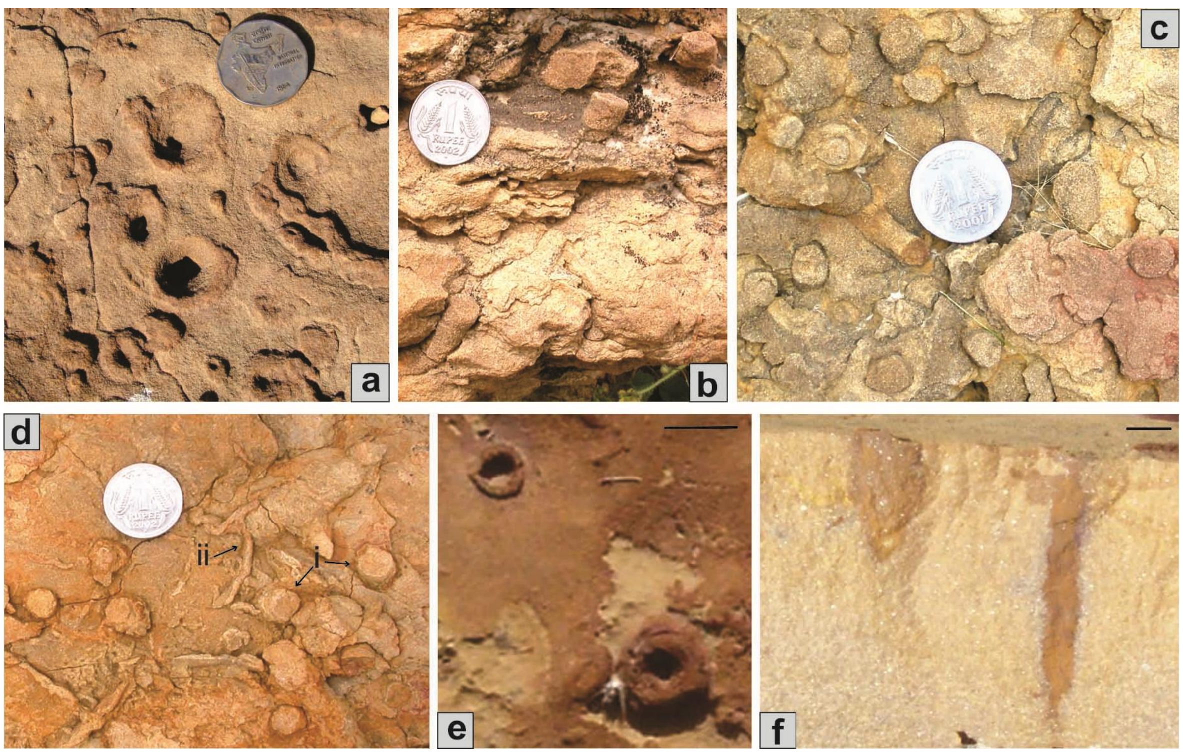

Plate 5.2 Vertical forms (Bar length= 1 cm; coin diameter= 2.5cm)

(a) *Monocraterian tentaculatum,* vertical cylindrical burrow with funnel-shaped opening; micritic sandstone of DHM; **(b)** *Skolithos linearis*, cylindrical burrow inclined to the bedding, Sandy allochem limestone of KSM; **(c)** *Skolithos linearis,* cylindrical burrow inclined to the bedding, sandy allochem limestone, DHM; **(d)** *Skolithos linearis*, cylindrical burrow inclined to the bedding, micritic sandstone, DHM; **(e)** *Skolithos linearis,* vertical cylindrical burrow, bioclastic packstone, MHM; **(f)** *Skolithos linearis*, vertical cylindrical burrow, bioclastic packstone, MHM.

Ichnospecies: *Monocraterian tentaculatum* TORELL, 1870

(Plate 5.2 a)

Diagnosis: Same as for ichnogenus

Description: Straight to slightly curved, unbranched cylindrical burrows, filled with surrounding substrate. Closely spaced or isolated on bedding plane, normal to steeply incline to the bedding plane, passing upward into ovate funnel, and downward into straight vertical and cylindrical. Several specimens show funnels with raised rims, which may reflect lining to the funnels. Funnel height is varying in different burrow population, diameter of the widest part varies from 2.0 to 3.0 cm and shaft diameter is 2.0 cm.

Occurrence: Micritic sandstone and sandy allochem limestone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remark: *Monocraterion* occurs with conditions of relatively rapid sedimentation and is considered to be the dwelling structure of a worm like organisms (Myers 1970, Barwis, 1985).

Ichnogenus: *Skolithos* HALDEMAN, 1840

Type ichnospecies: *Skolithos linearis* HALDEMAN, 1840

Diagnosis: Unbranched, vertical to steeply inclined, straight to slightly curved cylindrical to subcylindrical, lined or unlined structures with or without funnel-shaped top. Wall distinct or indistinct, smooth or rough, some specimen annulated; fill massive; burrow diameter in some individuals slightly inconstant (Schlirf, 2000).

Ichnospecies: *Skolithos linearis* HALDEMAN, 1840

(Plate 5.2 b-f)

Diagnosis: Cylindrical to subcylindrical, perfectly straight and vertical to slightly curved or inclined burrows. Burrow wall distinct to indistinct, may be annulated (Schlirf, 2000).

Description: Endichnal, full relief, cylindrical to sub-cylindrical, unbranched vertical to inclined pipes with distinct or indistinct walls commonly closely crowded or showing widely space gradation. The depth varies from 4 to 6 cm and diameter is about 10 to 15 mm. The burrow fill is sandy and the wall is thinly lined by fine sediments.

Occurrence: Micritic sandstone and sandy allochem limestone of Dingy Hill member and sandy allochem limestone of Kaladongar Sandstone member of Kaladongar Formation, Kaladongar range; and sandy micrite and pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: The *Skolithos linearis* is distinguished from the *S. verticalis* because the former is longer and sandy type of fill of the burrow, which is the characteristic distinguishing factor in them (Carmona et al, 2008). *Skolithos* is widely recognized in shallow water, intertidal deposits (Seilacher, 1967) and in various shallow marine environments (Fillion and Pickerill, 1990; Alpert, 1974), probably thought to be produced by annelids or phoronids (Alpert, 1974) and suspension feeding polychaetes like *Amphinomerostrata* and *Nereiscostoe* (Patel and Desai, 2009).

5.2.1.2.2 Horizontal forms

Ichnogenus: *Bifungites* DESIO, 1940

Type Ichnospecies: *Bifungites fezzanensis,* Hall 1852

Diagnosis: Structures dumbbell-like or arrow-shaped, ends commonly hemispherical, on bedding planes respectively an erosional interface, preserved as positive hyporelief or positive epirelief.

Ichnospecies: ?*Bifungites* isp.

(Plate 5.3 a)

Description: Preserved as positive epirelief, horizontal, blunt hammer-like structure. Burrow represents cylindrical tube (central cord) with nearly spherical end or dumbbell like structure. The length of the central cord is 8 mm and diameter of 9 mm; the hemispherical structure having maximum diameter of 20 mm.

Occurrence: Allochemic sandstone of Raimalro Limestone member, Goradongar Formation, Goradongar range.

Remarks: The specimen shows only one hemispherical structure with central cord, other part may be collapsed or eroded. *Bifungites* is interpreted as the domichnial burrow of some filter feeder such as polychaete/annelid (Pickerill and Forbes, 1977)

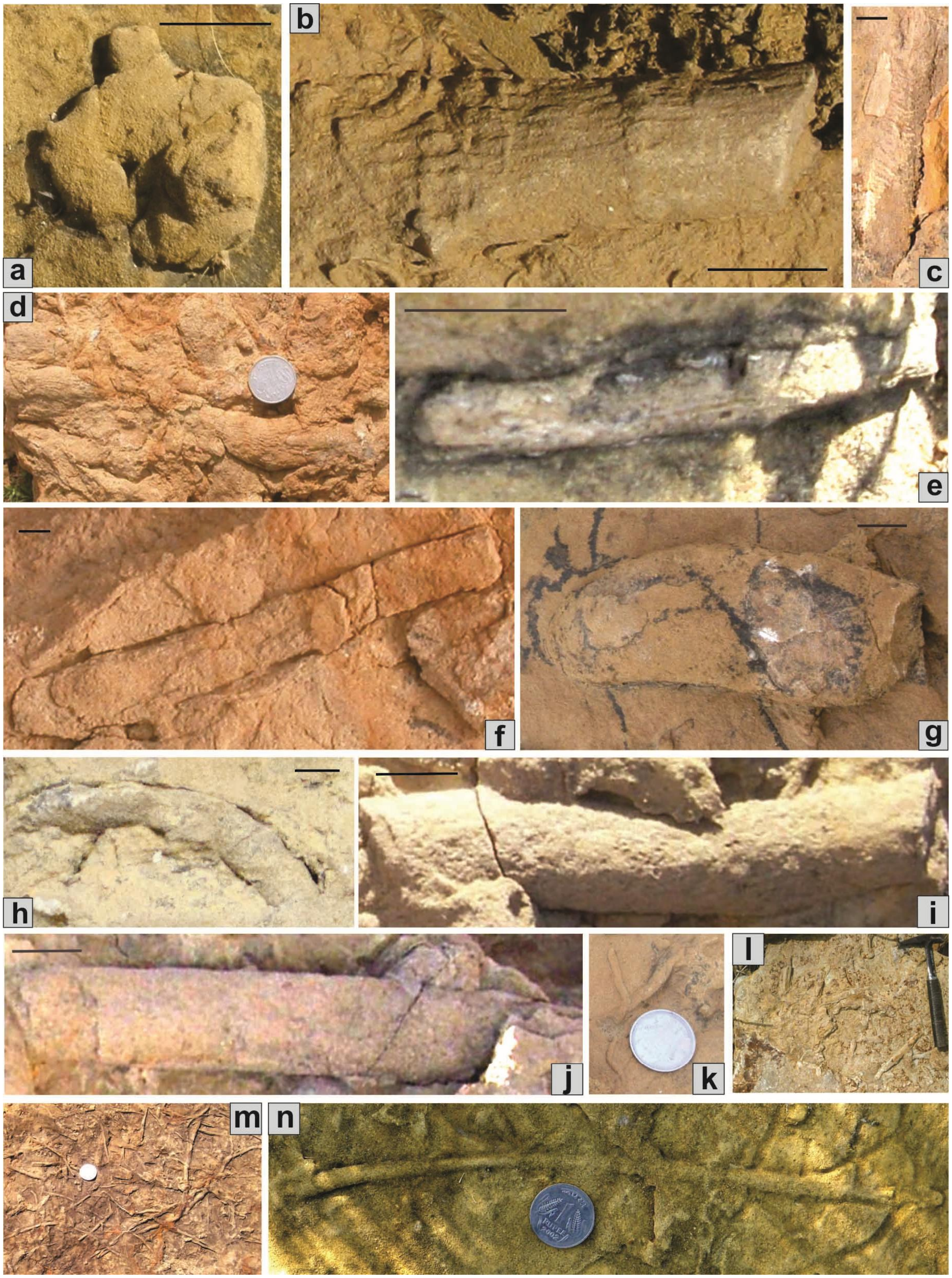
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Plate 5.3 Horizontal forms (Bar length = 1 cm; Coin diameter = 2.5 cm.)
(a) ?*Bifungites* isp., cylindrical tube with nearly spherical end, allochemic sandstone, RLM; **(b)** *Palaeophycus alternatus*, annulated and striated cylindrical burrow, micritic sandstone, GSM; **(c)** *Palaeophycus annulatus,* Horizontal lined burrow with annulations, micritic sandstone, DHM; **(d)** *Palaeophycus striatus,* Horizontal lined striated burrow, allochemic sandstone, BCSM; **(e)** *Palaeophycus striatus*, striated cylindrical lined burrow, micritic sandstone, GSM; **(f)** *Palaeophycus tubularis,* Horizontal lined burrow, allochemic sandstone, DHM; **(g)** *Palaeophycus tubularis,* Horizontal lined burrow, micritic sandstone, DHM; **(h)** *Palaeophycus tubularis,* Slightly curved lined burrow, sandy allochem limestone, KBM; **(i)** *Palaeophycus tubularis*, cylindrical lined burrow, micritic sandstone, MHM; **(j)** *Palaeophycus tubularis*, cylindrical lined burrow, micritic sandstone, MHM; **(k)** *Planolites beverleyensis;* Horizontal unlined branched burrow; **(l)** *Planolites beverleyensis;* Horizontal unbranched burrow; Scale: Hammer length = 40 cm; **(m)** *Planolites beverleyensis*, Micritic sandstone, MHM; **(n)** *Planolites beverleyensis*, Micritic sandstone, MHM.

Ichnogenus: *Palaeophycus* HALL, 1847

Type ichnospecies: *Palaeophycus tubularis* Hall, 1847

Diagnosis: Straight to slightly curved to slightly undulose or flexuous, smooth or ornamented, typically lined, essentially cylindrical, predominantly horizontal structures interpreted as originally open burrows; burrow-fill typically massive, similar to host rock; where present, bifurcation is not systematic, nor does it result in swelling at the sites of branching (Fillion and Pickerill, 1990).

Ichnospecies*: Palaeophycus alternatus* PEMBERTON AND FREY, 1982

(Plate 5.3 b)

Diagnosis: Alternately striate and annulate *Palaeophycus* of periodically varying diameter (Pemberton and Frey, 1982).

Description: Horizontal, subcylindrical, thinly lined, unbranched, straight to slightly curved, striated and annulated burrow; elliptical in cross-section with largest diameter of the burrow 18 mm; observed length of the burrow 50 mm.

Occurrence: Micritic sandstone of Gadaputa Sandstone member of Goradongar Formation, Goradongar range.

Remarks: The specimen with striae and annulations differentiates the ichnospecies *Palaeophycus alternatus* from the other ichnospecies of *Palaeophycus*. *Palaeophycus* is an open burrow and a eurybathic facies-crossing form, probably produced by polychaetes (Pemberton and Frey, 1982).

Ichnospecies: *Palaeophycus annulatus*, BADVE 1987.

(Plate 5.3 c)

Diagnosis: Simple, straight or slightly curved horizontal to inclined, unbranched cylindrical to sub cylindrical lined burrow filled material is identical to matrix. Commonly unbranched though may be branched occasionally; there is development of annulus on the surface of burrow.

Description: Cylindrical, unbranched, distinctly lined, relatively long burrow, with fine, continuous, parallel annulations on surface. The length of the burrow is 8.3 cm while the diameter varies from 1.7-1.9 cm.

Occurrence: Micritic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: The specimen is similar to the diagnostic characteristics of annulations of the *Palaeophycus annulatus* by Badve (1987) and the absence of transverse lines along with the annulations makes it to differ from the ichnospecies *P. alternatus*.

Ichnospecies: *Palaeophycus striatus* HALL, 1852.

(Plate 5.3 d and e)

Diagnosis: Thinly lined burrows ornamented with fine, continuous, parallel, longitudinal striae (Pemberton and Frey, 1982).

Description: Horizontal to slightly inclined, slightly curved, unbranched, distinctly lined, relatively long burrow, with fine, continuous, parallel and longitudinal striae. Burrows predominantly elliptical in cross-section; burrow diameter 2.5-2.7cm. Burrow length is 6.2 cm.

Occurrence: Allochemic sandstone of Babia Cliff sandstone member of Kaladongar Formation, Kaladongar range; micritic sandstone of Gadaputa Sandstone member and micritic sandstone of Modar Hill member.

Remark: The burrows are classified as *Palaeophycus striatus* because of their distinct lining showing fine, longitudinal striae. The striae are interpreted as produced by the organism's setae or bristles, which scratched the burrow wall as the animal moved (Schlirf, 2000). The ornamentation on the wall also suggests the sediments have had certain stiffness in order to preserve such structures.

Ichnospecies: *Palaeophycus tubularis* HALL, 1847
(Plate 5.3f-j)

Diagnosis: Smooth, unornamented burrows of variable diameter, thinly but distinctly lined (Pemberton and Frey, 1982).

Description: Endichnial or hypichnial, cylindrical to slightly flatted, straight to slightly curved more or less smooth, thin walled burrow, parallel to slightly oblique to the stratification. Branching is rare, burrow walls are irregular and the burrow fill is structureless and identical to host rock. Width and length of the burrow tubes are variable in different burrows population. Maximum observed length is 10 cm with diameter of 1.2 cm.

Occurrence: Sandy allochem limestone of Kuar Bet member, micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member of Kaladongar Formation, Kaladongar range; micritic sandstone of Gadaputa Sandstone and Modar Hill members of Goradongar Formation, Goradongar range.

Remarks: *Palaeophycus* Hall (1847) has confusing taxonomic nomenclatural history; and thus it is recognized on the basis of wall lining and burrow sculpting by Pemberton and Frey (1982). The given specimen *P. tubularis* is distinguished from other ichnospecies of *Palaeophycus* by the absence of striae and annulations.

Ichnogenus: *Planolites* NICHOLSON, 1873.

Type ichnospecies: *Planolites vulgaris* Nicholson and Hinde, 1875

Diagnosis: Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or ornamented, horizontal to slightly inclined burrows, circular to elliptical in cross-section, of variable dimensions and configurations. Burrow fill biogenic, essentially massive differing from host rock; where present, bifurcation is not systematic, nor does it result in swelling at the sites of branching (Fillion and Pickerill, 1990).

Ichnospecies: *Planolites beverleyensis* BILLINGS, 1862.

(Plate 5.3 k-n; Plate 5.5 b (ii))

Diagnosis: Relatively large, smooth, straight to gently curve or undulose cylindrical burrows (Pemberton and Frey, 1982).

Description: Hyporelief, predominantly cylindrical, smooth walled, unlined, unbranched to rarely branched, straight to gently curved burrows, more or less parallel to bedding plane. Dimension varies from different burrows population; length of burrow varies from 18 to 23 cm and diameter from 0.8 to 1.3 cm.

Occurrence: Micritic sandstone and allochemic sandstone of Dingy Hill member, micritic sandstone, allochemic sandstone and micritic mudrock of Babia Cliff sandstone of Kaladongar Formation, Kaladongar range; sandy allochem limestone of Goradongar Flagstone member, micritic sandstone and allochemic sandstone of Gadaputa Sandstone member, allochemic sandstone, sandy allochem limestone and pelloidal packstone of Raimalro Limestone member and micritic sandstone and sandy micrite of Modar Hill member.

Remarks: According to Häntzchel (1962) and Crime and Anderson (1985), *Planolites* is a broad ichnogenus ranging from Precambrian to Recent. *Planolites* is a eurybathic, extremely facies-crossing form, interpreted as pascichnion and referred to polyphyletic vermiform deposit-feeders producing active backfilling (Rodrı´guez-Tovar and Uchman, 2004).

5.2.1.2.3 U-shaped forms

Ichnogenus: *Arenicolites* SALTER, 1857

Type ichnospecies: *Arenicola carbonaria* BINNEY, 1852

Diagnosis: Vertical U-tubes without spreite (Fürsich 1974c)

Ichnospecies: *Arenicolites carbonarius* SALTER 1857.

(Plate 5.4, a and b; Plate 7.7a (ii))

Diagnosis: Simple, U-tubes without spreite, perpendicular to bedding plane (Häntzschel, 1975).

Description: Endichnial, full relief, vertically oriented, U-shaped, paired burrows. Burrow diameter is about 0.5-0.9 cm and burrow arms are about 1.5-2.5 cm apart. The burrows occur as paired, circular opening on the bedding surface; fill identical to the host sediment.

Occurrence: Micritic sandstone of Dingy Hill and Babia Cliff Sandstone members; and sandy allochem limestone of Dingy Hill and Kaladongar Sandstone members of Kaladongar Formation, Kaladongar range.

Remarks: Ethologically, *Arenicolites* represents dwelling burrows of suspension-feeders (e.g. Fürsich1975; Hakes 1977; Howard and Frey 1984; Pickerill et al 1984; Eager et al. 1985).

Ichnospecies: *Arenicolites statheri* BATHER, 1925

(Plate 5.4 c)

Diagnosis: Straight, symmetrical, U-shaped burrows (Fürsich, 1974b)

Description: Endichnial, full relief, vertically oriented, unlined, slightly curved, U-shaped burrow. Burrow diameter is about 10 mm and burrow arms are 3 mm apart, fill is identical to the host sediment.

Occurrence: Sandy micrite of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: *Arenicolites statheri* differs from other ichnospecies of *Arenicolites* because of their straight, vertical, closely spaced symmetrical U shaped tube. It is generally interpreted as domichnion of a suspension-feeding polychaete (Fürsich 1974c). *Arenicolites* are found in sediments ranging in age from Early Cambrian (Narbonne et al, 1987) to Holocene (Chamberlain, 1978).

Ichnospecies: *Arenicolites* isp.

(Plate 5.4 d and e; Plate 5.6 b (i))

Description: Endichnial, full relief, vertically oriented, lined as well as unlined burrows with paired opening with funnel shaped apertures. Burrow diameter is about 3-4 mm and burrow arms are about 2-4 mm apart. The burrows occur as paired, unfilled, funnel openings on the bedding surface.

Occurrence: Sandy micrite and pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: The vertical morphology of the paired burrow is not determined and therefore the identification to ichnospecies level is problematic. Ethologically, *Arenicolites* represents dwelling burrow of suspension-feeders (e.g. Fürsich 1975; Hakes 1977; Howard and Frey 1984; Pickerill et al 1984; Eager et al. 1985). The occurrence of wall lining or lack reflects the difference in the sediment cohesiveness/consistency, as the wall gives more stability to the burrow.

5.2.1.3 Branched Structures

5.2.1.3.1 Dichotomously branching forms

Ichnogenus: *Chondrites* VON STERNBERG, 1833

Type Ichnospecies: *Fucoides antiquus* Brongniart, 1828
Diagnosis: Dendritic, smooth walled, regularly ramifying small burrow systems that normally do not interpenetrate or interconnect. Diameter of components within a given system remains essentially constant (Pemberton and Frey, 1984).

Ichnospecies: *Chondrites targionii,* BRONGNIART, 1828
(Plate 5.4 f and g)

Diagnosis: *Chondrites* characterized by well expressed primary successive branching, which are commonly slightly curved. The angle of branching is usually sharp or obtuse. Most of the tunnels are few millimeters wide (Uchman, 1999)
Description: Endichnial, tree like branched tunnel system with slightly sinuous branches. The specimen shows slightly winding, negative epirelief, dominated by second order branching at an angle of 50^0 to 60^0. The color of the sediment fill is different from the color of the host rock.
Occurrence: Micritic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range; and sandy micrite of Modar Hill member of Goradongar Formation, Goradongar range.
Remark: According to Seilacher (1990) and Fu (1991), the trace maker of *Chondrites* may be able to live at the aerobic/anoxic interface as chemo-symbiotic organism.

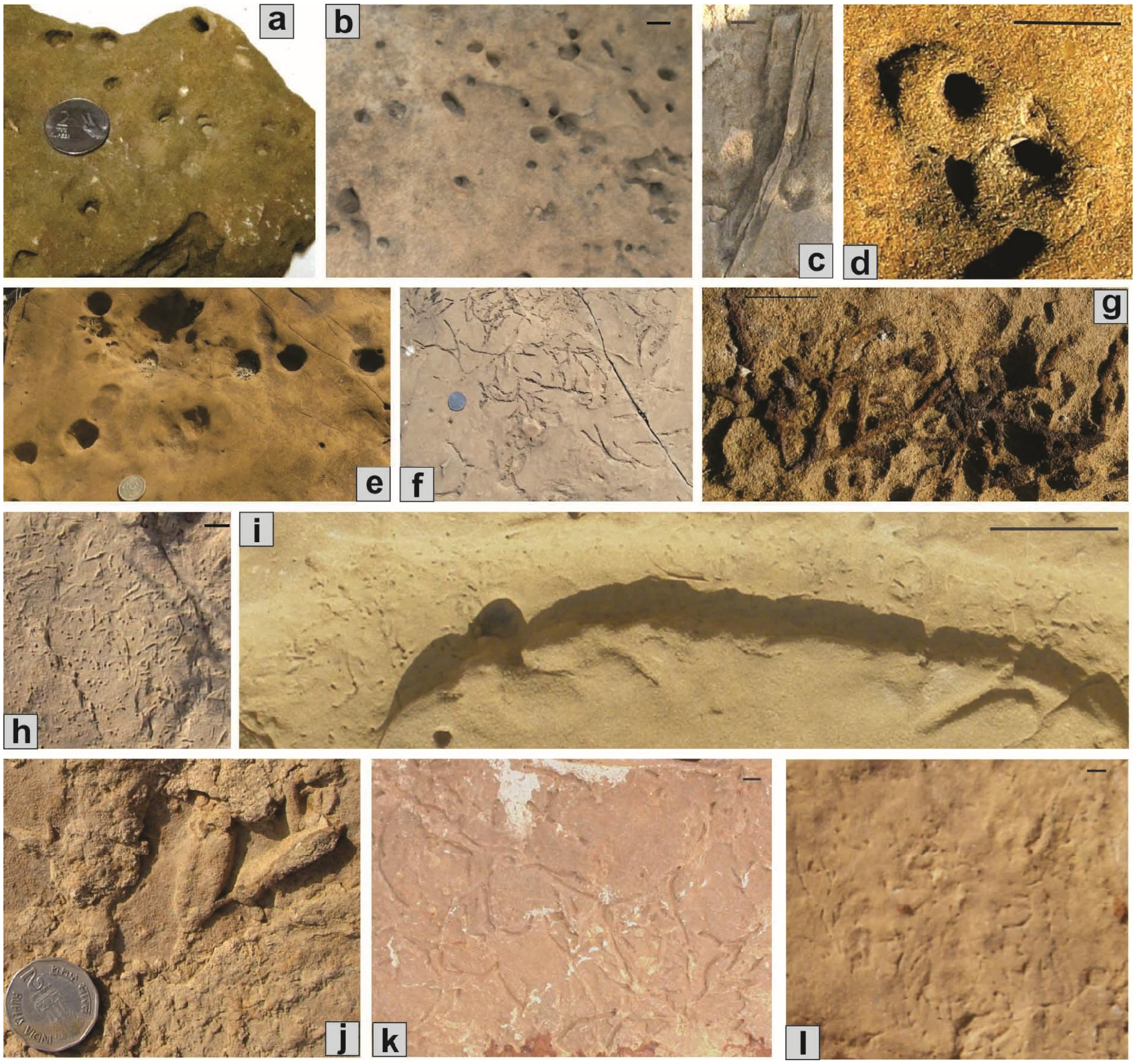

Plate 5.4 U-shaped forms (Bar length = 1 cm, Coin diameter = 2.5cm.).
(a) *Arenicolites carbonarius;* vertical U-shaped paired burrow; **(b)** *Arenicolites carbonarius;* U-shaped paired burrow; **(c)** *Arenicolites statheri*, Sandy micrite, MHM; **(d)** *Arenicolites* isp., Sandy micrite, MHM; **(e)** *Arenicolites* isp., Micritic sandstone, MHM; **(e)** *Chondrites targionii*; endichnial, full relief, parallel to bedding plane; **(f)** *Chondrites targionii*, Muddy micrite, MHM; **(g)** *Chondrites intricatus*; small, endichnial, full relief, parallel to bedding plane; **(h)** *Chondrites intricatus*, Sandy allochemic limestone, RLM; **(i)** *Dactylophycus* isp; branching bilobate burrow; **(j)** *Pilichnus dichotomus*; endichnial full relief, Horizontal winding branched strings; **(k)** ?*Pilichnus* isp. , Allochemic sandstone, GSM.

Ichnospecies: *Chondrites intricatus,* BRONGNIART, 1823

(Plate 5.4 h and i)

Diagnosis: Small burrow system with numerous downward radiating branches (FU 1991).

Description: Small tree-like burrow system with numerous downward radiating branches of flattened tunnel filled with lighter material than the host rock. The tube diameter is of 1 mm.

Occurrence: Micritic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range and in sandy allochem limestone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: *Chondrites intricatus* is mostly found in fine grained siliciclastic and carbonate rocks (Uchman, 1995). This ichnospecies differ from the rest in having small tube diameters.

Ichnogenus: *Dactylophycus* MILLER AND DYER, 1878

Type ichnospecies: *Dactylophycus tridigitatum,* Osgood, 1970.

Diagnosis: Delicately annulated bilobate burrows; small and radiate or randomly branching (Häntzschel, 1975).

Ichnospecies: *Dactylophycus* isp.

(Plate 5.4 j)

Description: Hypichnial, palmate branched with unevenly pinching and swelling short segments appearing as fusiform. The specimen shows full relief preservation, smooth ornamentation, and elliptical cross-section. The palmate branch length varies from 3.3-3.4 cm and maximum width increases at the centre varying from 0.7 to 1.2 cm. The palmately branching form joins each other by thin pinching segments of length and width of 0.65 cm and 0.25 cm respectively.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: Its phobotaxis and second order branching is typical of *Chondrites*, but the burrow tendency towards palmate rather than lateral branching led (Osgood, 1970**)** to relate *Dactylophycus* to *Phycodes* and *Arthrophycus* instead of *Chondrites*, and it is true that all of these are chondritids, i.e., radiating feeding burrows without a spreite (Rindsberg, 1994).

Ichnogenus: *Pilichnus* UCHMAN,1999

Type Ichnospecies: *Pilichnus dichotomus* Uchman 1999

Diagnosis: System of horizontal, straight, curved to irregularly winding, very thin sub-millimetric strings showing commonly dichotomous branches (Uchman, 1999)

Ichnospecies: *Pilichnus dichotomus* UCHMAN,1999

(Plate 5.4 k)

Diagnosis: As for ichnogenus.

Description: Full-relief, System of horizontal, straight, curved to irregularly winding, branched string without wall, preserved in full-relief on parting surface of calcareous sandstone. The strings are 0.15-0.35 mm wide. They are filled with dark argillaceous substance. Dichotomous, Y- shaped branches are commonest and very characteristic. T-shaped branches however also occur. When crowded, trace fossil may occur in regular nets.

Occurrence: Sandy allochem limestone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range.

Remarks: This form is very thin and differs from ichnogenus *Trichichnus*, in the horizontal orientation of burrows (Uchman, 1999).

Ichnospecies: ?*Pilichnus* isp.

(Plate 5.4 l)

Description: Endichnial, horizontal to gently incline with straight to slightly curved course, branched unlined burrow preserved in full-relief on parting surface of allochemic sandstone. The trails are 0.15-0.35 mm wide. Burrow filled with calcareous substance.

Occurrence: Allochemic sandstone of Gadaputa Sandstone member of Goradongar Formation, Goradongar range.

Remarks: This ichnogenera differs from the *Palaeophycus* and *Planolites* being very thin and from ichnogenus *Trichichnus*, in the horizontal orientation of burrows (Uchman 1999).

5.2.1.3.2 Y-T shaped branching forms

Ichnogenus: *Ophiomorpha* LUNDGREN, 1891

Type Specimen: *Ophiomorpha nodosa* LUNDGREN, 1891

Diagnosis: Simple to complex burrow systems lined at least partially with agglutinated pelletoidal sediment (Howard and Frey, 1984).

Ichnospecies: *Ophiomorpha nodosa* LUNDGREN, 1891

(Plate 5.5 a-e)

Diagnosis: *Ophiomorpha* with burrow walls consisting predominantly of dense, regularly distributed discoid, ovoid, or irregular polygonal pellets (Frey and Pemberton, 1999)

Description: Endichnial, full relief; horizontal, vertical, sub-vertical, branched or unbranched burrow covered with ovoid pelletoidal knobs and having diameter of 1.9-2.9 cm and length is about 36-74 cm. Burrows are filled with sediments similar to the surrounding substrate, but unfilled tube segments are also very common.

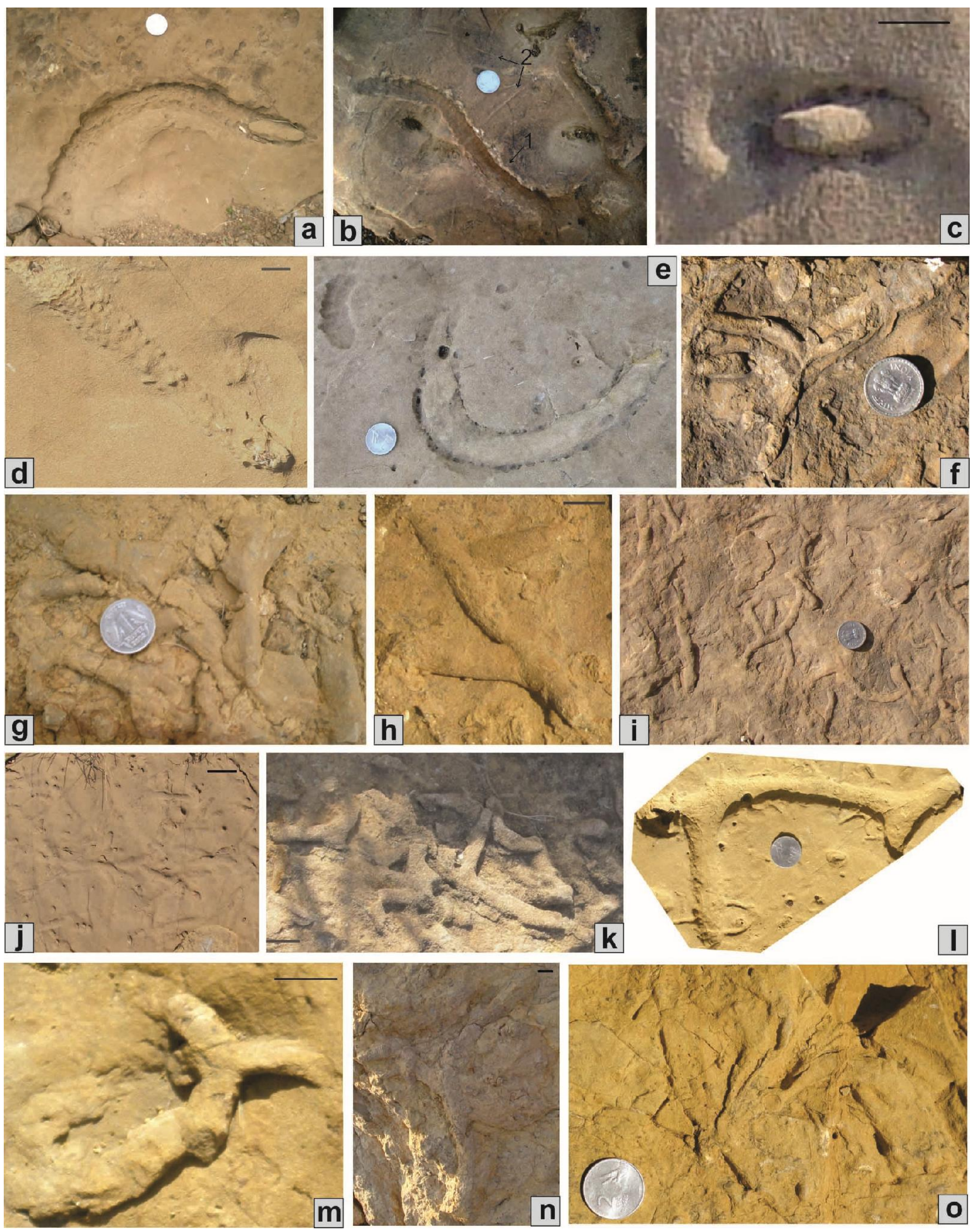

Plate 5.5 Y-T shaped branched, and bundled forms (Bar length = 1 cm; coin diameter= 2.5cm).
(a) *Ophiomorpha nodosa*; Horizontal component of three dimensional maze structure; **(b)** Horizontal component of maze structure of (1) *Ophiomorpha* nodosa associated with horizontal unlined burrow of (2) *Planolites beverleyensis*; **(c)** Sub-vertical component of the *Ophiomorpha nodosa*; **(d)** *Ophiomorpha nodosa*, sandy micrite, MHM; **(e)** *Ophiomorpha nodosa*, sandy micrite, MHM; **(f)** *Thalassinoides horizontalis,* Horizontal Y-shaped burrow; **(g)** *Thalassinoides horizontalis,* Horizontal Y-shaped burrow; **(h)** *Thalassinoides horizontalis*, allochemic sandstone, GFM; **(i)** *Thalassinoides suevicus,* three dimensional Y-shaped burrows; **(j)** *Thalassinoides suevicus,* three dimensional Y-shaped burrows; **(k)** *Thalassinoides suevicus*, allochemic sandstone, GFM; **(l)** *Thalassinoides suevicus*, Sandy allochem limestone, RLM; **(m)** *Thalassinoides* isp.; a curved arm, Y-shaped burrow, allochemic sandstone of DHM; **(n)** *Thalassinoides* isp.; a curved arm, Y-shaped burrow, RLM; **(o)** *Hartsellea sursumramosa*, Allochemic sandstone, GFM.

Occurrence: Micritic sandstone and allochemic sandstone of Dingy Hill member and sandy allochem limestone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range; and pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.
Remarks: *Ophiomorpha* occur predominantly in shallow water near-shore deposits (Weimar and Hoyt, 1964; Frey et al., 1978), but has also been reported, since the Mesozoic (Bottjer et al., 1987) from deep-sea deposits (Kern and Warme, 1974; Crimes, 1977; Crimes et al., 1981; Uchman, 1988, 1989, 1990, 1995). In Mesozoic-Cenozoic sediments, *Ophiomorpha* is produced mainly by shrimps comparable to recent callianassids (Weimar and Hoyt, 1964; Frey et al., 1978). Patel and Desai (2001, 2009) have also observed *Ophiomorpha nodosa* like burrows made by Stomatopodean (Squillidean) crustaceans, especially *Oratosquilla striata* in the runnels of the intertidal zone of the Mandvi area.

Ichnogenus: *Thalassinoides* EHRENBERG, 1944

Type Specimen: *Thalassinoides callianassae* Ehrenberg, 1944.
Diagnosis: Three dimensional burrow systems consisting predominantly of smooth-walled, essentially predominantly of smooth walled, essentially cylindrical components of variable diameter; branches Y- to T-shaped, enlarged at points of bifurcation (Howard and Frey, 1984).

Ichnospecies: *Thalassinoides horizontalis* MYROW, 1995

(Plate 5.5, f-h)

Diagnosis: Horizontal, branching framework of smooth-walled, unlined burrows, lacking vertically oriented offshoots. Burrow diameter consistent within individual specimens; constrictions or swellings at both junctions and inter-junction segments are notably absent.

Description: Smooth, unlined, three-dimensional Y-shaped branching horizontal burrows. Tunnels are straight to curve and burrows chiefly consist of horizontal tunnels that bifurcate at angle of 80^0-130^0. The length of burrow is 10-12 cm and diameter varies from 0.6-1 cm.

Occurrence: Micritic sandstone and allochemic sandstone of Dingy hill member of Kaladongar Formation, Kaladongar range; micritic sandstone of Gadaputa Sandstone member, sandy allochem limestone and oolitic packstone of Raimalro Limestone member.

Remarks: The specimen differs from the type material of Myrow (1995) in diameter and from *T. bacae* in the absence of the vertical shafts.

Ichnospecies: *Thalassinoides suevicus* REITH, 1932

(Plate 5.5, i-l)

Diagnosis: Predominantly horizontal, more or less regularly branched, essentially cylindrical burrow system; dichotomous bifurcations are more common than T-shaped branches (Howard and Frey, 1984).

Description: Endichnial, full relief, horizontal to slightly oblique three-dimensional burrow system, varying from 25 cm to 30 cm in length and from 1.5 to 3.5 cm in diameter. More or less regularly branched, connected to surface by more or less vertical shaft; dichotomous bifurcations are more common than T-shaped branches. The burrows fill differently as the colour, texture differ in the surrounding.

Occurrence: Micritic sandstone of Dingy Hill member; and allochemic sandstone and sandy allochem limestone of Dingy Hill and Babia Cliff Sandstone members of Kaladongar Formation, Kaladongar range; and sandy allochem limestone of Goradongar Flagstone and Raimalro Limestone members of Goradongar Formation, Goradongar range.

Remarks: *Thalassinoides* is generally interpreted as a fodinichnial burrow, passively filled, usually related to oxygenated situations and soft but fairly cohesive substrates (Rodrı´guez-Tovar and Uchman, 2004). According to Follmi and Grimm (1990), the crustaceans producing *Thalassinoides* may survive transport in turbidity currents and produce burrows under anoxic conditions for a limited number of days. *Thalassinoides* is a facies-crossing form, most typical of shallow-marine environment, and is produced mainly by crustaceans (Frey et al. 1984).

Ichnospecies: *Thalassinoides* isp.
(Plate 5.5 m and n)

Description: Burrows showing Y-shaped branching. The arms are slightly curved to sinuous. Burrow diameter is about 2cm and the length of each branch varies. The tunnels are curved and shows angle of bifurcation of about 130-150^0.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range and sandy allochem limestone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: Ichnogenus *Thalassinoides* is classified based on the presence of horizontal elements and branching characteristics. Six ichnospecies are currently recognized, namely; *T. saxonicus* Geinitz, 1842 (characterised by its large form with tunnels; Kennedy, 1967); *T. ornatus* Kennedy, 1967 (consisting of smaller ovate, horizontal to gently inclined burrows; Kennedy, 1967); *T. paradoxicus* (that branches forming complex boxwork patterns, generally irregular in geometry; Howard and Frey, 1984); *T. suevicus* Reith, 1932 (which is predominantly a horizontal form consisting of enlarged Y-shaped bifurcations; Howard and Frey, 1984); *T. horizontalis* (a strictly horizontal form); and *T. foedus* Mikulás, 1990 (that forms polygonal frameworks. *Thalassinoides* isp., herein, does not exhibit any of the aforementioned attributes which precludes the definite identification to an ichnospecies level.

5.2.1.3.3 Bundled forms

Ichnogenus: *Hartsellea* RINDSBERG, 1994

Type Ichnospecies: *Hartsellea sursumramosa* Rindsberg, 1994

Diagnosis: Burrow system consisting of central shaft curving upward and outward branching palmately in proximal part and laterally in distal part. Branches recurved, with outermost branches most recurved and excavated first. Distal branches markedly sinuous, phobotactic. Burrow walls lined possibly pelleted; fill with transverse structure.

Ichnospecies: *Hartsellea sursumramosa* RINDSBERG, 1994

(Plate 5.5 o)

Diagnosis: Same as for ichnogenus.

Description: Convex hyporelief, horizontal branched burrow, new branches issue from the outer curves of previous branches. The length of the burrow system is 84 mm and it covers an area of about 80 x120 mm.

Occurrence: Allochemic sandstone of Goradongar Flagstone member of Goradongar Formation, Goradongar range.

Remarks: *Hartsellea* is a system of upward-branching and thus the feeding appendages of its maker may be facing upward as shown by some scavenging and carnivorous polychaetes (Rindsberg, 1994). This specimen differs from *Chondrites* in having upward branching from a central shaft.

Ichnogenus: *Phycodes* RICHTER, 1850

Type Ichnospecies: *Phycodes circinatum* Richter, 1853

Diagnosis: Horizontal bundled burrows preserved outwardly as convex hyporeliefs. Overall patterns are reniform, fasciculate, flabellate, broom-like, ungulate, linear, falcate or circular. Some forms consist of a few main branches showing a spreite-like structure that gives rise distally to numerous free branches. In other forms the spreiten are lacking and branching tends to be second or more random. Individual branches are teeters and finely annulate or smooth (Fillion and Pickerill, 1990).

Ichnospecies: *Phycodes circinatum* RICHTER, 1853

(Plate 5.6 a (i))

Diagnosis: Same as for ichnogenus.

Description: Bundled structures of flabellate or broom-like pattern, consisting of horizontal tunnels. Proximal part of main tunnel unbranched while distally it divides into several cylindrical tunnels. Some annulations can be seen on the cylindrical tunnels. Tunnel fill is same as the substrate. Main tunnel is about 2-3 cm in diameter while the branches are 1-2 cm in diameter. The length of the tunnel ranges from 15-20 cm.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: *P. circinatum* is characterized by the bundled structures and annulations on the cylindrical tube.

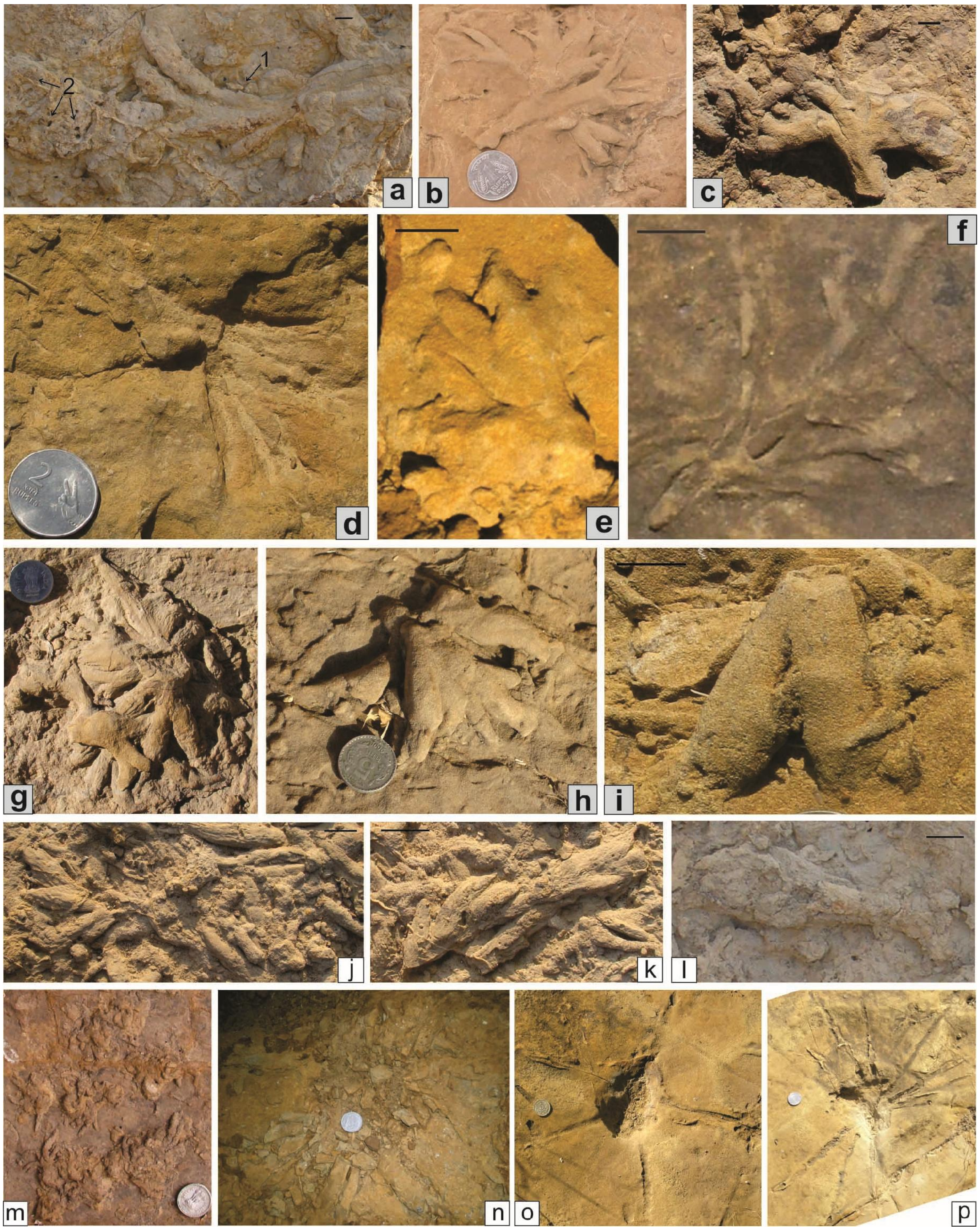

Plate 5.6 Branched and Rossette structures (Bar length = 1 cm; coin diameter= 2.5 cm).
(a) Broom like horizontal smoothly curved burrow 1. *Phycodes circinatum* 1 and vertical paired burrows 2. *Arenicolites* isp. in allochemic sandstone, DHM; **(b)** *Phycodes palmatus*, palmate burrow; allochemic sandstone, DHM and BCSM; **(c)** *Phycodes palmatus*, sandy allochem limestone, BCSM; **(d)** *Phycodes cf. palmatus,* allochemic sandstone, GFM; **(e)** *Phycodes cf. palmatus*, Micritic mudrock, GFM; **(f)** *Phycodes cf. curvipalmatum,* sandy micrite, MHM; **(g)** *Asterosoma radiciforme,* radial bulbs from vertical shaft, BCSM; **(h)** *Asterosoma radiciforme*; radial bulbs from vertical shaft, BCSM; **(i)** *Asterosoma* cf. *radiciforme*; resembling bulbed *Asterosoma radiciforme*, micritic mudrock, GFM; **(j)** and **(k)** *Asterosoma ludwigae,* branching bulb form, allochemic sandstone, BCSM; **(l)** Bulbs of the *Asterosoma ludwigae*; allochemic sandstone, DHM; **(m)** *Ichnocumulus radiates*, pustule shaped with radiating projections in allochemic sandstone, DHM; **(n)** *Phoebichnus trochoides*; irregular burrows radiating from central shaft; sandy allochem limestone, DHM; **(o)** and **(p)** *Phoebichnus trochoides*, allochemic sandstone, GSM,

Ichnospecies: *Phycodes palmatus* HALL, 1852

(Plate 5.6 b and c)

Diagnosis: Few thick and rounded branches that originate in a palmate or digitate form from nearly the same point (Fillion and Pickerill, 1990)

Description: Burrow system is long, palmately branching close together, with branches terminating in fan-shaped structure. The burrow system shows length of 8.2-9 cm and the branch diameter is varies from1-1.5 cm.

Occurrence: Allochemic sandstone of Dingy Hill and Babia Cliff Sandstone members and sandy allochem limestone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range.

Remarks: *Phycodes palmatum* is characterized by its palmate branching and differs from *P. curvipalmatum* by its larger size and lack of re-curvature.

Ichnospecies: *Phycodes* cf. *palmatus* HALL, 1852

(Plate 5.6 d and e)

Description: Horizontal, bundled burrows preserved outwardly as convex hyporelief. Overall pattern flabellate, consisting of a main stem that give rise to distally numerous free branches. The burrow system is 62 mm long with smooth or faintly developed transverse striae, individual branches varying in length from 20-22 mm and in width from 6-10 mm.

Occurrence: Sandy allochem limestone of Goradongar Flagstone member of Goradongar Formation, Goradongar range.

Remarks: Although the palmate branching style resembles the *Phycodes palmatum,* it is more regular in the type specimen and differs from *P. curvipalmatum* by its larger size and lack of curvature. . Vermiform annelids are considered to be possible producers of *Phycodes* (Fillion and Pickerill, 1990).

Ichnospecies: *Phycodes cf. curvipalmatum* POLLARD, 1981

(Plate 5.6 f)

Diagnosis: Horizontal, cylindrical, or compressed burrows, 1-2 mm in diameter, which are curved and branched either dichotomously or palmately, like the fingers of a hand (Pollard, 1981).

Description: Horizontal, ramifying and branching intrastratal burrows preserved outwardly as convex hyporelief. Burrow possesses a tube like form proximally that distally split into finger-like curved branches. The burrow system is 50 mm long with individual branches varying in width from 3-4 mm.

Occurrence: Sandy allochem limestone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: These small sized, highly variable burrows with curved branches appear similar to the *Phycodes curvipalmatum* Pollard, 1981. Vermiform annelids are considered to be the possible producers of *Phycodes* (Fillion and Pickerill, 1990).

5.2.1.4 Rosette Structures

5.2.1.4.1 Radial structures

Ichnogenus: *Asterosoma* VON OTTO, 1854

Type Ichnospecies: *Asterosoma radiciforme* Von otto, 1854

Diagnosis: Horizontal to inclined burrows, either with star-like arranged bulbs or bulbs that bud from a circular to elliptical tube in a dichotomously to fan-like pattern. Bulbs are concentrically to irregularly laminated with a small cylindrical, inner tube which lies in a sub-central position or distinctly eccentric. Burrow wall with or without longitudinal, subangular furrows and striae (Schlirf, 2000).

Ichnospecies: *Asterosoma radiciforme* VON OTTO, 1854
(Plate 5.6 g and h)

Diagnosis: As for ichnogenus.

Description: Sub-horizontal bulbs showing radial or star like orientation with tapering ends; preserved as full relief; walls show longitudinal furrows and striae. The bulb length varies from 4.9-6.6 cm; width is 1.3-1.5 cm; the burrow system covers an area of 10x13 cm^2.

Occurrence: Allochemic sandstone of Babia cliff sandstone member of Kaladongar Formation, Kaladongar range.

Remark: It is probably burrows with radiating feeding structures. The decapod crustaceans are the possible producers of the Mesozoic *Asterosoma* (Häntzschel, 1975; Altevogt, 1968).

Ichnospecies: *Asterosoma* cf. *radiciforme* VON OTTO, 1854
(Plate 5.6 i)

Description: Full relief, sub-horizontal bulbs showing 3-4 bulbs radiating from a central shaft normal to the bedding; the associated shafts are not well observable. The burrow system is 64 mm wide, while the individual bulb varies in length from 30-32 mm and diameter varies from 8-10 mm.

Occurrence: Sandy allochem limestone of Goradongar Flagstone member of Goradongar Formation, Goradongar range.

Remarks: It is probably a burrow with radiating feeding tubes. Decapod crustaceans are the possible producers of the Mesozoic *Asterosoma* (Altevogt, 1968; Häntzschel, 1975). The specimen shows only four bulbs radiating from the central shaft. This may suggest that the specimen belong to *A. radiciforme* which may be eroded or the specimen represents the 1st stage morphology of *Asterosoma* (Neto de Carvalho and Rodrigues, 2007).

Ichnospecies: *Asterosoma ludwigae* SCHLIRF, 2000
(Plate 5.6 j-l)

Diagnosis: *Asterosoma* with concentrically to irregularly laminated bulbs that bud form a circular to elliptical tube in a dichotomously to fan-like pattern.

Description: Various size of buds laterally dichotomously budding and bulbs are elliptical in cross-section and variable in shape; tapering at distally. The tube diameter is 0.6-1.1 cm. The long axis of bulbs is 2.3-4.3 cm, short axis 1.9-2.2 cm and height is 0.8 cm. The overall size of the burrow system is 10.2 cm in length and 2.2 cm in width.

Occurrence: Allochemic sandstone of Dingy Hill and Babia Cliff sandstone members of Kaladongar Formation, Kaladongar range.

Remarks: The concentric laminae represent the feeding behavior while the massive tubes represent the locomotion behavior (Schlirf, 2000). This ichnospecies differ from the other ichnospecies of the *Asterosoma* ichnogenus, in non-radiating and branching system.

Ichnogenus: *Ichnocumulus,* SEILACHER, 1956

Type Ichnospecies: *Ichnocumulus radiatus* SEILACHER, 1956

Diagnosis: Small pustule-shaped bodies possessing straight, radiate projections (Häntzschel, 1975).

Ichnospecies: *Ichnocumulus radiatus* SEILACHER, 1956

(Plate 5.6 m)

Diagnosis: Same as for ichnogenus.

Description: Small pustule shaped bodies possessing straight, radiate projections. The body diameter varies from 1.5-2 cm and the radial projection varies from 0.75-1cm in length.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: *Ichnocumulus* is reported from Jurassic sediments of south Germany as the resting traces made by an unknown animals hiding temporarily in sediments (Seilacher 1956).

Ichnogenus: *Phoebichnus* BROMLEY AND ASGAARD, 1972

Type Ichnospecies: *Phoebichnus trochoides* Bromley and Asgaard, 1972

Diagnosis: Central shaft, nearly vertical to bedding, with numerous, long, straight radial burrows oriented more or less parallel to bedding; radial burrows including distinct, annulated wall lining; concave towards central shaft (Häntzschel, 1975).

Ichnospecies: *Phoebichnus trochoides* BROMLEY AND ASGAARD, 1972
(Plate 5.6n-p)

Diagnosis: Same as for ichnogenus.

Description: Endichnial, full relief, with large, central vertical shaft from which irregular horizontal burrows radiate; burrow collapsed and central part appear as more irregular circular form with broken horizontal tubes. Diameter of the tubes are varies from 0.6-1 cm and length varies from 8-15 cm. The whole structure is affected by the erosional weathering processes leads to collapsed nature.

Occurrence: Sandy allochem limestone of Dingy Hill member and allochemic sandstone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range; and allochemic sandstone of Gadaputa Sandstone member of Goradongar Formation .

Remarks: Central shaft has been interpreted as dominichnia while the radial burrows are interpreted as fodinichnia of some unknown animal (Häntzschel, 1975).

5.2.1.5 Spreiten Structures

5.2.1.5.1 Vertical forms

Ichnogenus: *Diplocraterion* TORELL, 1870

Type ichnospecies: *Diplocraterion parallelum* TORELL, 1870.

Diagnosis: Vertical to oblique, U-shaped, single-spreite burrows; spreite may be unidirectional or bidirectional, continuous or discontinuous. Limbs unlined and smooth or with bioglyphs, sometimes with heavy lining; either parallel or diverging upward or downward; top of limbs sometimes with funnel shaped opening (Schlirf, 2005).

Ichnospecies: *Diplocraterion* isp.
(Plate 5.7 a (i), b)

Description: Vertical, smooth, unlined, U-shaped burrow appear as pair of circular openings on surface which is connected by spreite. The burrow tube is 0.5-1.8 cm apart, 0.6-2 cm in diameter; fill is identical to surrounding sediment.

Occurrence: Sandy allochem limestone of Dingy Hill member, pelloidal packstone of Kaladongar Sandstone member and micritic sandstone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range; and in micritic mudrock of Goradongar Flagstone member, allochemic sandstone of Gadaputa Sandstone member and pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.

Remark: The present trace fossil is kept under the *Diplocraterion* Torell, 1870 based on the essential diagnostic features but the vertical section could not be retrieved which makes it difficult to identify at ichnospecies level. It is the dwelling burrow of suspension feeding animal, probably living in environment of high wave energy (Goldring, 1962)

Ichnogenus: *Daedalus* ROUAULT 1850

Type Ichnospecies: *Vexillum desglandi* Rouault, 1850

Diagnosis: Subvertical spreiten structure made by lateral migration of a simple to spiral J-shaped burrow; burrows commonly self-intersecting.

Ichnospecies: *Daedalus* cf. *verticalis* SEILACHER, 2000

(Plate 5.7 c)

Diagnosis: Deep arthrophycid burrow resembling *Diplocraterion*, but made by protrusive vertical dislocation of a slightly inclined dead-end J-tube without a spiral turn.

Description: Deep burrow resembling *Diplocraterion,* but made by protrusive vertical dislocation of a slightly inclined dead-end J-tube without a spiral turn. The individual burrows are neither clustered into radial arrays, nor arranged parallel to each other. The burrow reaches a visible depth of 11 cm; diameter of the protrusive tube is 2.12 cm; and overall diameter of the tube is 8.13 cm.

Occurrence: Sandy allochem limestone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: It superficially resembles to *Diplocraterion* and lacks spirals but the origination from the vertical dislocation of a J- rather than a U-tube and larger vertical extension than its width clearly suggest as belonging to the arthrophycids. Although, *Daedalus* has not previously been reported from rocks younger than Silurian except in the Carboniferous of Alabama (Seilacher, 2000), the present ichnospecies shows a clear resemblance with the *Daedalus verticalis* Seilacher, 2000.

5.2.1.5.2 Horizontal forms

Ichnogenus: *Rhizocorallium* ZENKER, 1836

Type Ichnospecies: *Rhizocorallium jenense,* ZENKER, 1836

Diagnosis: Wedge-shaped, double-spreite burrows, built up of U-limbs, oblique to parallel towards bedding plane, width of 'U' constant or distally increasing; limbs distinct. Exterior smooth, or with longitudinal or transverse ridges and grooves (Emended by Schlirf, 2005)

Ichnospecies: *Rhizocorallium jenense* ZENKER, 1836
(Plate 5.7d-i)

Diagnosis: More or less straight, short U-shaped spreiten-burrows, commonly oblique to bedding plane and occasionally vertically retrusive (Fürsich, 1974c).

Description: Epichnial, positive semi relief, short, straight to slipper shaped, horizontal to sub horizontal, unbranched U-shaped tube containing spreiten. The tubes are filled with fine to medium grained sediments identical with the matrix; usually each arm of the tubes is 6.5 cm long and 1.2 cm wide.

Occurrence: Micritic sandstone of Dingy Hill member, allochemic sandstone of Babia Cliff Sandstone member of Kaladongar Formation, Kaladongar range; sandy allochem limestone of Goradongar Flagstone member, micritic sandstone, allochemic sandstone of Gadaputa Sandstone member of Goradongar Formation, Goradongar range.

Remarks: *R. jenense* is interpreted as burrows of suspension feeders (Fürsich 1974a, 1974b) or scavenging organisms (WorsleyandMork 2001). The structure usually represents a fodinichnial behavior (Fürsich 1998). The Rhizocorallid modification represented by the slipper shaped *Rhizocorallium* (Line drawing of Pl. VII, e) reflects a fixed two-stage program wherein the trace maker first increased the length of the tube by constructing inclined protrusive spreite and then switching to upward retrusive spreite (Seilacher, 2007).

Ichnospecies: *Rhizocorallium irregulare* MAYER, 1954
(Plate 5.7 j-m)

Diagnosis: Long sinuous bifurcating or planspiral U-shaped spreiten burrows; mainly horizontal (Fürsich, 1974b).

Description: Epichnial semi-relief, long, more or less sinuous to curved, U-shaped, horizontal, branching and planispiral form of spreiten burrows with stout tubes about 1-2 cm thick. Total burrow width is 6-10 cm. The spreite are less preserved, with tube representing pocket-like depressions. Burrow fill is identical to the host rock.

Occurrence: Micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill; sandy allochem limestone, pelloidal packstone and sandy micrite of Kaladongar Sandstone; and allochemic sandstone and sandy allochem limestone of Babia Cliff Sandstone members of Kaladongar Formation; bioclastic grainstone of Goradongar Flagstone member, micritic sandstone of Gadaputa Sandstone member, sandy allochem limestone and pelloidal packstone Raimalro Limestone member, and sandy allochem limestone, pelloidal packstone, and sandy micrite of Modar Hill member.

Remarks: *R. irregulare* represents the fodinichnia of deposit feeding organisms. Fürsich (1974b) regarded *Rhizocorallium* to be produced by Crustaceans based on scratch marks. But no scratch marks were observed on any of the specimen. The relatively small dimension of the trace fossil in comparison to the large body dimension of the crustacean shows that this trace maker can be ruled out. Hence the question of the possible producer remains open (Schlirf, 2000). There are several stages of feedings observed in the sediments of the Kaladongar Sandstone member (Line drawing of Pl. VII, k)

Ichnospecies: *Rhizocorallium uliarense* FIRTION, 1958

(Plate 5.7n and o)

Diagnosis: Long and coiled parallel U-shaped spreiten horizontal burrows with thick tubes

Description: Epichnial, long, U-shaped, horizontal, trochospiral spreiten burrows. Tubes are stout and parallel, 5 cm wide. Burrow fill is identical to the host rock.

Occurrence: Sandy allochem limestone of Kaladongar Sandstone member of Kaladongar Formation, Kaladongar range; Sandy allochem limestone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: This ichnospecies differs from the other ichnospecies of this ichnogenus in the stout nature of tubes and coiling of the burrow on the bedding plane (Fürsich, 1974c).

5.2.1.5.3 Wall like forms

Ichnogenus: *Teichichnus,* SEILACHER, 1955

Type ichnospecies: *Teichichnus rectus* SEILACHER, 1955.

Diagnosis: Long, straight, sinuous to zigzag-shaped, unbranched or branched, wall-like spreite structures, formed by vertical displacement of horizontal or oblique, erect to undulose tubes without wall-lining, resulting in a unilobed (gutter-shaped) or bilobate (double gutter shaped) spreite in frontal view. Bioglyphs may be present (Schlirf, 2005).

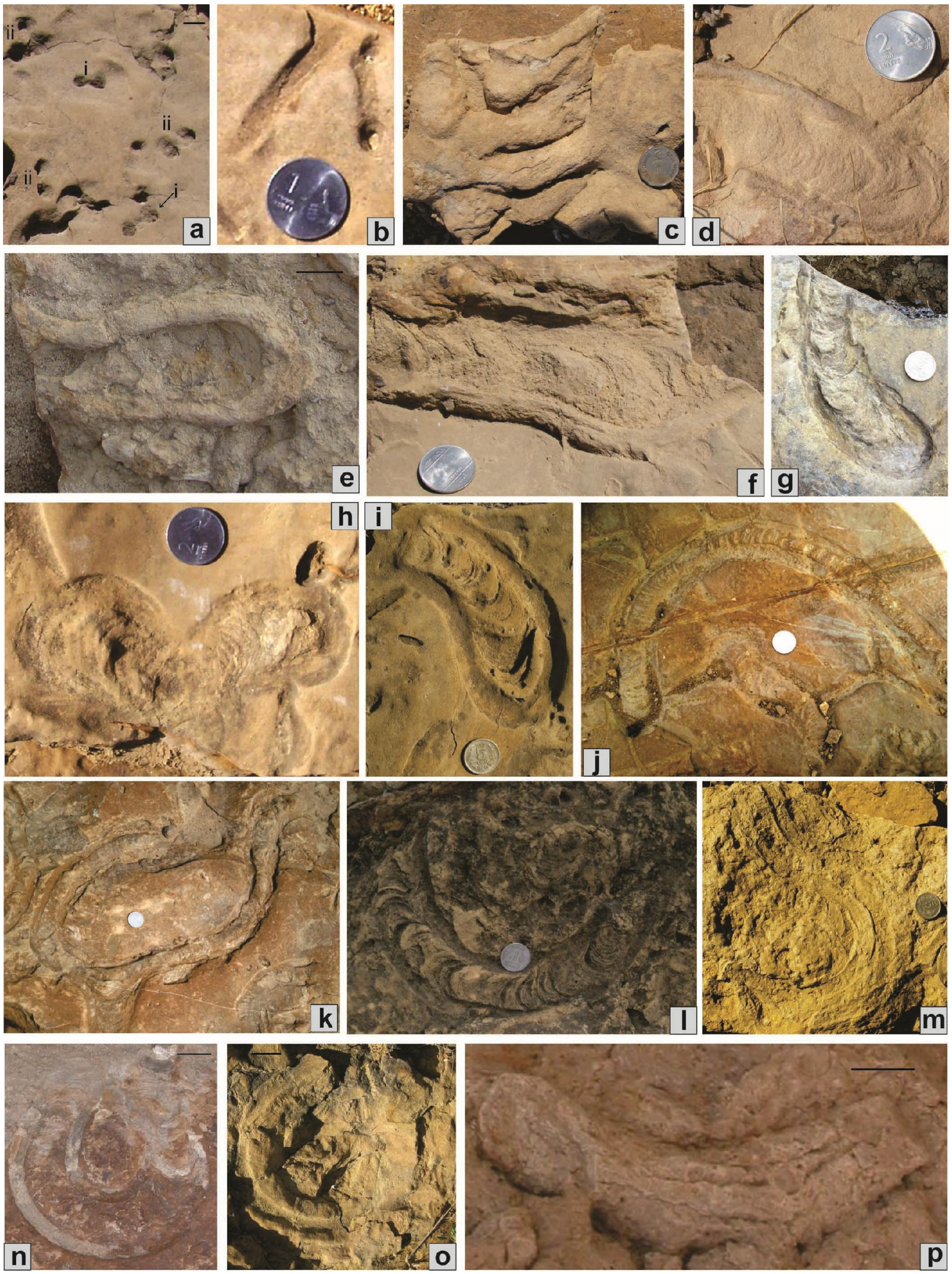

Plate 5.7 Spreiten structures (Bar length = 1 cm, Coin diameter= 2.5 cm)
(a) (i) U-shaped paired spreiten burrow *Diplocraterion* isp and (ii) U-shaped vertical paired burrow *Arenicolites carbonarius*; **(b)** *Diplocraterion* isp., allochemic sandstone, GSM; **(c)** Protrusive vertical J-tube *Daedalus* cf. *Verticalis*; **(d)** Horizontal, unbranched U-shaped spreiten burrow *Rhizocorallium jenense*; **(e)** Sub-horizontal, slipper shaped U-shaped burrow *Rhizocorallium jenense*, DHM; **(f)** *Rhizocorallium jenense;* horizontal U-shaped curved burrow; BCSM; **(g)** *Rhizocorallium jenense*, sandy micrite, MHM; **(h)** *Rhizocorallium jenense*, micritic mudrock, GFM; **(i)** *Rhizocorallium jenense*, micritic sandstone, MHM; **(j)** Long, more or less sinuous to curved U-shaped, horizontal burrow *Rhizocorallium irregular*,; KSM; **(k)** Long, lobate, U-shaped horizontal burrow *Rhizocorallium irregulare*;; KSM; **(l)** Long, circular U-shaped horizontal burrow *Rhizocorallium irregular*; **(m)** Long hook-like U-shaped horizontal burrow *Rhizocorallium irregulare,* allochemic sandstone, RLM; **(n)** Coiled, u-shaped horizontal, spreiten burrows *Rhizocorallium uraliense*, sandy allochem limestone, KSM; **(o)** Coiled, u-shaped horizontal, spreiten burrows *Rhizocorallium uraliense*, micritic sandstone, MHM; **(p)** Sinuous, unbranched, horizontal stacked flat U-shaped retrusive spreiten burrow *Teichichnus rectus*, sandy micrite, KSM.

Ichnospecies: *Teichichnus rectus*, SEILACHER, 1955

(Plate 5.7 p)

Diagnosis: Simple, straight or sinuous *Teichichnus* (Fürsich, 1974b).

Description: The Kachchh specimen of *T. rectus* include consistently straight to sinuous, unbranched, horizontal stacked flat U-shaped, retrusive spreiten burrow. The maximum observed length of the burrow is about 20.0 cm and 3.0 cm wide; with vertical shift about 2.5 cm wide in cross section at the end of the trace. Burrow filled is identical to host sediments.

Occurrence: Sandy micrite of Kaladongar Sandstone member of Kaladongar Formation, Kaladongar range.

Remark: Seilacher (1955) interpreted *Teichichnus* as the result of the vertical shift of horizontal burrow which might be U-shaped with pipe at the top. Seilacher (1957) compared these forms to the modern structure made by the recent polychaete *Nereis diversicolor*.

5.2.1.6 Winding and Meandering Structures

5.2.1.6.1 Smooth forms

Ichnogenus: *Circulichnus* VIALOV, 1971

Type ichnospecies: *Circulichnus montanus* Vyalov, 1971.

Diagnosis: A completed circular to oval interface trail or burrow (Vialov, 1971)

Ichnospecies: *Circulichnus montanus* VIALOV, 1971

(Plate 5.8 a)

Diagnosis: Same as for ichnogenus.

Description: Burrows wall smooth, unlined, cylindrical and circular in outline and preserved as full relief on bedding plane. The part of the photographed burrow is broken but it is essentially parallel to bedding plane. Diameter of the burrow varies from 1.0 to 1.2 cm. Burrow fill is diffeent from the host sediments.

Occurrence: Allochemic sandstone of Gadaputa Sandstone member of Goradongar Formation, Goradongar range.

Remarks: It is a mono specific ichnogenus described by Vyalov (1971) from the Triassic of the Pamirs. The present specimens are included within *C. montanus* based on the ovate shape and their connectivity. It ranges in age from Ordovician to Paleocene and is considered to be eurybathic (McCann and Pickerill, 1988).

Ichnogenus: *Cochlichnus* HITCHCOCK, 1858

Type Ichnospecies: *Cochlichnus anguineus* Hitchcock, 1858

Diagnosis: Regularly meandering, horizontal trails and burrows resembling sine curves. Sinuosity of the trail may be extremely regular or somewhat irregular (Pemberton and Frey, 1984; Fillion and Pickerill, 1990)

Ichnospecies: *Cochlichnus anguineus* HITCHCOCK, 1858

(Plate 5.8 b)

Emended Diagnosis: Regular, sinusoidal, horizontal trails and burrows resembling a compressed and stretched corkscrew. Overall width of an individual trace may change progressively (Gluszek, 1995).

Description: Burrow preserved in convex hyporelief, sediment filled identical to host rock. Sinuous trails preserved as mould of burrows on the upper surface of beds. Wave lengths and amplitudes are constant within a single burrow. Maximum length is about 20 cm and diameter of the feeding trail is about 0.7 cm.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: *Cochlichnus* are the crawling trace and probably the feeding structures of small worms or worm like animal (Eager et al, 1985) but the possible progenitors of this ichnospecies include annelids lacking well developed parapodia (Hitchcock, 1858, Hakes, 1976), nematodes lacking circular muscles (Clarke, 1964), and in lacustrine deposits, insect larvae (Metz, 1987). It has been reported in sediments of supposed low salinity paleoenvironment (Hakes, 1976).

Ichnospecies: *Cochlichnus* isp.

(Plate 5.8 c)

Description: Smooth, unbranched, lined, unornamented, regularly sinuously curved horizontal burrow preserved in full relief. Burrow circular to slightly elliptical in cross section; length is 170 mm. and diameter of 6 mm. Burrow fill is identical to surrounding rock. Wave lengths and amplitudes vary within a single burrow; mean wave length 55 mm and amplitude 0.4 -0.6 (mean 0.5 mm).

Occurrence: Micritic sandstone of Gadaputa Sandstone member, Goradongar Formation, Goradongar range.

Remarks: *Cochlichnus* ranges in age from Precambrian to Holocene and has a wide facies range, including lacustrine (*Mermia* ichnofacies) and shallow marine (*Cruziana* ichnofacies) settings (Lucas and Lerner, 2005). It is regarded as the trace of annelids feeding within the sediment, locomotion trace of nematodes (Fillion and Pickerill, 1990).

Ichnogenus: *Didymaulichnus* YOUNG, 1972

Type Ichnospecies: *Fraena lyelli* Rouault, 1850

Diagnosis: Smooth, furrow-like horizontal trails or burrows, bisected longitudinally by a narrow median groove if preserved in hyporelief (Fillion and Pickerill, 1990)

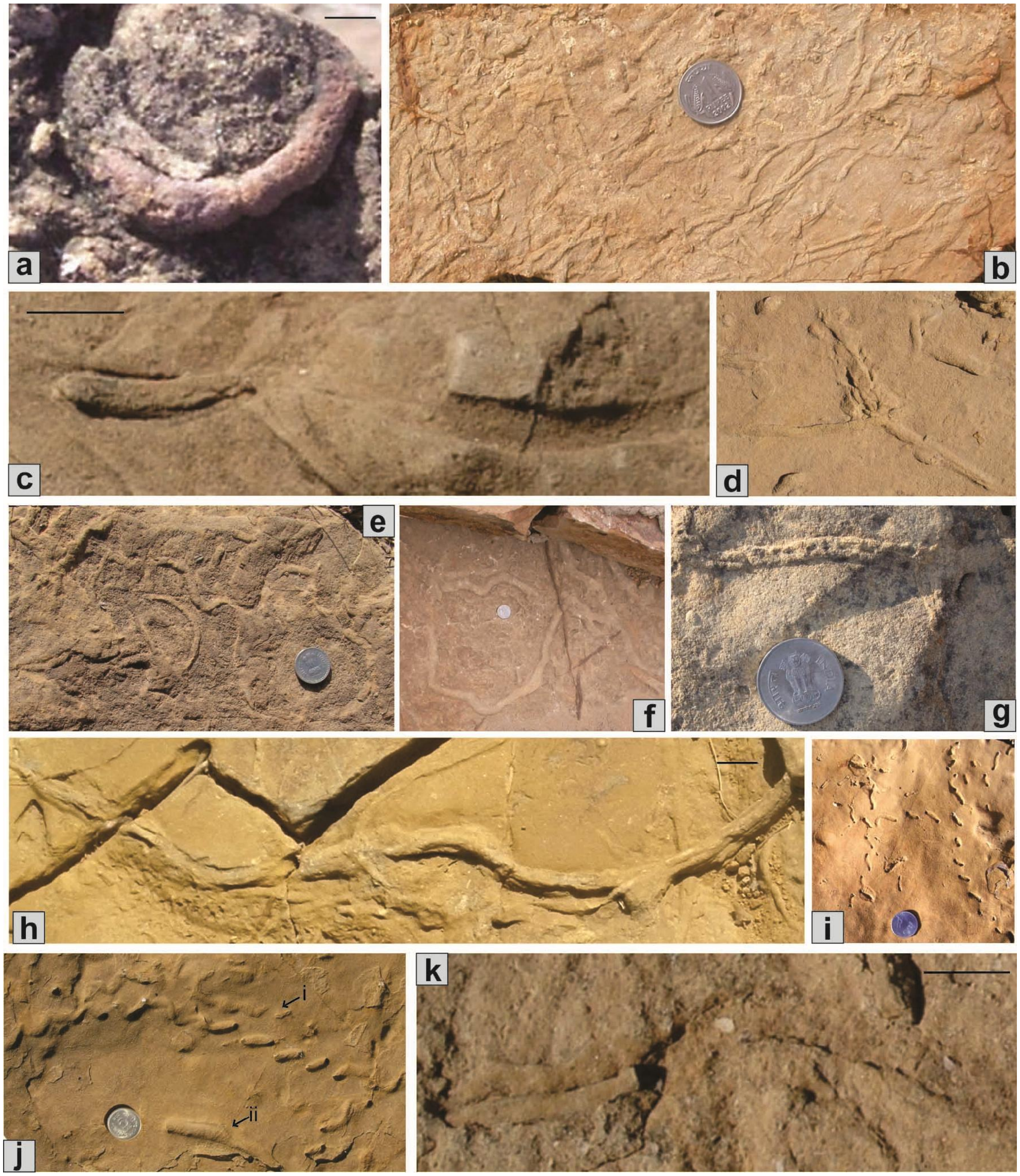

Plate 5.8 Winding and meandering structures (Bar length= 1 cm; coin diameter=2.5cm)
(a) *Circuliuchnis montanus*, allochemic sandstone, GSM; **(b)** Moulds of sinuous trails *Cochlichnus anguineus,* allochemic sandstone, DHM; **(c)** *Cochlichnus* isp., allochemic sandstone, GSM; **(d)** Simple, smooth, gently curving bilobate trails *Didymaulichnus lyelli*, Micritic mudrock , BCSM; **(e)** *Didymaulichnus lyelli*, allochemic sandstone, DHM; **(f)** Long, smooth, unbranched arcuate & looped burrow *Gordia arcuata*, allochemic sandstone, DHM: **(g)** *Gordia arcuata,* sandy allochem limestone, BCSM; **(h)** *Gordia* isp., sandy allochem limestone, RLM; **(i)** *Helicolithus sampelayoi*, bioclastic packstone, MHM; **(j)** (i) *Helicolithus sampelayoi*, & (ii) *Planolites beverleyensis*, bioclastic packstone, MHM; **(k)** *Aulichnites parkerensis*, bioclastic packstone, MHM.

Ichnospecies: *Didymaulichnus lyelli* ROUAULT, 1850

(Plate 5.8 d and e)

Diagnosis: Same as for ichnogenus.

Description: Simple, smooth, gently curving bilobate trails about 2.5 cm wide, preserved in convex hyporelief; parallel to the bedding; lobes separated by distinct furrow.

Occurrence: Allochemic sandstone of Dingy Hill member and micritic mudrock of Babia Cliff sandstone member of Kaladongar Formation, Kaladongar range.

Remarks: The present material is assigned to *Didymaulichnus lyelli* due to its lack of a) marginal bevels characteristics of *D. miettensis*, b) alternating burrow depths characteristic of *D. alternatus*, c) lateral ridges characteristics of *D. rouaulti* and d) marginal bevels and larger size characteristics of *D. tirasensis*. This ichnogenus represents the crawling trail of molluscan origin (Hantzschel 1975).

Ichnogenus: *Gordia* EMMONS, 1844

Type Ichnospecies: *Gordia marina* Emmons, 1844

Diagnosis: Unbranched, predominantly horizontal trails or burrows that wind or loop but do not regularly meander, with a marked tendency to level crossing; burrow-fill structureless (Pickerill and Peel, 1991).

Ichnospecies: *Gordia arcuata* KSIAZKIEWICZ, 1977

(Plate 5.8f and g)

Diagnosis: Hypichnial, thread-sized meandering groove casts in which only apical arcuate bends are developed.

Description: Arcuate or looped, thick, usually long, smooth, thin rope sized, unbranched burrows having length about 30.0 cm and diameter about 1.8 cm. The burrow diameter is throughout constant and fill is identical to matrix.

Occurrence: Allochemic sandstone of Dingy Hill and sandy allochem limestone of Babia Cliff Sandstone members of Kaladongar Formation.

Remarks: This specimen is included in *Gordia* because they lack the regular sinuous curve of *Cochlichnus*, the loose meanders of *Helminthopsis* and regular meanders of *Cosmorhaphe*. *Gordia* is a feeding burrow of worm like animal (Crimes et al., 1977).

Ichnospecies: *Gordia* isp.

(Plate 5.8 h)

Description: Irregularly looping, long, slender, worm-like trail with small enlargement at wave crests. Trails of variable lengths, limbs representing positive amplitudes are long and gentle while limbs forming negative amplitudes (troughs) are short and steeper. The width of the string is about 5.4 mm and the length of the undulating string is about 238.7 mm. Preserved as convex hyporelief, and burrow fill is identical to host sediment.

Occurrence: Sandy allochem limestone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: The makers of the *Gordia* are probably priapulids, feeding on the nutrient-rich sediment (Wang et al., 2009). The hypichnial strings may be classified as feeding burrow or feeding trails while the hypichnial furrow as the locomotion trail of a polychaete worm (Książkiewicz, 1977). It differs from above described *Cochlichnus* by lacking a regular sine curve.

Ichnogenus: *Helicolithus* AZPEITIA MOROS, 1933

Type Ichnospecies: *Helicolithus sampelayoi* Azpeitia Moros, 1933

Description: Small, horizontal, meandering trace fossils with horizontal second-order helicoidal turns. Changes of screw direction at every turn of first-order meanders (Uchman 1995)

Ichnospecies: *Helicolithus sampelayoi* AZPEITIA MOROS, 1933

(Plate 5.8i and j(i))

Diagnosis: *Helicolithus* with simple, short, regular helicoidal undulations (Uchman 1999)

Description: Small, horizontal, zigzags pattern with alternate right and left turn, in either of cases it appear as parallel ridges or grooves, but other turn is always concealed, in some case right and left turns exposed on surface and appear as zigzag patterns. Length of each turn is variable, 12 to15 mm and diameter is constant, being 4 mm.

Occurrence: Pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: *Heilicolithus* is similar to *Helicodromites* but much smaller in size and interpteted as graphoglyptid agrichnion (Seilacher, 2007). At deeper part it shows simple short helicoidal undulations (Uchman, 1999). The specimen does not show change of sigmoidality and thus differs from the ichnospecies *Heilicolithus tortuosus* (Seilacher, 2007).

Ichnogenus: *Aulichnites* FENTON AND FENTON, 1937

Type Ichnospecies: *Aulichnites parkerensis* Fenton and Fenton, 1937

Diagnosis: Preserved in convex epirelief with a bilobate upper surface. May show a unilobate convex-downward lower surface, in which case lateral margins of both surfaces intersect. Upper surface may show transverse, concave-convex striations. Lobes separated by median furrow (Fillion and Pickerill, 1990)

Ichnospecies: *Aulichnites parkerensis* FENTON AND FENTON, 1937

(Plate 5.8k)

Diagnosis: Same as for ichnogenus.

Description: Horizontal, straight to sinuous, two closely spaced parallel trails separated by a deep furrow and preserved as epichnial ridges. Photograph shows specimen having annulations in the eroded part. Each trail has a width of about 3-6 mm and length of about 80 mm.

Occurrence: Pelloidal packstone of Modar Hill member of Goradongar Formation, Goradongar range.

Remarks: *Aulichnites* is considered as the crawling traces of gastropods and the annulated lobes are presumably related to the peristaltic movements (Frey and Howard, 1990).

5.2.1.6.2 Winding (helicoidal) structures

Ichnogenus: *Gyrolithes* SAPORTA, 1884

Type ichnospecies: *Gyrolithes davreuxi* SAPORTA, 1884.

Diagnosis: Systems built up of tubular structures with circular to elliptical cross section, more or less describing one or more dextral, sinistral or mixed circular helix structures (coils) essentially upright in the sediment; coils may be connected to each other by horizontal to oblique or vertical unbranched or branched tubular structures; with or without wall-lining; exterior morphology smooth, knobb, with criss-cross ridges and grooves or longitudinal ridges and grooves; radius of individual whorls may increase, decrease or remain constant; diameter of tubular structures may vary.

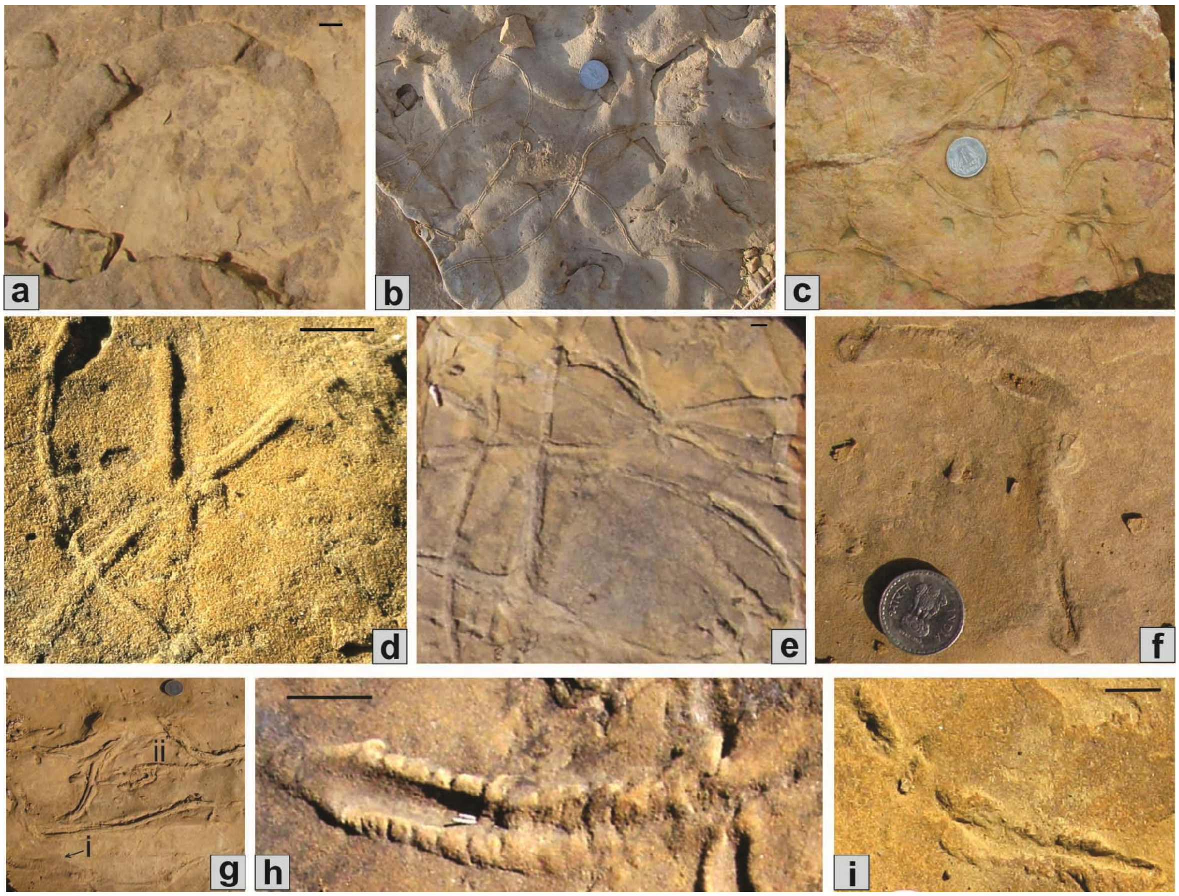

Plate 5.9 Winding, and Plaited forms (Bar length= 1 cm, coin diameter = 2.5 cm)
(a) Endichnial, unornamented coiled burrow *Gyrolithes* isp., allochemic sandstone, DHM; **(b)** Biserially arranged plaited ridge burrow *Gyrochorte comosa*, allochemic sandstone, DHM, Chhappar bet; **(c)** *Gyrochorte comosa*, sandy allochem limestone, BCSM; **(d)** and **(e)** *Gyrochorte comosa*, bioclastic packstone, MHM; **(f)** Slightly curved small keel-like trail *Protovirgularia dichotoma*, DHM; **(g)** *Protovirgularia dichotoma* observed as (i) small keel-like slightly curved trail and (ii) fused appendages forming parallel ridges; DHM; **(h)** *Protovirgularia* cf. *dichotoma*, allochemic sandstone, GSM; **(i)** *Protovirgularia* isp., allochemic sandstone, RLM.

Ichnospecies: *Gyrolithes* isp.

(Plate 5.9 a)

Description: Full relief, endichnial, sinistrally coiled unlined burrow, without surface ornamentation. The burrow filled is identical to host sediment. The burrow diameter is about 2cm.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation, Kaladongar range.

Remarks: *Gyrolithes* isp. is differ from the other ichnospecies by lacking median furrow and probably made by decapods crustaceans (Hantzschel, 1975).

5.2.1.6.3 Plaited forms

Ichnogenus: *Gyrochorte* HEER, 1865

Type ichnospecies: *Gyrochorte comosa* HEER, 1865

Diagnosis: Epirelief, preserved as plaited ridges with biserially arranged, obliquely aligned pads of sediment, separated by median furrow. Hyporelief shows smooth biserial grooves separated by median ridge. Course straight to strongly winding, direction changes sharply. Parts of the trace may intersect. Ridges and their grooves separated by a vertical distance (Schlirf, 2000).

Ichnospecies: *Gyrochorte comosa* HEER, 1865

(Plate 5.9 b-e)

Diagnosis: As for ichnogenus.

Description: Epirelief, long, sinuous and curved, horizontal trails consist of plaited ridges with biserially arranged long parallel ridges on the upper surface of the bedding plane, with width 0.4 – 0.6 cm and maximum observed length is 88.14 cm. Frequent crossing over in such a way that the earlier formed ridges are not destroyed.

Occurrence: Micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member; and micritic sandstone, sandy allochem limestone and micritic mudrock of Babia Cliff Sandstone member of Kaladongar Formation; and sandy allochem limestone of Goradongar Flagstone member, sandy allochem limestone of Raimalro Limestone member, sandy allochem limestone, pelloidal packstone, and pelloidal grainstone of Modar Hill member of Goradongar Formation.

Remark: *Gyrochorte comosa* can be distinguished from other ichnospecies of *Gyrochorte* through its lack of a) oblique incisions characteristic of *G. burtani* Książkiewicz, 1977, b) imbricate asymmetrical riblets characteristic of *G. imbricate* Książkiewicz, 1977, and c) densely spaced irregular incisions characteristic of *G. obliterata* Książkiewicz, 1977.*Gyrochorte* producer must have been a detritus-feeding worm-like animal, probably an annelid that created a bilobed, vertically penetrating and sometime plaited meandering trace (Gibert and Benner, 2002).

Ichnogenus: *Protovirgularia* M'COY, 1850

Type ichnospecies: *Protovirgularia dichotoma* M'COY, 1850.

Diagnosis: Horizontal or subhorizontal cylindrical trace fossil, trapezoidal, almond-shaped or triangular in cross section, distinctly or indistinctly bilobate. Internal structure, if preserved, formed by successive pads of sediment that may be expressed as ribs on the exterior. Ribs arranged in chevron-shaped, biserial pattern along external or internal dorsal part. Occasionally with smooth mantle on exterior covering the structure and/or with oval mound-like terminations of the trace (Uchman 1998).

Ichnospecies: *Protovirgularia dichotoma* M'COY, 1850

(Plate 5.9f and g)

Diagnosis: Unbranched, keel-like trail, typically, but not universally, with median ridge or furrow form where paired, lateral, wedge-shaped appendages, commonly only few millimeters in length and of even or variable spacing, originate. Lateral appendages normal or at acute angle to median ridge or furrow (Han and Pickerill, 1994).

Description: Horizontal to sub horizontal, straight to gently curved, small keel like trail. Burrows composed of biserially arranged, paired, lateral appendages (Pl. IV, i) originating normal or at acute angle to median furrow or lateral appendages fused together (Pl.IV, j) and forming parallel ridges. The length of the burrow is 6-7 cm; width of the burrow varies from 1-3 cm. The pads consist of same material as the surrounding matrix.

Occurrence: Micritic sandstone of Dingy Hill member of Kaladongar Formation.

Remarks: It is generally considered to be made by bivalves (Seilacher and Seilacher 1994 Ekdale and Bromley 2001).

Ichnospecies: *Protovirgularia* cf. *dichotoma* M'COY, 1850
(Plate5.9 h)

Description: Positive hyporelief, small keel-like trail, wide, and slightly curved. Lateral appendages are normal or at acute angle to median ridge or furrow (Han and Pickerill 1994). The length of the burrow is 75 mm and 8 mm wide.

Occurrence: Allochemic sandstone of Gadaputa Sandstone member, Goradongar Formation.

Remarks: The present ichnospecies show a close resemblance with the *Protovirgularia dichotoma*. The producer of this trace is considered to be made by bivalves (Seilacher and Seilacher, 1994).

Ichnospecies: *Protovirgularia* isp.
(Plate 5.9 i)

Description: Slightly curved, small keel-like trail. Lateral pads show an acute angle to median ridge or furrow at the curving part of the burrow. The length of the burrow is 70 mm and the width ranges from 3-4 mm.

Occurrence: Allochemic sandstone of Raimalro Limestone member of Goradongar Formation, Goradongar range.

Remarks: *Protovirgularia* can be differentiated from biserial arthropod tracks by strict symmetry of impressions on the two sides, from bilobed, *Scolicia* by the angularity of the chevrons, from *Cruziana* by the cross-section and the non-scratched morphology of the chevrons and from *Gyrochorte* by being a positive hyporelief (Seilacher and Seilacher, 1994). This specimen differs from the rest ichnospecies of *Protovirgularia*, in respect to the width of the trail.

5.2.1.6.4 Meniscate forms

Ichnogenus: ***Beaconites*** VYALOV, 1962

Type Ichnospecies: *Beaconites antarcticus* Vyalov, 1962

Diagnosis: Small cylindrical, unbranched, walled, meniscate burrow. Straight or sinuous, horizontal or more rarely inclined or vertical. Weakly to strongly arcuate meniscate packets or segments enclosed by distinct, smooth and unornamented burrow linings (Keighley and Pickerill, 1994)

Ichnospecies: *Beaconites coronus* FREY, PEMBERTON and FAGERSTROM, 1984
(Plate 5.10 a-c)

Diagnosis: Predominantly horizontal, more rarely inclined to vertical, distinctly lined, gently winding, small meniscate burrow. Relatively short (with respect to burrow width) meniscate packets, or segments, of alternating sediment type. Menisci are gently to moderately arcuate (Keighley and Pickerill, 1994).

Description: Small, almost straight to gently winding, horizontal to slightly inclined, non branching, distinctly lined, meniscate burrow. Burrow diameter varies from 10 to 12mm, length varies from 70 to 90 mm and menisci 1 to 3 mm in width.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation; and allochemic sandstone of Gadaputa Sandstone member and pelloidal packstone of Modar Hill member.

Remarks: The burrows are assigned to *Beaconites coronus* because of their distinct wall and almost straight to gently curved meniscate packets of various sediment compostition. The possible producer of *B. coronus* needs body appendages in order to sort and move the sediment and thus arthopod seems to be more likely possible producers.

Ichnospecies: *Beaconites antarcticus* VIALOV, 1962
(Plate 5.10 d)

Diagnosis: Same as for ichnogenus

Description: Full relief, horizontal, sinuous, unbranched, thick-walled, meniscate burrow. Menisci form heterogeneous thick backfill of unequal thickness and merge laterally with each other but become distinct at burrow wall-sediment interface. The diameter of burrow is ~40 mm and the length is about 320 mm.

Occurrence: Pelloidal packstone and sandy micrite of Modar Hill member, Goradongar Formation, Goradongar range.

Remarks: The Kachchh specimen'*Beaconites antarcticus*' is a lined burrow which is a prime characteristic of the ichnogenus *Beaconites* (Keighley and Pickerill,1994) and can be distinguishes it from the other ichnospecies by having thicker packets.

Ichnogenus: *Bichordites* PLAZIAT AND MAHMOUDI 1988

Type Ichnospecies: *Bichordites monastiriensis* PLAZIAT AND MAHMOUDI, 1988.

Diagnosis: Predominantly horizontal, cylindrical, straight to winding, unbranched, meniscate composite burrow, slightly concave along the base and the top, and with central cord. At least the upper part of the burrow contains a double row of menisci. The cord is preferentially preserved; it is heart-shaped to ovoid in cross-section, tapers locally and is interrupted. A longitudinal median shallow groove along the top of the cord locally passes into an indistinct crest. Locally, the cord is covered with external irregular constrictions or transverse striae (Emended by Uchman, 1995).

Ichnospecies: *Bichordites* isp.
(Plate 5.10 e)

Description: Horizontal, cylindrical, unbranched, horizontal to gently inclined meniscate concave burrow with a central cord. The burrow is 15 to 20 mm in diameter and 30-40 mm long, central cord is about 20 mm long and diameter of 12 mm.

Occurrence: Sandy micrite of Modar Hill member, Goradongar Formation.

Remarks: *Bichordites* is produced by spatangoid echinoids with a single drainage tube, which belong to the so called *Echinocardium* group (Plaziat and Mahmoudi, 1988).

Ichnogenus: *Nereites* MAC LEAY, 1839

Type Ichnospecies: *Nereites cambriensis* MacLeay, 1839

Diagnosis: Usually selectively preserved, winding to regularly meandering, approximately horizontal trails, consisting of median backfilled tunnel enveloped by even to lobate zone of reworked sediment. Generally, only external part of enveloping zone preserved as densely packed chain of uni-serial or multi-serial small depressions or pustules (Uchman, 1995).

Ichnospecies: *Nereites missouriensis* WELLER, 1899
(Plate 5.10 f)

Diagnosis: Variably preserved, loosely meandering to winding *Nereites* with wide, central backfilled tunnel and envelope zone of similar thickness, which occasionally displays low side lobes. The exterior may be expressed as uni- or multi-serial chain of closely packed sediment pustules. The interior may be preserved as a row of at least uniserial closely packed sediment depressions, or as strongly flattened burrows, which form usually colour-contrasted strips on parting surfaces with poorly preserved or not-preserved side lobes (Uchman, 1995).

Description: Shallow, epichnial, winding, exceptionally coiled grooves consisting of juxtaposed oval dimples surrounded by about 1 mm thick zone of disturbed sediments with occasionally elevated edges bordering the grooves. The grooves are 12-15 mm wide and up to 1 mm deep.

Occurrence: Sandy allochem limestone of Dingy Hill member of Kaladongar Formation.

Remarks: It is interpreted as the internal meandering grazing trails (Seilacher and Meischner, 1965). Various producers have been suggested: worms (Richter 1928), gastropods (Raymond 1931; Abel 1935), or crustaceans (Fraipont, 1915). *N. missouriensis*is eurybathic form and has been reported mainly from flysch deposits from the late Precambrian (Crimes 1987) to the Miocene (D'Alessandro 1980).

Ichnogenus: *Rhabdoglyphus* VASSOEVICH, 1951

Type ichnospecies: *Rhabdoglyphus grossheimi* Vassoevich, 1951

Diagnosis: Cylindrical tubes consisting of short, closely spaced, invaginated "calyces," some with short branches; preserved in convex hyporelief (Häntzschel, 1975).

Ichnospecies: *Rhabdoglyphus* isp.
(Plate 5.10 g)

Description: Convex hyporelief, cylindrical tubes consisting of uniformly shaped invaginated calyces. The length of the whole trace is 190 mm and diameter of 10 mm. Calyces vary in length from 15 to 20 mm and the diameter from 8 to 10 mm.

Occurrence: Allochemic sandstone of Raimalro Limestone member of Goradongar Formation.

Remarks: *Rhabdoglyphus* is considered to have been produced by gastropods, amphipods or holothurians (Bouček and Elias, 1962). According to Osgood (1970), swellings of the burrow represent periodic anal constrictions and expansion by polychaete worm while advancing by bolting.

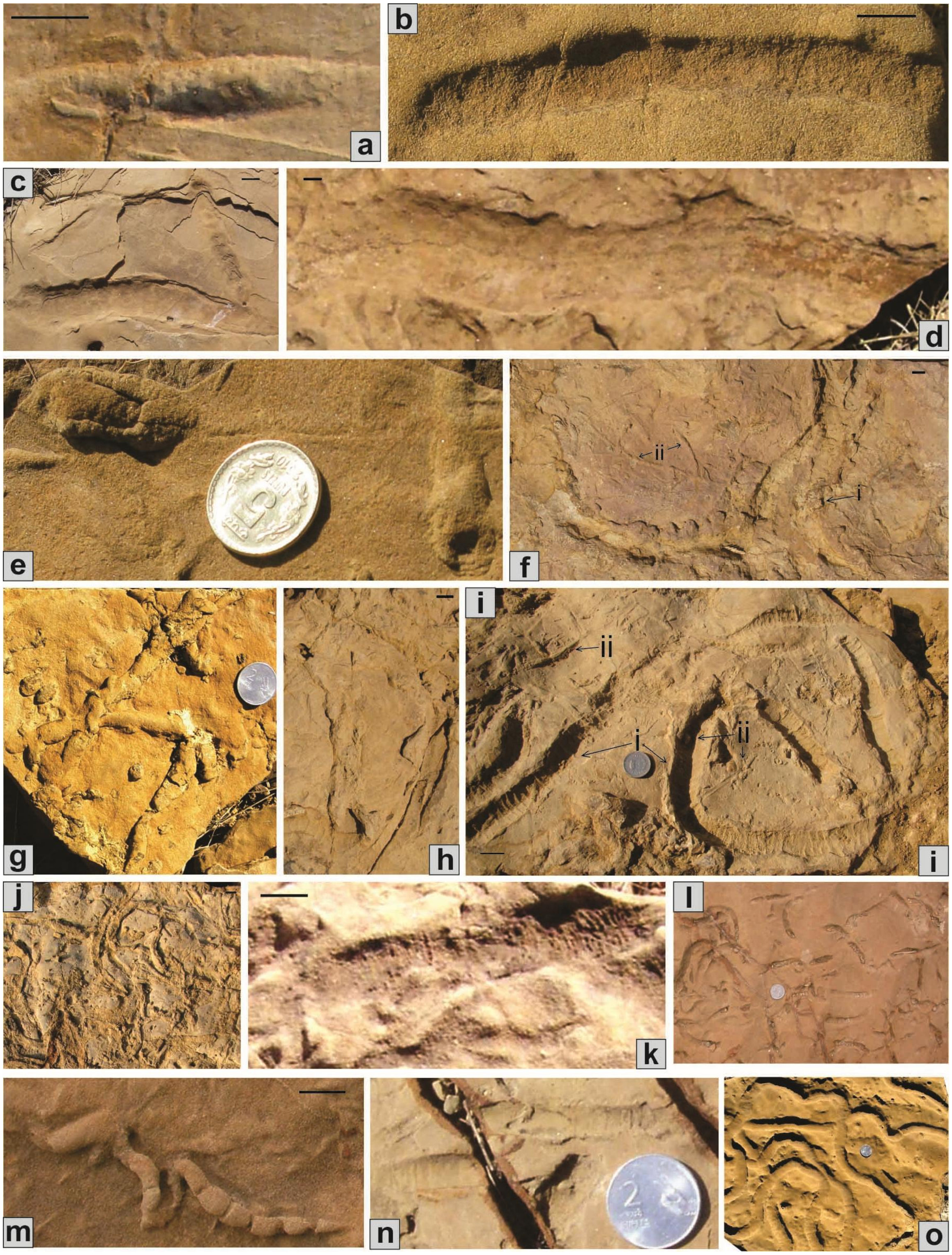

Plate 5.10 Meniscate forms (Bar length= 1 cm; coin diameter= 2.4 cm)
(a) Horizontal, unbranched, lined, meniscate burrow *Beaconites coronus*; **(b)** *Beaconites coronus*, allochemic sandstone, GSM; **(c)** *Beaconites coronus*, bioclastic packstone, MHM; **(d)** *Beaconites antarcticus*, bioclastic packstone, MHM; **(e)** *Bichordites* isp, sandy micrite, MHM; **(f)** (i) *Nereites missouriensis,* Epichnial, winding with elevated edges bordering the grooves associated with (ii) *Palaeophycus tubularis*, sandy allochem limestone of DHM; **(g)** *Rhabdoglyphus* isp., allochemic sandstone, RLM; **(h)** *Scolicia prisca;* cylindrical body with arched dorsal side and a flat bottom; sandy allochem limestone, DHM; **(i)** Negative epirelief, bilaterally symmetrical long band-like surface trail *Scolicia prisca*, sandy allochem limestone, DHM; **(j)** Irregular, winding burrow *Scolicia* isp., allochemic sandstone, DHM; **(k)** Non-compartamentalized heterogeneous unbranched thin meniscate segmented burrow *Taenidium barretti*, sandy micrite, MHM; **(l)** Horizontal, slightly curved, cylindrical meniscate tubes *Taenidium serpentinum* having length equal to its width*,* Bar length= 4 cm; **(m)** Horizontal, cylindrical meniscate burrow *Taenidium serpentinum*; **(n)** *Taenidium serpentinum*, Bioclastic packstone, MHM; **(o)** *Taenidium serpentinum*, Bioclastic packstone, MHM.

Ichnogenus: *Scolicia* DE QUATREFAGES, 1849

Type Ichnospecies: *Scolicia prisca* De Quatrefages, 1849

Diagnosis: Variably and commonly selectively preserved, simple, winding, meandering to coiling bilobated or trilobated back-filled burrows with two parallel, locally discontinuous, sediment strings along their lower side. Cross-section approximately oval in outline. Lower side between the strings flat or slightly concave up. Backfill laminae composite, may be biserial on the upper side. Washed-out forms preserved as hypichnial bilobate ridges (Uchman, 1995)

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Ichnospecies: *Scolicia prisca* DE QUATREFAGES, 1849

(Plate 5.10 h and i)

Diagnosis: *Scolicia* preserved usually as epichnial trilobite furrow with concave, semicircular bottom and oblique slopes, densely packed fine transverse ribs at the bottom, more loose, asymmetrical and thicker ribs on the slopes. Two parallel strings may occur along the edges of the bottom. Proportion of bottom to slopes may vary in different specimens (Uchman, 1995)

Description: Horizontal bilaterally symmetrical surface trail of negative epirelief, consisting of great variability, long band-like morphology. Cylindrical bodies appear with an arched dorsal side and a flat bottom. The washed out forms preserved as hypichnial bilobate ridges. The overall diameter of the trail is about 2.3-2.5 cm and is long about 65-70 cm.

Occurrence: Sandy allochem limestone of Dingy Hill member of Kaladongar Formation.

Remarks: This ichnotaxon is usually preserved in the middle part of turbidites at the transition from sandstone to mudstone. The substrate properties and degree of weathering may influence the expression of the ribs at the bottom (Uchmann, 1999). The specimen found in the Sandy allochem limestone of Dingy Hill member of Kaladongar Formation, differs from the *Subphyllochorda* in the taponomic position and the kind of preservation (Fig. 5.1). It represents the characteristic of *Paleobullia* Götzinger and Becker, 1932, but it is kept under *Scolicia prisca* as suggested and regarded by Uchman (1995). The looped and unbranched trails typical of the grazing trails of the gastropods (Seilacher, 1953) and the bilobate with transverse markings typical of its surface trails (Schäfer, 1972) suggest gastropods to be the trace makers. This ichnogenus *Scolicia* is considered as a facies-crossing trace fossil (Seilacher, 1964).

Ichnospecies: *Scolicia* isp.

(Plate 5.10 j)

Description: Hypichnial shallow grooves, gently curved, cross-over crawling trails, feebly developed actively developed forward banding biogenic laminae; length of trails are variable and width of about 1-2 cm. Trail morphology varies in given specimen, broadening and narrowing of trails observed frequently as well as washed out leaving trails of cast.

Occurrence: Allochemic sandstone of Dingy Hill member of Kaladongar Formation.

Remarks: *Scolicia* isp., represents as shallow groove on the rippled surface, characteristic features may obscured by substrate consistency but overall morphology reflect the crawling trails which correspond to locomotion activity of echinoids (Uchman, 1995).

Ichnogenus: *Taenidium* HEER, 1877

Type ichnospecies: *Taenidium serpentinum* Heer, 1877.

Diagnosis: Variably oriented, unlined, straight, winding, curved or sinuous, essentially cylindrical, meniscate backfilled trace fossils. Straight successive branching may occur, but true branching is absent (Keighley and Pickerill, 1994).

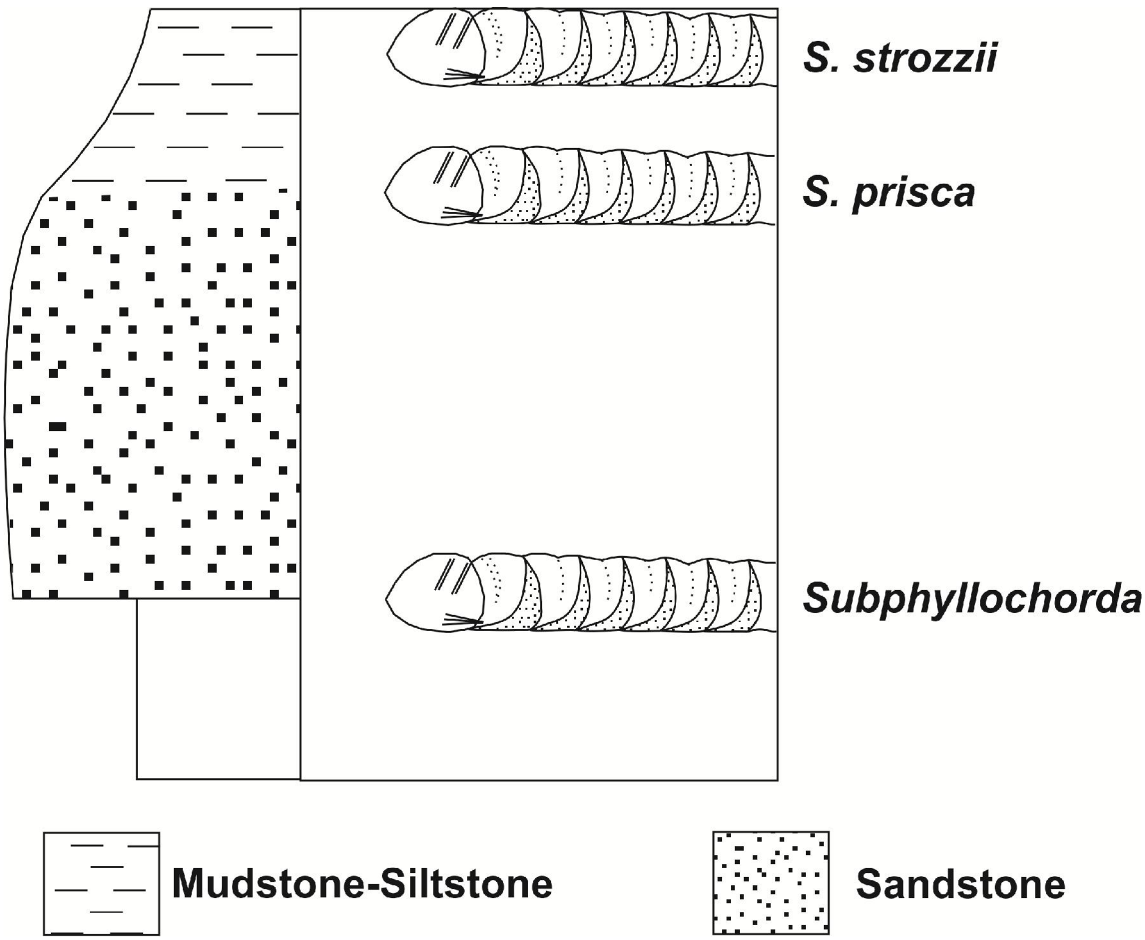


Figure-5.1 Different types of Scolicia burrow in relation to depth of burrowing/taphonomic position in the flysch deposits (redrawn from Uchman, 1995)

Ichnospecies: *Taenidium barretti* BRADSHAW, 1981

(Plate 5.10 k)

Diagnosis: Straight to variably meandering, unbranched, unwalled, meniscate backfilled burrow. Menisci are commonly hemispherical, deeply arcuate to bell-shaped, tightly packed or stacked, forming non-compartmentalized backfill or thin meniscate segments (Schlirf, 2000).

Description: Full relief, straight to slightly sinuous, unbranched, unwalled, meniscate burrow with irregular boundary, subparallel to the bedding plane. Menisci are hemispherical to arcuate, tightly packed, forming non-compartmentalized heterogeneous backfill. The width of burrow range from 10 -12 mm and the length is about 73 mm.

Occurrence: Sandy micrite of Modar Hill member of Goradongar Formation

Remarks: The unwalled nature of the specimen differentiates it from *Beaconites*. *Taenidium baretti* show heterogenous fill similar to *Taenidium dieslingi* but differs from the latter in lack of compartamentalized and distinct packeting (Keighley and Pickerill,1994).

Ichnospecies: *Taenidium serpentinum* HEER, 1877

(Plate 5.10 l-o)

Diagnosis: Serpentiform *Taenidium* having well-spaced, arcuate menisci; distance between menisci about equal to or little less than burrow width. External moulds may show slight annulations corresponding to menisci, or fine transverse wrinkling. Secondary subsequent branching and intersections occur. Boundary sharp and lacks lining (Keighley and Pickerill, 1994)

Description: Endichnial to hypichnial, concave and convex hyporelief burrows, active fill identical to matrix. Horizontal, straight, cylindrical tubes up to 8.0 cm long and 0.3 to 1.0 cm wide; having 0.5 cm diameter, symmetrically arranged distinct transverse annulations. Burrow typically unbranched having segmentation on surface by annular constrictions.

Occurrence: Allochemic sandstone of Babia Cliff Sandstone member of Kaladongar Formation; and micritic sandstone of Gadaputa Sandstone member, and sandy allochem limestone and pelloidal packstone of Modar Hill member of Goradongar Formation.

Remarks: *Taenidium* has been reported from the Mesozoic and Cenozoic flysch of Europe (Heer, 1877) and from the Ordovician deposits of the Ouachita Mountain (Chamberlain, 1971). The cylindrical burrow exhibits typical periodic filling of tunnel in backward direction.

Ichnogenus: *Virgoglyphus* PATEL, JAQUILIN AND BHATT, *In press*

Type ichnospecies: *Virgoglyphus modari*

Diagnosis: Predominantly horizontal, segmented burrow consisting of overlapping cylindrical tubes with horn like extension on one side; extended up to emerging of the next tubes or beyond this tube; successive tubes progressively decreasing in dimensions, preserved as endichnia.

Remarks: Outwardly the burrow assigned here are similar to the *Rhabdoglyphus* VASSOEVICH, which also includes cylindrical tubes having invaginated calyces, but these calyces are of uniform shape. According to Książkiewicz (1977), all short articulated rods consisting of uniformly shaped and relatively large limbs may be grouped as *Rhabdoglyphus*.

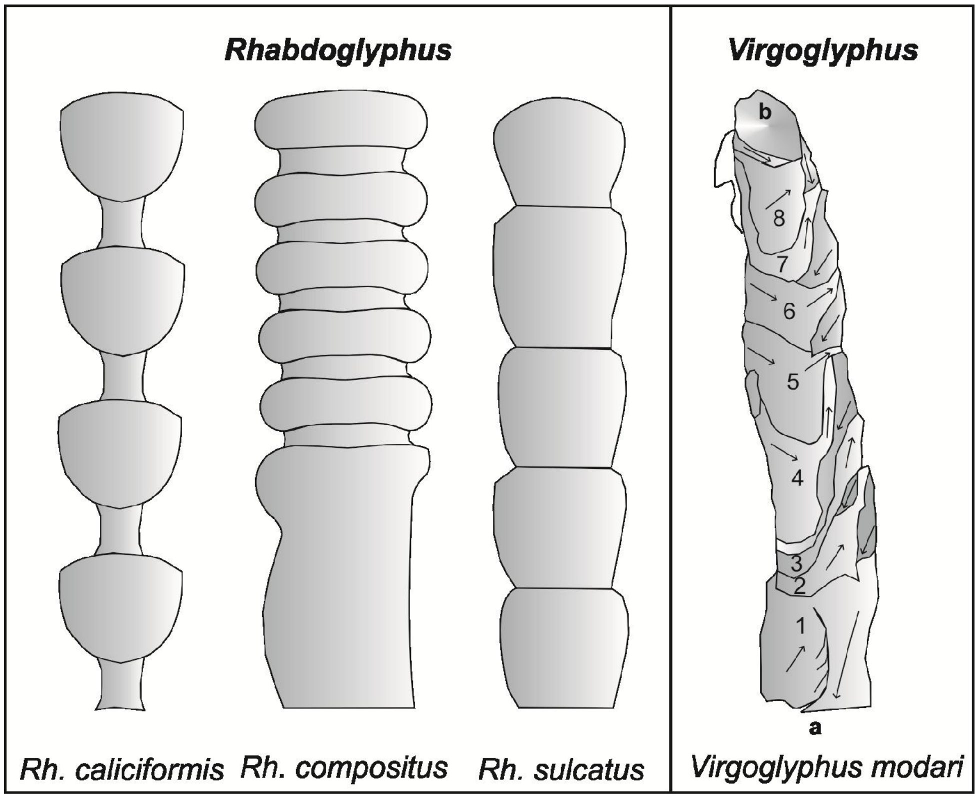


Figure- 5.2 Comparision of *Virgoglyphus* Patel, Jaquilin and Bhatt, *in press* with the similar forms of *Rhabdoglyphus* Vassoevich, 1951 and the schematic representation of feeding pattern of the trace maker of *Virgoglyphus* n. gen.

Ichnospecies: *Virgoglyphus modari* PATEL, JAQUILIN AND BHATT, *In press*

(Plate 5.11a)

Diagnosis: As for ichnogenus

Description: Essentially horizontal, segmented burrow consisting of overlapping tubes; each correspondingly fit in to next higher one and forming a bamboo-like structure. Each segment shows variable dimension and unevenly distributed for the entire length of the burrow. The horn-like structure is present on one side and extended up to or beyond the segment. The initial part of the burrow wall is pelleted but successive segments are unornamented. The holotype is 120 mm long and diameter is varies from 15-18 mm. The burrow fill is identical to host sediment.

Occurrence: Pelloidal packstone of Modar Hill member of Goradongar Formation

Remarks: *Virgoglyphus modari* occurs in sandy micrite of the Modar Hill member of the Goradongar Formation at Modar hill. This new form of trace shows overlapping tubes which indicate periodically active fill of the burrow. The producer seems to start its move from "a" ending to "b" (Fig. 5.2) which shows an escape-like structure. Though the structure seems to be similar to the *Rhabdoglyphus* burrows, it does not follow its overall pattern of structure and has non-uniform calyces or segments no.1 to 8 (Fig.5.2). The burrow structure reveal an irregular pattern of feeding; wherein the producer might have moved, turned around and proceeded further to form a cover like structure overlapping the previous one, as depicted in the line drawing (Fig. 5.2). The overall structure and the size of the burrow suggest crustaceans to be its producer but to assign it particularly to this originator is difficult because of the paucity of the materials.

Ichnogenus: *Walcottia* GLOCKER, 1841

Type Ichnospecies: *Walcotiia rugosa* Miller and Dyer, 1878

Diagnosis: Slender vermiform trace fossils preserved as convex hyporeliefs or convex epirelief that possess obliquely directed paired lobes. The closely spaced lobes are ridge-like and tend to obscure the body. The form tapers at one end and terminates at the other in a structureless ovoid mass. Alternatively, shell-like coverings composed of small plates or rings, or longitudinal grooves from which issue oblique striae may be present (Osgood, 1970)

Remarks: The *Walcottia rugosa* is considered as the junior synonym of *Protovirgularia rugosa* by Seilacher and Seilacher (1994) but the taxonomic status of other forms of ichnospecies of *Walcottia* ichnogenus, namely, *W. cookana, W.sulcata, W.devilsdingli* and *W. imbricata*, remains equivocal (Rindsberg, 1994; Stanley and Pickerill, 1998). However, *Walcottia devilsdingli* is considered under separate ichnogenera *"Walcottia"* by Allington-Jones *et al*. (2010), and later taxonomy is retained and described considering the morphological similarities (Jaquilin et al, 2012; Patel et al., *In press*).

Ichnospecies: *Walcottia devilsdingli* BENTON AND GRAY 1981
(Plate 5.11 b-f)

Diagnosis: Unbranched horizontal burrow, circular to elliptical in cross-section, displaying symmetrically arranged irregular scratch marks at various points along the sides and behind the ovoid expanded burrow ends.

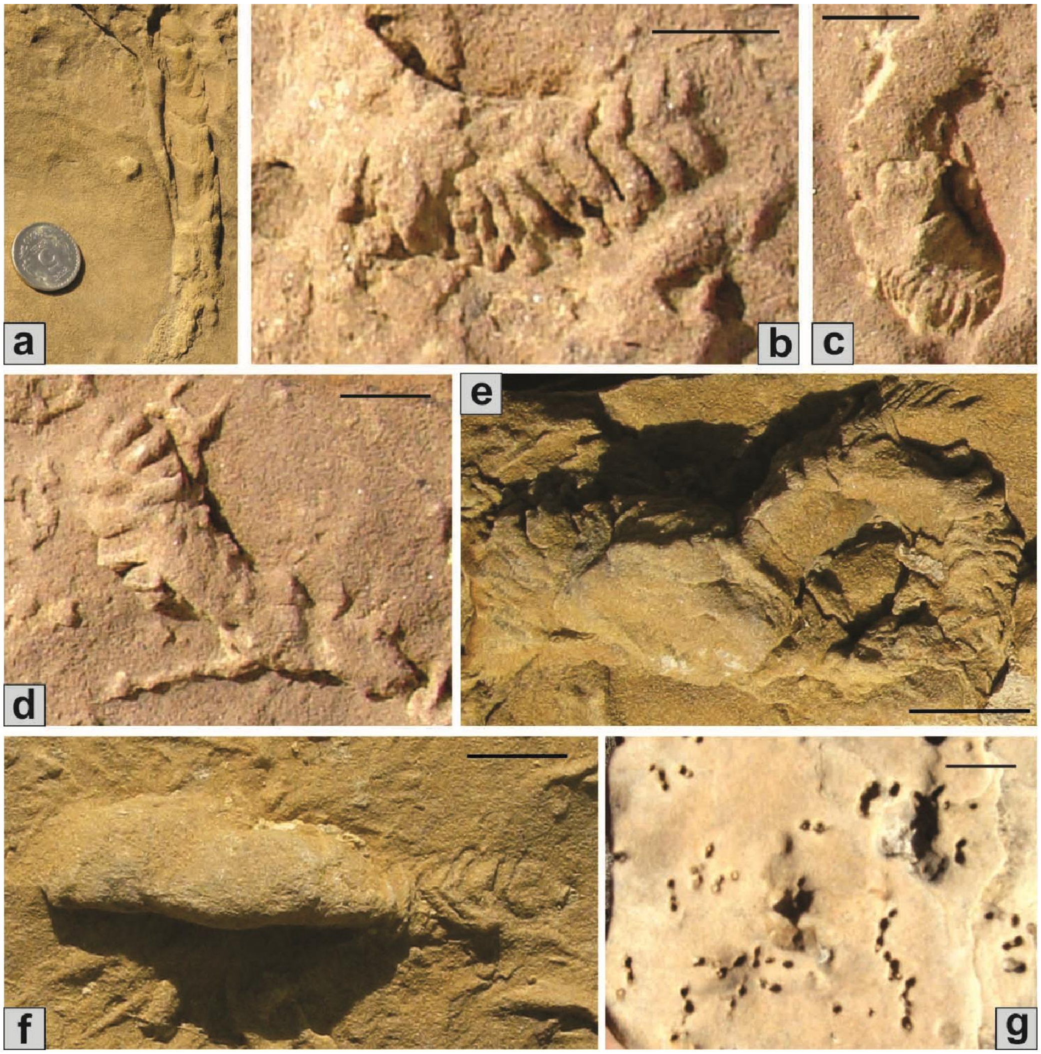


Plate 5.11 Meniscate burrows and U-shaped borings (Bar length= 1 cm, coin diameter = 2.5 cm). **(a)** *Virgoglyphus modari* n. isp., Bioclastic packstone, MHM; **(b), (c),** and **(d)** Unbranched horizontal backfilled burrow *Walcottia devilsdingli*, allochemic sandstone, DHM; **(e)** Cylindrical chevron-like surface sculptured curved burrows *Walcottia devilsdingli*, allochemic sandstone, RLM; **(f)** Cylindrical chevron-like surface sculptured straight burrows *Walcottia devilsdingli*, allochemic sandstone, RLM; **(g)** Cylindrical boring bent in a narrow U shaped gallery *Caulostrepsis taeniola,* sandy allochem limestone, RLM.

Description: Hypichnial, cylindrical straight to curved full burrows with chevron-like surface sculpture is the characteristics of the ichnogenus. Burrow width in unscratched areas varies, maximum being of 60 mm; sculpture burrow length is 40 to 50 mm and diameter of 10-14 mm, and the cross-section is elliptical to circular. It consists of arcuate, uniformly bent segments, each 6-12 mm long, separated by very narrow and shallow grooves; the figured specimen shows 5 to 10 scratch marks but numbers of scratch marks varies in different burrow populations.

Occurrence: Allochemic sandstone of Dingy Hill member and Raimalro Limestone member (Tuga village) of Kaladongar and Goradongar Formations respectively.

Remarks: The specimen differs in dimension from the *Beaconites* (smaller dimension) and *Imbrichnus* (larger dimension). The maker of the *Walcottia* was evidently slow-moving organisms that did not travel far before resting. The ovate to amygdaloid form of the resting trace strongly suggests bivalves as the chief makers (Rindsberg, 1994).

5.2.2 BORING:

5.2.2.1 U-Shaped

Ichnogenus: *Caulostrepsis* Clarke, 1908

Type ichnospecies: *Caulostrepsis taeniola*, Clarke, 1908

Diagnosis: U-shaped tunnels with spreite, corresponding to tiny *Rhizocorallium,* sometimes radiating inward from comminssure of brachiopods; commonly found in shells of brachiopods, mollusks, and echinoids (Häntzschel, 1975).

Ichnospecies: *Caulostrepsis taeniola*, Clarke, 1908
(Plate 5.11 g)

Diagnosis: Gallery cylindrical, bent in a narrow U which is sometimes enlarged in the shape of a tongue. The inward-facing margins of the limbs are always interconnected by a distinct vane. Limbs closer or partially fused towards the apertural extremity. Transverse section is dumbbell-shaped, aperture '8'-shaped (Bromley and D'Alessandro 1983).

Description: Cylindrical gallery bent in a narrow U-shape. The inward facing margin of the limbs of the U-shaped boring is interconnected by a distinct vane. Limbs closer or partially fused towards the apertural extremity. Dumbbell shaped in transverse section and 8-shaped aperture.

Occurrence: Sandy allochem limestone of Raimalro Limestone member of Goradongar Formation exposed near Dhorawar village.

Remarks: The ichnogenus *Caulostrepsis* are known to occur from numerous rockground and shells ranging in age from Devonian to Recent (Taylor and Wilson, 2003). Polychaetes like Spionid (Häntzschel, 1975) and small eunicid *Lysidiceninetta* (Bromley, 1978) are reported as the possible producer of the trace.

CHAPTER-6
ICHNOFOSSIL ANALYSIS

6.1 INTRODUCTION

Trace fossils are biologically produced sedimentary structures (MacEachern and Pemberton, 2007), whose preservation are influenced by the taphonomic aspects; and essentially have no biostratinomy, because they are always produced in place. The rocks of the Patcham Island comprises of total 67 ichnospecies of 43 ichnogenera. These trace fossils are trusted as in situ indicators of palaeoenvironments in Middle Jurassic strata as only under unusual circumstances, they are washed around or abraded by physical agents. These trace fossils recur throughout the sequence. The frequency of their occurrence within each member of the Kaladongar and Goradongar Formations are also observed (Table-1).

These trace fossils also provide the ethologic and ecologic information about the members of the fauna that could not be derived from either the soft or hard parts of the animal (Frey, 1973; Pemberton et al, 1992). Ethology along with the oxygen level condition is greatly influenced by the substrate consistency (Ekdale and Mason, 1988). These trace fossils are analysed for the ichnoassemblage and ichnofacies within the substrate which can significantly complicate reconstructions of paleobathymetry, paleosalinity or paleo-oxygenation of the depositional environment.

6.2 ETHOLOGY

Trace fossils are the tangible evidence of the behaviour of animals (Bromley, 1996). The classification given by Seilacher (1953a, 1964a) is based on the most fundamental aspects of ethology. The original system consists of five categories, viz., (1) "Cubichnia", the resting trace; (2) "Repichnia", the lomotion trace; (3)

“Pascichnia”, grazing traces; (4) “Fodinichnia”, the feeding trace; and (5) “Domichnia”, the dwelling traces; these are the basic building blocks of behavioural interpretation in ichnology and are used in the following analysis. Overlapping between the groupings is unavoidable at certain levels whereas some are easily placed within the classification.

No	Ichnospecies	Kaladongar Formation			Goradongar Formation			
		DHm	KSm	BCSm	GFm	GSm	RLm	MHm
	Burrows							
1.	*Arenicolites carbonarius*	C	R	R	-	-	-	-
2.	*Arenicolites statheri*	-	-	-	-	-	VR	VR
3.	*Arenicolites* isp	-	-	-	-	R	VR	C
4.	*Asterosoma ludwigae*	VR	-	R	-	-	-	-
5.	*Asterosoma radiciforme*	-	-	R	VR	-	-	-
6.	*Asterosoma cf. radiciforme*	-	-	-	VR	-	-	-
7.	*Aulichnites parkerensis*	-	-	-	-	-	-	VR
8.	*Beaconites coronus*	VR	-	-	-	VR	-	VR
9.	*Beaconites antarcticus*	-	-	-	-	-	-	VR
10.	*Bergaueria* cf. *hemispherica*	-	-	VR	-	-	-	-
11.	*Bichordites* isp.	-	-	-	-	-	-	VR
12.	*Bifungites* isp.	-	-	-	-	-	VR	-
13.	*Chondrites intricatus*	VR	-	-	-	-	VR	-
14.	*Chondrites targionii*	VR	-	-	-	-	-	R
15.	*Circulichnus montanus*	-	-	-	-	VR	-	-
16.	*Cochlichnus anguineus*	VR	-	-	-	-	-	-
17.	*Cochlichnus* isp.	-	-	-	-	VR	-	VR
18.	*Dactylophycus isp.*	VR	-	-	-	-	-	-
19.	*Daedalus* cf. *verticalis*	VR	-	-	-	-	-	-
20.	*Didymaulichnus lyelli*	VR	-	VR	-	-	-	-
21.	*Diplocraterion* isp.	R	-	VR	VR	VR	VR	VR
22.	*Gordia arcuata*	VR	-	VR	-	-	-	-
23.	*Gordia* isp.	-	-	-	-	-	VR	-
24.	*Gyrochorte comosa*	C	-	R	VR	-	VR	R
25.	*Gyrolithes isp.*	VR	-	-	-	-	-	-
26.	*Hartsellea sursumramosa*	-	-	-	VR	-	-	-
27.	*Helicolithus sampelayoi*	-	-	-	-	-	-	C
28.	*Ichnocumulus radiatus*	VR	-	-	-	-	-	-
29.	*Laevicyclus* isp.	VR	-	-	-	-	VR	-
30.	*Lockeia amygdaloides*	-	-	VR	-	-	VR	-
31.	*Lockeia siliquaria*	VR	-	R	-	-	VR	-
32.	*Margaritichnus reptilis*	VR	-	-	-	-	-	-
33.	*Monocraterion tentaculatum*	R	-	-	-	-	-	-
34.	*Nereites missouriensis*	VR	-	-	-	-	-	-
35.	*Ophiomorpha nodosa*	R	-	VR	-	R	-	R
36.	*Palaeophycus alternatus*	-	-	-	-	VR	-	-

37.	*Palaeophycus annulatus*	VR	-	-	-	-	-	-
38.	*Palaeophycus striatus*	-	-	VR	-	VR	-	-
39.	*Palaeophycus tubularis*	C	-	-	VR	VR	-	R
40.	*Phoebichnus trochoides*	VR	-	VR	-	VR	-	-
41.	*Phycodes circinatum*	VR	-	-	-	-	-	-
42.	*Phycodes cf. curvipalmatum*	-	-	-	-	-	-	VR
43.	*Phycodes palmatus*	VR	-	R	-	-	-	-
44.	*Phycodes* cf. *palmatus*	-	-	-	VR	-	-	-
45.	*Pilichnus dichotomus*	-	-	VR	-	-	-	VR
46.	*Pilichnus* isp	-	-	-	-	VR	-	VR
47.	*Planolites beverleyensis*	R	VR	C	R	R	R	C
48.	*Plug shaped form* cf. *B*	VR	-	-	-	-	-	-
49.	*Protovirgularia dichotoma*	VR	-	-	-	-	-	-
50.	*Protovirgularia* cf.*dichotoma*	-	-	-	-	VR	-	-
51.	*Protovirgularia* isp	-	-	-	-	-	VR	-
52.	*Rhabdoglyphus* isp	-	-	-	-	-	VR	-
53.	*Rhizocorallium jenense*	VR	-	-	VR	R	VR	VR
54.	*Rhizocorallium irregulare*	C	C	R	R	R	C	C
55.	*Rhizocorallium uraliense*	-	VR	-	-	-	-	VR
56.	*Scolicia prisca*	VR	-	-	-	-	-	-
57.	*Scolicia isp.*	VR	-	-	-	-	-	-
58.	*Skolithos linearis*	R	VR	-	-	R	-	R
59.	*Taenidium baretti*	-	-	-	-	-	-	VR
60.	*Taenidium serpentinum*	-	-	VR	-	R	-	VR
61.	*Teichichnus rectus*	-	VR	-	-	-	-	-
62.	*Thalassinoides horizontalis*	R	-	-	VR	VR	-	R
63.	*Thalassinoides* isp.	VR	-	-	-	-	VR	-
64.	*Thalassinoides suevicus*	C	-	-	VR	VR	R	-
65.	*Virgoglyphus modari*	-	-	-	-	-	-	VR
66.	*Walcottia devilsdingli*	VR	-	-	-	-	VR	-
Borings								
1.	*Caulostrepsis taeniola*	-	-	-	-	-	VR	-

Table-6.1 Trace fossil frequency in the Middle Jurassic rocks of the Patcham Island (VR-very rare, < 3 specimen; R-rare, when 3-9 specimen; C-common, 10-25 specimen and A-abundant, >25 specimen).

There are certain "difficult" ichnogenera that are placed under different ethological category by different ichnologists, for e.g., Frey and Pemberton (1985) classified *Zoophycos* and *Planolites* as pascichnia and fodinichnia, respectively, whereas Ekdale (1985) placed these same genera in the fodinichnia and pascichnia, respectively. In the present study, the *Planolites* are placed under pascichnia as per the view of Ekdale (1985). Total of 67 ichnospecies are recognized that represents diverse ethological characteristic namely, domichnia, fodinichnia, pascichnia, repichnia and cubichnia (Table. 2). The ethological categorization of these trace fossils are carried out in order to understand their ethological diversity in various lithofacies (Table. 3).

Resting traces, or cubichnia, include traces made by organisms that have dug into the substrate in order to rest, hide, or perform other relatively stationary actions such as respiration or rehydration for a relatively brief period of time (Martin, 2006). In most cases, a thin veneer of sediment is sufficient for the animal to conceal; so, cubichnia tend to be much shallower than they are broad (Frey and Seilacher, 1980). The trace may retain the sculpture made by the digging appendages since the animals burrow into the sediment once and then remain nearly motionless.

ETHOLOGY	BEHAVIOR	TRACE FOSSILS	PRODUCERS
CUBICHNIA	Temporary immobility	*Bergaueria cf. hemispherica* *Ichnocumulus radiates* *Lockeia amygdaloide* *Margaritichnus reptilis* *Plug shaped form cf. B*	Coelenterates *Unknown* Burrowing bivalves Worm-like animal ?Small burrowing ray
DOMICHNIA	Dwelling	*Arenicolites carbonarius, A.statheri, A. isp.* *Lockeia siliquaria* *Diplocraterion isp* *Monocraterion tentaculatum* *Ophiomorpha nodosa* *Palaeophycus alternatus, P.annulatus, P.striatus, P.tubularis* *Skolithos linearis*	Worms Burrowing bivalves Worms Worm-like animal Crustaceans Polychaetes Annelids and polychaetes
REPICHNIA	Directed locomotion	*Didymaulichnus lyelli* *Gyrochorte comosa* *Nereites missouriensis* *Scolicia prisca*, *S.*isp.	Molluscans Annelids Gastropods/crustacean Gastropods
PASCICHNIA	Locomotion + Feeding	*Circulichnis montanus* *Planolites beverleyensis*	Polyphyletic vermiform

FODINICHNIA	Dwelling + Feeding	*Asterosoma radiciforme, A.ludwigae*	Decapod crustacean
		Aulichnites parkerensis	Gastropod
		Beaconites antarcticus, B.coronus	Arthropods
		Bifungites isp.	Polychaete annelid
		Chondrites targionii, C.intricatus	Chemosymbiotic animal
		Cochlichnus anguineus, C.isp.	Annelids
		Daedalus cf. verticalis	Arthropods
		Dactylophycus isp.	
		Gordia arcuata, G.isp.	Annelids
		Gyrolithes isp	Decapods crustacean
		Hartsellea sursumramosa	Polychaetes
		Helicolithus sampelayoi	Graphoglyptid
		Laevicyclus isp.	Annelid
		Phoebichnus trochoides	Unknown animal
		Phycodes circinnatum, P.palmatum, P. cf. palmatum	Vermiform annelids
		Pilichnus dichotomus	
		Protovirgularia dichotoma, P. cf. dichotoma, P.isp	Bivalves
		Rhizocorallium irregulare, R.jenense, R.uraliense	Crustacean or scavengers
		Taenidium serpentinum, T.barretti	Polychaetes/Crustaceans
		Teichichnus rectus	Polychaetes
		Thalassinoides horizontalis, T.suevicus, T.isp.	Crustaceans
		Rhabdoglyphus isp	
		Virgoglyphus modari	Polychaete worm
		Walcottia devilsdingli	Bivalves

Table-6.2 Ethological grouping of trace fossils and their possible producers.

FACIES	CUBICHNIA	REPICHNIA	PASCICHNIA	FODINICHNIA	DOMICHNIA
Allochemic Sandstone	*Ichnocumulus radiates, Margaritichnus reptiles, Plug shaped form* cf. B	*Scolicia* isp., *Didymaulichnus lyelli, Gyrochorte comosa*	*Circuliuchnus montanus Planolites beverleyensis*	*Asterosoma radiciforme, A.ludwigae, Beaconites coronus, Cochlichnus anguineus, C.*isp., *Gordia arcuata, Gyrolithes* isp, *Bifungites* isp., *Dactylophycus* isp., *Hartsellea sursumramosa, Phoebichnus trochoides, Phycodes circinnatum, P.palmatum, Phycodes cf. palmatum, Protovirgularia* cf. *dichotoma, P.*isp, *Rhizocorallium irregular, R.jenense, R.uraliense, Taenidium serpentinum,Thalassinoides horizontalis, T.suevicus, T.*isp., *Rhabdoglyphus* isp, & *Walcottia devilsdingli*	*Arenicolites* isp., *Diplocraterion* isp, *Lockeia siliquaria, Ophiomorpha nodosa, Palaeophycus alternatus P.striatus, P.tubularis*
Micritic Sandstone	*Bergaueria* cf. *hemispherica, Lockeia amygdaloides*	*Gyrochorte comosa*	*Planolites beverleyensis*	*Chondrites intricatus, C.targionii, Laevicyclus* isp., *Protovirgularia dichotoma, Rhizocorallium irregular, R.jenense, Taenidium serpentinum , Thalassinoides horizontalis, T.suevicus, T.*isp., and *Walcottia devilsdingli*	*Arenicolites carbonarius, Lockeia siliquaria, Ophiomorpha nodosa, Monocraterion tentaculatum, Palaeophycus annulatus, P.striatus, P.tubularis*
Micritic Mudrock		*Didymaulichnus lyelli, Gyrochorte comosa*	*Planolites beverleyensis*	*Rhizocorallium irregulare*	*Lockeia siliquaria*
Sandy Allochem Limestone	*Lockeia amygdaloides*	*Gyrochorte comosa, Nereites missouriensis, Scolicia prisca, S.*isp.	*Planolites beverleyensis*	*Chondrites intricatus, Daedalus* cf. *verticalis, Gordia arcuata, G.*isp., *Phoebichnus trochoides, Phycodes palmatum, Rhizocorallium irregularre, R.jenense, R.uraliense, Thalassinoides suevicus, Pilichnus dichotomus*	*Arenicolites carbonarius, Diplocraterion* isp, *Ophiomorpha nodosa, Monocraterion tentaculatum, Palaeophycus tubularis*
Sandy Micrite			*Planolites beverleyensis*	*Beaconites antarcticus, Chondrites targionii, Rhizocorallium irregulare, Taenidium barrette, Teichichnus rectus*	*Arenicolites statheri*, *A.* isp., *Skolithos linearis*
Ferruginous Sandstone				*Rhizocorallium irregulare,* R. *jenense*	*Arenicolites* isp., *Diplocraterion* isp., *Monocraterion* isp., *Skolithos linearis*
Allochemic Limestone		*Gyrochorte comosa*	*Planolites beverleyensis*	*Aulichnites parkerensis, Beaconites antarcticus, B.coronus, Helicolithus sampelayoi, Laevicyclus* isp., *Phycodes palmatum, Rhizocorallium irregulare, Taenidium serpentinum, Thalassinoides horizontalis Virgoglyphus modari*	*Arenicolites* isp., *Diplocraterion* isp., *Lockeia siliquaria, Ophiomorpha nodosa, Skolithos linearis*

Table-6.3 Ethological grouping of trace fossils in each sedimentary facies.

Traces made as permanent or long-term homes are classified under this category, i.e., the burrows or borings consisting of originally open hollows, or of a permanent cavity filled by the tracemaker, reflecting to some degree the outline of the maker and in many cases with sculpture reflecting its appendages or its method of excavation. These traces are simple to U-shaped, Y-shaped, or complexly branched, typically vertical to oblique near the surface but commonly incorporating horizontal elements at depth; fill usually passive; walls commonly lined.

Those traces that are made while moving from one place to another are termed as the locomotion traces. These traces are generally simple and shallow, either continuous or discontinuous; may incorporate resting traces. Trackways made up of repeated sets of discontinuous impressions reflecting the maker's appendages and their motion in the substrate; trails consisting of continuous grooves or ridges of sediment with more or less parallel sides, in some cases meniscate or annulated. Those traces that are made by surface-feeding are termed as grazing traces. These includes shallow grooves and pits, either continuous or discontinuous, generally reflecting maximum utilization of a substrate surface, as in meandering, coiled, or otherwise patterned course.

The traces of deposit-feeding with the substrate are termed as feeding traces. This includes burrows, or borings originally held open only termporarily; traces simple to complex; orientation variable; fill commonly active; complex burrows with repeatedly branched probes or with gradually shifting burrows (spreite); pattern commonly showing avoidance of reburrowing previously used sediment; wall usually with minimal or no lining.

6.3 TRACE FOSSIL ASSEMBLAGES

Trace fossils are the tool in recognizing the palaeoenvironment and their biota (Uchman and Gaździcki, 2006). Ichnoassemblage is the basic collective term, embracing all the trace fossils occurring within a single unit of rock and is non-committal to the origin of the collection of trace fossils; may have been emplaced simultaneously as a single ecologically-related group, or may represent several overprinted events of bioturbation (Bromley, 1996). The presence of trace fossils in the sequence of the Kaladongar and

Goradongar Formations exhibits recurring pattern in their occurrence. Each sedimentary bed/unit shows an ecologically related group of trace fossils which demonstrates nine trace fossils assemblages which includes *Arenicolites*, *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites/Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages. These assemblages are characterized by a particular association of trace fossils and are named after the dominant ichnogenus; which indicate hydrodynamic condition, mode of food supply, oxygenation conditions, substrate conditions and bathymetry. Each ichnoassemblage is illustrated diagrammatically at respective places and trace fossils numbers therein are in accordance with the Table.1.

6.3.1 *ARENICOLITES* ASSEMBLAGE:

The *Arenicolites* assemblage consists of trace fossils such as *Arenicolites carbonarius*, *Arenicolites statheri* and *Arenicolites* isp, associated with *Asterosoma ludwigae, Chondrites intricatus*, *Chondrites targionii*, *Diplocraterion* isp., *Gyrochorte comosa*, *Helicolithus sampelayoi*, *Ophiomorpha nodosa*, *Palaeophycus tubularis, Phycodes circinatum, Planolites beverleyensis*, *Rhizocorallium irregulare*, *Rhizocorallium jenense*, *Skolithos linearis*, *Taenidium serpentinum* and *Thalassinoides suevicus* (Fig. 6.1).

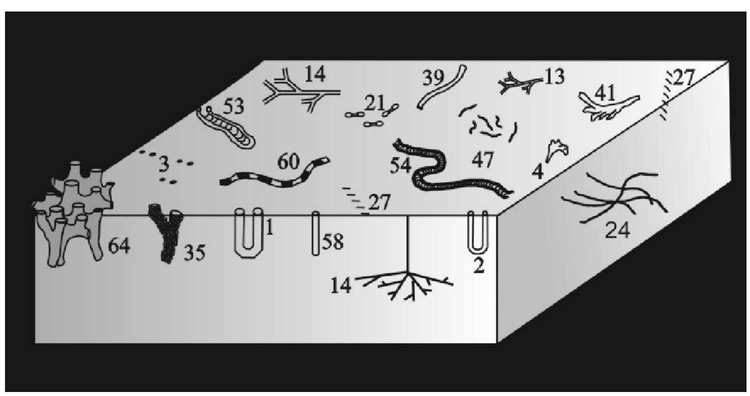


Figure-6.1 Diagrammatic representation of *Arenicolites* assemblage.

It is observed in the sandy allochem limestone of Kuar Bet member; micritic sandstone and sandy allochem limestone of Dingy Hill member; sandy allochem limestone of Kaladongar Sandstone member; and micritic sandstone of Babia Cliff Sandstone member of Kaladongar Formation. In Goradongar Formation, it is observed in micritic sandstone of Gadaputa Sandstone member; sandy allochem limestone of Raimalro Limestone member;

and sandy allochem limestone, allochemic limestone and sandy micrite of Modar Hill member.

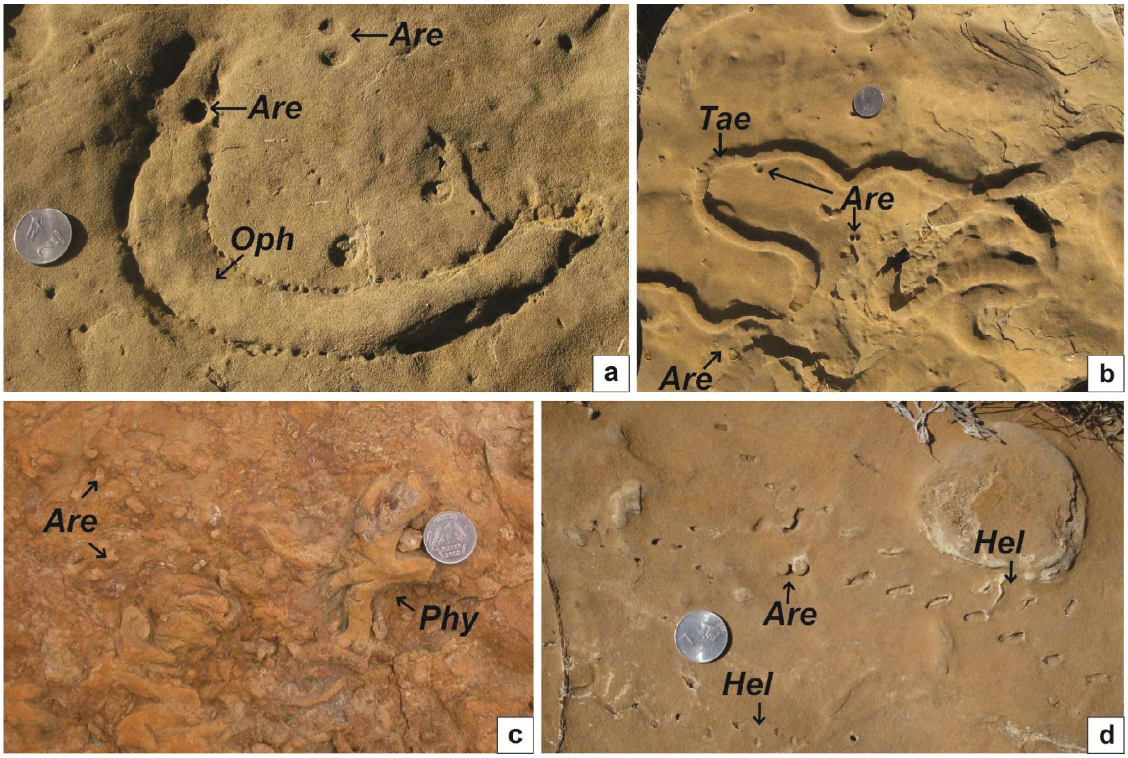


Plate 6.1 Trace fossils of *Arenicolite* assemblage (scale-2 cm, coin diameter): **(a)** *Arenicolites* isp. (*Are*) and *Ophiomorpha nodosa* (*Oph*) in sandy micrite of MHM; **(b)** *Arenicolites* isp. (*Are*) and *Taenidium serpentinum* (*Tae*) in micritic sandstone of GSM; **(c)** *Arenicolites* isp. (*Are*) and *Phycodes palmatum* (*Phy*) in allochemic sandstone of BCSM; **(d)** *Arenicolites* isp. (*Are*) and *Helicolithus sampelayoi* (*Hel*) in allochemic limestone of MHM.

This ichnoassemblage either shows predominance of suspension feeders or mixer of suspension and deposit feeders at different stratigraphic levels in different facies. The *Arenicolites* assemblage showing association with the trace fossils such as *Diplocraterion* isp., *Ophiomorpha nodosa* (Plate 6.1a) and *Skolithos linearis* and the rippled surface as associated sedimentary structures in micritic sandstone facies shows predominance of suspension feeders and also represents high energy depositional regime of upper shoreface to middle shoreface. The *Arenicolites* assemblage showing association with *Chondrites targionii, Planolites beverleyensis, Phoebichnus trochoides, Palaeophycus tubularis, Rhizocorallium jenense, Rhizocorallium irregulare, Taenidium serpentinum* (Plate. 6.1b) and *Phycodes palmatum* (Plate 6.1c) represents the erosional and the depositional trace suites in sandy micrite, sandy allochem limestone and micritic sandstone facies and represents the suspension as well as the deposit feeders.

The presence of graphoglyptid *Helicolithus sampelayoi* (Fig. 6.1, d) in allochemic limestone facies indicates the high energy storm event where the opportunistic animal had changed their behavior and the *Arenicolites* represented the post-storm event. The presence of *Chondrites* also indicates low oxygenated condition level on the substrate in direct contact with the oxygen deficient bottom waters (Neto de Carvalho and Rodrigues, 2007). The trace fossils association of this ichnoassemblage shows dominance of annelids and polychaetes, and presence of crustaceans as producers. The association of these trace fossils represents the high wave and current energy conditions of upper shoreface to lower shoreface or due to the high energy/storm events.

6.3.2 *ASTEROSOMA* ASSEMBLAGE:

The *Asterosoma* assemblage is characterised by *Asterosoma ludwigae, Asterosoma radiciforme,* and *Asterosoma* cf. *radiciforme* associated with the trace fossils such as *Arenicolites* isp., *Planolites beverleyensis, Gyrolithe* isp., and *Phycodes palmatum* (Fig. 6.2). It is observed in the micritic sandstone of Dingy Hill member; in allochemic sandstone of Babia Cliff Sandstone member; and in sandy allochem limestone of Goradongar Flagstone member.

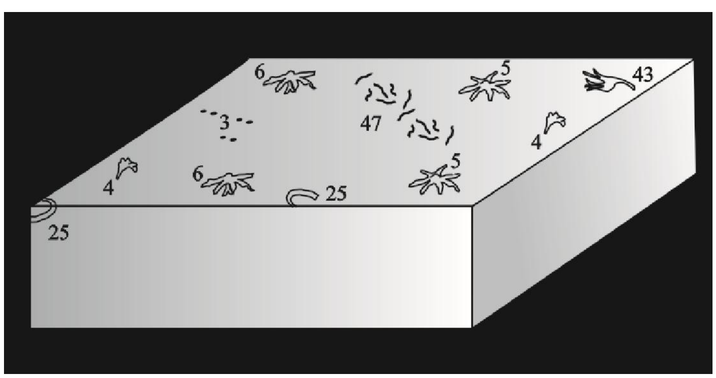


Figure-6.2 Diagrammatic representation of *Asterosoma* assemblage.

The *Asterosoma* assemblage shows predominance of the deposit feeders. The *Asterosoma* shows various morphological changes from abundant single bulb forms of *A.*

ludwigae associated with *Arenicolites* isp. in Dingy Hill member (Plate 6.2a) to *A. radiciforme* associated with *Phycodes palmatus* in Babia Cliff Sandstone member (Plate 6.2b), which also suggests a change of substrate conditions from micritic sandstone to allochemic sandstone, respectively.

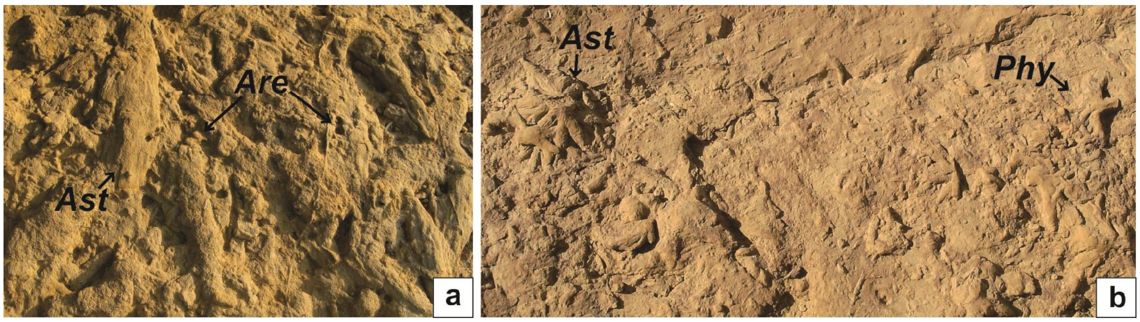


Plate 6.2 Trace fossils of *Asterosoma* assemblage: **(a)** *Asterosoma ludwigae* (*Ast*) and *Arenicolites* isp. (*Are*) in micritic sandstone of DHM; and **(b)** *Asterosoma radiciforme* (*Ast*) and *Phycodes palmatum* (*Phy*) in allochemic sandstone of BCSM.

Presence of *A. ludwigae* in Dingy Hill member represents firm, stable sediments (Schlirf, 2003). This assemblage shows presence of feeding burrows only which suggests better oxygenated conditions prevalent during the deposition. The most probable dominant producer of this assemblage is crustacean decapods. They represent low energy depositional regime ranging from the transitional zone of shoreface- offshore condition.

6.3.3 *GYROCHORTE* ASSEMBLAGE:

Gyrochorte assemblage is characterized either by the predominance of *Gyrochorte comosa* or is observed to be associated with the trace fossils such as *Didymaulichnus lyelli, Palaeophycus tubularis, Planolites beverleyensis* (Plate 6.3a)*, Rhizocorallium irregulare* (Plate 6.3b) and *Thalassinoides* suevicus (Fig. 6.3).

This ichnoassemblage is observed in the sandy allochem limestone of Kuar Bet member;micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member; micritic sandstone, sandy allochem limestone and micritic mudrock of Babia Cliff Sandstone member; sandy allochem limestone and allochemic limestone of Modar Hill member.

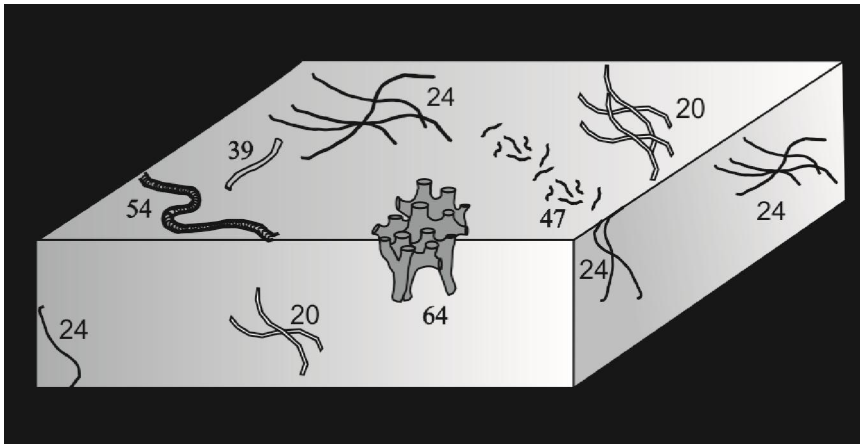


Figure-6.3 Diagrammatic representation of *Gyrochorte* assemblage.

The *Gyrochorte* assemblage shows predominance of deposit feeders as well as the suspension feeders. The most probable dominant producers of these traces are crustacean and polychaetes. This assemblage suggest an intermediate to low energy conditions suggesting the transitional zone between the low energy offshore and the wave and storm influenced shoreface environment, extending to the low energy offshore regions.

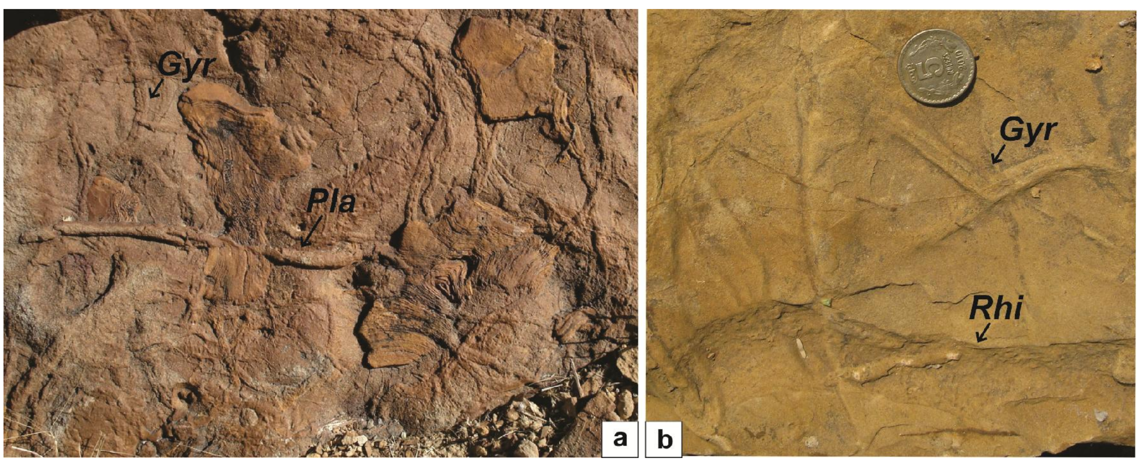


Plate 6.3 Trace fossils of *Gyrochorte* assemblage: **(a)** *Gyrochorte comosa* (*Gyr*) and *Planolites beverleyensis* (*Pla*) in micritic mudrock of BCSM; **(b)** *Gyrochorte comosa* (*Gyr*) and *Rhizocorallium irregulare* (*Rhi*) in sandy micrite of DHM.

6.3.4 *OPHIOMORPHA* ASSEMBLAGE:

Ophiomorpha assemblage is characterized either by monodominant presence of *Ophiomorpha nodosa* (Plate 6.4a) or its association with trace fossils such as *Planolites* *beverleyensis* (Plate 6.4b), *Gyrochorte comosa, Arenicolites* isp., *Cochlichnus* isp., *Rhizocorallium irregulare*, *Rhizocorallium jenense* (Plate 6.4b), *Palaeophycus tubularis*, *Helicolithus sampelayoi* and *Thalassinoides suevicus* (Fig. 6.4).

It is observed in micritic sandstone and allochemic sandstone of the Dingy Hill member; micritic sandstone and sandy allochemic limestone of the Babia Cliff Sandstone member; micritic sandstone of Gadaputa Sandstone member; allochemic limestone of Raimalro Limestone member; and micritic sandstone, allochemic limestone and sandy micrite of Modar Hill member.

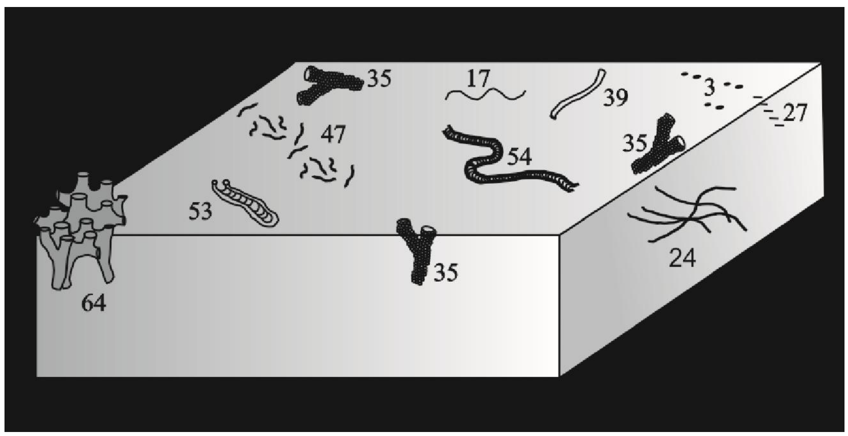


Figure-6.4 Diagrammatic representation of *Ophiomorpha* assemblage.

The presence of *Ophiomorpha* indicates shifting, unconsolidated sandy substrates in the marine settings (Ekdale, 1988) while the co-occurrence of *Helicolithus* and *Ophiomorpha* indicates the storm influenced shelf sequence. The pascichnial trail such as *Helicolithus* was produced by sediment feeders in the muddy sea floor during long periods between the high energy events. In contrast, the post-depositional traces (*Ophiomorpha*) were dug in the high energy event sand soon after it was deposited and before sedimentation once again covered it.

This assemblage represents mixers of suspension feeders and deposit feeders. The absence of the iron oxide rim surrounding the burrow wall of the *Ophiomorpha* and the dominance of suspension feeders indicates high oxygen content in the sediments. The most probable makers of this assemblage are studied and considered to be crustaceans either decapod-*callianasa major* (Weimer and Hoyt, 1964; Frey et al, 1978) or stomatopod-*Oratosquilla striata* (Patel and Desai, 2009) in the recent intertidal environments. This assemblage represents high energy conditions for the opportunistic behavior suggesting the shoreface to foreshore environment and storm influenced sediments.

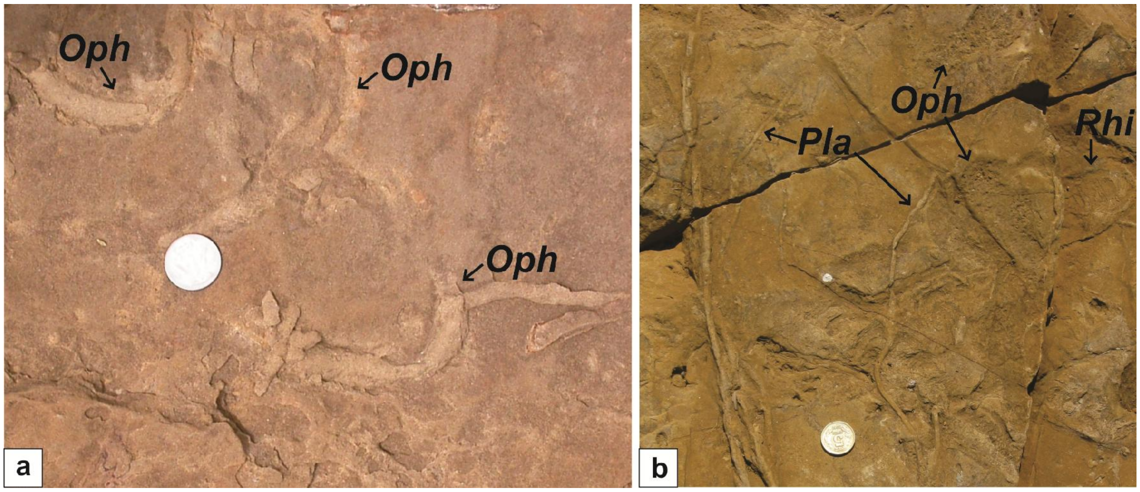


Plate 6.4 Trace fossils of *Ophiomorpha* assemblage: **(a)** monodominant presence of *Ophiomorpha nodosa* (*Oph*) in micritic sandstone of DHM; and **(b)** association of *Ophiomorpha nodosa* (*Oph*), *Planolites beverleyensis* (*Pla*) and *Rhizocorallium jenense* (*Rhi*) in allochemic limestone of RLM.

6.3.5 *PHYCODES* ASSEMBLAGE:

Phycodes assemblage represents an assemblage of trace fossils (Fig.6.5) such as *Phycodes circinatum* (Plate 6.5a), *Phycodes palmatus* (Plate 6.5b), *Phycodes cf. curvipalmatum Phycodes cf. palmatus, Asterosoma radiciforme* and *Arenicolites* isp (Plate 6.5a).

It is observed in micritic sandstone of Dingy Hill member; allochemic sandstone and sandy allochem limestone of Babia Cliff Sandstone member; and allochemic limestone of Goradongar Flagstone member.

This assemblage shows predominance of deposit feeders over the suspension feeders. The most probable maker of these traces is vermiform annelids and crustaceans. This assemblage represents dominance of fodinichnial structures which suggests a well oxygenated condition in the low energy conditions of the offshore to transition-shoreface environment.

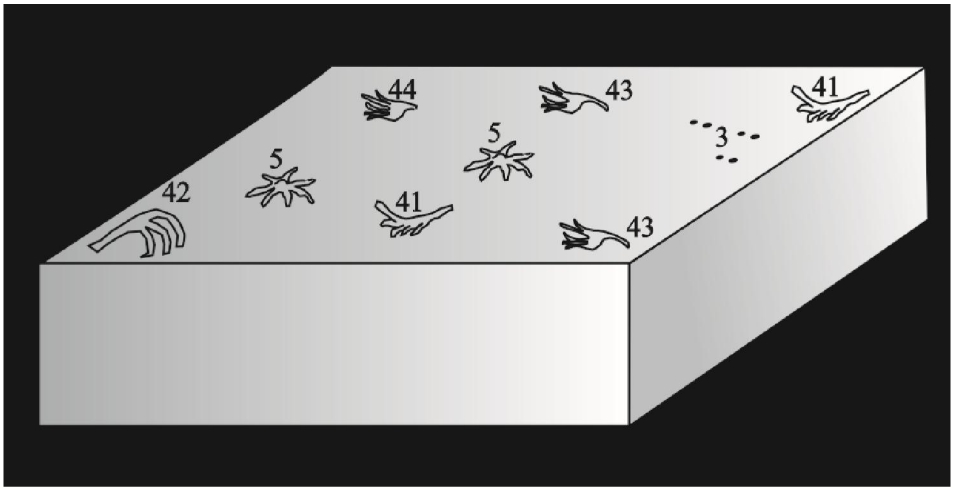


Figure-6.5 Diagrammatic representation of *Phycodes* assemblage.

Plate 6.5 Trace fossils of *Phycodes* assemblage: **(a)** association of *Phycodes circinatum* (*Phy*) and *Arenicolites* isp. in micritic sandstone of DHM, **(b)** Monodominant presence of *Phycodes palmatum* (*Phy*) in sandy allochem limestone of BCSM.

6.3.6 *PLANOLITES-PALAEOPHYCUS* ASSEMBLAGE:

Planolites-Palaeophycus assemblage consists of trace fossils such as *Planolites beverleyensis* (Plate 6.6a-c), *Palaeophycus tubularis* (Plate 6.6a), *Palaeophycus alternatus* and *Palaeophycus striatus* (Plate 6.6b), associated with *Arenicolites* isp., *Nereites missouriensis, Phycodes palmatum, Scolicia prisca, Skolithos* isp., *Rhizocorallium irregulare, Asterosoma cf. radiciforme* (Plate 6.6c), *Ophiomorpha nodosa* and *Helicolithus sampelayoi* (Fig.6.6).

This assemblage is observed insandy allochem limestone of Kuar Bet member; micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member; sandy allochem limestone of Kaladongar Sandstone member; micritic sandstone, allochemic sandstone and micritic mudrock of Babia Cliff Sandstone member; allochemic limestone and micritic mudrock of Goradongar Flagstone member; micritic sandstone, allochemic sandstone and allochemic limestone of Gadaputa Sandstone member; allochemic limestone of Raimalro Limestone member; and micritic sandstone, sandy allochem limestone, allochemic limestone and sandy micrite of Modar Hill member.

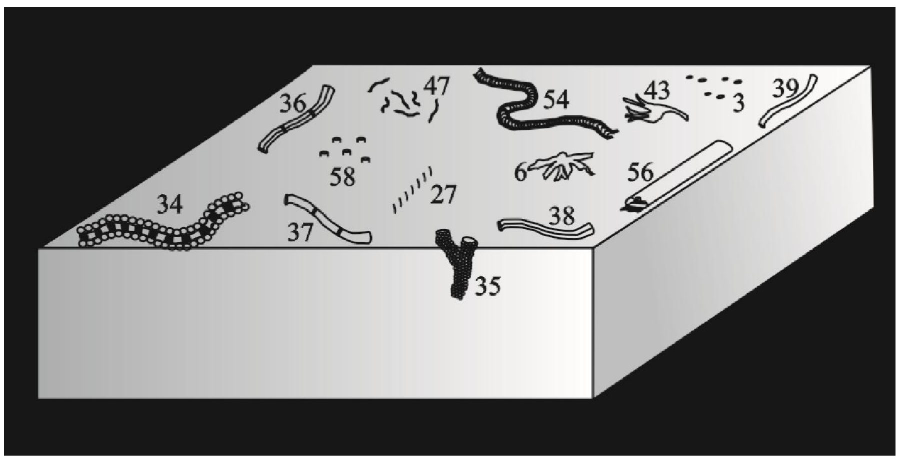


Figure-6.6 Diagrammatic representation of *Planolites-Palaeophycus* assemblage.

It is considered as the vagile and semi-vagile, middle level deposit feeder structures, present in oxygenated situations, which are intermediate to equilibrium or climax, trace fossils (Bromley, 1990). Because of lower energy level, less abrupt shifting of sediments and less change in temperature and salinity, *Planolites*-*Palaeophycus* assemblage is characterized by feeding and grazing traces of most probably originators such as polychaetes. The large, semi-permanent, mainly horizontal tunnel system-exhibiting exclusively deposit feeding traces, and high abundance, is also indicative of extremely quiet water conditions with less reworking where organic matter was being deposited along with the sediments.

In modern environments, *Scolicia* is interpreted as related to large amounts and high quality of benthic food (Wetzel, 2008). Moreover, the presence of *Scolicia*, which is produced by stenohaline echinoids, shows that at least locally the salinity was normal (Uchman and Gaździcki, 2006). Habitats with high benthic food content and poorly oxygenated pore water containing *Nereites* have also been described in the fossil record

(Ekdale and Mason, 1988; Wetzel and Uchman, 1998). Thus the presence of *Scolicia* and *Nereites* indicate a large amount and high quality of bethic food as well as poorly oxygenated condition and is suggestive of a very low energy environment. This assemblage represents transitional zone to lower shoreface environment, somewhat quieter offshore conditions; most probably the lowest energy levels (Fürsich and Heinberg, 1983).

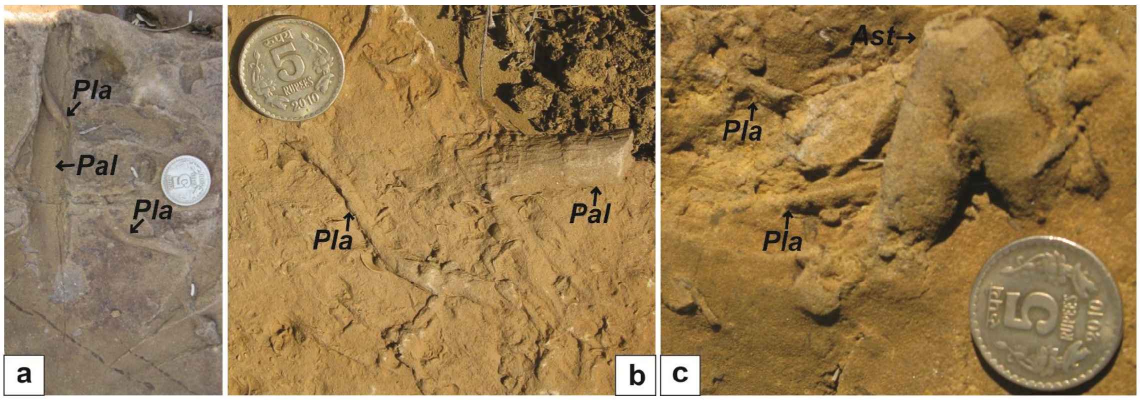


Plate 6.6 Trace fossils of *Planolites-Palaeophycus* assemblage: **(a)** *Palaeophycus tubularis* (*Pal*) and *Planolites beverleyensis* (*Pla*) in allochemic limestone of Raimalro Limestone member; **(b)** *Palaeophycus striatus* (*Pal*) and *Planolites beverleyensis* (*Pla*) in micritic sandstone of Gadaputa Sandstone member; **(c)** *Planolites beverleyensis* (*Pla*) and *Asterosoma* cf. *radiciforme* (*Ast*) in sandy allochem limestone of Goradongar Flagstone member.

6.3.7 *RHIZOCORALLIUM* ASSEMBLAGE:

Rhizocorallium assemblage shows monodominant presence of *Rhizocorallium irregulare* (Plate 6.7a) and *R.jenense* (Plate 6.7b) or association of *R irregularre, R jenense* and *R uraliense* with *Planolites beverleyensis* (Plate 6.7c), *Arenicolites* isp, and *Thalassinoides suevicus* (Fig. 6.7).

It is observed in sandy allochem limestone of Kuar Bet member; micritic sandstone, sandy allochem limestone and sandy micrite of Dingy Hill member; quartz arenite and sandy allochem limestone of Kaladongar Sandstone member; allochemic sandstone and sandy allochem limestone of Babia Cliff Sandstone member; sandy allochem limestone and allochemic limestone of Goradongar Flagstone member;micritic sandstone, allochemic sandstone and allochemic limestone of Gadaputa Sandstone member; sandy allochem limestone and allochemic limestone of Raimalro Limestone member; sandy allochem limestone, allochemic limestone and sandy micrite of Modar Hill member.

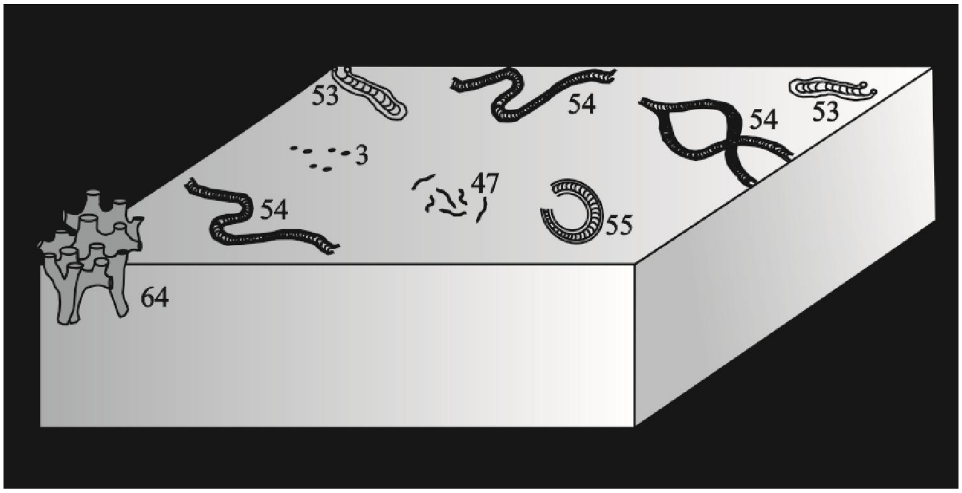


Figure-6.7 Diagrammatic representation of *Rhizocorallium* assemblage.

The trace fossil *Rhizocorallium jenense* reflects a generalized suspension-feeding mode of life for its trace makers, involving a concentration of nutrients in the water column that is probably related to storms (Rodríguez-tovar and Pérez-valera, 2008) and is usually related to unstable sedimentary environments, i.e. foreshore high energy regimes (Fürsich 1975); it is also related to more intermediate shoreface depths (Worsley & Mork 2001). *R. irregulare* interpreted to have a deposit-feeding mode of life, provides evidence for comparatively organic-poor sediments (Rodri´guez-tovar and Pe´rez-valera, 2008) suggest a low to medium energy condition.

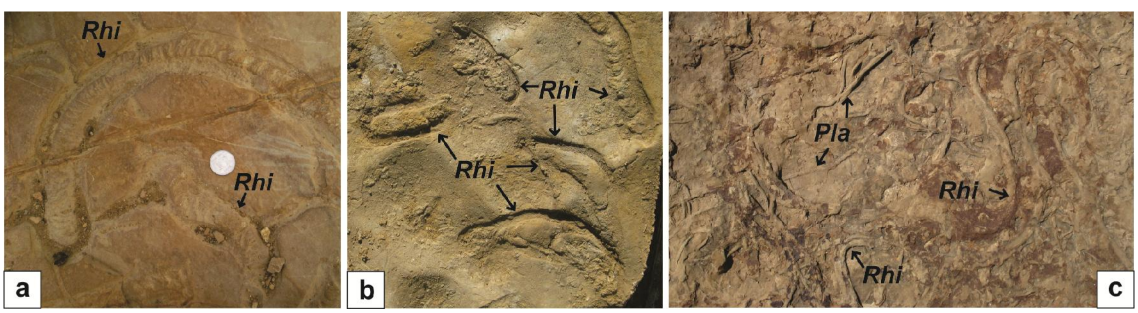


Plate 6.7 Trace fossils of *Rhizocorallium* assemblage: **(a)** monodominant presence of *Rhizocorallium irregulare* (*Rhi*) in sandy allochem limestone of Kaladongar Sandstone member, **(b)** monodominant *Rhizocorallium jenense* (*Rhi*) in sandy allochem limestone of Babia Cliff Sandstone member; and **(c)** association of *Rhizocorallium irregulare* (*Rhi*) and *Planolites beverleyensis* (*Pla*) in allochemic limestone of Gadaputa Sandstone member.

The various modifications in the Rhizocorallid form such as the slipper shaped *Rhizocorallium*, small stout *Rhizocorallium*, are suggestive of the changing substrate condition. This assemblage most frequently recurs through the sequence and is dominated by the deposit and suspension feeders. The large, semi-permanent, mainly horizontal tunnel system-exhibiting exclusively deposit feeding traces, and their very high diversity, is indicative of extremely quiet water conditions with little reworking where organic matter was being deposited along with the sediments. This assemblage consists of structures formed by deposit feeders and mobile voracious were living in offshore-transition-shoreface environment.

6.3.8 *SKOLITHOS* ASSEMBLAGE:

Skolithos assemblage is mostly characterized by the presence of monodominant trace fossil of *Skolithos linearis* (Plate 6.8a). It also is found associated with the trace fossils such as *Planolites beverleyensis* (Plate 6.8b)*, Palaeophycus tubularis* (Plate 6.8b) and *Bichordites* isp, *Arenicolites* isp., *Asterosoma cf. ludwigae* and *Thalassinoides suevicus. Rhizocorallium jenense, Monocraterion tentaculatum* and *Diplocraterion* isp (Fig. 6.8).

It is observed in micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member; quartz arenite and sandy allochem limestone of Kaladongar Sandstone member; quartz arenite and micritic sandstone of Gadaputa Sandstone member; allochemic limestone and sandy micrite of Modar Hill member.

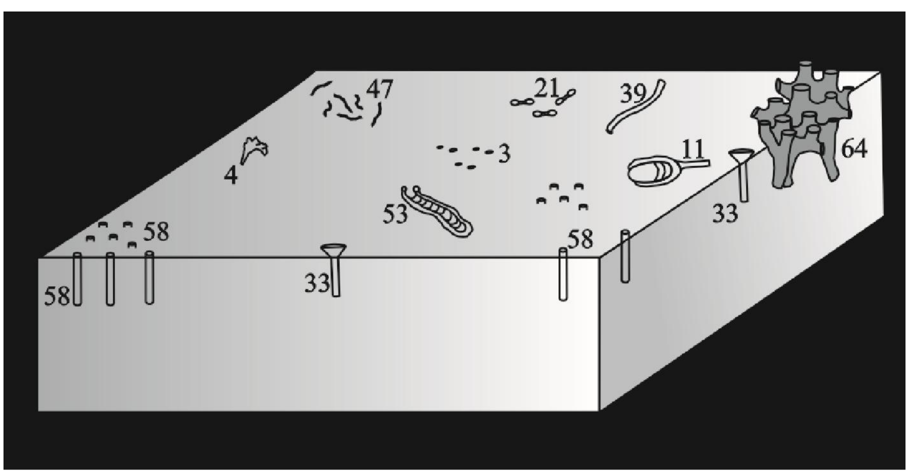


Figure-6.8 Diagrammatic representation of *Skolithos* assemblage.

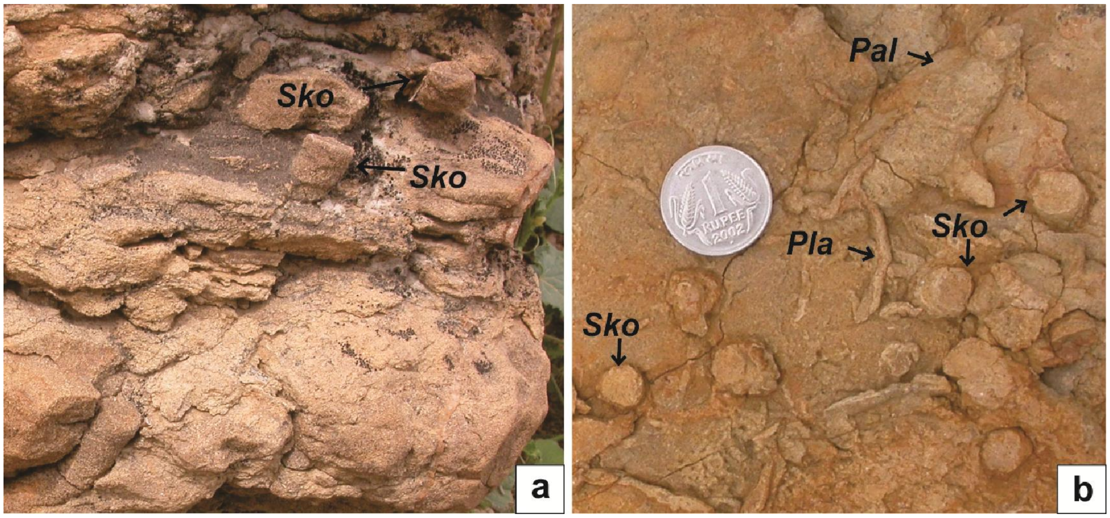


Plate 6.8 Trace fossils of *Skolithos* assemblage: **(a)** monodominant presence of *Skolithos linearis* (*Sko*) in sandy allochem limestone of Kaladongar Sandstone member; and **(b)** association of *Skolithos linearis* (*Sko*), *Palaeophycus (Pal)* and *Planolites beverleyensis* (*Pla*) in micritic sandstone of Dingy Hill member.

The *Monocraterion* and *Skolithos* both are made by similar trace makers but represent different sedimentation rates; the *Skolithos* represents slow sedimentation while the *Monocraterion* represents the rapid sedimentation. The *Skolithos* assemblage represents biogenic structures of suspension as well as the deposit feeders. The most probable maker of the trace fossils are vermiform annelids. This assemblage represents high level of wave or current energy conditions of the tide influenced shoreface-foreshore environment and shoal deposits of the offshore region.

6.3.9 *THALASSINOIDES* ASSEMBLAGE:

Thalassinoides assemblage is either characterized by monodominant *Thalassinoides suevicus* (Plate 6.9a) or an association of *Thalassinoides suevicus*, *T. horizontalis,* and *Thalassinoides* isp., with *Rhizocorallium irregulare, Arenicolites* isp., *Planolites beverleyensis, Rhizocorallium jenense* (Plate 6.9b), *Gyrochorte comosa, Skolithos linearis, Thalassinoides horizontalis, Palaeophycus striatus* and *Diplocraterion parallelum* (Fig. 6.9).

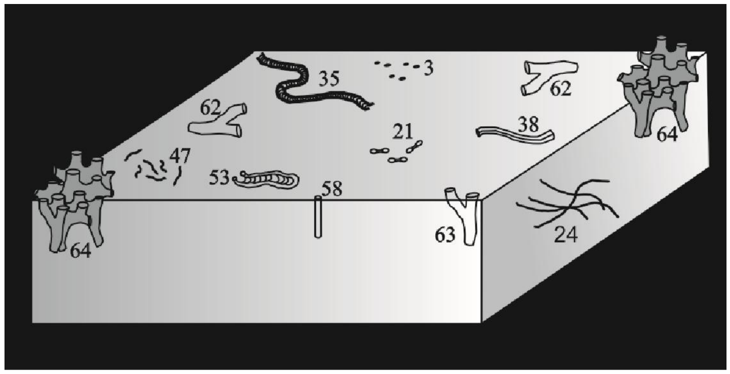


Figure-6.9 Diagrammatic representation of *Thalassinoides* assemblage.

It is observed in sandy allochem limestone of Kuar Bet member; micritic sandstone, allochemic sandstone and sandy allochem limestone of Dingy Hill member; allochemic sandstone and sandy allochem limestone of Babia Cliff Sandstone member; micritic sandstone of Gadaputa Sandstone member; and sandy allochem limestone of Raimalro Limestone member.

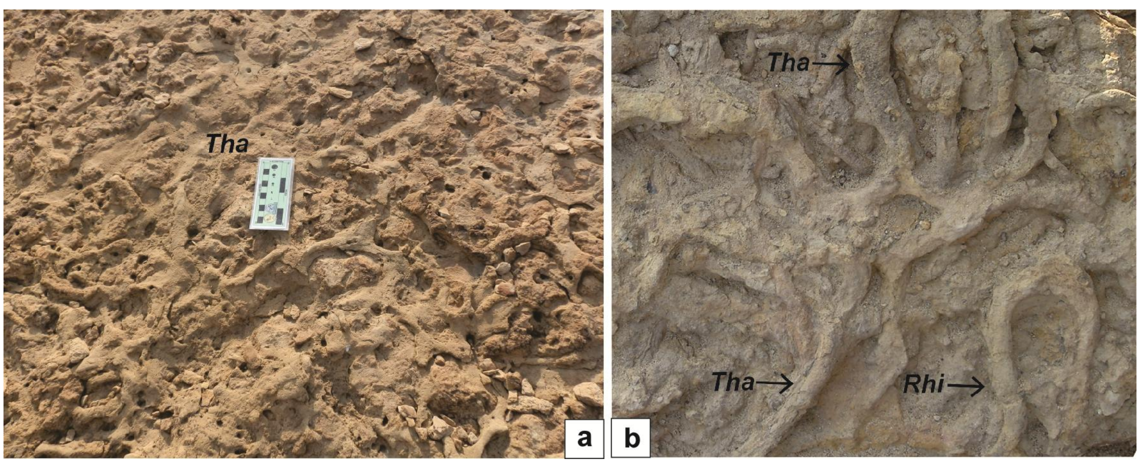


Plate 6.9 Trace fossils of *Thalassinoides* assemblage: **(a)** monodominant presence of *Thalassinoides suevicus* (*Tha*) in sandy allochem limestone of Dingy Hill member exposed at Chhappar bet; and **(b)** *Thalassinoides suevicus* (*Tha*) associated with *Rhizocorallium jenense* (*Rhi*) in micritic sandstone of Dingy Hill member exposed at Kaladongar range.

The *Thalassinoides* are frequently related to the oxygenated situations and soft but fairly cohesive substrates (Bromley and Frey, 1974; Kern and Warme 1974; Ekdale et al 1984; Bromley 1996). This assemblage shows predominance of deposit as well as suspension-feeder crustaceans and polychaetes. The presence of suspension feeder's behavior in the given environmental condition indicates that the opportunistic animals had also exploited similar kind of niches. The dominance of horizontal feeding structures suggest low to moderate energy conditions, unstable, soft, unconsolidated substrate of the shoreface environment and the shoal deposits of the offshore region.

6.4. ICHNOFACIES

An ichnofacies is an association of trace fossils that recurs in time and space, and that directly reflects environmental conditions such as bathymetry, salinity and substrate character (Bromley, 1996). Initially, Seilacher (1967) established six ichnofacies namely, *Skolithos, Cruziana, Zoophycus, Nereites, Glossifungites* and *Scoyenia* ichnofacies, named after characteristic ichnogenera. Further, new ichnofacies were erected and their status in archytypical ichnofacies were considered by Pemberton and MacEachern (1995), namely *Psilonichnus* ichnofacies for sand prone substrate (Frey and Pemberton. 1987), *Trypanites* ichnofacies for hard ground substrste (Frey and Seilacher (1980), *Teredolites* ichnofacies for xylic substrate (Bromley et al. (1984), *Mermia* ichnofacies for lacustrine setting (Buatois and Mángano, 1995) and *Coprinisphaera* for paleosols (Genise et al, 2000). Subsequently, many more ichnofacies were erected by number of workers which were highlighting the environmental implications are to be considered subset of archytypical ichnofacies.

Mesozoic sequence of the Patcham Island mainly comprises of mixed siliciclastic-carbonate sediments; pure limestone bands with intercalated calcareous and argillaceous shales. The Patcham Island sediments depict nine ichnoassemblage which recur throughout the sequence and are indicative of the characteristic environmental conditions. These assemblages are intimately related to shallow marine ichnofacies and typically show development of *Skolithos* and *Cruziana* ichnofacies type conditions. Few ichnoassemblage represents mixed *Skolithos-Cruziana* ichnofacies which are often observed at different stratigraphic levels and development of *Glossifungites* ichnofacies. Moreover, the development of the *Skolithos* ichnofacies type of condition in mixed siliciclastic-carbonate sediments is also somewhat different from the idealized model proposed for the clastic sequence by Seilacher (1967) and, Pemberton and MacEachern (1995).

6.4.1 *SKOLITHOS* ICHNOFACIES:

Skolithos ichnofacies is characterized by most common ichnogenera like *Skolithos* and *Ophiomorpha* along with *Thalassinoides, Arenicolites, Diplocraterion* and *Monocraterion.* These trace fossils are developed in clean, well sorted, loose or shifting substrate, having frequent physical reworking of sediments and abrupt changes in the rates of deposition and erosion. Thus their occurrence strongly reflects the adaptation of the communities to the ongoing high hydrodynamic energy and shifting sands. The *Skolithos* assemblage, *Arenicolites* assemblage and *Ophiomorpha* assemblage represents the *Skolithos* ichnofacies. It is observed in sandy allochem limestone of Kuar Bet member; allochemic sandstone of Dingy Hill member; in quartz arenite and sandy allochem limestone of Kaladongar Sandstone member; micritic sandstone of Babia Cliff Sandstone member; quartz arenite and micritic sandstone of Gadaputa Sandstone member; in sandy allochem limestone of Raimalro Limestone member. This ichnofacies represents the high energy condition of foreshore to shoreface environment.

6.4.2 *CRUZIANA* ICHNOFACIES:

Cruziana ichnofacies which is characterised by most common ichnogenera like *Asterosoma*, *Chondrites, Gordia, Nereites, Scolicia, Palaeophycus, Phoebichnus, Phycodes, Pilichnus, Planolites, Rhizocorallium, Taenidium,* and *Teichichnus*. It is typically developed in the poorly sorted sediments in either moderate energy condition of shallow waters below fair weather wave base and above storm wave base or low energy levels in offshore quieter waters. The *Asterosoma* assemblage, *Gyrochorte* assemblage, *Phycodes* assemblage, *Planolites/Palaeophycus* assemblage, *Rhizocorallium* assemblage and *Thalassinoides* assemblage represents *Cruziana* ichnofacies. These ichnofacies recur in allochemic sandstone, sandy allochem limestone, micritic mudrock of the Dingy Hill Member; sandy allochem limestone and quartz arenite of Kaladongar Sandstone member; micritic sandstone, allochemic sandstone, micritic mudrock, sandy micrite and sandy allochem limestone of Babia Cliff Sandstone member; sandy allochem limestone and allochemic limestone of Goradongar Flagstone member; micritic sandstone, allochemic sandstone, and allochemic limestone of Gadaputa Sandstone member; sandy allochem limestone and allochemic limestone of Raimalro Limestone member; micritic sandstone and allochemic limestone of Modar Hill member. This ichnofacies represents moderate to low energy condition of shoreface to offshore environment.

6.4.3 MIXED *SKOLITHOS-CRUZIANA* ICHNOFACIES:

The facies consisting of the mixed *Skolithos-Cruziana* ichnofacies is characterised by trace fossils like *Skolithos, Monocraterion, Thalassinoides* associated with *Rhizocorallium, Asterosoma, Phycodes, Gyrochorte* etc. It is consisting of ethologically diverse group of trace fossils of vertical and horizontal structures suggesting that structures are independent of taphonomic restrictions rather than the bathymetry. When sedimentation rates are too low, the organic material concentrates near the sediment surface, and organisms preferentially exhibit interface-feeding styles (i.e. modified *Skolithos* behaviour) whereas when the sedimentation rates are too high, the redox boundary encompasses most of the organic matter and resources quickly becomes inaccessible (Zonneveld et al., 2001). Moreover, when the sedimentation rates are ideal, a thin zone of exploitable resources, several centimetres to decimetres in thickness, exists in which horizontal deposit feeders thrives. It is typically developed under stressed conditions such as a storm event or high energy conditions in low energy environmental settings. It is observed in micritic sandstone, allochemic sandstone and sandy allochem limestone of the Dingy Hill member; sandy allochem limestone and sandy micrite of Kaladongar Sandstone member and sandy allochem limestone, micritic sandstone, allochemic sandstone and micritic mudrock of the Babia Cliff Sandstone member; allochemic limestone of Raimalro Limestone member; and micritic sandstone, sandy allochem limestone, allochemic limestone and sandy micrite of Modar Hill member. This mixed *Skolithos-Cruziana* ichnofacies represents the stressful environment having variable substrate consistency and fluctuating energy conditions (Pemberton et al, 2004; Jaquilin et al, 2012a).

6.4.4 *GLOSSIFUNGITES* ICHNOFACIES:

Glossifungites Ichnofacies is characterised by U-shaped polychaete borings *Caulostrepsis taeniola* recording the domiciles of suspension feeders or passive carnivores. It is found in wide range of environments but develops only in firm, unlithified substrates such as dewatered muds or compacted sands (MacEachern et al, 2007).

The reported *Caulostrepsis* are generally kept under the *Trypanites* ichnofacies (e.g., Martinell and Domènech, 1995; Gibert et al, 2007; Santos et al, 2010) but due to the occurrence in the sandy allochem limestone of Raimalro Limestone member; it is kept under the *Glossifungites* ichnofacies. The burial, compaction, dewatering and subsequent erosional exhumation in offshore sediments of Raimalro Limestone member produced the firmground for this ichnofacies. This formational compaction and dewatering is well supported by the presence of the synaeresis cracks (Fig. 4.10, e) reported by Patel et al (2013). However, the scarce occurrence of these bioerosive activities is considered as restricted conditions and the extent wide range of substrate adaptations for *Caulostrepsis* boring.

6.5 ICHNOLOGICAL-SEDIMENTOLOGICAL MODEL

The most fundamental tenets of modern ichnofacies analysis are to integrate all the available evidence and utilize in the interpretation (Pemberton et al, 2012). These collective observations should be placed in the context of proximality trends, where emphasized from a sedimentological viewpoint or an ichnological one. MacEachern et al (1999) discussed the ichnological and sedimentological characteristics of depositional complexes of clastic dominated shoreface environments. The structural and textural assessment of the mixed siliciclastic-carbonate dominated sediments of the Patcham Island with their associated trace fossils indicate a wide range of depositional facies belts including offshore, transitional zone, lower, middle, upper shoreface and foreshore (Fig. 6.10). The ichnoassemblage recur predominating or subordinating with other trace fossil assemblage throughout the sequence. Based on the dominant structures depositional processes and the facies, the behaviour of the trace fossils vary throughout the sequence ranging from minor to dominant (Fig. 6.10). Each of these behaviors shows a dominant to minor range of ichnoassemblage recurring throughout the sequence and further representing the particular ichnofacies range in the Patcham Island.

The sedimentological and ichnological entities represent depositional regime ranging from foreshore to offshore region. Certain ichnoassemblages are association vertical traces which are of *Skolithos* ichnofacies but yet are represented in the low energy deposits, for e.g., in offshore regions. These ichnoassemblages belong to the mixed *Skolithos-Cruziana* ichnofacies as mentioned earlier in Section 6.4.3. This sudden occurrence may be due to the stressed environment but may be also attributed to some geomorphic entities in particular environment. For e.g., a shoal deposit in the offshore region may show offshore deposits at the base but as the shoal grows in height the surface are frequently encountered by the tides and waves which may show deposits or trace fossils particularly of shoreface region (Fig. 6.11). Thus the lateral and vertical continuity helped us to recognise such deposits in the Patcham Island broadening our knowledge about the trace fossils and their relationship with the structures and facies.

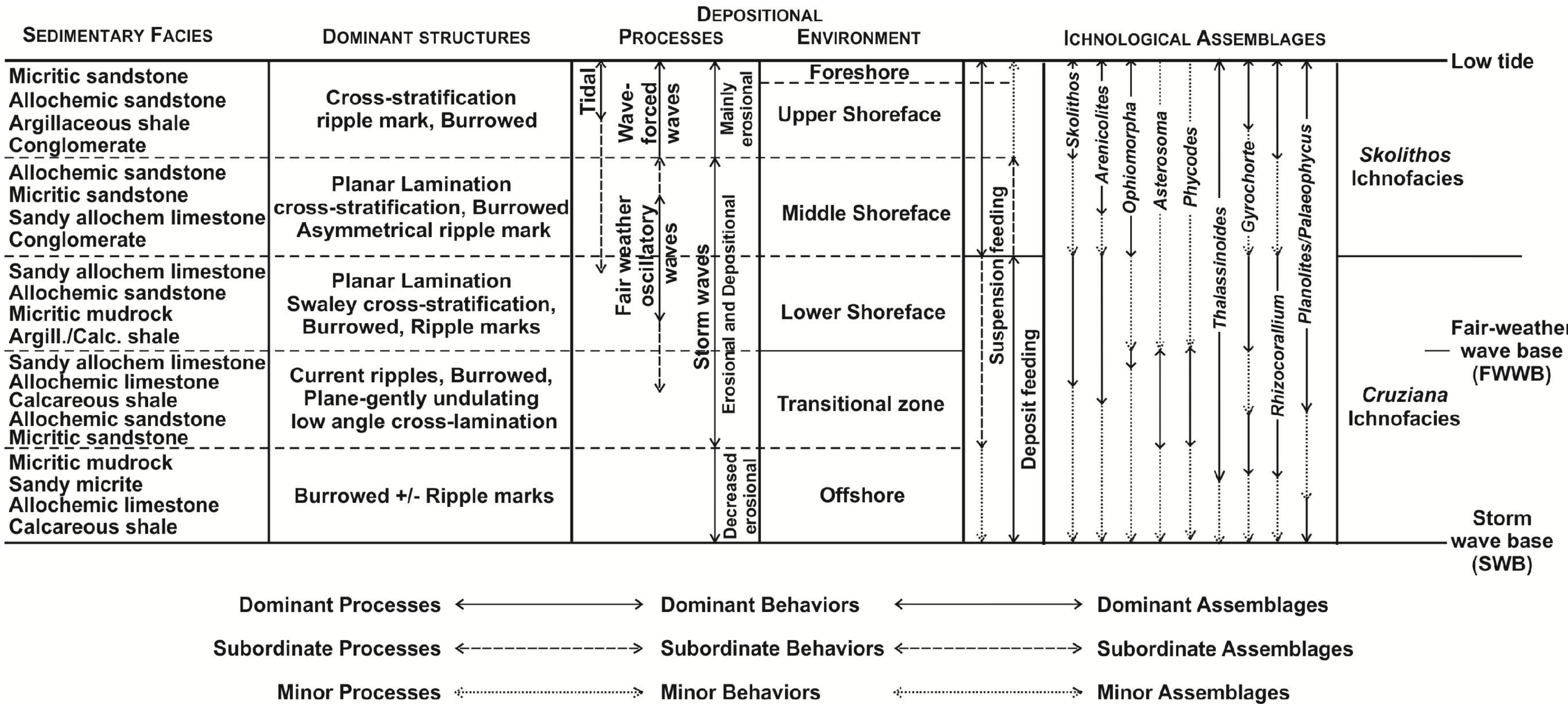


Figure-6.10 An ichnological-sedimentological model for mixed siliciclastic-carbonate sediments dominated shoreface deposits of the Middle Jurassic (Bajocian-Callovian), Patcham Island (modified after MacEachern et al, 1999).

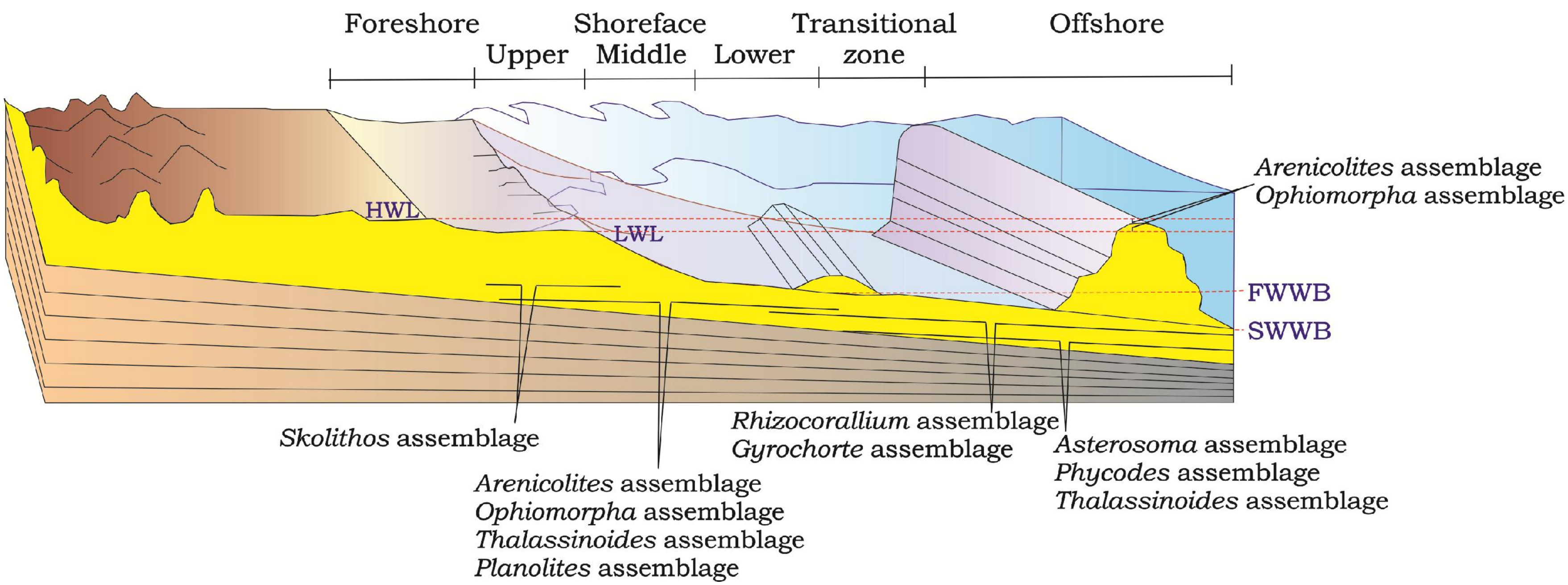


Figure-6.11 Schematic illustration represents nature of ichnoassemblages of the shallow marine depositional regime, Middle Jurassic of Patcham Island.

CHAPTER-7
SEQUENCE STRATIGRAPHIC ANALYSIS: TRANSGRESSIVE-REGRESSIVE SEQUENCES

7.1 BACKGROUND

Sequence stratigraphy addresses the strata stacking patterns and changes thereof in a chronological framework and lay stress on cyclicity, temporal framework, genetically related strata and the interplay of accommodation and sedimentation (Catuneanu et al, 2009). The stratal stacking patterns respond to the interplay of changes in rates of sedimentation and base level, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation and downcutting. From the environmental perspective, each stratal stacking pattern defines a particular genetic type of deposit which may include tracts of several age-equivalent depositional systems.

7.1.1 SEQUENCES:

Sloss et al (1949) defined the concept of "sequence" in the context of stratigraphy as a large-scale unconformity-bounded unit and later on redefined by Mitchum (1977) in the context of the seismic stratigraphy as "a relatively conformable succession of the genetically related strata bounded by unconformities or their correlative conformities". In other words, the "stratigraphic sequence" represents the product of sedimentation during a full stratigraphic cycle of change in accommodation or sediment supply, irrespective of whether all parts of the cycle are formed or preserved and the sequence boundaries may be unconformable or conformable portion of the bounding surface. As a result, the stratigraphic sequence, commonly known as the depositional sequences, have a predictable internal structure of surfaces and systems tracts (suites of coexisting depositional systems, such as coastal plains, continental shelves, and submarine fans).

There are several models of systems tracts within depositional sequences for example, the four system tract model, wherein all the depositional sequences contain the following systems tract in the order: Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), Highstand Systems Tract (HST), and falling-stage systems tract (Regressive System

Tract- RST). Here, a sequence accordingly, begins with the slow rise following a fall in sea level, and continues through the next fall in sea level. These system tracts are bounded by important named surfaces: the lowstand and transgressive system tracts are separated by the transgressive surface; the transgressive and highstand system tracts are separated by the maximum flooding surface; and the highstand and falling-stage systems tract are separated by the basal surface of forced regression.

Therefore, a sequence may be subdivided into component system tracts (Brown and Fischer, 1977) which consist of packages of strata that correspond to the specific genetic type of deposits and interpreted based on the stratal stacking pattern in the position of the sequence and type of the bounding surfaces. The sequence boundary of a sequence depends on the scale of sequence, depositional setting, and the mechanisms driving stratigraphic cyclicity.

7.1.2 PARASEQUENCES:

"Parasequences" is defined as "a stratigraphic unit composed of a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative conformities" (Mitchum, 1977) and is geographically restricted to the coastal to shallow water settings, where marine flooding surfaces may form (Catuneanu et al, 2010). Parasequences may be stacked to form progradational, aggradational and retrogradational parasequence sets, which typify the systems tracts (Van Wagoner et al., 1990). The mapability of the parasequences depends on the development of their bounding surface and it marks a difference between the concept of sequence within the coastal and shallow water systems (Catuneanu et al, 2009).

The flooding surfaces that define the top and bottom of the parasequence display abrupt contacts of relatively deeper-water facies lying directly on top of relatively shallow-water facies. Therefore, the Walther's Law cannot be applied across the flooding surfaces. Moreover, the limited usage of the parasequence term, by authors, to shallow-marine cycles developed without intervening relative sea-level falls, while others extending the term to successions recording full cycles of relative sea level change or even in deep-water and alluvial settings, has increased confusion in its meaning.

Parasequences and sequences are also considered to be objects of the same rank that differs only in their bounding surfaces and internal architectures and which may also pass laterally each other (Nummedal et al, 1993; Zecchin, 2010). Thus, instead of a term like "parasequence" which is tied to a specific architecture and depositional environment, a generic and descriptive terminology is used by several authors (Walker, 1992; Zecchin, 2007). The present study follows the concept of "facies" are used instead of "parasequence"

7.1.3 STACKING PATTERNS:

The method of sequence stratigraphy emphasizes changes in depositional trends (i.e., progradation, retrogradation, aggradation, erosion) and the resulting stratal stacking patterns through time, which are controlled by shifts in the balance between accommodation (space available for sediments to fill) and sediment supply (Weimer and Posamentier, 1993; Emery and Myers, 1996; Posamentier and Allen, 1999; Catuneanu, 2002, 2006; Catuneanu et al., 2009; Martins-Neto and Catuneanu, 2010). This balance between the accommodation space and the sediment supply controls the manifestation of transgressions and regressions. In vertical stacking patterns, progradation implies a facies succession where proximal facies gradually replaces the distal facies with time and generates a coarsening upward succession in a shallow water setting. Retrogradation displays the proximal facies at the base that grade upwards to the distal facies at the top and generates a fining upward trend in a shallow water setting (Fig. 7.1).

7.1.4 GENETIC TYPES OF DEPOSITS: SYSTEMS TRACTS:

A sequence may be subdivided into component systems tracts, which consist of packages of strata that correspond to specific genetic types of deposits ("Forced regression", "Normal Regressive" and "Transgressive") with a distinct geometry and facies preservation style (Catuneanu et al., 2009). The original definition of systems tract as stated by Brown and Fisher (1977) is "Systems tract is a linkage of contemporaneous depositional systems, forming the subdivision of as sequence". It is interpreted based on the stratal stacking patterns, its position within the sequence, and the types of bounding surfaces. The changes in stratal stacking patterns are driven by corresponding changes in shoreline trajectory that then defines the "conventional" systems tracts.

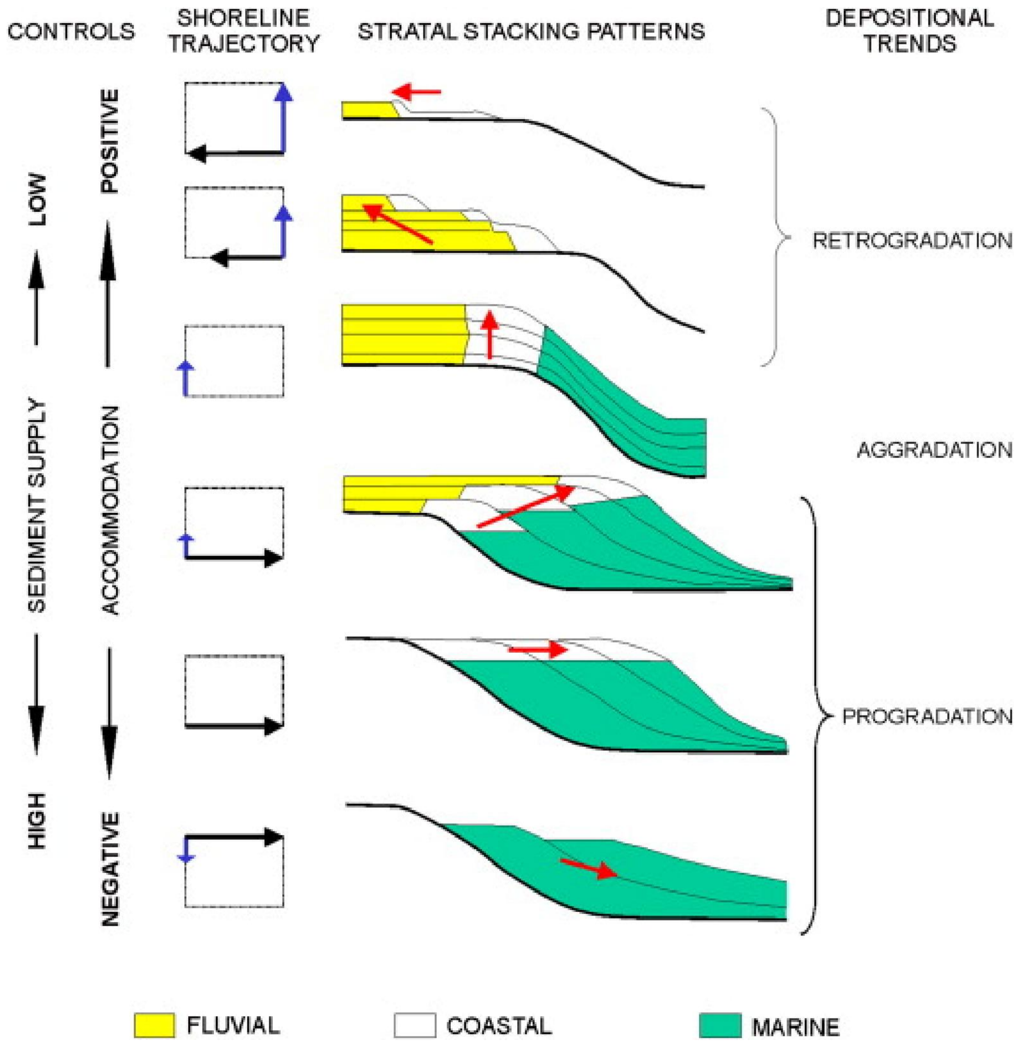


Figure-7.1 Responses of the depositional trends to the interplay of accommodation and the sediment supply (Martins-Neto and Catuneanu, 2010).

The systems that prograde with time and record a basinward decrease in the elevation of the coastline are the product of the base level fall and represent the "forced regression" deposits. It displays progradational and downstepping stacking patterns. The systems tract nomenclatures applicable to these deposits are "early low stand", "late highstand", "forced-regressive wedge" and "falling stage".

The systems that prograde with time during stages of base level rise or stillstand are the "normal regressive" deposits. In a normal scenario, two normal regressions may be expected during a full cycle of base level change: a lowstand normal regression that follows that onset of base level rise after a period of base level fall and a highstand normal regression

Stratigraphic surfaces	**Definition**	**Alternative terms**	**Origin**	**Timing**
Subaerial unconformity (Sloss et al, 1949)	Unconformity that forms under subaerial conditions, mainly as a result of fluvial or wind degradation	*Lowstand unconformity* (Schlager, 1992); *Regressive surface of fluvial erosion* (Plint & Nummedal, 2000); *Fluvial entrenchment /incision surface* (Galloway, 2004)	Fluvial erosion or bypass, pedogenesis, wind degradation, dissolution or karstification	During base level fall; during periods of transgression accompanied by coastal erosion; during periods of climate driven increased fluvial discharge, or tectonic driven isostatic rebound and increased topographic gradients
Correlative conformity (Posamentier et al, 1988)	Surface that marks a change in shoreline trajectory from highstand normal regression to forced regression	*Basal surface of forced regression* (Hunt & Tucker, 1992)	Paleoseafloor at the onset of base level fall at the shoreline	Onset of forced regression
Correlative conformity (Hunt & Tucker, 1992)	Surface that marks a change in shoreline trajectory from forced regression to lowstand normal regression.	-	Paleoseafloor at the end of the base level fall at the shoreline	End of forced regression
Maximum flooding surface (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989)	Surface that marks a change in shoreline trajectory from transgression to highstand normal regression.	*Final transgressive surface* (Nummedal et al, 1993); S*urface of maximum transgression (*Helland-Hansen & Gjelberg 1994); *Maximum transgressive surface* (Helland-Hansen & Martinsen 1996)	Change in depositional trends (coastal retrogradation to progradation) during base level rise	End of transgression
Maximum regressive surface (Helland-Hansen & Martinsen, 1996)	Surface that marks a change in shoreline trajectory from lowstand normal regression to transgression.	*Transgressive surface (*Posamentier and Vail, 1988); *Top of lowstand surface* (Vail et al, 1991); *Initial transgressive surface* (Nummedal et al, 1993); *Conformable transgressive surface* (Embry, 1995); S*urface of maximum Regression* (Helland-Hansen & Gjelberg, 1994; Mellere and Steel, 1995) & *maximum. progradation surface* (Emery & Myers, 1996)	Change in depostional trends (coastal progradation to retrogradation) during base level rise	End of regression
Transgressive ravinement surface (Galloway, 2001)	Erosional surface that forms during transgression in wave- or tide-dominated settings.	*Transgressive surface of erosion* (Posamentier and Vail, 1988)	Wave or tidal-current scouring in the coastal to upper shoreface settings.	During transgression.
Regressive surface of marine erosion (Plint, 1988)	Subaqueous erosional surface that forms during base level fall in wave dominated settings	*Regressive ravinement surface* (Galloway, 2001) & *regressive wave ravinement* (Galloway, 2004)	Wave scouring in the lower shoreface to inner shelf settings	During forced regression

Table-7.1 Definition, origin, and timing of sequence stratigraphic surfaces.

during the late stage of base level rise. These normal regression deposits display a combination of progradational and aggradational depositional trends. The systems tract nomeclatures applicabale to lowstand normal regressive deposits are “late lowstand” and “lowstand” while to highstand normal regressive deposits are “highstand” or “early highstand” systems tract.

The landward shift or marine or lacustrine systems, triggered by a rise in base-level at rates higher than the rates of sedimentations at the shoreline is termed as the “transgressive” deposits. It is thus driven by the base level rise and includes characteristic retrogradational geometries. These deposits belong to the transgressive systems tract. All the systems tracts are not necessarily found in each sequence, either because of the shape of the base-level curve did not allow one or more systems tracts to form, or because subsequent erosion. Similarly, not all the sequences need to be divided into “conventional” systems tracts defined above.

7.1.5 SEQUENCE STRATIGRAPHIC SURFACES:

Sequence stratigraphic surfaces are the surfaces that can serve, at least, in part, as boundaries between different genetic types of deposit (Catuneanu et al, 2009). There are seven sequence stratigraphic surfaces; namely, subaerial unconformity, correlative conformity (in the sense of Posamentier et al, 1988), correlative conformity (in the sense of Hunt and Tucker, 1992), maximum flooding surface, maximum regressive surface, transgressive ravinement surface, and regressive surface of marine erosion (Table.1); among which four corresponds to event of the base level cycle and three others form during stages between such events.

The criteria that can be used to identify each sequence stratigraphic surface include: the conformable versus unconformable nature of the contact, the depositional systems below and above the contact, the depositional trends below and above the contact, the types of substrate-controlled ichnofacies associated with the contact, and stratal terminations associated with the contact (Catuneanu et al., 2009). All the type of data does not contain the recognition of all sequence stratigraphic surfaces, and not all the sequence stratigraphic surfaces are present in every depositional setting.

7.1.6 SEQUENCE BOUNDARY:

Across the existing sequence stratigraphic models, the sequence stratigraphic surfaces may be considered a sequence boundary, as systems tract boundary, or even a within-systems tract contact. A generic definition of a sequence that satisfies all approaches, while leaving the selection of sequence boundaries to the discretion of the individual, provide the flexibility that allows one to adapt to the particularities of each case study (Catuneanu et al., 2009). Accordingly, the stratigraphic patterns have to be analysed on a case-by-case basis to decide which set of surfaces represented in that particular succession can provide the best boundaries for correlating and mapping "relatively conformable successions of genetically related strata."

In the case of drowning, the contact between carbonates and the overlying fine-grained hemipelagic facies has been termed the "drowning unconformity" (Schlager, 1989), and has been designated as a special type of sequence boundary in mixed carbonate-siliciclastic successions (Schlager, 1999). The selection of stratigraphic surfaces considered by the "depositional," "genetic stratigraphic" and "transgressive-regressive" sequence models for the nonmarine and marine portions of the sequence boundary is listed with its merits and pitfalls in Table.2.

7.2. SEQUENCE STRATIGRAPHIC ANALYSIS OF PATCHAM ISLAND

The elevation of the stratigraphic surface to sequence boundary is attempted for the relatively conformable succession of the Patcham Island, and hence, a model dependent workflow is considered for sequence stratigraphic analysis (Catuneanu et al, 2009). The exposed sequence of the Kaladongar and Goradongar Formation is represented into four parts: (1) composite litholog of Kuar bet, (2) Dingy Hill, (3) Chappar Bet and (4) composite litholog comprising the Kuran, Babia Cliff, Raimalro and Sadhara Hill; and Dhorawar, Paiya, Tuga, and Juna villages; which are further detailed and analysed below to interpret the rock records.

Transgressive-regressive (T-R) sequences, proposed by Embry and Johannessen (1992) and Catuneanu et al (2009) are used to define the sequential filling of this part of the

SEQUENCE	SEQUENCE BOUNDARY	PITFALLS	MERITS
Depositional Sequence	Subaerial Unconformities	1. Its potentially cryptic expression when represented by paleosols; 2. It, fully or portions thereof, may be eroded during subsequent transgression; and 3. The dependency on base-level falls to define sequences.	1. Subaerial unconfomities commonly mark significant hiatuses in the stratigraphic record. 2. Recognizes the importance of separating forced regressive, normal regressive and transgressive deposits as distinct genetic units.
Genetic Stratigraphic Sequence	Maximum Flooding Surfaces	1. Inclusion within the individual sequence where subaerial unconformities are present, leads to the placement of genetically unrelated strata (from below and above the subaerial unconformity) within the same "sequence." 2. The timing of formation of maximum flooding surfaces depends on sedimentation, and hence they may be more diachronous, especially along strike.	1. Maximum flooding surfaces are among the easiest distinguishable sequence stratigraphic surfaces in all marine depositional systems, and with any type of data set. 2. The definition of this stratigraphic sequences is independent of subaerial unconformities, and, implicitly, of base-level fall. 3. This model can be applied to all types of cycles, including those that develop during continuous base-level rise
Transgressive-regressive sequence	Composite sequence boundary which includes the subaerial unconformity and the marine portion of the maximum regressive surface	1. Maximum regressive surfaces may be cryptic in deep-water systems, where they may occur within an undifferentiated succession of leveed channel low-density turbidites 2. The formation of maximum regressive surfaces depends on sedimentation, and hence they may be highly diachronous along strike 3. The fluvial and marine segments of the sequence boundary are of different ages, and so they may only connect physically where the intervening lowstand normal regressive deposits are missing and 4. All "normal" and "forced" regressive deposits are included within one "regressive systems tract," which may be considered an over-generalization	1. This model emphasizes the importance of subaerial unconformities and 2. The ease of recognition of maximum regressive surfaces in shallow-water systems.

Table-7.2 Selections of stratigraphic surfaces considered by different stratigraphic models for non-marine and marine portions of sequence boundaries with it merits and pitfalls.

Kachchh basin. The T-R sequence stratigraphy subdivides the stratigraphic successions into the transgressive-regressive couplets with the top of the regressive systems tracts as the sequence boundary (Embry and Johannessen, 1992; Embry 1993; Catuneanu 2006; Catuneanu et al., 2009). This concept suggests the fact that the frequently corresponding intervals of increasing and decreasing influence from land in deep water deposits correspondto subdivide the shallow water deposits into shoaling and deepening intervals. A hierarchy of cycles has been proposed for T-R sequences by Embry (1993) and Catuneanu (2006). The range of base-level fall and the degree of change in sedimentary regime at the R/T sequence boundaries as well as the degree of deformation that occurred during the formation of the boundary distinguishes the sequence ranks. This hierarchy does not change the internal architecture of the T-R sequences. Accordingly, this principle holds for a wide range of scales in time and space; and could serve as the basis of a scale invariant model of stratigraphic sequences (Schlager, 2010).

These middle Jurassic sediments, ranging in age from Bajocian to Callovian, can be explained in terms of one large scale transgressive sequence (+ 462 m)., composed of four mid-scale or T-R sequences (mean thickness 115 m), with several small scale cycles or T-R cycles (average thickness: 33m). The portion of the Middle Jurassic sediments present in the Kaladongar and Goradongar Formations represents Bajocian to Callovian age (Fürsich et al., 2001) which suggests a time interval as an average of 6.9 My and therefore suggest that the large scale sequence is a 2nd order sequence and the mid-scale sequences are of 3rd order sequences (mean duration of 1.1 My). The T-R cycles fall within the ranges of 4th order units, with an average duration of ~0.5 My. Each cycle comprises of two parts; 1.Transgressive system tract (TST), characterized by low terrigenous influx and high carbonate productivity that marked an increase in the accommodation space and 2. Regressive system tract (RST) characterized by high terrigenous influx and low-carbonate productivity marked decrease in the accommodation space; separated by the flooding surfaces. The material based stratigraphic surfaces identified in the sequence are regressive surface (RS), flooding surface (FS), and drowning unconformity (DU).

7.2.1 TRANSGRESSIVE-REGRESSIVE SEQUENCES OF KUAR BET SECTION:

The composite litholog of Kuar bet represents total thickness of the Mesozoic rocks in the column is +248 m: the lower +41.80 m fining (thinning) upward succession, the middle

179.9 m siliciclastic dominant coarsening (thickening) upward sequence and the upper 26.40 m carbonate dominant fining (thinning) upward succession in foreshore to shoreface environment. The sequence represents three regressive surface (RS), two flooding surface (FS), and one transgressive lag deposits (TLD) (Fig. 2).

An asymmetric cycle of deepening-shallowing phase is apparently observed from the arrangement of the facies. The deepening phase is represented by comparatively little sediment compared to the sediments recording the shallowing phase. Thus, the sedimentary cycle represents major Transgressive system tract (TST) and Regressive system tract (RST) deposits. Each system tract is described below with the stratigraphic surfaces and is coupled with facies analysis to interpret the depositional trends.

7.2.1.1 4th Order Transgressive-Regressive Cycles (TRC)

This transgressive-regressive cycle constitutes the fundamental units of the Kuar bet member of the Kaladongar Formation. They show a significant variation in thickness and mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern. These help in identifying the fundamental T-R sequences. Each cycle is bounded by flooding surfaces indicated by vertical and abrupt facies variations.

7.2.1.2 3rd Order Transgressive-Regressive Sequence (TRS)

Two T-R cycles have been identified in the 3rd order of hierarchy of the sequence with a mean thickness of about 96 m. Each of these cycles of the sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.

7.2.1.2.1 Transgressive-regressive cycle (TRC) - I

The lower +41.80 m fining (thinning) upward succession and the middle ~179.9 m coarsening upward succession of Kuar Bet represents the Transgressive-Regressive cycle (TRC)- I. The TRC- I show presence of stratigraphic surfaces such as *Flooding surface* (FS), *Transgressive lag deposit* (TLD) and *Regressive surfaces* (RS). In the Transgressive-Regressive Cycle-I of the Kuar Bet sequence, the flooding surface is observed in the allochemic sandstone overlying the shale facies. It shows non bioturbation in the underlying strata and increasing bioturbation in the overlying strata. Transgressive lag usually record the time intervals and are thin, relatively coarse grained beds that contain pebbles, shell fragments, intraclasts and bivalve shells, suggesting the storm influenced deposition above fair weather wave base. Quartz pebble conglomerate is interpreted as a transgressive lag deposit; all the finer material winnowed away leaving only the coarsest and most resistant grains to form the bedforms. The conglomerate consisting of bivalves and fossil wood overlying the sandy allochem limestone represents the transgressive lag deposits in the Kuar Bet member exposed at Kuar Bet. The regressive surface is observed at the quartz arenite and mark the top of the Regressive System Tract – I

7.2.1.2.1.1 Transgressive System Tract (TST) - I

This system tract is dominated by 41.80 m thick sequence of mixed siliciclastic-carbonate and shale facies. These mixed siliciclastic-carbonate deposits are characterized by upward increase in the carbonate content. Body fossils such as bivalves, corals and fossil wood are observed. It also consists of trace fossils such as *Arenicolites, Diplocraterion*, *Palaeophycus, Rhizocorallium* and *Thalassinoides* are present in this system tract. Accordingly, the shales facies consisting of gypsum suggest that the sediments were deposited in quiet water, protected, lagoon environment, with low wave and current energy, sudden appearance of massive limestone bed over the shale may be indicative of precipitation of calcareous materials in normal marine environment.

The overlying graded sandstone showing ripple marks, sharp erosional base associated with the flute cast, and trace fossils *Diplocraterion* and *Rhizocorallium* underlain by the cross bedded sandstone suggest a high energy condition or may be post-storm event indicator. The trace fossil content in the TST-I represents *Rhizocorallium* assemblage representing the mixed *Skolithos*-*Cruziana* ichnofacies which suggest a stressed environmental conditions. The presence of conglomerate facies embedded with the fossil wood and the concavo-convexo bivalve fossils also indicate some high energy event that reworked the fossils and redeposited in the basin. This set of facies association is thus indicative of being formed during the late transgression or the early sea level regression (Fürsich and Pandey, 2003).

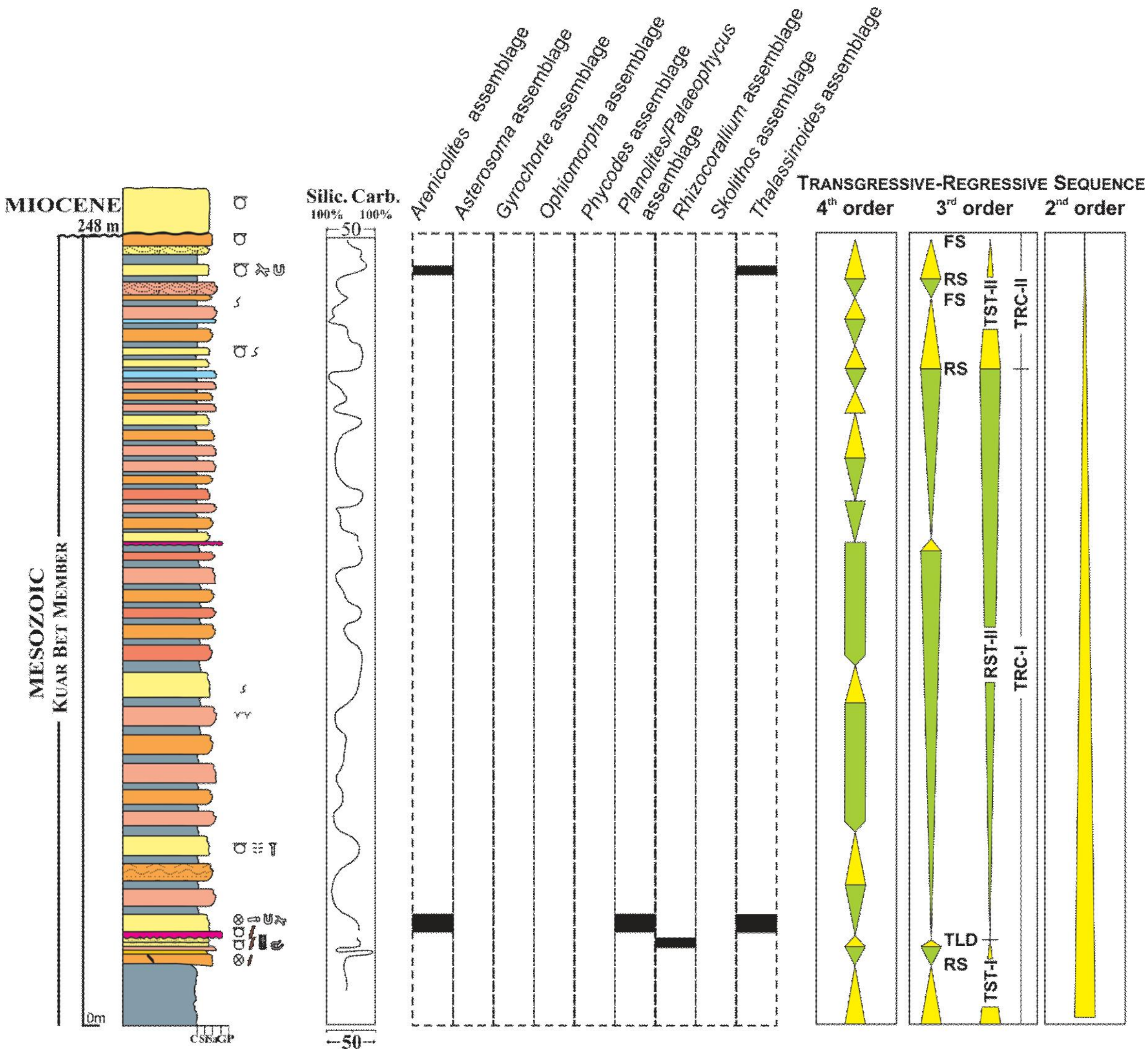


Figure-7.2 Composite litholog showing siliciclastic-carbonate curve, ichnoassemblages and sequences of 4^{th}, 3^{rd}, and 2^{nd} order Transgressive-regressive cycles in Kuar Bet.

7.2.1.2.1.2 Regressive System Tract (RST) - I

This system tract is dominated by ~179.9 m thick sequence of intercalated mixed siliciclastic-carbonate sediments and shale facies. Body fossils contain disarticulated and broken fragments of bivalves. The trace fossils present are *Arenicolites, Monocraterion, Palaeophycus, Planolites,* and *Thalassinoides.* The lower part of this regressive phase of the cycle represents moderate to low bioturbation, and shows thick shale intercalated with the mixed siliciclastic-carbonate sediments and presence of ripple marks while the upper part of the phase represents massive sediments showing thin shale facies intercalated with the mixed siliciclastic-carbonate sediments.

The upper part of the sequence shows lack of the sedimentary structures and presence of some lenses of conglomerate. The start of the Regressive System Tract (RST) shows presence of *Arenicolites*, *Planolites* and *Thalassinoides* assemblages representing the *Skolithos* ichnofacies which indicate the high energy conditions in the soft substrate condition. The analysis of the facies association and the trace fossil content represent the coarsening upward succession showing the progradational and aggradational trend of deposition suggesting the deposition during the regressive phase of sea level.

7.2.1.2.2 Transgressive-regressive cycle (TRC) – II

Transgressive-Regressive Cycle-II comprises of ~26.40 m thick intercalated sequence of mixed siliciclastic-carbonate and shale facies. This T-R cycle represents shallowing and deepening phase of the sequence and shows presence of one *Regressive surface* (RS) and two flooding surfaces (FS). The top of the cross bedded micritic sandstone represents minor regression within the transgressive system tract-II. The flooding surfaces are observed in the allochemic sandstone within the transgressive phase and in sandy allochem limestone at the top of the sequence. These flooding surfaces are developed on a high energy transgressive surface within the Transgressive system tract (TST) – II. The regressive deposits of Regressive System Tract (RST) – I is not observed in the Kuar Bet sequence either due to the erosion or may be concealed below the overlying Miocene beds (Fig. 2a).

7.2.1.2.2.1 Transgressive System Tract (TST) - II

This system tract is 26.40 m thick sequence of mixed siliciclastic-carbonate sediments intercalated with the shale facies. The TST-II is characterized by upward increase in carbonate content and is fossiliferous and bioturbated in nature. The sandy allochem limestone represents a relatively quiet marine condition of the later stage of transgressive highstand and possibly the minor regressive phases of the sea level cycle. It is overlain by the intercalated fossiliferous cross bedded mixed siliciclastic carbonate sediments and shale facies representing the minor regression in a tidally influenced environment.

The association of the bioturbated, fossiliferous thin sandy allochem limestone intercalated with the shale represents a low energy marine environment deposited with low supply of sediments or low accommodation space. This transgressive system tract shows presence of *Arenicolites* and *Thalassinoides* assemblages representing the *Skolithos* ichnofacies which is indicative of the high energy conditions within the transgressive phase. Thus, these sediments mark the minor regression in the early TST while the fossiliferous, bioturbated unit at the top represent the dominant retrogradational deposit of the TST-II.

7.2.2 TRANSGRESSIVE-REGRESSIVE SEQUENCES OF CHHAPPAR BET SECTION:

The sequence exposed at the Chhappar Bet comprises ~120 m thick mixed siliciclastic-carbonate sediments intercalated with shale facies. The sequence represents two transgressive-regressive cycles (TRC) - I and II. It represents the lower +66.3 m thick coarsening upward sequence, the middle ~37.8 m thick fining upward sequence and the upper ~15.5 m thick coarsening upward sequence in the shoreface region. The sequence represents two major regressive surfaces and one flooding surface; and the sedimentary cycle represents two major Regressive system tract and one Transgressive system tract.

7.2.2.1 4th Order Transgressive-Regressive Cycles (TRC)

The sediments exposed at Chhappar Bet represent transgressive-regressive cycle which constitutes the fundamental units of the Dingy Hill member of the Kaladongar Formation. They show a significant variation in thickness with a mean thickness of 14 m. These TRC mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern; bounded by flooding surfaces which further helped in identifying the fundamental T-R sequences.

7.2.2.2 3rd Order Transgressive-Regressive Sequence (TRS)

Two TR cycles have been identified in the 3rd order of hierarchy of T-R sequence with a mean thickness of about 52 m. Each cycle of this sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.

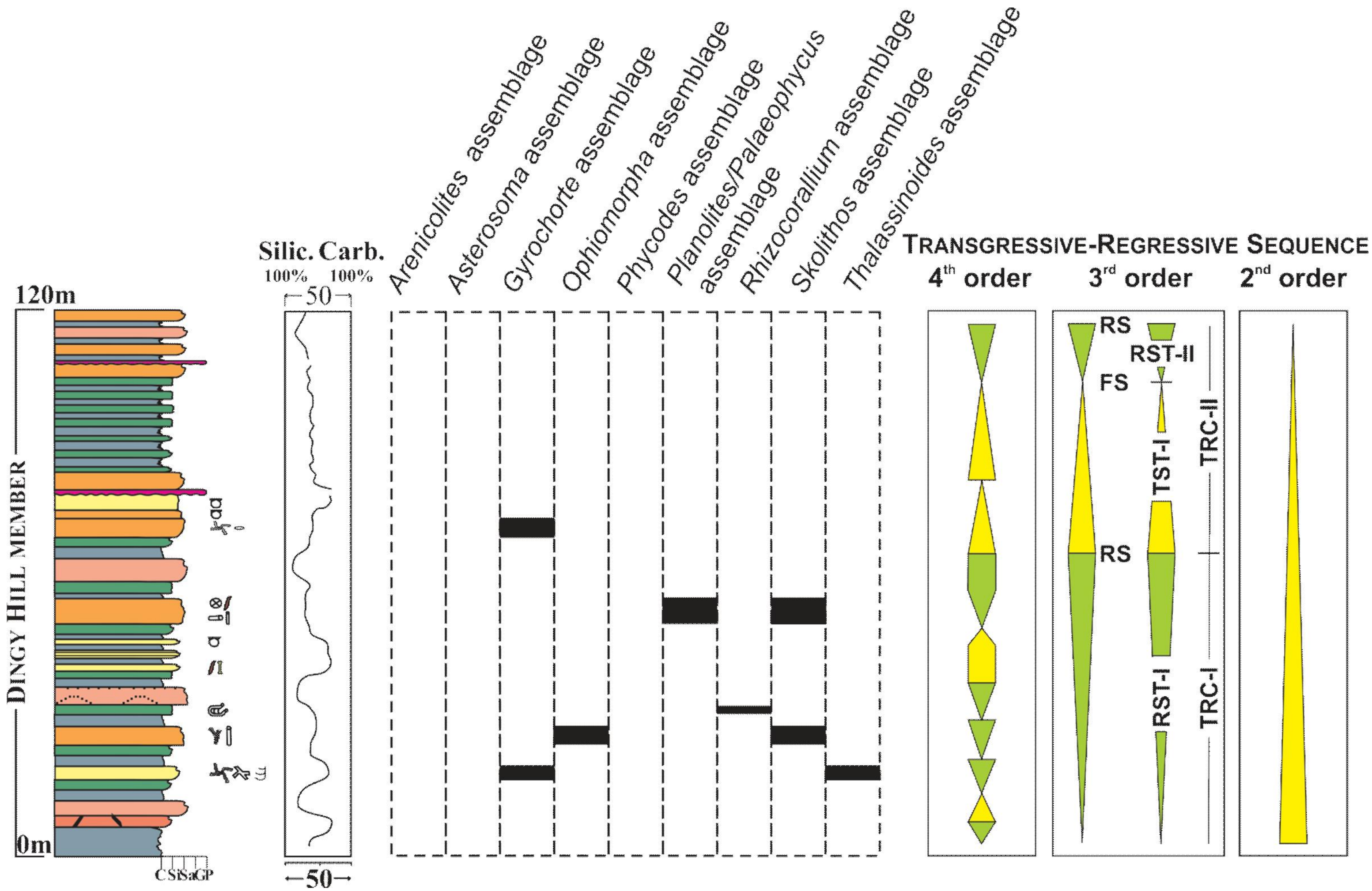


Figure-7.3 Litholog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Dingy Hill member of Chhappar Bet.

7.2.2.2.1 Transgressive-regressive cycle (TRC) - I

The transgressive-regressive cycle – I represents ~66.28 m thick sequence of mixed siliciclastic-carbonate sediments intercalated with the shale facies. This cycle represents shallowing phase and consist of Regressive system tract (RST) – I. The Transgressive system tract (TST) – I of the 3rd order is not exposed in the study area.

7.2.2.2.1.1 Regressive System Tract (RST) – I

The regressive system tract – I represents ~66.28 m thick deposits of intercalation of allochemic sandstone, micritic sandstone and sandy allochem limestone with micritic mudrock and shale facies; and sandy micrite occasionally. The regressive system tract is separated from the transgressive system tract by the regressive surface present above the micritic sandstone. The admixture sediments of carbonate and siliciclastics alternating with the shale facies generate a fluctuating siliciclastic-carbonate curve during the regressive phase.

The trace fossil assemblage represents the presence of *Thalassinoides* and *Gyrochorte* assemblage representing a mixed *Skolithos*-*Cruziana* ichnofacies which grade into the *Ophiomorpha* and *Skolithos* assemblage representing the *Skolithos* ichnofacies which then grade into *Planolites-Palaeophycus* assemblage representing *Cruziana* ichnofacies at the top. Overall trace fossil analysis of these sediments suggest that the *Skolithos* ichnofacies were dominant conditions during this phase with some intermittent *Cruziana* ichnofacies and mixed *Skolithos*-*Cruziana* ichnofacies indicative of change in energy conditions, substrate and bathymetry.

7.2.2.2.2 Transgressive-regressive cycle (TRC) – II

The Transgressive-Regressive cycle – II represents ~ 53.3 m thick deposits of intercalated mixed siliciclastic-carbonate and shale facies. This T-R cycle represents the second cycle of the Transgressive-Regressive sequence of the Chhappar bet and shows the transgressive and regressive phase of the cycle i.e., Transgressive System Tract (TST)-II and Regressive System Tract (RST) - II respectively.

7.2.2.2.2.1 Transgressive System Tract (TST) – II

The Transgressive System Tract-II represents ~37.8 m thick deepening upward sequence. The lower part of this system tract is represented by the retrogradational deposits of shale and miciritic mudrock intercalated with micritic sandstone grading into allochemic sandstone. The siliciclastic proportions decreases and the non-bioturbated sequence grade to presence of *Gyrochorte* assemblage which represents the *Cruziana* ichnofacies suggesting a moderate to low energy conditions of the shoreface. These deposits then aggrade but becomes fossiliferous in nature which further grade into the sandy allochem limestone overlain by the conglomerate facies indicating a depositional hiatus (i.e. a period of non-deposition).

These facies association represented a phase of retrogradational and aggradation representing the transgression phase within the Transgressive system tract-II. The next phase of deposition started with the allochemic sandstone which graded into the succession of intercalated micritic mudrock and shale facies. The presence of micritic mudrock and shale facies suggests very low energy conditions. The top of these facies association represents the Flooding Surface (FS) separating TST-II from the RST-II of the T-R sequence.

7.2.2.2.2.2 Regressive System Tract (RST) – II

The Regressive System Tract- II represents ~ 15.5 m thick deposits of intercalated allochemic sandstone-shale grading to micritic-sandstone shale facies. These facies association represents the progradational and aggradational depositional trend defining the Regressive system tract of this T-R Cycle. These facies association do not show presence of any biological or biogenic evidences. The shale facies above the micritic sandstone facies indicate the end of the regressive which may be continuing further with this pause (cannot be judged because of the absence of the overlying sediments). This is termed as the Regressive Surface (RS) of this system tract.

7.2.3 TRANSGRESSIVE-REGRESSIVE SEQUENCE OF DINGY HILL:

The sequence exposed at the Dingy Hill member comprises ~173 m thick mixed siliciclastic-carbonate sediments intercalated with shale facies. The sequence represents a single transgressive-regressive cycles (TRC) - I. It represents the lower +150.3 m thick fining upward sequence, and the upper ~22.4 m thick coarsening upward sequence developed in shoreface region.

7.2.3.1 4th Order Transgressive-Regressive Cycles (TRC)

The sediments exposed at Dingy Hill represent the fundamental units of the Dingy Hill member of the Kaladongar Formation which comprises of transgressive-regressive cycle showing a significant variation in thickness with a mean thickness of 21 m. These TRC mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking pattern; bounded by flooding surfaces which further helped in identifying the fundamental 3rd order T-R sequences.

7.2.3.2 3rd Order Transgressive-Regressive Sequence (TRS)

One Transgressive-Regressive Cycle has been identified in the 3rd order of hierarchy of transgressive-regressive sequence with a mean thickness of about 86 m. The sequence is bounded by the regressive surface which also marks the sequence boundary bounding them.

7.2.3.2.1 Transgressive-regressive cycle (TRC) - I

The Transgressive-Regressive cycle – I comprises ~172.7 m thick deposit of mixed siliciclastic-carbonate sediments intercalated with shale facies. These deposits represent the sediments of the transgressive phase and the regressive phase of the cycle. This T-R cycle represents Transgressive System Tract and Regressive System Tract. It represents aggradation, progradation and retrogradational depositional trend and shows presence of one Flooding Surface (FS) separating the Transgressive System Tract (TST) and Regressive System Tract (RST).

7.2.3.2.1.1 Transgressive System Tract (TST) – I

The Transgressive System Tract comprises ~150.3 m thick deposit of mixed siliciclastic-carbonate sediments intercalated with shale facies. The lowermost exposed bed shows a retrogradation represented by cross-bedded micritic sandstone grading to the sandy allochemic limestone which then show aggradation. These beds are overlain by the conglomerate facies which suggest a break in the deposition.

The lower grading admixture also shows a gradation in the trace fossil contents; the lower beds shows presence of *Arenicolites*, *Gyrochortes* and *Planolites*-*Palaeophycus* assemblage while the sandy allochem limestone facies presence of *Planolites*-*Palaeophycus*, *Rhizocorallium* and *Skolithos* assemblage which represents the representing a mixed *Skolithos*-*Cruziana* ichnofacies showing gradation from the dominance of vertical structures to horizontal structures. These sediments and the trace fossil content represents a transgressive phase within the TST-I.

The micritic sandstone-shale facies overlies the conglomerate facies which is again underlaid by the allochemic sandstone-shale facies consisting *Planolites*-*Palaeophycus* assemblage and shows a retrogradational depositional trend. The succession again is overlain by the micritic sandstone-shale facies grading into allochemic sandstone-shale facies consisting *Thalassinoides* assemblage which also shows the retrogradational depositional trend and the overall succession represents the retrogradation within the aggradational depositional trend. This succession is overlain by the sandy micrite that shows presence of *Gyrochorte* and *Rhizocorallium* assemblages representing the *Cruziana* ichnofacies; capped by the conglomerate facies indicating the stormy condition. These successions represent the second phase of transgression within the transgressive phase TST-I, in the exposed part of the sequence of the Dingy Hill.

These sediments are further overlain by the mixed siliciclastic-carbonate sediments, micritic sandstone, allochemic sandstone and sandy allochem limestone representing retrogradations and presence of *Rhizocorallium* assemblage representing *Cruziana* ichnofacies. This succession shows presence of allochemic limestone on the top which marks flooding surface; the peak of the 3rd order transgression, i.e., the end of the Transgressive System Tract-I of the TRC-I and the onset of the Regressive System Tract-I of TRC-II.

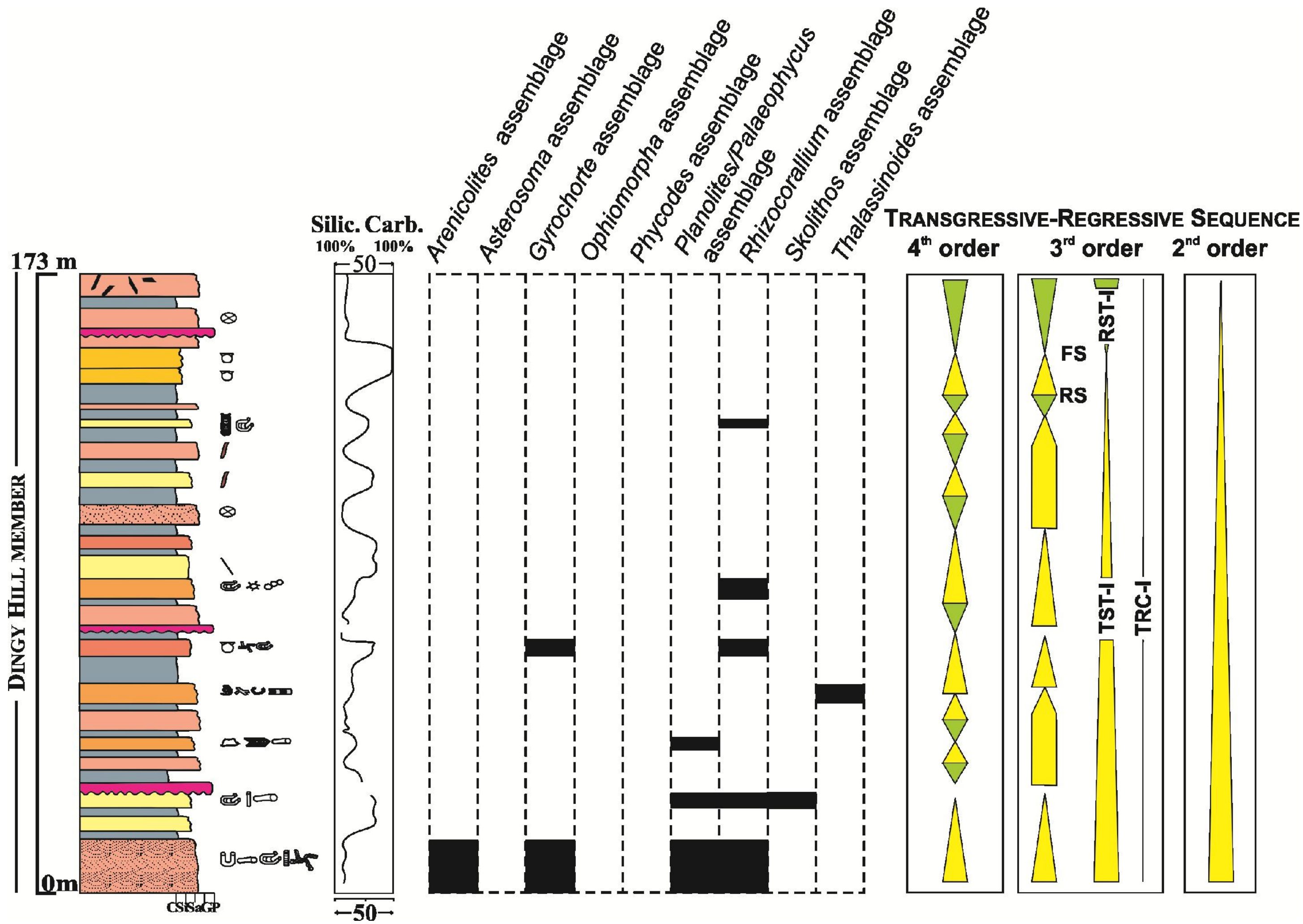


Figure-7.4 Litholog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Dingy Hill member of Dingy Hill of Kaladongar Range.

7.2.3.2.1.2 Regressive System Tract (RST) – I

The Transgressive-Regressive cycle comprises ~22.4 m thick coarsening upward sequence of micritic sandstone facies with shale and conglomerate facies. The allochemic limestone facies grades to the micritic sandstone facies which represents the aggradation within the progradational trend. This micritic sandstone however shows presence of conglomerate facies within the deposit which indicate a minor redepositonal or erosional phase (a phase of depositional hiatus); the micritic sandstone facies is massive in nature which dykes intruded in them and some embedded corals are also observed.

7.2.4 TRANSGRESSIVE-REGRESSIVE SEQUENCE OF COMPOSITE SECTION OF KALADONGAR AND GORADONGAR RANGES:

The lithosections exposed at Babia Cliff; Raimalro and Modar Hill; Sadhara dome; and exposures near Kuran, Paiya, Dhorawar, Tuga villages were studied and analysed to prepare a composite litholog for the Kaladongar and Goradongar Range. This composite litholog exposes Kaladongar as well as Goradongar Formation and attain a thickness of 462 m and mainly consists of relatively conformable succession of mixed siliciclastic-carbonate sediments.

It also displays cyclic patterns of shallow marine deposits which formed in the shoreface to offshore region. The sediments and the trace fossil content of the sequence of the Island represent many shallowing and deepening events of 4^{th} order and four 3^{rd} order T-R cycles.

7.2.4.1 4^{th} Order Transgressive-Regressive Cycles (TRC)

The 4^{th} order transgressive-regressive cycle constitutes the fundamental units of the Kaladongar and Goradongar formation and show a significant variation in thickness with a mean thickness of 14 m. These T-R cycles mark a deepening and a shallowing upward trend representing retrogradational, aggradational and progradational stacking patterns that identify the fundamental 3^{rd} order T-R sequences.

7.2.4.2 3rd Order Transgressive-Regressive Sequence (TRS)

Four TRC have been identified in the 3rd order of hierarchy with a mean thickness of about 131.69 m. Each cycle of the sequence is bounded by the regressive surfaces which also mark the sequence boundary bounding them.

7.2.4.2.1 Transgressive regressive cycle (TRC) – I

The Transgressive Regressive Cycle -I comprises ~80.95 m thick deposits of mixed siliciclastic-carbonate sediments intercalated with shale facies. This cycle shows presence of aggradation, retrogradation and progradation depositional trends within the sediments which recognizes shallowing phase of the cycle. The transgressive deposits of the cycle are not observed in the sequence which may be due to either erosion of the thin transgressive bed or may be present in the subsurface. The regressive phase are represented by the Regressive system tract (RST) – I.

7.2.4.2.1.1 Regressive System Tract (RST) – I

The Regressive system tract- I is characterized by the +80.95 m thick coarsening and shallowing upward sedimentary cycles consisting of mixed siliciclastic-carbonate sequence of Dingy Hill member (Fig. 2) of the Kaladongar Formation. These sediments consist of trace fossils like *Arenicolites, Chondrites, Daedalus, Didymaulichnus, Gyrochorte*, *Lockeia, Monocraterion*, *Ophiomorpha, Planolites, Palaeophycus, Phoebichnus, Protovirgularia, Rhizocorallium, Skolithos,* and *Thalassinoides*. The lower part of the RST-I consist of intercalated micritic sandstone-shale sequence is characterized by mainly horizontal traces like *Chondrites* and *Planolites, Palaeophycus, Rhizocorallium* in the lower part and vertical structures like *Arenicolites, Monocraterion*, *Skolithos,* and *Thalassinoides* in the upper part.

While the upper of the RST-I is consists of massive thick micritic sandstones are consisting of abundant burrows of *Skolithos* and *Ophiomorpha* with few horizontal structures like *Planolites* and *Protovirgularia.* The sediment characteristics and trace fossils of the RST-I marked gradual shallowing upward of the sequence from middle to upper shoreface environments. Late regressive conditions are represented by the amalgamated micritic sandstone bed which records aggradational condition in the regressive phase. These regressive deposits are separated from the transgressive deposits by regressive surface (RS).

7.2.4.2.2 Transgressive - regressive cycle (TRC) -II

The transgressive-regresssive cycle (TRC) - II comprised ~ 322.43 m thick sequence of mixed siliciclastic-carbonate sediments of Dingy Hill member, Kaladongar Sandstone member and Babia Cliff Sandstone member of Kaladongar Formation. It consists of Transgressive system tract and Regressive system tract representing deepening and shallowing phases in the cycle.

7.2.4.2.2.1 Transgressive System Tract (TST) – II

The transgressive system tract-II is characterized by ~63 m thick deepening and fining upward sequence of mixed siliciclastic carbonate sediments of Dingy Hill member of Kaladongar Formation. The sediments consist of trace fossils like *Nereites, Rhizocorallium* and *Scolicia*.

TST-II consists of micritic mudrock and sandy allochemic limestone, percentage of carbonate; including allochems are increases in upward direction. Sandy allochemic limestone of the TST-II is bioturbated and consists of horizontal crawling traces with few isolated feeding burrow. The litho units of the TST-II display major transgression in the retrograde deposits. The sedimentary features and trace fossils suggest a significant change in bathymetry and indicate the deepening of the basin. Transgressive conditions are represented by retrogradational deposits above the regressive phase and the top of the TST-II is represented by the flooding surface (FS).

7.2.4.2.2.2 Regressive System Tract (RST) – II

Regressive system tract-II is represented by ~259.43 m thick coarsening and shallowing upward sequence of the mixed siliciclastic carbonate sediments of the Dingy Hill member, Kaladongar member and Babia cliff sandstone member of Kaladongar Formation. It consist of trace fossils like *Arenicolites carbonarius, Asterosoma radiciforme, Beaconites, Berguaria, Cochlichnus, Dactylophycus, Didymaulichnus lyelli, Diplocraterion parallelum,* *Gordia arcuata, Gyrochorte comosa, Halopoa* isp*, Lockeia siliquaria, Ophiomorpha nodosa, Planolites beverleyensis, Palaeophycus tubularis, Phycodes palmatum, Phoebichnus trochoides, Pilichnus dichotoma, Rhizocorallium irregulare, Rhizocorallium jenense, Skolithos linearis, Taenidium, Teichichnus, Thalassinoides horizontalis* and *Thalassinoides suevicus.*

Sedimentary structures like cross bedding and ripple marks is observed in dingy hill member and Babia cliff sandstone member. Bivalve and gastropods shells, and echinoids tests and their spines are observed in the Babia cliff sandstone member whereas only bivalve shells are observed in dingy hill and Kaladongar sandstone members.

The start of the regressive phase is indicated by the flooding surface (FS) marked on sandy allochemic limestone. The initial phase of the RST-II consists of micritic mudrock (silt-size qtz ~60%) which progressively change to allochemic sandstone to thick micritic sandstones. Latter rock type shows textural variations with presence of physical structures (X-bedding and wave ripples) indicate the shallowing upward. RST-II also comprises of relatively thin beds of sandy allochemic limestone, micritic mudrock and muddy micrite with ethologically diverse groups of trace fossils that marked the minor transgressions. The micritc sandstone indicates shoal deposits in the prograding environment of upper offshore/transitional to middle shoreface zone**.**

7.2.4.2.3 Transgressive-regressive cycle (TRC) –III

The Transgressive-Regressive cycle – III comprises ~111.3 m thick sequence of Babia cliff sandstone member, Goradongar flagstone member, Gadaputa sandstone member, Raimalro limestone member and Modar Hill member. It shows aggradation, progradation and retrogradation depositional trend and represents deepening and shallowing phase of Transgressive System tract and Regressive System tract respectively.

7.2.4.2.3.1 Transgressive System Tract (TST) – III

This is characterized by ~31.1m thick fining and deepening upward sequence of Babia cliff sandstone member, Goradongar flagstone member, Gadaputa sandstone member and Raimalro limestone member. These sediments show presence of bivalve shells, echinoide spines and the trace fossils like *Arenicolites carbonarius, Arenicolites statheri, Asterosoma radiciforme, Beaconites coronus, Bifungites, Chondrites intricatus, Circulichnus montanus, Cochlichnus* isp, *Diplocraterion parallelum, Diplocraterion isp, Gyrochorte, Hartsellea sumsumramosa, Laevicyclus, Lockeia amygdaloides, Lockeia siliquaria, Oldhamia radiate, Ophiomorpha nodosa, Palaeophycus alternatus, Palaeophycus striatus, Palaeophycus tubularis, Phoebichnus trochoides, Phycodes palmatum, Pilichnus dichotoma, Planolites beverleyenis, Protovirgularia dichotoma, Rhabdoglyphus, Rhizocorallium irregularre, Rhizocorallium jenense, Skolithos linearis, Taenidium serpentinum, Thalassinoides horizontalis, Thalassinoides isp, Thalassinoides suevicus, Treptichnus pedum* and *Walcottia devilsdingli.*

The regressive surface delineates the transgressive deposits TST-III from the regressive deposits of RST-II. The geometry of the beds sediments characteristics and presence of trace fossils suggest lower shoreface to offshore region. The later phase of TST-III show major retrogradation in the retrogradation-aggradational sequence and top allochemic (oolitic) limestone (Raimalro limestone member) mark the drowning unconformity/flooding surface (DU/FS).

7.2.4.2.3.2 Regressive System Tract (RST) – III

This system tract is characterized by ~80.23 m thick coarsening and shallowing upward sequence of mixed siliciclastic-carbonate rocks with thin bands of ferruginous sandstone and allochemic limestone. The mixed siliciclastic-carbonate sediments are moderately bioturbated and consist of trace fossils like *Rhizocorallium irregularre, Quebecichnus, Arenicolites carbonarius, Diplocraterion parallelum, Planolites beverleyensis, Taenidium serpentinum, Gyrochorte comosa* and *Palaeophycus tubularis.*

The maximum sediment flux or the regressive part is represented by the siliciclastic sediments (sandstone) at the lower part of the sequence of the modar hill member, which may indicative sudden drop of base level due to tectonism or eustatic changes. The rise of the base level or decreased in clastic influx is suggestive by the limestone near the top of the regressive sequence of the RST-III.

These sediments show retrogradation and aggradation in the major prograding sediments which suggests the environmental influence in the stacking pattern (Potma et al, 2001). The aggradational micritic sandstone sediments indicate the intervening stand still condition of the sea and continual sediment supply resulting to attain a thickness of ~50 m. The top of the prograding RST-III is marked by the regressive surface (RS).

7.2.4.2.4 Transgressive-regressive cycle (TRC) -IV

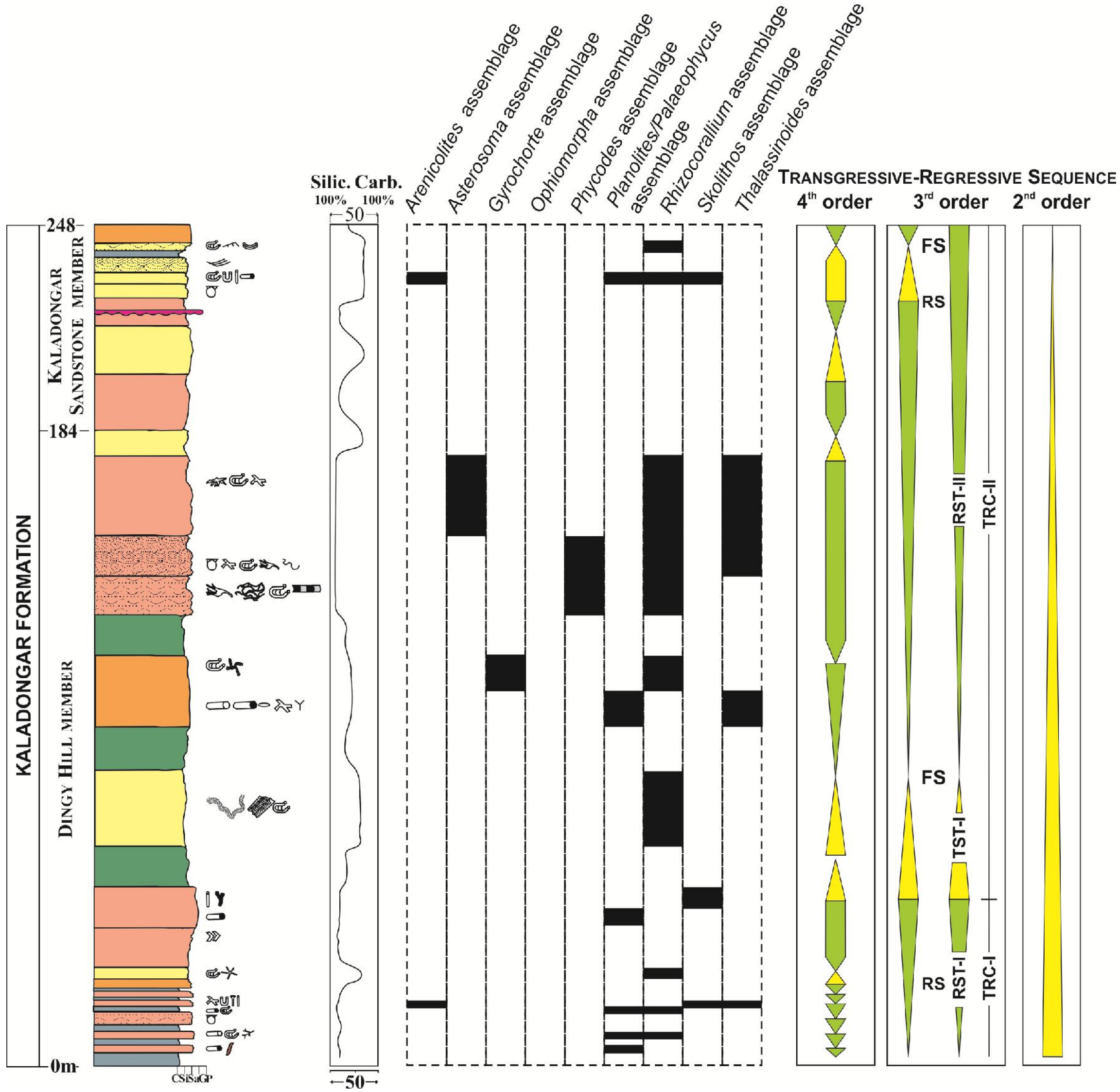
The Transgressive-Regressive Cycle – IV comprises of ~12.1 m thick sequence of coarsening and shallowing upward sequence. The cycle shows presence of aggradation, progradation and retrogradation depositional trends and represents the Transgressive System Tract and Regressive System Tract.

7.2.4.2.4.1 Transgressive System Tract (TST) - IV

This system tract deposits are comprises of ~ 9.9 m fining upward sequence of intercalated sandy allochemic limestone-shale to limestone-shale sequence. The TST-IV records the increasing of carbonate rich sediments and their thickness in upward direction represent aggradational pattern within the retrogradation deposits. The allochemic limestones are devoid of oolites but dominated by bioclastic mudstone/wackestone mark the maximum flooding surface (MFS/FS) of the sediments of the Patcham Island.

7.2.4.2.4.2 Regressive System Tract (RST) – IV

It is characterized by ~2.2 m thin sequence of coarsening and shallowing upward sequence of mixed siliciclastic-carbonate sediments. The base of the deposit of this system tract represents micritc mudrock above the maximum flooding surface. The presence of ripple marks and the cross-beddings in overlying micritic sandstone suggest tidally influence lower shoreface condition. Top of the RST-IV represent sandy micrite, capped by muddy micrite - a transgressive deposit may indicate an end of the regressive phase and an onset of the transgressive phase which is not observed in the sediments of the Patcham Island due to the stratigraphic gap.


KALADONGAR FORMATION
KALADONGAR SANDSTONE MEMBER
DINGY HILL MEMBER
248
184
0m
C Si Sa G P
Silic. Carb.
100% 100%
50
Arenicolites assemblage
Asterosoma assemblage
Gyrochorte assemblage
Ophiomorpha assemblage
Phycodes assemblage
Planolites/Palaeophycus assemblage
Rhizocorallium assemblage
Skolithos assemblage
Thalassinoides assemblage
TRANSGRESSIVE-REGRESSIVE SEQUENCE
4th order
3rd order
2nd order
FS
RS
RST-II
TRC-II
TST-I
RST-I
TRC-I

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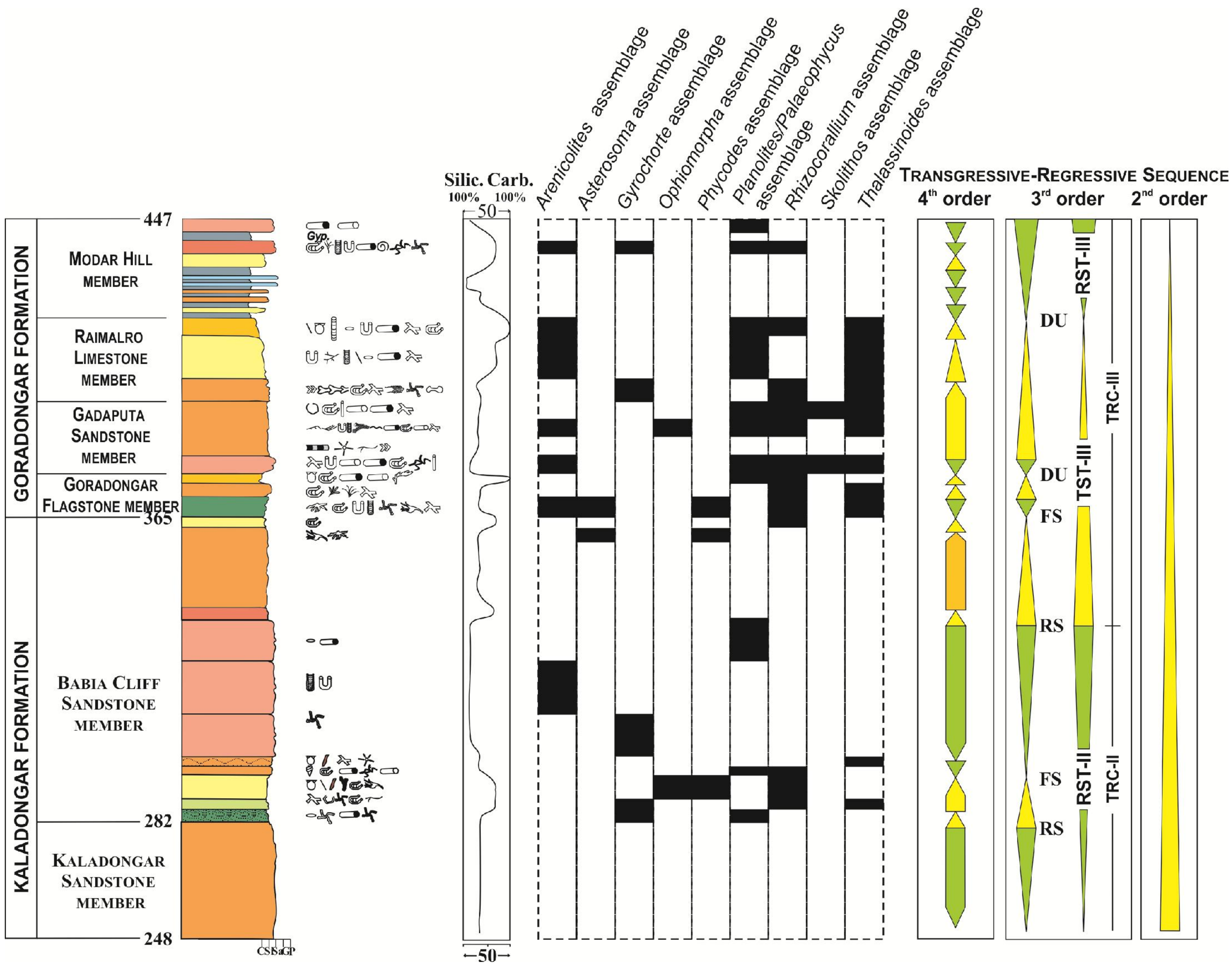

GORADONGAR FORMATION
KALADONGAR FORMATION
MODAR HILL MEMBER
RAIMALRO LIMESTONE MEMBER
GADAPUTA SANDSTONE MEMBER
GORADONGAR FLAGSTONE MEMBER
BABIA CLIFF SANDSTONE MEMBER
KALADONGAR SANDSTONE MEMBER
447
365
282
248
Gyp.
CSfSaGP
Silic. Carb.
100% 100%
50
Arenicolites assemblage
Asterosoma assemblage
Gyrochorte assemblage
Ophiomorpha assemblage
Phycodes assemblage
Planolites/Palaeophycus assemblage
Rhizocorallium assemblage
Skolithos assemblage
Thalassinoides assemblage
TRANSGRESSIVE-REGRESSIVE SEQUENCE
4th order
3rd order
2nd order
DU
DU
FS
RS
FS
RS
RST-III
TST-III
TRC-III
RST-II
TRC-II

Continued…

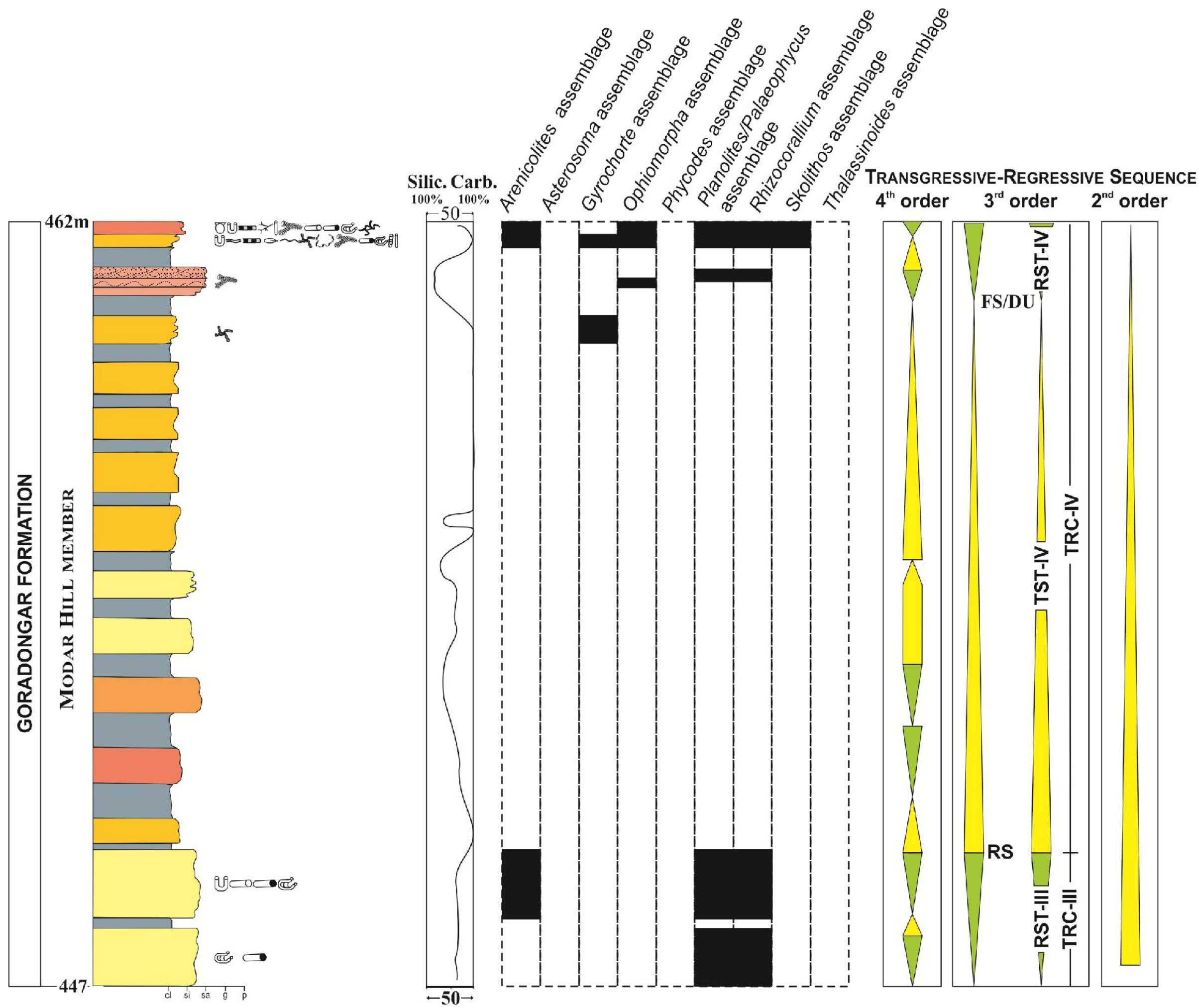

Figure-7.5 Composite Litholog showing siliciclastic-carbonate curve, associated ichnoassemblages and 4th, 3rd, and 2nd order Transgressive-Regressive sequences of Kaladongar Formation and Goradongar Formation exposed at Kaladongar and Goradongar Ranges.

7.2.5 2nd ORDER TRANSGRESSIVE-REGRESSIVE SEQUENCE:

The 2nd order transgressive-regressive cycle constitute the major unit of the Patcham Island constituting the 3rd order transgressive-regressive sequences. The overall pattern of the depositional trend represents a major sequence of transgression during the deposition of the sediments of the Patcham Island.

A noteworthy aspect of the 2nd order sequence of the Patcham Island is the common aggradational or even progradational deposition in the major transgressive deposits showing the retrogradation. Such depositional trend reflects the influence of the environmental factors on the stratigraphic stacking patterns (Potma et al, 2001). The sequence shows an asymmetrical change throughout but an overall depicts the slowly transgressive sea over the Patcham Island, Kachchh Basin.

7.3 TRANSGRESSIVE-REGRESSIVE SEQUENCE STRATIGRAPHIC MODEL

Trace fossils are analyses in context of sequence stratigraphic analysis, for e.g., *Diplocraterion parallelum* has been linked to transgressive and marine flooding surfaces (Dam, 1990; Taylor and Gawthorpe, 1993; Goldring et al., 1998) as well as to sequence boundaries (Olo´riz and Rodrı´guez-Tovar, 2000) and *Rhizocorallium jenense* is generally related to transgressive surface, produced during a period of non-deposition, before and at the beginning of the subsequent deposition (Uchman et al 2000). The absence or non-preservation of hardground *Glossifungites* ichnofacies in the sequence makes the identification of the boundaries difficult on the basis of trace fossils (Pemberton and MacEachern, 1992). However, the present study incorporated the possibility of the sedimentary deposits coupled with ichnoassemblages as useful in identifying the sequence stratigraphic surfaces and sequence boundaries.

The trace fossils of the Patcham Island is represents recurring ichnoassemblages namely; *Arenicolites*, *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites-Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages are studied in order to unravel the relationship with the sedimentary packages and stratigraphic surfaces (Fig. 7.6). The e studied sections of Kuar Bet, Chhappar Bet, Dingy Hill, and Kaladongar and Goradongar ranges display depositional trends of progradation, retrogradation and aggradation which represents four 3rd order transgressive-regressive cycle (RST-I, II, III, IV & TST- II, III, IV) bounded by three regressive surfaces (Fig. 7.2, 7.3, 7.4 and 7.5).

The geomorphic, tectonic and dynamic settings have a strong influence on the way in which the changes in accommodation are expressed or preserved (Catuneanu et al 2009). According to them sequence may be preserved in multiple combinations in the terms of component systems tracts and every sequence whose framework is linked to changes in shoreline trajectory consists of one or more of the same genetic types of deposits (i.e., normal regressive and transgressive). The sedimentological and the ichnological characteristics display a wide range of depositional facies belts including (a) foreshore, (b) shoreface, (c) transitional, and (d) offshore facies (Fig. 7.6).

(a) The foreshore facies comprises of micritic sandstone, allochemic sandstone (Fig. 4.5a), sandy allochem limestone and argillaceous shale. It is characterised by planar laminations, cross-bedding and ripple marks. It shows presence of trace fossils such as *Arenicolites*, *Monocraterion*, *Ophiomorpha*, *Planolites*, *Palaeophycus*, *Skolithos* and *Thalassinoides* which are related to the Seilacher's (1967) *Skolithos* ichnofacies. It is observed in the Kuar Bet member of the Kuar Bet. This depositional facies comprises the transgressive TST-I and the regressive RST-I deposits of Transgressive-regressive cycle-I of the sequence (Fig. 7.6).

(b) The shoreface facies consists of the upper, middle and the lower shoreface sub-facies.

The upper shoreface sub-facies comprises of thick allochemic sandstone (Fig. 4.5a) and micritic sandstone intercalated with the argillaceous shale facies. It is observed in the Kuar Bet and its equivalent Dingy Hill member of Kaladongar Formation. It is characterized by the low angle cross-beddings and ripple marks (Fig. 4.4 c; Fig. 4.6 b) and also shows presence of trace fossils such as *Arenicolites, Monocraterion Ophiomorpha, Planolites/Palaeophycus, Skolithos* and *Thalassinoides* which are related to the Seilacher's (1967) *Skolithos* ichnofacies and Proximal *Cruziana* ichnofacies (MacEachern and Pemberton 1992). The presence of cross-bedding and wave rippled structures indicate wave dominated environment in regressive setting. Thick allochemic sandstone (20m) and micritic sandstone (45m) suggests the deposits of the barrier bar and also reflect a continued supply of the clastic sands but the sub-angular to sub-rounded, moderately sorted grains (Fig. 4.5 a, b, d and f) reflect winnowing and grain attrition by wave action. Thus, the physical and biogenic structures and the nature of the sediments indicate moderate to relatively lower energy conditions in upper shoreface facies and geometry and contact of the beds represent a barrier bar deposits.

The middle shoreface lies between the lower and upper shoreface intervals and consists of non-bioturbated micritic mudrock, highly-bioturbated allochemic sandstone, micritic sandstone (Fig. 4.7 a) and argillaceous-rich shale facies. It is characterised by planar lamination, cross-bedding and asymmetrical-linguoidal ripples marks (Fig. 4.4 b, Fig. 4.6 c). The rate of bioturbation varies widely showing non-bioturbated to highly-bioturbated layers of *Arenicolites, Chondrites, Didymaulichnus, Laevicyclus, Lockeia, Ichnocumulus, Margaritichnus, Ophiomorpha, Plug shaped form, Walcottia Palaeophycus Planolites,* and *Rhizocorallium.* It also shows presence of body fossils such as bivalves, corals and fossil wood (Fig. 4.4 g and h). The middle shoreface sub-facies is observed in the Kuar Bet and the Dingy Hill members.

The lower shoreface consists of sandy allochem limestone and micritic mudrock. This sub-facies is characterized by thin laminations, cross-bedding and ripple marks. It is intensely bioturbated and consists of diverse groups of trace fossils represented by both vertical (*Skolithos, Arenicolites* and *Daedalus*) and horizontal (*Gyrochorte*, *Planolites*, *Palaeophycus*, *Didymaulichnus*, *Rhizocorallium* and *Thalassinoides*) traces. This facies characteristically intercalate with the argillaceous-rich shale layers and locally with the intraformational conglomerate. It is observed in the Kuar Bet/Dingy Hill, Babia Cliff Sandstone and Modar Hill members. The shoreface (Upper to Lower) depositional facies is observed in the TST-II and RST-I, RST-II, and RST-IV of the transgressive-regressive cycle of the sequence.

(c) Transitional facies comprises of micritic mudrock, sandy allochem limestone, allochemic sandstone and micritic sandstone. It shows presence of planar laminations, low angle cross-laminations, and ripple marks and trace fossils such as *Arenicolites, Asterosoma, Beaconites, Cochlichnus, Dactylophycus*, *Diplocraterion, Gyrochorte*, *Halopoa, Lockeia*, *Ophiomorpha, Palaeophycus*, *Planolites*, *Phycodes Protovirgualaria, Rhizocorallium*, *Skolithos, Thalassinoides* which represents diverse assemblages (*Asterosoma, Gyrochorte, Planolites-Palaeophycus Ophiomorpha, Skolithos, Thalasssinoides, Rhizocorallium* and *Phycodes*) which represents the mixed *Skolithos-Cruziana* and *Cruziana* ichnofacies. It is observed in the Dingy Hill, Babia Cliff sandstone, Kaladongar Sandstone, Goradongar Flagstone and Modar Hill members representing the TST-III and TST-IV and RST-II, and RST-III of the Patcham Island sequence.

(d) The offshore facies consists of muddy micrite, sandy micrite, micritic mudrock, sandy allochem limestone and allochemic limestone which are variably intercalated with thin calcareous rich shale layers. It is characterised by planar laminations, cross-bedding and ripple marks and trace fossils such as *Arenicolites, Didymaulichnus, Diplocraterion, Gyrochortes, Lockeia, Planolites, Palaeophycus, Rhizocorallium* and *Teichichnus* which represents *Rhizocorallium, Planolites/Palaeophycus* and *Gyrochorte* assemblages and also represent the distal part of the *Cruziana* ichnofacies (MacEachern and Pemberton 1992). It is observed in the Kaladongar Sandstone, Babia Cliff Sandstone, Goradongar Flagstone, Gadaputa Sandstone, Raimalro Limestone and Modar Hill members which represents the TST-II, RST-II, and TST-III of the sequence.

The relationship of the trace fossils and the depositional trends shows frequent and abundant recurrence of *Planolites-Palaeophycus, Skolithos, Arenicolites* and *Rhizocorallium* assemblages in the regressive deposits while *Rhizocorallium, Planolites-Palaeophycus,* and *Gyrochorte* assemblages in the transgressive deposits (Fig. 7.6). *Ophiomorpha* and *Thalassinoides* assemblages are representing the intermittent high energy conditions and/or opportunistic conditions in the regressive as well as in transgressive deposits. The *Rhizocorallium* ichnoassemblage (*Cruziana* ichnofacies) recur conspicuously in the sequence and mark the flooding surface (TST-II and TST-III) while *Arenicolites, Skolithos* and *Ophiomorpha* ichnoassemblages (*Skolithos* ichnofacies) associated with *Gyrochorte* assemblage (*Cruziana* ichnofacies) seem to mark the regressive surface (RST-II and RST-III). Ichnoassemblages reveals the transgressive-regressive cycles and helped in distinguishing the various system tracts developed in the sequence of Mesozoic of Patcham Island.

7.4 REGIONAL AND GLOBAL CORRELATION

The sediment of the Patcham Island and their associated trace fossils are significant evidence of slowly transgressing sea over low energy coastlines of initially rifting Kachchh basin. The Jaisalmer sedimentary basin is a shelf basin neighbouring the Kachchh basin, a rift basin in the south. During Jurassic, both the basin was at a distance of about 2^0 latitude and was situated in the subtropical belt (Ziegler et al, 2003; Wang et al, 2005).

The Late Bajocian transgression of Kachchh Basin of Gujarat resulted into the inundation of sea which started the first marine transgression covering the western Rajasthan shelf (Narayanan et al, 1961; Singh et al., 1982). The depositional trends of both the basin show comparatively gradual deepening of basin and an increase in marine sediments during the late Bajocian time (Pandey and Choudhary, 2007). Moreover, based on faunal studies, Bajocian to Bathonian sediments of Jaisalmer Basin can be broadly correlated with those of the Kachchh Basin (Pandey et al., 2006). The present investigation of comparable time slice of Patcham Island sediments of Kachchh basin also shows similar depositional trend. Moreover, the Callovian deposits of Jaisalmer shows transgression at the lower part which then shows regressive shallow marine deposits in the upper part (Pandey et al., 2010); sedimentological and ichnological data of the of the Callovian of the Patcham island also shows similar trend inthe Kachchh basin.

On comparison with the global sea level changes during the Callovian stages, and their 3rd order sequences given by Haq et al (1987), Hallam (2001), and Hardenbol et al (1998), the overall transgression seems to be correlative to the Bajocian-segment representing the world-wide transgression of Toarcian to the Bathonian time. However the sedimentary record of the Callovian sediments of the studied section of the Kachchh Basin seems to be incomplete like the neighbouring Jaisalmer Basin (Krishna, 1987) and the trend is also different from the eustatic curve.

These long-term changes may be therefore indicative of some local factors such as tectonics during the Callovian times. The transgressive event is similar to the Tethyan/Boreal scheme of Hardenbol et al (1998) and the T-R facies cycle of Jacquin et al (1998), indicating that the sedimentation pattern was majorly influenced by the the regional as well as the global factors.

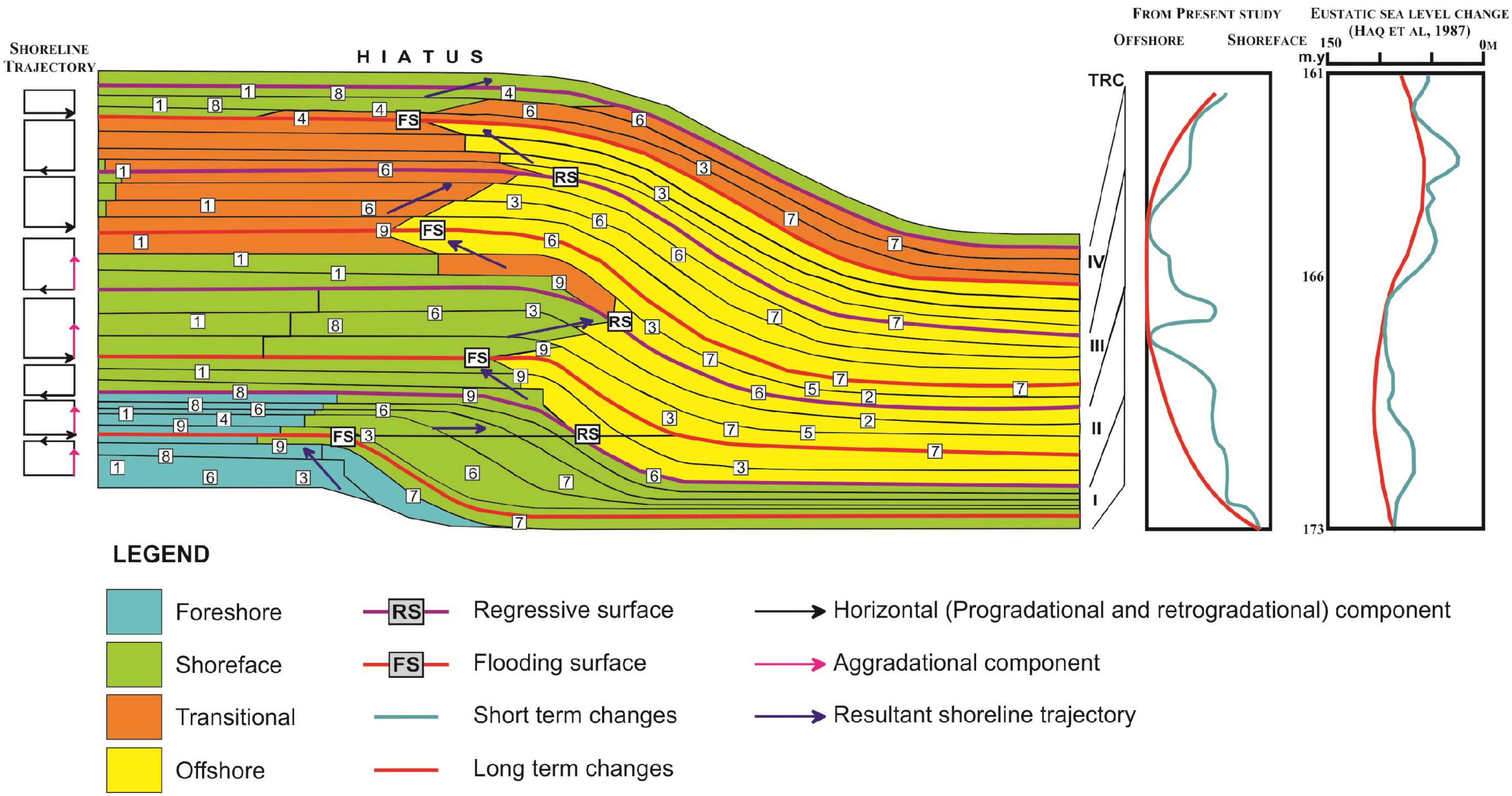

Figure-7.6 Sequence stratigraphic model of Patcham Island showing change in shoreline trajectory with associated ichnoassemblages and depositional trends in the strata stacking pattern and relative short-term and long-term changes compared to the eustatic sea level. (1) *Arenicolites*, (2) *Asterosoma*, (3) *Gyrochorte*, (4) *Ophiomorpha* (5) *Phycodes*, (6) *Planolites/Palaeophycus*, (7) *Rhizocorallium*, (8) *Skolithos* and (9) *Thalassinoides* ichnoassemblages.

CHAPTER-8
DISCUSSION AND CONCLUSIONS

The Middle Jurassic sequence of Patcham Island represent total nine sedimentary facies: a) six mixed siliciclastic-carbonate facies namely, micritic sandstone, allochemic sandstone, sandy allochem limestone, micritic mudrock and sandy micrite facies; and b) pure sedimentary facies namely, ferruginous sandstone, allochemic limestone, shale and conglomerate facies. These sedimentary facies also show variations in the proportion of clastics and nonclastics components. The nonclastic compositional variations are well documented in allochemic limestone facies, which is consisting of varying proportion of allochems like mollusks (bivalves and gastropods), coralline algae, echinoderms, foraminifers, with oolites and carbonate grains. The variation in carbonate constituents represented by allochemic limestone facies is indicative of changes in bathymetry, salinity, and energy conditions. Likewise, the facies analysis of the overall sediments of the Patcham Island suggests change in the depositional factors such as energy conditions, salinity levels, and agitation conditions etc in the depositional regime of foreshore to offshore.

These sediments show presence of abundant and ethologically diverse trace fossils. Total 67 ichnospecies of 43 ichnogenera were identified which demonstrated nine trace fossils assemblages namely, *Arenicolites*, *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites/Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages. The assemblages characterized by a particular association of trace fossils indicate hydrodynamic condition, mode of food supply, oxygenation conditions, substrate conditions and bathymetry. The shallow sea floor marked the foreshore-upper shoreface by the presence of the *Skolithos* and *Ophiomorpha* assemblages, members of the *Skolithos* ichnofacies whereas the deepest sea floor position as the offshore marked by the presence of *Planolites-Palaeophycus, Rhizocorallium* and *Gyrochorte* assemblages, the members of the distal *Cruziana* ichnofacies (MacEachearn and Pemberton, 1992). The gradual deepening in the shoreface is marked by *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites-Palaeophycus* and *Phycodes* assemblages; the members of the proximal *Cruziana* ichnofacies (MacEachearn and Pemberton, 1992) and typically marked the middle/lower shoreface to transitional environment.

The data of sedimentary facies coupled with ichnoassemblage/ichnofacies revealed that the Middle Jurassic sequence of the Patcham island comprises of aggradation, progradation and retrogradation deposits of shallow marine environments; which displayed four 3rd order transgressive-regressive asymmetrical sedimentary cycles (RST-I, II, III, IV & TST- II, III, IV) bounded by three regressive surfaces. The aggradational sequence represents the standstill conditions of the sea while the other progradational and retrogradational sequence represents the regressive and transgressive condition of the sea respectively (refernce). The shallowing upward and symmetrical cycles occur in protected lagoon-shoreface areas (Dingy Hill member of Chhappar bet) and in open-marine, high energy domain (upper part of the Ding Hill member; Kaladongar Sandstone; Babia Cliff Sandstone; and Modar Hill members). While the deepening upward and aggradational cycles are generated in low energy, sub wave-base in open marine areas (Dingy Hill member of Dingy hill and Kaladongar range; Goradongar Flagstone; Gadaputa sandstone; and Raimalro Limestone members).

These sedimentary cycles reflect similarity with the typical rift sequence suggested by Martins-Neto and Catuneanu (2010). Accordingly the absence of the Lowstand systems tract (LST) in the sediments of Patcham Island may be considered due to the strong asymmetrical shape of the base level curve, with fast rise followed by prolonged still stand. The transgressive deposits does not show any ravinement surface which indicates that it is characteristically of low energy coastlines and are typically developed in the mud dominated successions (Cattaneo and Steel, 2003). Moreover, the common aggradational or even retrogradational deposition in the highstand systems tract reflects the influence of environmental factors on stratigraphic stacking patterns (Potma et al, 2001).

The first 3rd order transgressive-regressive cycle (TRC-I) suggests that the transgressive deposits (TST-I) are deposited in the foreshore to shoreface environment whereas the regressive depostis (RST-I) are deposited in the high energy shoreface condition. The second 3rd order cycle of transgression-regression (TRC-II) suggests the transgressive deposits (TST-II) in the lower shoreface to transition environment while the regressive deposits of RST-II can be interpreted as those deposited in the shoreface to transition zone. The third 3rd order transgressive-regressive cycle (TRC-III) formed the transgressive deposits (TST-III) in the transitional to offshore zone whereas the regressive deposits (RST-III) in the offshore to transitional zone. The fourth 3rd order transgressive-regressive cycle (TRC-IV) formed the transgressive deposits (TST-IV) in the transitional zone whereas the regressive deposits (RST-IV) in the lower shoreface zone. The sedimentation pattern and the varying proportion of clastic/nonclastic grains in the sequence/composition suggest fluctuations of sea levels and sediment influx; carbonate productivity is increases with increasing depth and decreasing energy, which also halted the deposition of clasic grains. Therefore, this sequence represents number of cycles of transgression and regression but overall indicates a slowly transgressive sea during the deposition of the mixed siliciclastic-carbonate sediments in siliciclastic platform to carbonate ramp conditions during the Bajocian to Callovian time.

Most carbonates are biogenic in origin and therefore the siliciclastic and carbonate sediments are found to be mutually exclusive within modern environments; the fine-grained siliciclastics frequently dilute carbonate sediments and negatively affect carbonate production by reducing the light available to autotrophs and/or covering filter-feeding organisms (Flugel, 2010). Coeval carbonate and siliciclastic sedimentation thus requires specific conditions: terrigenous influx has to be low enough to allow the growth of carbonate-producing organisms, which can be achieved by a temporary shift of the siliciclastic depocenter (e.g. abandonment of delta lobes), the winnowing of fine-grained material by currents, or spatial separation of siliciclastic and carbonate depocenters. The mixed siliciclastic-carbonate deposits of the Patcham island characterised by land-derived siliciclastic sediments are trapped in foreshore and shoreface environments and contemporaneous deposition of carbonate sedimentation takes place in offshore settings; similar type of deposits are observed in modern environment at eastern Nicaragua coast and Great Barrier Reef (Mount, 1984) .

The formation of carbonate platforms (Goradongar Flagstone, Gadaputa Sandstone and Raimalro Limestone member) during the Bathonian times within siliciclastic settings (Kaladongar Formations) require combinations of adaptive strategies by carbonate-producing organisms and sheltering mechanisms that protect the organisms from unfavorable influences where the sheltering mechanisms include an elevated position (e.g. basement uplift) within areas dominated by siliciclastic sedimentation; longshore currents that screen off suspended siliciclastic grains; local subsidence traps; or sea-level rise resulting in the reduction of siliciclastic influx; and favoring carbonate deposition (Blair 1988; Brachert 1992; Philip 1993; Leinfelder 1994; Okhravi and Amini 1998; Sanders and Höfling 2000; Khetani and Read 2002).

The transgressive phase of TRC-III and IV shows presence of limestone with mixed siliciclastic-carbonate sequence which may be developed during an offshore siliciclastic sediment starvation (Brett, 1995) or due to the development of the conditions responsible for the increase in carbonate production (Lukasik and James, 2003; Pomar and Kendall, 2007). The Allochemic carbonates represents the keep up margin formed at the platform while the micrite rich carbonate sequences suggest the catch up carbonate highstand representing a relatively slow rate of accumulation (Sarg, 1988). This change in the depositional system (depositional bias) as well as environmental changes strongly influenced the sequence patterns (Tucker et al, 1990). This also explains the aggradational or even retrogradational deposition in the regressive system tracts of TRC-II and III (Potma et al, 2001) and the drastic reduction in the carbonate productivity indicated by the drowning unconformities (Schlager, 1992).

The mixed siliciclastic-carbonate sediment of the Patcham Island and their associated trace fossils are significant evidence of slowly transgressing sea over low energy coastlines of initially rifting Kachchh basin during Bajocian to Callovian time. These sequences are compared and studied with the equivalent Jaisalmer basin for regional constraints and the global sequences of the Bathonian to Callovian time for the global constraints. The Bajocian sediments of the Kaladongar Formation show similar depositional system in the equivalent Jaisalmer basin (Pandey and Choudhary, 2007). Both the depositional trends show comparatively gradual deepening of basin and an increase in marine sediments during the late Bajocian time. Moreover, the overall transgressive trend of the Formation seems to be correlative to the segment representing the world-wide transgression of Toarcian to the Bathonian time (Haq et al, 1987, Hallam, 2001) and is seen precisely correlated with the eustatic sea level of Haq et al., 1987 (Fig. 7.6). This transgressive event is similar to the Tethyan/Boreal scheme of Hardenbol et al 1998 and the T-R facies cycle of Jacquin et al, 1998. The sequence stratigraphic analysis of the sedimentary sequence of Middle Jurassic of Patcham Island revealed that the depositions of sediments were influenced by both regional and global factors.

The present study on sequence stratigraphic analysis based on sedimentological and ichnological aspects provide important conclusions as the following:

- The Middle Jurassic sequence of Patcham Island is exposed at Kaladongar and Goradongar hill ranges, as well as at Kuar bet, Chappar Bet and Ding Hill and attain composite thickness of + 462 meter.

- This sequence comprises of two Formations: the lower Kaladongar Formation and the upper Goradongar Formation which are further divided into three (Dingy Hill/Kuar Bet, Kaladongar Sandstone and Babia Cliff Sandstone) and four (Goradongar Flagstone, Gadaputa Sandstone, Raimalro Limestone, and Modar Hill) members respectively.

- The stratigraphic sequence comprises mixed siliciclastic-carbonate sediments with subordinate shale, limestone, sandstone and shale which are further divided into nine sedimentary facies, namely, allochemic sandstone, micritic sandstone, micritic mudrock, sandy allochem limestone, sandy micrite, allochemic limestone, ferruginous sandstone, shale and conglomerate facies.

- Presence of intraformational conglomerates facies indicates typical characteristic of storm generated deposits.

- The whole sequence is highly fossiliferous and contains mainly bivalves, gastropods, cephalopods, echinoderms, corals, foraminifers, fossil wood etc. Sequence is also highly bioturbated and consisting of total 67 ichnospecies of 43 ichnogenera which recur throughout the sequence and can be classified under five ethological groups Cubichnia, Repichnia, Pascichnia, Fodinichnia and Domichnia.

- A new ichnogenus *Virgoglyphus* and its type ichnospecies *Virgoglyphus modari* has been reported from the study area.

- Nine trace fossil assemblages namely, *Arenicolites*, *Asterosoma*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, *Planolites/Palaeophycus*, *Phycodes*, *Ophiomorpha* and *Skolithos* assemblages were observed to represent the recurring ecologically related group of trace fossils.

- These association of trace fossils that recurred in time and space directly reflected environmental conditions such as bathymetry, salinity and substrate characters and represented three ichnofacies namely, *Skolithos* ichnofacies, *Cruziana* ichnofacies and mixed *Skolithos-Cruziana* ichnofacies.

- The sedimentological and ichnological characteristics indicate a wide range of depositional facies belts including foreshore, shoreface, transitional and offshore; and comprised of sedimentary facies and depositional trend within the sequence.

- The sedimentary layers coupled with the ichnoassemblages were used in identifying the sequence stratigraphic surfaces and sequence boundaries which identified the large scale transgressive-regressive (T-R) sequence of 2nd order and four mid-scale sequence of 3rd order with several small scale cycles or 4th order unit of Transgressive-Regressive (T-R) cycles.

- The material based stratigraphic surfaces identified in the Patcham Island sequence are regressive surface (RS), flooding surface (FS), and drowning unconformity (DU) and every framework of sequence is linked to changes in the shoreline trajectory and consisted of two genetic types of deposits: normal regressive and transgressive.

- The 3rd order cycles (TRC-I, TRC-II, TRC-III, TRC-IV) are bounded by three regressive surfaces and are comprised of two parts; the transgressive system tract and the regressive system tract separated by the flooding surfaces.

- The first 3rd order transgressive-regressive cycle (TRC-I) represents deposition in the foreshore to shoreface environment; the second 3rd order cycle of transgression-regression (TRC-II) represents in the lower shoreface to transition environment; The third 3rd order transgressive-regressive cycle (TRC-III) was formed in the transitional to offshore zone; and the fourth 3rd order transgressive-regressive cycle (TRC-IV) formed in the transitional zone to lower shoreface zone.

- The stratigraphic sequence of the Patcham Island is corelatable with the equivalent Jaisalmer Basin and other world-wide Bajocian-Callovian deposits which also suggest that the deposition was influenced by the regional as well as the global factors.

The sequence stratigraphic analysis of the Middle Jurassic rocks of the Patcham Island with the sedimentological and ichnological aspects revealed development of asymmetrical cycles of transgression and regression in an overall slowly transgressive sea during the deposition in the siliciclastic platform to carbonate ramp conditions during the Bajocian to Callovian time.

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1. Satish J. Patel, **Jaquilin K. Joseph**, and Nishith Y. Bhatt ((*In press a*). Sequence Stratigraphic Analysis of the Mixed Siliciclastic-Carbonate Sediments (Middle Jurassic) of the Patcham Island, Kachchh, Western India: An Ichnological Approach. Journal Geological Society of India, sp vol.

2. Satish J. Patel, **Jaquilin K. Joseph**, and Nishith Y. Bhatt (*In press b*). Ichnology of the Goradongar Formation, Goradongar Hill range, Patcham Island, Kachchh, Western India. Jour. Geol. Soc. Ind.

3. Satish J. Patel, **Jaquilin K. Joseph**, and Nishith Y. Bhatt (2013). Facies controlled synaeresis cracks in Middle Jurassic of Patcham Island, Kachchh, Western India. Journal Geological Society of India, v.82, pp. 9-14.

4. Nishith Y. Bhatt, Satish J. Patel, and **Jaquilin, K. Joseph.** (2012) Significance of Trace fossils in Transgressive-regressive cycles: an example from the Callovian-Oxfordian sediments of the Gangeshwar Dome, SE of Bhuj, Mainland Kachchh, India. Proceedings of the Annual International Conference on Geological & Earth Sciences (GEOS 2012), doi: 10.5176/2251-3361_GEOS 12.31 (GSTF digital library), Singapore, pp. 42-47.

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10. Satish J. Patel, **Jaquilin K. Joseph**, and Nishith Y. Bhatt. (2010). Sequence stratigraphic significance of sedimentary cycles and trace fossils in the Middle Jurassic rocks of Kuar Bet area, Patcham Island, Kachchh, Western India. Gondwana geological Magazine, sp vol. 12, pp. 189-197.

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5

Sequence Stratigraphic Analysis of the Mixed Siliciclastic-Carbonate Sediments (Middle Jurassic) of the Patcham Island, Kachchh, Western India: An Ichnological Approach

Satish J. Patel[1], **Jaquilin K. Joseph**[1] and **Nishith Y. Bhatt**[2]
[1]Department of Geology, The M. S. University of Baroda, Sayajiganj, Vadodara – 390 002
[2]Department of Geology, M.G. Science Institute, Navrangpura, Ahmedabad – 380 009
Email: sjpgeology@gmail.com

Abstract

The Middle Jurassic (Bajocian to Callovian) sequence of the Patcham Island, Kachchh, comprises mixed siliciclastic-carbonate sediments displaying transgressive-regressive cycles that record changes in the relative sea level condition. These mixed siliciclastic carbonate sediments are of varying composition representing six sedimentary facies namely, micritic sandstone, allochemic sandstone, sandy allochemic limestone, sandy micrite, muddy micrite, and micritic mudrock along with the grey shale, allochemic limestone and ferruginous sandstone facies. These sedimentary facies are bioturbated with a total of 65 ichnospecies of 42 ichnogenera which are recurring throughout the sequence. The trace fossils are further grouped into nine trace fossil assemblages based on environmentally related traces based on diversity, frequency and preservational aspects (viz., *Arenicolites, Asterosoma, Gyrochorte, Ophiomorpha, Planolites/Palaeophycus, Phycodes, Rhizocorallium, Skolithos* and *Thalassinoides* assemblages). The sedimentary units (packages) coupled with ichnoassemblages reveal three transgressive system tracts (TST) and four regressive system tracts (RST) separated by flooding surfaces representing 3rd order transgressive-regressive (T-R) cycles bounded by regressive surfaces. In the T-R cycle, presence of the *Rhizocorallium* ichnoassemblage (TRC-II) and *Arenicolites, Thalassinoides* with *Planolites-Palaeophycus* assemblages (TRC-III) mark the flooding surfaces while the *Skolithos* assemblage with the *Planolites-Palaeophycus* assemblage (TRC-I), *Arenicolites* assemblage (TRC-II) and *Planolites-Palaeophycus* assemblage (TRC-III) mark the regressive surfaces. These soft ground ichnoassemblages mark the *Skolithos* and *Cruziana* ichnofacies conditions

ICHNOLOGY OF THE GORADONGAR FORMATION, GORADONGAR HILL RANGE, PATCHAM ISLAND, KACHCHH, WESTERN INDIA

SATISH J. PATEL[a,*], JAQUILIN K. JOSEPH[a] AND NISHITH Y. BHATT[b]

[a]Department of Geology, The Maharaja Sayajirao University of Baroda, Vadodara-390 002.
[b]Geology Department, M.G. Science Institute, Navrangpura, Ahmedabad-390 009.

Abstract: The Middle Jurassic Goradongar Formation exposed in Goradongar hill represents a mixed siliciclastic-carbonate succession with shales and limestones. They contain a large number of well preserved trace fossils. Total 44 ichnospecies of 31 ichnogenera; representing diverse ethology, were grouped in five ichnoassemblages (*Planolites*, *Palaeophycus*, *Gyrochorte*, *Rhizocorallium* and *Arenicolites* assemblage). These recurring ichnoassemblages represent the *Cruziana* ichnofacies and occasionally a mixed *Skolithos*-*Cruziana* ichnofacies. Patterns of diversity and density of the trace fossils reveal changes in bathymetry, oxygen level, trophic level and the substrate conditions at the time of deposition. These paleoenvironment and palaeo-oceanography changes are co-relatable to world-wide Bathonian-Callovian (Middle Jurassic) deposits.

Keywords: Ichnology; Goradongar Formation; Jurassic; Kachchh; India.

INTRODUCTION

Kachchh Basin has fascinated many geologists and palaeontologists since the middle of the 19th century for its abundant fossil content, well exposed sedimentary sequence and various mineral deposits (Pandey and Fürsich, 1998). The Patcham Island lies at the west of the island belt region of the Kachchh Basin (Fig.1). The most conspicuous features of the island are the Kaladongar and the Goradongar Hill Ranges which run in the NNW-SSE direction. Various workers (Biswas, 1977; Pandey and Agrawal, 1984b; Fürsich et al., 1994; Pandey and Fürsich, 1998; Ray et al., 2006) have studied the Patcham Island on stratigraphy and palaeontology aspect; and recently, sequence stratigraphic aspects of the Kuar Bet, a small islet of Patcham island (Patel et al 2010) and ichnological aspect of the Kaladongar Formation of Patcham Island (Jaquilin et al 2012), have been studied. However, the ichnological signatures in the Goradongar Formation of Kachchh are yet to be investigated and analysed.

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Facies Controlled Synaeresis Cracks in Mixed Siliciclastic-Carbonate Sediments of Middle Jurassic of Patcham Island, Kachchh, Western India

Satish J. Patel[1], Jaquilin K. Joseph[1] and Nishith Y. Bhatt[2]
[1]Department of Geology, The M. S. University of Baroda, Sayajiganj, Vadodara – 390 002
[2]Department of Geology, M.G. Science Institute, Navrangpura, Ahmedabad – 380 009
Email: sjpgeology@gmail.com

Abstract: Synaeresis cracks are observed at different stratigraphic levels in shallow marine mixed siliciclastic-carbonate sediments of the Middle Jurassic rocks of the Patcham Island, Kachchh, Western India. Cracks are preserved as cast or grooves in micritic sandstone of the Kuar bet member of Kaladongar Formation and sandy allochem limestone of the Raimalro Limestone member of Goradongar Formation. It bear distinct morphology of simple, straight to gently curved, spindle-shaped, irregular, unbranched to branched at acute angle; interconnected curlicue forms of non-orthogonal pattern. The X-radiography shows sharp margin and tapering twigs which support to nullify the possible biogenic origin. These cracks are developed at sediment-water interface and sediment-sediment interface in aqueous conditions, where partial dewatering of sediments causes reduction of sediment volume and loss of plasticity. Formation of cracks are also post-depositional phenomenon operated during initial phase of diagenesis where induced stress is generated due to compaction of sediments and neomorphism/recrystallisation of the susceptible carbonate grains.

Keywords: Synaeresis cracks, Shallow marine, Sandy allochemic limestone, Middle Jurassic, Kachchh, Gujarat.

INTRODUCTION

Cracks are of varying shape, pattern and origin; found in a variety of rocks and in diverse environments, since Precambrian. It is classified into four types; based on their origin: desiccation crack, sub-aqueous shrinkage crack (synaeresis crack), the sandstone dykes and transposed sand sheets, and ice-wedge polygons (Collinson and Thompson, 1981). It indicates the sub-aerial exposure (Tucker, 2011) which significantly marks the sub-aerial unconformity in a sequence. The geologic significance of the synaeresis cracks were first reported by Jüngst (1934). It was considered to be originated sub-aqueously at the sediment-water interface (Wheeler and Quinlan, 1951). Later on experimental works done on the sub-aqueous formation of cracks in clay sediments (White, 1961; Dangeard et al. 1964; Burst, 1965; Kuenen, 1965) indicate that all cracks preserved in ancient sediments having similar morphology were formed sub-aqueously at the sediment-water interface (Picard, 1966, 1969; Donovan and Foster, 1972). The experiments and occurrence of these cracks has led that the synaeresis crack is originated sub-stratally in mud (Richter, 1941; Shrock, 1948; Rich, 1951; Glaessner, 1969; Plummer and Gostin, 1981) and in earthquake induced dewatering of argillaceous sediments (Pratt, 1998).

Long sinuous to spindle-shaped cracks had often been misinterpreted as worm burrows (Endo, 1933; Yabe, 1939; Faul, 1950; Alf, 1959; Frarey and McLaren, 1963; Hofmann, 1967; Bose, 1977; Dawson, 1980). Few researchers had even classified them as a new ichnogenera *Manchuriophyus* Endo 1933 and *Rhysonetron* Hofmann 1967, for vermiform (sinuous) and fusiform (spindle) respectively. Crampton and Carruthers (1914), Burollet et al. (1969) and Patel et al. (2010) ascribed the cracks and their infills to the action of burrowing organisms. However, three dimensional structures recorded as *Yakutatia* burrows (Patel et al. 2010) are rather re-interpreted here to be of inorganic origin and discussed further in view of synaeresis cracks.

The present study is focused on mixed siliciclastic-carbonate sediments exposed at three different localities: Kuar Bet, an inlet situated at NNW of Patcham Island; and Paiya and Dhorawar villages, in Goradongar hill range of Patcham Island (Fig.1). The paper illustrates the different types of observed synaeresis cracks and discusses their

Significance of trace fossils in Transgressive-Regressive Cycles: an example from the Callovian-Oxfordian sediments of the Gangeshwar Dome, SE of Bhuj, Mainland Kachchh, India

Nishith Y. Bhatt
Geology Department,
M.G. Science Institute,
Ahmedabad- 380 009, India
Email: nybhattmg@yahoo.com

Satish J. Patel* and Jaquilin K. Joseph
Department of Geology,
The M. S. University of Baroda,
Vadodara-390 002, India
*E-mail: sjpgeology@gmail.com

Abstract - The Callovian-Oxfordian sediments, exposed in the Gangeshwar dome, SE of Bhuj (Kachchh), represent 247 m thick highly bioturbated sequence, comprising of sandstone, siltstone, shale and limestone. The presence of trace fossils suites, reflecting the characteristics of the behavioral patterns, are intimately related to the depositional processes that helped in identifying depositional facies associations viz., Middle Shoreface (A), Lower Shoreface (B) and Offshore (C) facies. This has also helped in sequence stratigraphic analysis for identifying two 3rd order transgressive-regressive cycles (TRC); regressive system tract (RST-I) and transgressive system tract (TST-II); wherein the TST-I is unexposed. The trace fossils show a change from the proximal *Cruziana* to *Skolithos* ichnofacies in the regressive phase while from the mixed *Cruziana-Skolithos* to distal *Cruziana* ichnofacies in the transgressive phase and also marked the regressive surface and the transgressive surface of erosion. The trace fossils at the base of the TST-II and the transgressive lag deposits in the retrograding deposits suggested the still stand in the relative sea level. The sedimentary facies associations and associated trace fossils reflecting the nature of transgressive-regressive cycles, controlled by either regional tectonic or sea level rise, coincides with the eustatic sea level changes of the Callovian-Oxfordian times.

Keywords-T-R cycle; shoreface-offshore zone; Gangeshwar dome; Kachchh; India

I. INTRODUCTION

Trace fossils reflect the behavioral patterns and are proved to be potential environmental indicators. They are very sensitive to water energy, substrate and other ecological parameters suggesting a narrow facies range which ultimately relate to the particular depositional environment [1][2]. The trace fossils are also well employed in recognition of the various types of discontinuities in the records and their use in the depositional sequence stratigraphic studies are well documented [3][4][5]. The concept of the sequence stratigraphy has drastically changed in the last few years and the transgressive-regressive sequence has emerged as the only genetically consistent unit that can be delineated practically and in scientific manner [6]. Accordingly, the transgressive-regressive sequence employs a subaerial unconformity or shoreface ravinement-unconformity and a maximum regressive surface for the unconformable and conformable portions of the sequence boundary respectively.

The study area, Gangeshwar dome (Fig.1), is a stretched doubly anticline covering small east-west extending anticlines and synclines and is a part of the Amundra-Ler anticline, a small uplift along the Katrol Hill Fault and exposes mostly the rocks of the Jumara Formation [7]. It comprises of ~247m thick exposed succession of Jumara Formation (Fig.2) studied at six localities: near Jamaywadi; Jogi Timba and Ler villages, behind Gangeshwar Mahadev temple; and on right and left bank of Gunawari river. The earlier workers have studied on the stratigraphic, sedimentologic and paleontologic aspects; moreover, trace fossil study has also been dealt recently by [8]. The integrated approach of sedimentologic and ichnologic aspects are dealt for first time for sequence stratigraphic analysis of the Gangeshwer dome succession in order to understand the transgressive-regressive cycles. It also reveals the usefulness of trace fossils in delineating the stratigraphic surfaces and the depositional trends in the T-R cycles.

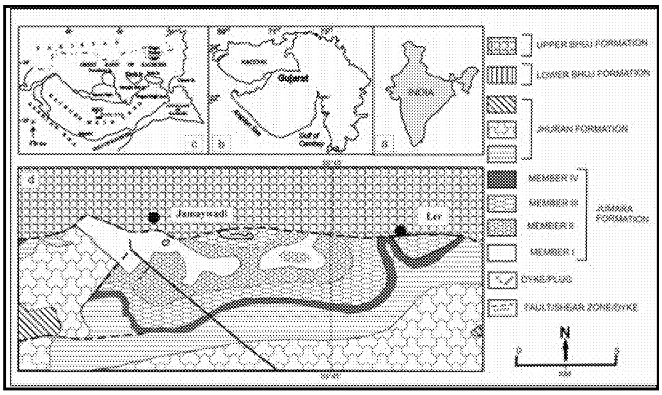

Figure 1. Geological & Location map of the Study area.

II. GEOLOGICAL SETTING

The Kachchh is a pericratonic basin rifted in Triassic period resulting in the marine sedimentation from the Tethys during the Bajocian time [9]. The Mesozoic rocks of the basin got uplifted as six uplifts during the Tertiary period. The mainland Kachchh is one of those six uplifts of the Kachchh basin. This uplift is bounded by a number of faults and the Katrol hill fault is one of the primary fault passing along the study area in east-west direction [7]. The rocks exposed in the Gangeshwar dome belong to the Jumara Formation ranging

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Deepening upward sequence of Callovian-Oxfordian Gangta bet, Wagad, Eastern Kachchh, India

Satish J. Patel and Jaquilin K. Joseph
Department Of Geology,
M.S. University of Baroda,
Vadodara- 390 002, India.
E-mail: sjpgeology@gmail.com

***Abstract*—**The Callovian-Oxfordian Gangta bet succession shows transgressive-regressive cycles of deposition that corresponds to the change in the relative sea level as well as regional factors. The succession of the Gangta bet member of the Khadir Formation comprises of lower siliciclastic and upper carbonate sequence representing eight facies association namely, ferruginous sandstone, shale, cross bedded sandstone, sandy shale, conglomerate, intercalated calcareous sandstone-siltstone-shale, ripple marked sandstone, intercalated limestone-shale facies. The calcareous sandstone-siltstone-shale, ripple marked sandstone and sandy shale are bioturbated and consists of 27 ichnospecies of 19 ichnogenera. These trace fossils show recurrent pattern of occurrence exhibiting *Cruziana* ichnofacies type condition. The intercalated sandstone-siltstone-shale and the limestone-shale facies consist of ammonites belonging to the *Athleta*, *Maya* and *Kranaus-helenae* zones suggesting Late Callovian to the Middle Oxfordian age. These sediments also represents three 3rd order transgression-regression cycles (RST-I and TST-II) in an overall transgressive phase of 2nd order. The trace fossils and sedimentary characteristics helped in delineating the stratigraphic surfaces representing the flooding and regressive surfaces. The present Callovian-Oxfordian sedimentation patterns with the ammonite zones across the world indicate that the global sea level and the regional factors were responsible for the changes in the paleo-depositional conditions in the Gangta bet.

Keywords-ichnology; lithofacies; sequence stratigraphy; Jurassic; Gangta Bet; Eastern Kachchh; India

I. INTRODUCTION

The Jurassic rocks of the Kachchh are known for their rich occurrence of megafaunal and diversified trace fossil [1][2][3][4][5][6][7]. The study area, Gangta Bet is a highly denuded domal structure of about 5 km in diameter, situated in the northwestern part of the Wagad Highland (Fig.1). It is one among the small uplift close to the major uplift that got exposed during the pre-Tertiary time [8].

The rocks of the Gangta bet are equivalent to the Bambhanka Member of the Khadir Formation and are collectively named as Gangta member by [8]. The lower part of the Bambhanka member comprises of sandstone similar to its underlying Gadhada sandstone member, differentiated on the basis of the important fossiliferous bands of the former member, which are are also well exposed in Gangta Bet. The eastern part of the Kachchh, particularly Khadir, Bela islands and Wagad Highland, have been studied for sedimentological [9], palaeontological [10][11][12], stratigraphic [8] and ichnological aspects [1][2][13]. However, the detailed integrated study of sedimentology and ichnology for the sequence stratigraphic analysis of the Gangta Bet has not yet been carried out.

The present study deals with the study of ichnology and sedimentology to understand the paleoenvironment and the sequence stratigraphy of the area. These integrated study compared with the ammonite zones and worldwide events suggest the regional and the global changes during the deposition of the Jurassic rocks of the Gangta Bet.

II. METHODS AND MATERIALS

Two major traverses were taken in the east and west direction from the core of the Gangta dome. The rock types, type of contacts, lateral and vertical continuity and facies variations were studied in each bed and a generalized litholog was prepared. Moreover, systematic sampling from the gently dipping younger strata of the Upper-Middle Jurassic succession, covering most of the Gangta Bet was also carried out. The trace fossils were observed, photographed and recorded on the litho-sections.

The sedimentological and ichnological analysis were further carried out in order to understand the stratigraphic packages and to indentify the depositional trends and surfaces. These deposits were then correlated with the world-wide deposits to study the global and regional factors.

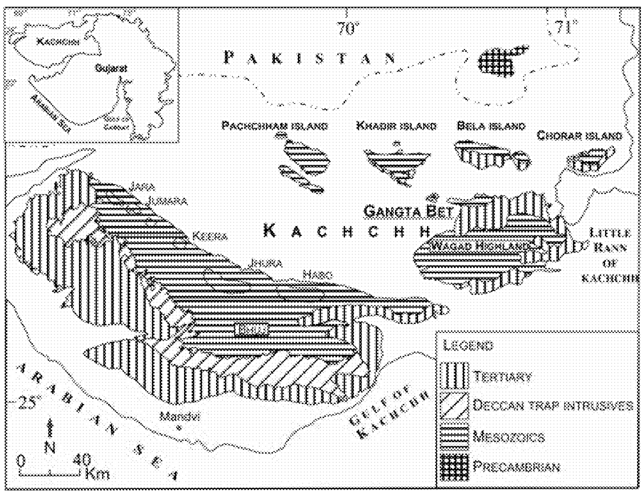

Figure 1. Location and Geological map of the Gangta Bet.

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AMMONITE ZONATION OF THE JURASSIC ROCKS OF THE GANGTA BET AREA, WAGAD REGION, EASTERN KACHCHH, INDIA

SATISH J. PATEL PARUL N. JOSHI and **JAQUILIN K. JOSEPH**

DEPARTMENT OF GEOLOGY, THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA, VADODARA-390 002
E-mail: sjpgeology@gmail.com

ABSTRACT

Gangta Bet, a structurally controlled elliptical dome, occurs as small detached landmass situated on the western fringe of Wagad highland and comprises thick marine clastic and non-clastic sequence of the Upper-Middle Jurassic period. It comprises 103 meter thick exposed sequence, which consists of various types of sandstones, shale, conglomerate, and limestone. Top part of the sequence is composed of abundant ammonitic fauna; the intercalated calcareous sandstone-shale consists of *Peltoceras athleta, Peltoceratoides semirugosum;* the Gangta ammonite band, a limestone unit, occurs near the top of the sequence as an important marker horizon and consists of *Mayaites (mayaites) maya, Mayaites* sp. *Perisphinctes (Arisphinctes) helenae, Perisphinctes (kranosphinctes) kranaus Perisphinctes (Dichotomosphinctes)* and *Perisphinctes* sp., belonging to super family Stephanocerataceae and Perisphinctaceae. The ammonite species of Gangta Bet display three Biozones and five subzones which indicate that the age of the Gangta Bet rocks ranges from Late Callovian to Early Middle Oxfordian.

Keywords: Ammonite, Biostratigraphy, Late Callovian to Early Oxfordian, Gangta Bet, Wagad region, Eastern Kachchh, India

INTRODUCTION

Wagad region is a most conspicuous highland area in the eastern part of Kachchh Mainland and comprises a thick sequence of Mesozoic and Cenozoic sediments. Attempts have been made by various workers to develop biostratigraphic zonation of the Jurassic of Kachchh. Many of them confined their studies only to the section exposed at Jumara dome, the so called type section of the Chari Formation. Waagen (1876), the proponent of the original four-fold rock-stratigraphic divisions, divided the Jurassic of Kachchh into eight biostratigraphic units. His 'Patcham Group' includes only one unit, 'Chari Group' four units, 'Katrol Group' two units and 'Umia Group' one unit. He mentioned that these units had their own ammonite taxa. As such, they are virtually assemblage zones according to modern concept. Later, Spath (1933) introduced sixteen biostratigraphic divisions within the Mesozoic of Kachchh. Biswas (1977) proposed a lithostratigraphic classification of Kachchh and recognized a number of stratotypes. The present study is mainly concerned with biostratigraphy and the authors prefer to use the classification of Biswas (1977). Recently, Agrawal and Pandey (1985) made a detailed biostratigraphic study of the rocks of Gora Dongar in Patcham Island; it was followed by work on Keera dome by Bardhan and Datta (1987), on Jara dome by Kanjilal and Prasad (1992) and on Keera and Jara Domes of the western mainland Kachchh by Prasad (1998).

Gangta Bet occurs between the island belt and Wagad highland, between N 23°46' and N 23°43' longitude, E 70°30' and 70°33' latitude (Fig.1).The purpose of the present work is to study the ammonite fauna for biozonation of the Gangta Bet sequence and to correlate with the zones of the neighbouring area (Mainland Kachchh).

GEOLOGICAL SETTING

Khadir Formation (Biswas 1977), which is divided into five ascending members: (1) Cheriya Bet Conglomerate Member, (2) Hadibhadang Shale Member, (3) Hadibhadang Sandstone Member, (4) Gadhada Sandstone Member and (5) Bambhanka/ Gangta Member. The Gangta Member is the youngest member of the Khadir Formation and is considered as equivalent to the Bambhanka Member. The rocks of the Bambhanka Member are more argillaceous and exposed at the Bambhanka, Kakindia bet, Karabir and Gorabir, south of the Khadir Island. The rocks of the Gangta Member is well exposed in Gangta bet, the western part of the Wagad Highland and considered to be the type section of the topmost unit of the Khadir Formation (Biswas, 1977).

The stratigraphic sequence of the study area consists of the topmost member of the Khadir Formation, i.e. Gangta Member, which is mainly exposed in the Gangta Bet area of eastern Kachchh. It comprises 103 m thick fining upward sequence of ferruginous sandstone-shale intercalations at the base and intercalated calcareous sandstone shale in the middle and capped by the fossiliferous ammonite rich limestone shale sequence (Fig.2). At places, the sandstone grades into intraformational conglomerate which contains flat pebbles of mud and balls of sandstones. The Gangta ammonite band is an important marker near the top of this sequence. A thin ferruginous conglomerate containing ammonite and fossil wood occurs at the top of the formation.

BIOCHRONOLOGY

The rapid evolution, pelagic habit and the near worldwide distribution of many species of the ammonites make it one of the most important index fossils for the biochronological dating. Biochronozones, the standard zones, create a standard reference for temporal correlation within a given region (Collomon, 1984; Smith *et al.,* 1988). The collection of the zonal index species is not required to indicate the presence of a zone; instead, it can be recognized by a specific assemblage of temporally restricted species (Smith *et al.,* 1988; Clapham *et al.,* 2002). The comparison of local biostratigraphic successions with the biochronological standard (e.g. a zonation) allows not only to assign relative ages to rocks, but also to estimate

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Sedimentology and Depositional Environments of the Kaladongar Formation (Middle Jurassic), Patcham Island, Kachchh, Western India

Jaquilin K. Joseph[1], Satish J. Patel[1]* and Nishith Y. Bhatt[2]

[1]*Department of Geology, The Maharaja Sayajirao University of Baroda, Vadodara - 390 002, India*
[2]*Geology Department, M. G. Science Institute, Navrangpura, Ahmedabad - 380 009, India*
**E-mail: sjpgeology@gmail.com*

Abstract

The rocks of the Kaladongar Formation, consisting of oldest Mesozoic sequence of the Kachchh basin, are exposed in the Patcham Island, Kachchh, western India. This formation attains a thickness of 464 m and is divided into three members, namely; Dingy Hill Member/ Kuar Bet Member, Kaladongar sandstone Member and Babia Cliff sandstone member. Each Member of this formation is characterized by various mixed siliciclastic-carbonate sediments which are either intercalated by calcareous or argillaceous shale. Mixed siliciclastic-carbonate sediment forms as the most conspicuous and distinctive rock types in each of the member and show wide range of distinguishing petrographic/sedimentological as well as biological characteristics including textures, mineralogy and matrix; six rock types identified include micritic sandstone, allochemic sandstone, sandy allochemic limestone, micritic mudrock, sandy micrite and muddy micrite. The whole sequence displays various types of sedimentary structures like asymmetrical ripples, planar laminations, cross-bedding, lingoid ripples, climbing ripples, interference ripples, herringbone structure and convolute bedding. The petrographic study reveals that the proportions of clastic and nonclastic sediments of the Kaladongar Formation reflected genetic control through the sequence which marked the change in the base level and/or sediment supply. The sediment characteristics and presence of physical sedimentary structures indicates that the deposition of the rocks of the Kaladongar Formation took place in the foreshore/shoreface to offshore-shoal environment above the maximum fair weather wave base in fluctuating energy conditions.

Keywords : Kaladongar Formation, Middle Jurassic, western India, mixed siliciclastic-carbonate sediments, depositional environment

Introduction

Patcham Island, the western-most island in the island belt area of the Kachchh, exposes the oldest Mesozoic sequence of the Kachchh basin (Fig.1). This pericratonic basin has six uplifts; the Mainland, island belt (Patcham island, Khadir island, Bela island and Chorar island) and Wagad uplifts (Biswas, 1977). A pioneer work on the depositional environment of the Mesozoic sediments has been carried out by Biswas (1981). Though studies based on various geological aspects have been carried out by many workers in the Patcham Island (Biswas, 1977, Singh and Jaitly, 1983; Jaitly and Singh, 1984; Howard and Singh, 1985; Jaitley, 1986; Fürsich *et al.,* 1994; Jaitly, 2000; Fürsich *et al.,* 2001; Pandey *et al.,* 2002; Jana and Hilton, 2007; Patel *et al.,* 2010), detailed aspects on sedimentological and depositional environment of the rocks of the Kaladongaer Formation of the Patcham island is yet to dealt.

The present study is carried out in Kuar bet, the Chappar Bet, Dingy Hills, Kuran-Kaladongar and the Babia Hill of the Kaladongar Hill ranges in order to study the sediments of the Kaladongar Formation. This formation has been previously well studied for its abundance in bivalves, gastropods and corals (Fürsich *et al.,* 2000, Pandey and Fürsich, 1993, Fürsich and Heinze, 1998). The depositional environment of the Kuar bet along with its sedimentary cycles and trace fossils have been discussed by Patel *et al.* (2010), but the sedimentological analysis in the aspect of the mixed siliciclastic-sediments and the depositional environment is not yet been attempted. Therefore, the present study is carried out in order to understand various depositional processes operating during the deposition of the rocks of the Kaladongar Formation. A generalize a 3-D model of the depositional environment has been drawn which could help in understanding the change in the base level and/or sediment supply.

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TRACE FOSSILS FROM THE JURASSIC ROCKS OF GANGTA BET, EASTERN KACHCHH, WESTERN INDIA

SATISH J. PATEL[1], VYOMA NENUJI[2] and JAQUILIN K. JOSEPH[1]

[1]Department of Geology, M.S. University of Baroda, Vadodara- 390 002
[2]Department of Earth and Environmental Science, 801 Leroy Place # 3145, Socorro, NM 87801, USA
E-mail:sjpgeology@gmail.com

ABSTRACT

The Jurassic rocks are well exposed in Gangta Bet of the Wagad region, Eastern Kachchh. The succession consists of thick arenaceous unit overlain by the calcareous sandstone-siltstone-shales and capped by the algal limestone. The Lower sandstone units are highly ferruginized, fractured, weathered and exposed in core of the Gangta Dome. The calcareous sandstone-siltstone units are marked by well-preserved trace fossils. Total 27 ichnospecies of 19 ichnogenera falling in five ethological categories are identified from the Gangta Bet. The recurrent pattern of the trace fossil assemblages exhibit bathymetric controls and display development of *Cruziana*-like ichnofacies characterizing subtidal conditions of depositional environment. The algal limestone band over the trace fossil horizon is interrupted by the ripple calcareous sandstone and characterized by *Maya* and *Helenae* Assemblage Zones of Early- Middle Oxfordian age.

Keywords: Trace fossils, Ichnoassemblage, Jurassic, Gangta Bet, Eastern Kachchh, India

INTRODUCTION

The Jurassic rocks of Kachchh are world famous for their rich megafaunal remains; however, it also shows preservation of rich and diversified trace fossils in both the clastic and nonclastic rocks (Shringarpure 1986; Kulkarni and Ghare 1989; Kulkarni and Borkar, 2000; Fürsich 1998; Patel *et al.*, 2008, 2009, 2010). The study area, Gangta Bet (N 23°46' and N 23°43' lat, E 70°30' and 70°33' long.), is a highly denuded domal structure of about 5 km in diameter, situated in the northwestern part of the Wagad Highland (Fig.1).

The rocks of Gangta bet is equivalent to the Bambhanka Member of the Khadir Formation and named as the Gangta member by Biswas (1977). The lower part of the Bambhanka member comprises sandstone similar to its underlying Gadhada sandstone member, which is differentiated on the basis of the important fossiliferous bands of the former member also well exposed in Gangta Bet.

The eastern parts of the Kachchh, particularly the Khadir Bela islands and Wagad Highland, have been studied for sedimentological (Mishra and Biswas, 2009), palaeontological (Moser *et al.*, 2006; Krishna *et al.*, 2009), stratigraphic (Biswas, 1977) and ichnological aspects (Shringarpure, 1986; Kulkarni and Ghare, 1989). However, the detailed sedimentological and ichnological analysis of the Gangta Bet succession has not yet been carried out. The main focus of the present study is to describe the taxonomy, ethology, and palaeoecological parameters of trace fossils along with the sedimentological aspects in order to infer the probable depositional environment of the Jurassic rocks of Gangta Bet.

METHODS AND MATERIALS

From the core of the Gangta dome, two different traverses were taken in the east and west directions. The rock types, type of contacts, lateral and vertical continuity and facies variations were studied in each bed and a generalized litholog was prepared (Fig.2). Moreover, the systematic sampling from the gently dipping younger strata of the Middle Jurassic succession, covering most of the Gangta Bet area was also carried out. The trace fossils were observed, photographed and recorded on the litho-sections. They were further studied for ichnoassemblage and ichnofacies analysis.

STRATIGRAPHY AND AGE

The Khadir Formation is subdivided into five members, viz., the Cheriya Bet Conglomerate Member, the Hadibhadang Shale Member, the Hadibhadang Sandstone Member, the Gadhada Sandstone Member and the Bambhanka/Gangta Member, in ascending order (Biswas 1977).

The Gangta Member comprises ~103 m thick sequence of fining upward ferruginous sandstone–shale intercalations overlain by calcareous sandstone-siltstone-shale intercalations and capped by the fossiliferous, ammonite rich limestone and shale sequence. Intraformational conglomerates containing elongated pebbles of mudstone and sandstones often occur with the sandstone units. The units representing the *Athleta* Assemblage zone (Late Callovian) and *Maya-Helenae* Assemblage Zones (Lower-Middle Oxfordian) are important marker horizons in Gangta Bet, which are comparable to various parts of the Mainland Kachchh (Prasad, 1998). A few beds of the Gangta Member are bioturbated and highly fossiliferous which are rich in body fossils (rhynchonellids, terebratulids, ammonites, bivalves, gastropods, belemnites, etc.).

FACIES ASSOCIATION

The term "facies" is used both in a descriptive and an interpretive sense in which the descriptive facies include certain observable attributes of the sedimentary rock bodies that can be interpreted in terms of depositional processes (Miall 1984). Based on the field observations and petrographic studies, eight facies associations, viz., ferruginous sandstone facies, shale facies, cross-bedded sandstone facies, sandy shale facies, conglomerate facies, intercalated calcareous sandstone-siltstone-shale facies, rippled mark sandstone facies, and limestone-shale facies have been identified. A brief description of these facies is as follows:

Ferruginous Sandstone Lithofacies

This facies is about 2m thick succession exposed at core

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Trace Fossil Assemblages in Mixed Siliciclastic-Carbonate Sediments of the Kaladongar Formation (Middle Jurassic), Patcham Island, Kachchh, Western India

Jaquilin K. Joseph[1], Satish J. Patel[1] and Nishith Y. Bhatt[2]
[1]Department of Geology, The Maharaja Sayajirao University of Baroda, Vadodara - 390 002
[2]Geology Department, M.G. Science Institute, Navrangpura, Ahmedabad – 390 009
Email: jaquilinjoseph@gmail.com

Abstract: The Middle Jurassic rocks of the Kaladongar Formation well exposed in the Kaladongar Hill range of the Patcham Island and Kuar Bet of the Northern Kachchh comprises of ~450 m thick sequence of mixed siliciclastic-carbonate sediments intercalated with shales. These Mixed siliciclastic-carbonate sediments show wide variation in textural and mineralogical composition and represent genetically related six rock types: micritic sandstone, allochemic sandstone, sandy allochemic limestone, micrtic mudrock, sandy micrite and muddy micrite; which are highly bioturbated and show behaviourally diverse groups of trace fossils. Total 34 ichnogenera are identified, which includes, *Arenicolites, Asterosoma, Beaconites, Bergaueria, Chondrites, Cochlichnus, Dactylophycus, Daedalus, Didymaulichnus, Diplocraterion, Gordia, Gyrochorte, Gyrolithes, Ichnocumulus, Laevicyclus, Lockeia, Margaritichnus, Monocraterion, Nereites, Ophiomorpha, Palaeophycus, Phoebichnus, Phycodes, Pilichnus, Planolites, Plug Shaped Form, Protovirgularia*, *Rhizocorallium, Scolicia, Skolithos, Taenidium, Teichichnus, Thalassinoides* and *Walcottia.* These trace fossils are classified into six morphological groups namely, circular and elliptical structures; simple structures; branched structures; rosette structures; spreiten structures; and winding and meandering structures. These trace fossils are further group into eight assemblages which occurred together into mixed siliciclastic-carbonate sediments, include, *Asterosoma* assemblage, *Gyrochorte* assemblage, *Rhizocorallium* assemblage, *Thalassinoides* assemblage, *Planolites-Palaeophycus* assemblage, *Phycodes* assemblage, *Ophiomorpha* assemblage and *Skolithos* assemblage. The recurring pattern of these assemblages through the sequence displays the development of *Skolithos* and *Cruziana* ichnofacies and at places the mixed *Skolithos-Cruziana* ichnofacies which suggest a low wave and current energy conditions with intervening period of high wave and current energy conditions and an intermediate period of stressful environments, respectively. Sedimentological and ichnological data suggest that the deposition of the mixed siliciclastic-carbonate sediments of the Kaladongar Formation took place in the foreshore to offshore environment under fluctuating wave and current energy condition.

Keywords: Mixed siliciclastic-carbonate sediments, Trace fossil Assemblages, Shallow marine, Kaladongar Formation, Middle Jurassic, Kachchh, Western India.

INTRODUCTION

The Kachchh basin was situated at the western margin of the Indian plate (Biswas 1982) opening into the so-called Malagassy gulf, southern extension of the Tethyan Ocean (Fürsich et al 2004), wherein the sedimentation started in the Bajocian or possibly Alenian time (Pandey and Dave, 1993) during the Jurassic period. These early sediments are well exposed at the islands bordering the south of the Great Rann of Kachchh (Biswas, 1977).

The Patcham Island, the westernmost island in the island belt area, exposes the oldest rock of the Mesozoic era which is highly fossiliferous containing abundant body fossils of bivalves, gastropods, brachiopods, corals and echinoderms. These rocks are classified into two formations; the Lower Kaladongar Formation and the Upper Goradongar Formation. The reference of sedimentology, stratigraphy and paleontology studies of the study area identifies the gap in systematic record on trace fossils of Kaladongar Formation. However, ichnological investigations have been done in many parts of the Mainland Kachchh and Wagad region by Howard and Singh (1985); Shringarpure (1986); Kulkarni and Ghare (1986, 1989, 1991); Fürsich (1998) and Patel et al. (2008, 2009).

The sedimentary rocks of the Kaladongar Formation are

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Sequence Stratigraphic Significance of Sedimentary Cycles and Trace Fossils in the Middle Jurassic Rocks of Kuar Bet Area, Patcham Island, Kachchh, Western India

Satish J. Patel[1]*, Jaquilin K. Joseph[1] and Nishith Y. Bhatt[2]

[1]*Department of Geology, M. S. University Baroda, Vadodara-390 002*
[2]*Geology Department, M.G. Science Institute, Ahmedabad-380 009*
**E-mail: sjpgeology@gmail.com*

Abstract

The oldest Jurassic sediments belonging to the Dingy Member of the Kaladongar Formation of the Kachchh basin are exposed as an isolated uplift in the Kuar Bet area, NW of Patcham Island. The exposed succession is about ~226m thick and comprises of mixed siliciclastic-carbonate and fine to coarse grained clastic sediments and further divided into seven facies associations which consist of genetically related sediments. These facies are further analyzed by microfacies which are repeated throughout the sequence. The Sequence is bioturbated at places and consists of *Arenicolites, Diplocraterion, Monocraterion, Palaeophycus, Planolites, Rhizocorallium, Thalassinoides* and *Yakutatia.* The sedimentary cycles and the trace fossils show pattern of strongly asymmetric shallowing-deepening cycles. The major HST and TST represents three regressive surface, two transgressive lag deposits, two drowning unconformity and a flooding surface. The cyclic sedimentation patterns reflect cyclicity in the environment of deposition from foreshore to lower shoreface and the trace fossils have responded to genetically related sequence surfaces to the particular environments.

Keywords: Sequence stratigraphy, Sedimentary cycles, Trace fossils, Middle Jurassic, Patcham Island, Kachchh.

Introduction

The sequence stratigraphy based on the aspects of sedimentary rocks is well established, however, there are comparatively less attempt to explore the significance of trace fossils in the sequence stratigraphy (Frey and Howard, 1990; Pemberton and MacEachern, 1995). The work on sequence stratigraphy of the Jurassic rocks of Kachchh is also limited (Biswas, 1991; Fürsich and Oschmann, 1993, Fürsich *et al.* 2001 and Fürsich and Pandey, 2003), whereas the work on trace fossils is comparatively more (Badve and Ghare, 1978; Howard and Singh, 1985; Ghare and Kulkarni, 1986; Shringarpure, 1986; Kulkarni and Ghare, 1989 and 1991; Fürsich, 1998 and Patel *et al.,* 2008). These authors have mainly carried out studies in the Mainland Jurassic rocks.

The trace fossils are significant tool to delineate the stratigraphic boundaries related to the sequence stratigraphy (MacEachern *et al.,* 2007). Interpretation of the origin of the discontinuity provides an idea about the depositional environments and the characters of allocyclic control on depositional systems (MacEachern *et al.,* 2007). Paleontological, stratigraphical and sedimentological approaches to the trace fossils and trace fossil suite aid in the recognition of different palaeoenvironments, discontinuity and their genetic interpretation (Pemberton *et al.,* 2000).

The present study provides information about the development of sedimentary cycles and response of animal communities to the sediments during the deposition of the Kuar bet rocks.

Geological Setting

The Kachchh pericratonic rift, situated at the southern edge of the Indus shelf at right angles to the southern Indus fossil rift, evolved within the Mid-Proterozoic-Aravalli-Delhi fold belt (Biswas, 2005) in the Triassic and formed the Kachchh basin which was inundated by the sea no later than the early Mid Jurassic (Fürsich *et al.,* 2001). The marine sedimentation prevailed throughout the Jurassic and was terminated by Mid Cretaceous times (Fürsich, 1998). The Jurassic rocks occur in the Kachchh in two belts: NW-SE string of domes on the Mainland and the E-W trending series of hills