SEQUENCE STRATIGRAPHIC ANALYSIS OF THE BAGH GROUP OF GUJARAT, WESTERN INDIA

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By

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MARCH, 2022

CERTIFICATE

This is to certify that Apurva Shitole has prepared her thesis entitled "***Sequence stratigraphic analysis of the Bagh Group of Gujarat, Western India***" for the award of degree of Ph.D. in Geology from The Maharaja Sayajirao University of Baroda under my guidance. She has completed all requirements as per Ph.D. regulations of the University. I am satisfied with the analysis of the data, interpretation of results, and conclusions drawn. I recommend the submission of the thesis.

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DECLARATION

I, Apurva Shitole, declare that the research work incorporated in the present thesis entitled "***Sequence stratigraphic analysis of the Bagh Group of Gujarat, Western India***" is original and was carried out at the Department of Geology, The Maharaja Sayajirao University of Baroda.

This work (in part or in full) has not been submitted to any other institute or university to award a degree or diploma.

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ABSTRACT

The ENE-WSW trending Lower Narmada Valley (LNV) comprises an almost complete sequence of the Cretaceous Period and preserves imprints of the major Cretaceous global events like sea-level rise, Deccan volcanism and mass extinctions. The LNV is divided in to Eastern Lower Narmada Valley (ELNV) and the Western Lower Narmada Valley (WLNV) and the latter is investigated geologically in the present study. The purpose of the research was to propose a lithostratigraphy and to analyze the sedimentological, ichnological and sequence stratigraphy aspects to interpret the paleoecology and depositional environment and correlate with the pervasive Tethyan basins.

To achieve the above goals, systematic studies were carried out in the exposed sequence of the Bagh Group at thirty-two localities; lithologs were constructed for the LNV. The earlier lithostratigraphy consist informal units, ambiguous boundaries and lacks the stratotypes. Moreover, there exists multiplicity in the nomenclature of the units with several homonyms and synonym and number of informal units, which has created chaos in the literature. Based on field observations, laboratory studies, vertical and lateral lithological variations; lithostratigraphy is revised for WLNV as per the International Subcommission on Stratigraphic Classification, emphasizing the retention of the original units and new units are proposed wherever necessary. The study describes the units with their historical background, intent and utility, designation, stratotype, boundaries, age, depositional environment and are compared with the ELNV units.

The new data is generated on sedimentology and ichnology of the Cretaceous WLNV sequence. The sedimentological characteristics revealed fourteen lithofacies which were interpreted for the depositional environment. Total 26 ichnospecies belonging to 17 ichnogenera were identified and analyzed for ethological categorization, ichnoassemblages and ichnofacies, which led to interpretation of paleoecological and paleoenvironmental conditions of the WLNV basin. The lithostratigraphic, sedimentological, and ichnological data are integrated for the identification and analysis of systems tracts, sequence boundary, sequence stratigraphic surface, and minor within-trend surfaces. Sea-level curve is drawn based on shoreline trajectory and compared with the eustatic curve and finally, reconstructed a sequence stratigraphic model for the Cretaceous Bagh Group sequence of the WLNV. The data of the WLNV is further correlated with pervasive Cretaceous Tethyan basins like ELNV, Eastern Desert, Saurashtra, Carnarvon, Mahajanga, Cauvery and Kachchh to understand the rift events and eustatic sea-level changes.

CHAPTER 1
INTRODUCTION

1.1 PALEOGEOGRAPHY OF INDIA

The Late Triassic breakup of Pangea resulted in two supercontinents- Laurasia and Gondwanaland. Consequently, rifts developed propagating southwards between Africa and India-Madagascar and between India and Australia and thus started the breakup of Gondwanaland (Royer et al., 1992). According to Reeves (2009), the separation of Gondwanaland began in the middle Jurassic (167 Ma) when the eastern Gondwanaland (India, Australia, Madagascar, Antarctica) separated from Africa along the NNE-SSW trend due to the Karoo plume (Besse and Courtillot, 1988; Segev, 2002). Except for the Karoo rifting (300-200 Ma) in central Gondwana, the first movement between the eastern and western Gondwanaland along the Davie Fracture Zone and the Lebombo Explora Fracture Zone took place, which defines the eastern and western limits of the Africa-Antarctica Corridor (AAC). Ocean formation started with Madagascar, Mozambique, and Somalia pull-apart basins (Besse and Courtillot, 1988) between Africa and Antarctica (Fig.1) at around 167-145 Ma (Reeves, 2009). The opening of the Indian Ocean initiated the breakup of eastern Gondwanaland, which comprised of India, Antarctica, and Australia (Powell et al., 1988). Before the separation, a continental extension phase in Permian-Triassic formed the Gondwana basins, which started with sagging along the weak zones (Lawver et al., 1992; Biswas, 1999).

Hay et al. (1999) and Skelton (2003) opined that the two supercontinents, Laurasia and Gondwana, were separated by the Tethys Sea during the Early Cretaceous. The Tethys remained a narrow opening, the Mediterranean Sea in the present day. The Central Atlantic existed at the beginning of the Cretaceous. The North Atlantic migrated northwards during the Early Cretaceous; however, South Atlantic was separated from the pre-existing Central Atlantic basin.

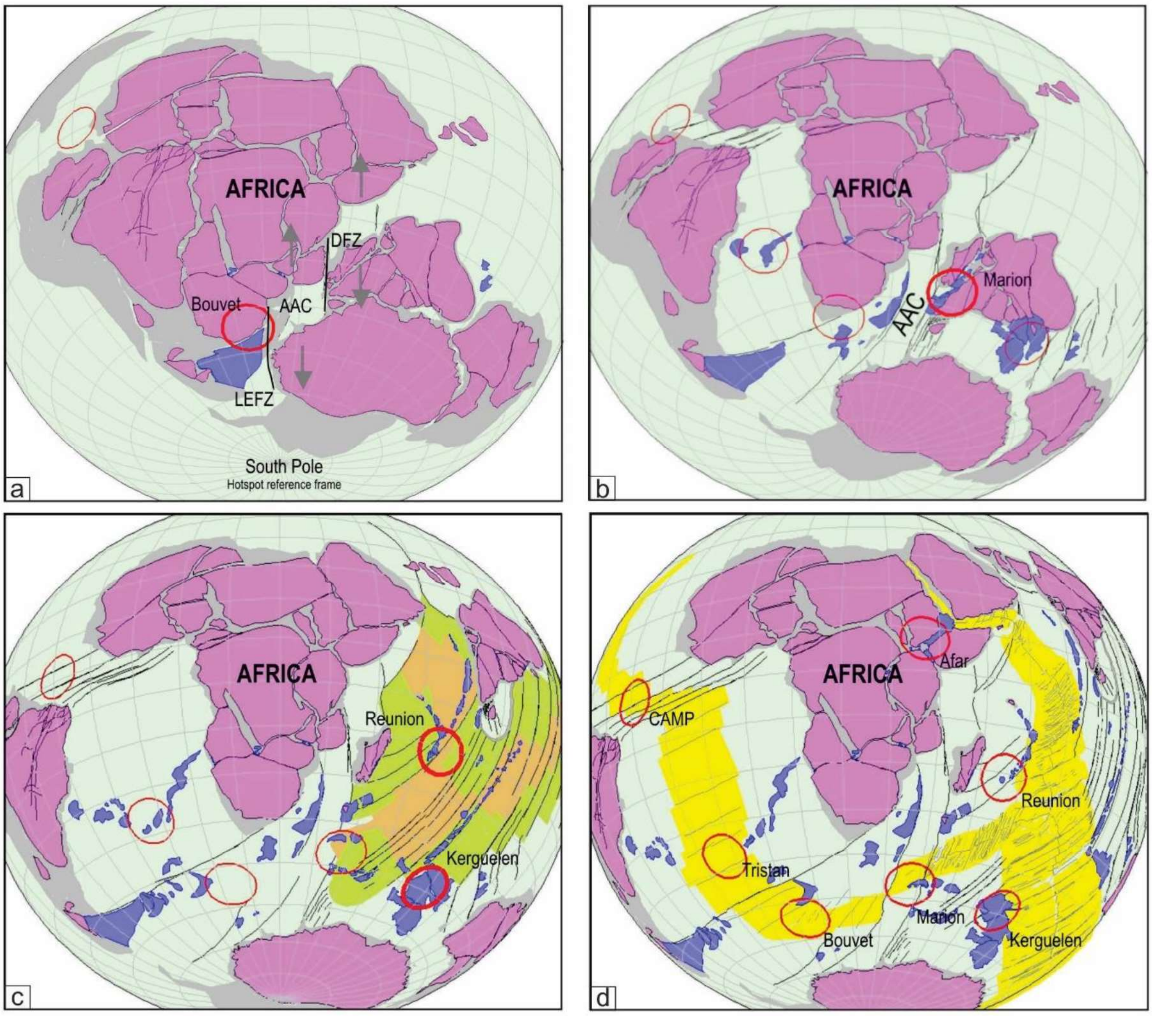


Figure 1.1 Phases of Gondwana breakup (after Reeves, 2009). a. Breakup between eastern and western Gondwana controlled by the strike-slip movement between Davie and the Lebombo-Explora fracture zones at 145 Ma, creating Africa-Antarctica Corridor (AAC); India and Antarctica started splitting at 130 Ma. b. 93 Ma, India migrated at its southernmost point; the outbreak of Marion hotspot initiated breakup of India from Madagascar-Africa and at 90 Ma the breakup between India and Madagascar. c. Post-breakup from Madagascar, India initiated a rapid NE drift. d. Present-day situation; Marion, Kerguelen, Reunion, Bouvet, Tristan, Afar, and CAMP hotspot, which played a significant role in the dispersal of continents, are shown.

At the end of the Cretaceous, the northern and southern parts of the Atlantic joined and created a continuous north-south oceanic divide between America and Africa. At the same time, the African/Arabian continent rotated anticlockwise and drifted northward, closing the Tethys Ocean, and India started drifting northward, opening the Indian Ocean (Skelton, 2003).

Gibbons et al. (2013) suggested that the Enderby margin was continent-ocean boundary of eastern India and Antarctica lied south of the South Kerguelen Plateau separated in the Late Jurassic. The Greater India (India, Madagascar, and Seychelles) started moving away from the East Gondwana after a spreading reorganization at 136 Ma, 100 km northwest of Australia, where the mid-oceanic ridge that separated Greater India from combined Australia-Antarctica migrated from north to south and reached the southern tip of India at 126 Ma. The new spreading ridge detached India from northwest Australia, and the Indian plate moved in an anticlockwise direction. India separated from the joint landmass of Antarctica and Australia at 130 Ma (Veevers and McElhinny, 1976, Powell et al., 1988; Besse and Courtillot, 1988). The India-Antarctica and India-Australia breakups were considered contemporaneous, with spreading between India and East Antarctica at 130 Ma (Gaina et al., 2007). After 136 Ma, the new ocean separating India and Antarctica migrated westwards, separating Sri Lanka from India and then from Antarctica at around 110 Ma. During Early Cretaceous (130-140 Ma), South America started separating from Africa and opened the proto-south Atlantic Ocean (Reeves, 2009). Around 130 Ma, the eastern Gondwana started its separation with the Indian plate moving southward less rapidly than the combined Australia-Antarctica (Reeves, 2009). The Elan Bank (continental fragment) too separated from India and migrated to Antarctica due to the ridge jump phenomenon at 120 Ma (Gaina et al., 2007).

According to Richards et al. (1989), mantle plumes are related with a continental breakup. The Kerguelen plume is associated with the separation of eastern Gondwanaland and the formation of 132 Ma old Bunbury basalts of Australia (Frey et al., 1996), 118 Ma old Rajmahal Traps of India (Kent et al., 2002), and 115Ma old ultramafic lamprophyres of east Antarctica margin (Cofflin et al., 2002). Coffin et al. (2002) explained the role of the Kerguelen hotspot (130-125 Ma) in the separation of eastern Gondwana; it occurred closely around the breakup of India and Antarctica. The Kerguelen hotspot-related magma output commenced at a very low rate at 132 Ma with Casuarina-type Bunbury basalt. The casuarina ages (128-132 Ma) coincide with the onset of seafloor spreading between Australia and India. The magma output at an intermediate rate during 123 Ma generated Gosselin-type Bunbury basalt, which can be correlated with the onset of seafloor spreading between Australia and Antarctica and at an increased rate from 120-110 Ma in Southern Kerguelen Plateau, Rajmahal Traps, and lamprophyres on Indian and Antarctic margins. It ceased after 110 Ma while contributing to Elan Bank. Between 105-100 Ma, formed the central Kerguelen Plateau, similar to the southern Kerguelen Plateau. Several ridges are identified, which are associated with the hotspot. The broken ridge formed between 100-95 Ma, while the oldest part of Ninety East Ridge formed between 95-82 Ma, buried beneath the Bengal fan sediments. The Ninety East Ridge and the Skiff bank are generated between 82-38 Ma, and the Northern Kerguelen Plateau formed between 40 Ma to present. Their study suggests that Elan Bank and Southern Kerguelen Plateau were attached to India before separating from Antarctica. During the Early Cretaceous, India with Madagascar drifted from Antarctica, extending the Indian Ocean towards the east (Skelton, 2003). Gaina et al. (2007) suggest 600 Km of sinistral followed by 500 Km dextral strike-slip movement between India and Madagascar during 120 Ma.

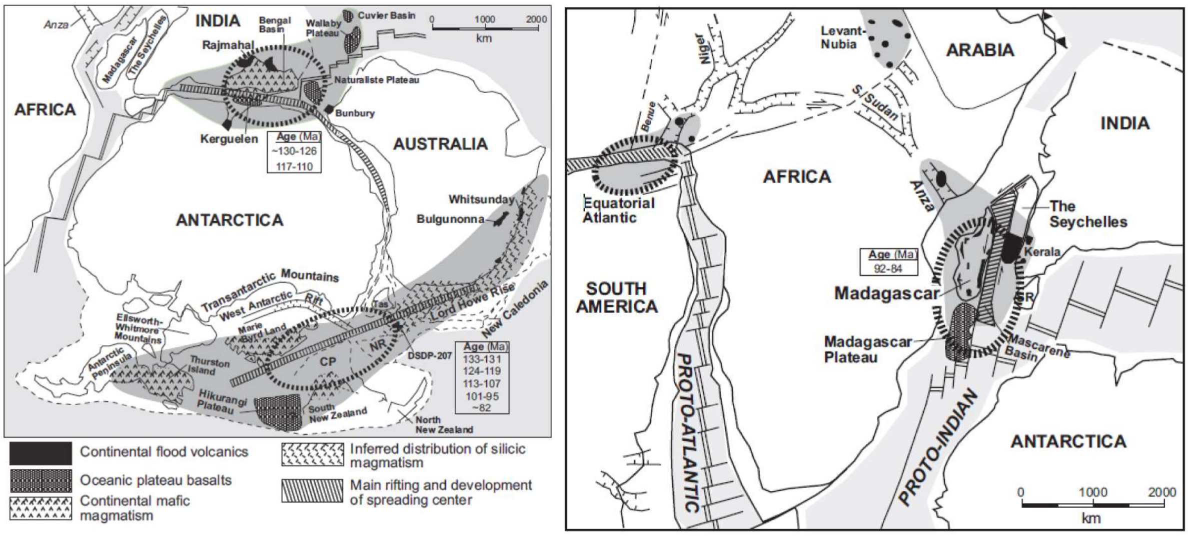


Figure 1.2 Reconstruction of Early Cretaceous Gondwana (eastern and central) after Segev (2002) showing a. showing plume province of the Rajmahal and Kerguelen, the breakup between India and Antarctica, and the passive rifting between Australia and Antarctica. b. Madagascar igneous and plume province, and the separation of Madagascar and Seychelles.

The two-way strike-slip motion is attributed to the contemporaneous seafloor spreading in Enderby and west Somali basins, which moved India opposite to Madagascar. The study also suggests 200 Km of extension between India and Sri Lanka between 120-126 Ma.

Gibbons et al. (2013) observed distinct north to northeast fracture zones in the Enderby fracture zones, one of which is the Kerguelen fracture zone, attributed to India's change in direction from northwest to northeast. They formed around 100 Ma when the early Indian Ocean underwent major spreading reorganization. The onset of relative motion between India and Madagascar at 100 Ma is similar to the Kerguelen fracture zone and its associated ridge at India; the eighty-five east ridge old fracture zone relates to the 100 Ma (Krishna et al., 2006; Gibbons et al., 2013). India separated from Madagascar in Late Cretaceous due to spreading in the Mascarene basin (Storey et al., 1995). The linearity of the east coast of Madagascar supports the strike-slip faulting before the opening of the basin (Dyment, 1991).

The separation between India and Western Australia began around 132 MY with the plateau basalts along the Cuvier and Gascoyne Abyssal Plains. Here, the plateau basalts comprise the Wallaby and Naturaliste plateau comparable with the Rajmahal, Bengal, and Sylhet traps related to the Kerguelen-Rajmahal plume in NE India. The plume migrated SE between India and the combined Australia and Antarctica and lasted 20 MY (Segev, 2002). However, the main basalt outpouring along the margin of India and Antarctica (Bengal, Rajmahal, and Kerguelen) occurred during 117, and 109 MY, and the Ocean Island magmatism in the eastern Indian Ocean (Ninety east and broken ridges) is related with the late-stage volcanism which continued till Tertiary (Segev, 2000, 2002). The volcanics are covered by sediments and dips seaward in the Bengal basin and the Kerguelen oceanic plateau, filling the gap between India and Antarctica after their separation (Crawford and von Rad, 1994; Kent, 1991). The reorganization at 110 MY attached India and Madagascar to Africa separated from Antarctica and Australia by transferring rifting from Mozambique and Somalia basin to the newly formed Indian Ocean. The Late Cretaceous volcanics at Madagascar related to the Marion mantle plume lasting for 8 MY are related to the intrusions in Kerala, India (Radhakrishna et al., 1999). Studies of Storey et al. (1995) on Madagascar's volcanic rocks and dikes suggested its emplacement by Marion hotspot at ~87.6 Ma. They played an active role in the breakup of Madagascar and India by providing a path for the propagation of the Mascarene ridge. This plume generated large amounts of melt in Madagascar, Madagascar plateau, and Seychelles (Fig. 1.1, 1.2), and at ~80 MY, India separated from Madagascar, Africa, and Arabia (Besse and Courtillot, 1988). The growth of the Indian Ocean favored the splitting of eastern Gondwanaland (India, Antarctica, and Australia). Later India began its rapid northwards journey. The Late Cretaceous passage of India over the Reunion hotspot resulted in large-scale Deccan volcanism lasting from 65-68 MY depositing widespread tholeiitic flood basalts is related to the volcanism observed in Seychelles (Courtillot et al., 1986; Segev, 2000). This event was coeval with the breakup of India from Seychelles (Collier et al., 2008). According to Aitchison et al. (2007), most scientific papers and textbooks today assume that the Indian plate collided with the southern margin of the Eurasian plate at 55 Ma (Eocene) and ended its northward movement, resulting in Alpine- Himalaya. However, the age (55 Ma) is wrongly interpreted based on an inappropriate combination of proxies from several unrelated episodes. Aitchison et al. (2007), based on field evidence and published data, proposed that the two plates collided at ~34 Ma (Eocene/Oligocene boundary). India's northward movement rate was ~6.6 cm/yr between 120 and 73 Ma, which increased to 21.1 cm/yr between 73 and 57 Ma. Throughout the Cretaceous, Australia remained attached to Antarctica and South America. (Hay et al., 1999). At 53 Ma, Australia and Antarctica separated at the end of the Paleocene (Veevers and McElhinny, 1976).

1.2 CRETACEOUS PERIOD

The Cretaceous period serves as an important time slice in the history of the earth considering the series of global events it has witnessed in the 79 MY span, including the splitting of continents, global sea-level changes, climatic changes, large-scale volcanism, ocean anoxic events, and mass extinction. These topics are essential for studying their implications on paleoenvironmental response. The climate-ocean system experienced increased tectonism, global surface and deep-water temperature, the CO_2 concentration of ocean and atmosphere, and Oceanic Anoxic Events (Ramkumar, 2015).

1.2.1 GLOBAL SEA-LEVEL

Global sea-level experienced high during most of the Mesozoic and by a fall in the late Cretaceous (Haq, 2014; Müller et al., 2008). The Cretaceous period recorded sea-level changes of more than 100m (Haq et al., 1987). Boulila et al. (2011) suggested 25-120 m of sea-level difference can be caused by glacio-eustasy, the only known cause which created sea-level changes of this order (Ramkumar, 2015). However, the problem in accepting the above assumption arises because of the extreme greenhouse conditions existing during this time (Ramkumar, 2015). Oxygen isotope studies of foraminifera on the Mid-Cenomanian Demerara rise suggest mid-Cretaceous to be an ice-free period with a maximum temepratures around the Cenomanian-Turonian boundary (~90 Ma) (Moriya et al., 2007). According to Pugh et al. (2014), the polar regions experienced ice-free summers, which increased the sea levels and led to the flooding of continents. Long periods of greenhouse conditions (Hunter et al., 2008) and poles free of ice (Hay, 2011) existed during the Cretaceous, which negates the role of ice volume change to sea-level fluctuations (Ramkumar, 2015). However, the integrated studies of several stratigraphic disciplines of Upper Turonian- Lower Coniacian marine deposits of the Tethyan Himalayan zone suggest that the regressions during ~90-89.8 Ma and ~92-91.4 Ma are due to the expansion of continental ice sheets (Chen et al., 2015). The finding upholds the concept of ephemeral polar ice sheets even during the greenhouse consitions (Ramkumar, 2015). Even studies of Flögel et al. (2011) indicate the existence of large volumes of snow in Late Cretaceous greenhouse conditions. Sea level in Cretaceous was about 50-70 m above present at ~80 Ma and rose to 70-100 m from 60-50 Ma and fell by ~70-100 m since 50 Ma (Miller et al., 2005). Studies by Kominz et al. (2008) suggest a peak sea level of ~75-110 m during the Cretaceous, close to the 100±50 m of Miller et al. (2005). Valanginian onwards till the end of Cretaceous, the sea-level remained high, with a peak during the Turonian (Ruban, 2015), with significant sea-level falls during Aptian, mid-Cenomanian, late-Turonian, and late Maastrichtian (Haq et al., 1987) and rose during mid-Santonian, mid-Campanian and early Maastrichtian (Ruban, 2015). The fall in the Turonian was followed by a rise in the Coniacian-Santonian (Kominiz et al., 2008); however, Haq's (2014) reconstruction suggests a fall throughout Turonian-Santonian. Ruban (2016) observed that no definite fall/rise could be suggested for the Campanian based on the uncertain observations of Haq (2014) and Kominz et al. (2008) however, the studies of Spasojevic and Gurnis (2012) and Müller et al. (2008) suggest a eustatic fall.

Initially, the glacio-eustatic cause was suggested for the sea-level fluctuations in the Cretaceous. However, when the sea level temperature difference from pole to the equator of mid-Cretaceous (24°C-30°C) was found comparable with the present day (50°C) (Hay, 2011), the cause was discarded (Ramkumar, 2015). Boulila et al. (2011) suggested that the Mesozoic greenhouse gases are related to the eccentricity cycles, with orbital forcing affecting sea-level change. The pervasive nature of carbonate platforms during complete Cretaceous period was ascribed to high eustatic sea level and climatic optimum due to seafloor spreading and high levels of atmospheric carbon dioxide (Phelps et al., 2015). Most of the oceanic crust produced in the Cretaceous resulted in high sea-level, high CO_2, warm global temperatures, and buoyant ridges displacing seawater onto low-lying parts of continents (Hays and Pitman, 1973; Larson, 1991). The middle-late Cretaceous water had low oxygen content compared with the present day (Jenkyns, 1980). Zorina et al. (2008) observed three global significant sedimentation breaks in the Late Cretaceous at the Albian/Cenomanian, Santonian/Campanian, and Maastrichtian/Danian boundaries which Ruban (2016) observed to coincide with the low stands of eustatic and global sea level of Kominz et al. (2008) and Haq, (2014).

1.2.2 DECCAN VOLCANISM

According to Sinton and Duncan (1997), the Cenomanian-Turonian boundary witnessed volcanism at the Caribbean oceanic plateau, Ontong Java oceanic plateau, and the Madagascar flood basalt volcanism. The Madagascar volcanism occurred during the separation of India from Madagascar. The three volcanic eruptions reduced the O_2 in the seawater by oxidation of hydrothermal material and increased biological productivity due to the release of bio limiting Fe nutrient in water consumed by phytoplankton together with O_2 to cause the bloom. Their modeling suggests that in the poorly ventilated Cretaceous Ocean, depletion of O_2 and carbon burial in seafloor sediments due to massive volcanism created oceanic anoxic events.

Skelton (2003) opined that India's famous continental flood basalt eruption is the Deccan Trap which occurred around 63-68 Ma ago with its peak around 5, 00,000 years of the end of the Cretaceous. Volcanoes play an essential role in changing the earth's climate by releasing gases like H_2O, HCl, HF, CO_2, and SO_2 into the atmosphere. SO_2 has a high potential in disrupting climate compared with CO_2 because SO_2 is released in large amounts compared with the existing number in the atmosphere. In contrast, the amount of CO_2 released is the same order as other sources. The total CO_2 released by Deccan volcanism was about $2.6\text{-}9.0\times10^{15}$ Kg which increased the CO_2 level to 75 ppm leading to global warming of 1-2°C, which is significantly less to cause a global climate change and extinction at the Cretaceous-Tertiary (K-T) boundary.

According to McLean (1985), the Deccan Traps covered parts of Central and western India, and the volcanism continued for about 0.53-1.36 Ma. The Deccan volcanism is linked with the K/T boundary mass extinction. Mantle degassing was a significant event during the K/T transition. The basaltic lava of 2.6×10^{6} km^2 was released in a short duration, and the excess CO_2 produced during the volcanism accumulated in the atmosphere and the marine mixed layer severely affected the carbon cycle.

1.2.3 EXTINCTION EVENTS

During the Cretaceous period, the Indian subcontinent was located in the latitude between ~30°S to 60°S (Boucot et al., 2013), separated from Australia, Africa, and Antarctica. Much extinction has been recorded in the geological history of the earth. However, the extinction at the Cretaceous-Tertiary (K/T) boundary is the major one, which recorded a significant faunal turnover and eliminated a large part of fauna living on the earth. 50-60% of marine genera became extinct at the Cretaceous-Tertiary (K/T) boundary (Sepkoski, 1990; Fig. 1.3). According to Skelton (2003), marine invertebrates like ammonites, inoceramids, rudists and certain species of corals, microfossils (foraminifers, coccoliths, and radiolarian), fishes, non-archosaurian marine reptiles, and non-avian dinosaurs became extinct while certain genera of echinoderms showed a reduction in number. Other groups of microfossils, such as benthic foraminifers, dinoflagellates, and diatoms, were less affected. In contrast, some groups like corals, brachiopods, snakes, lizards, turtles, birds, and certain mammal species survived the extinctions and are still present. The extinction also affected the diversity of terrestrial plants and insects feeding upon them. Studies by Perch-Nielsen et al. (1982) suggest $\delta^{13}C$ values becoming negative in the planktonic foraminifera at the K/T boundary seen at several sites worldwide. The Cretaceous sedimentary record provides critical insight into the mechanism of the events.

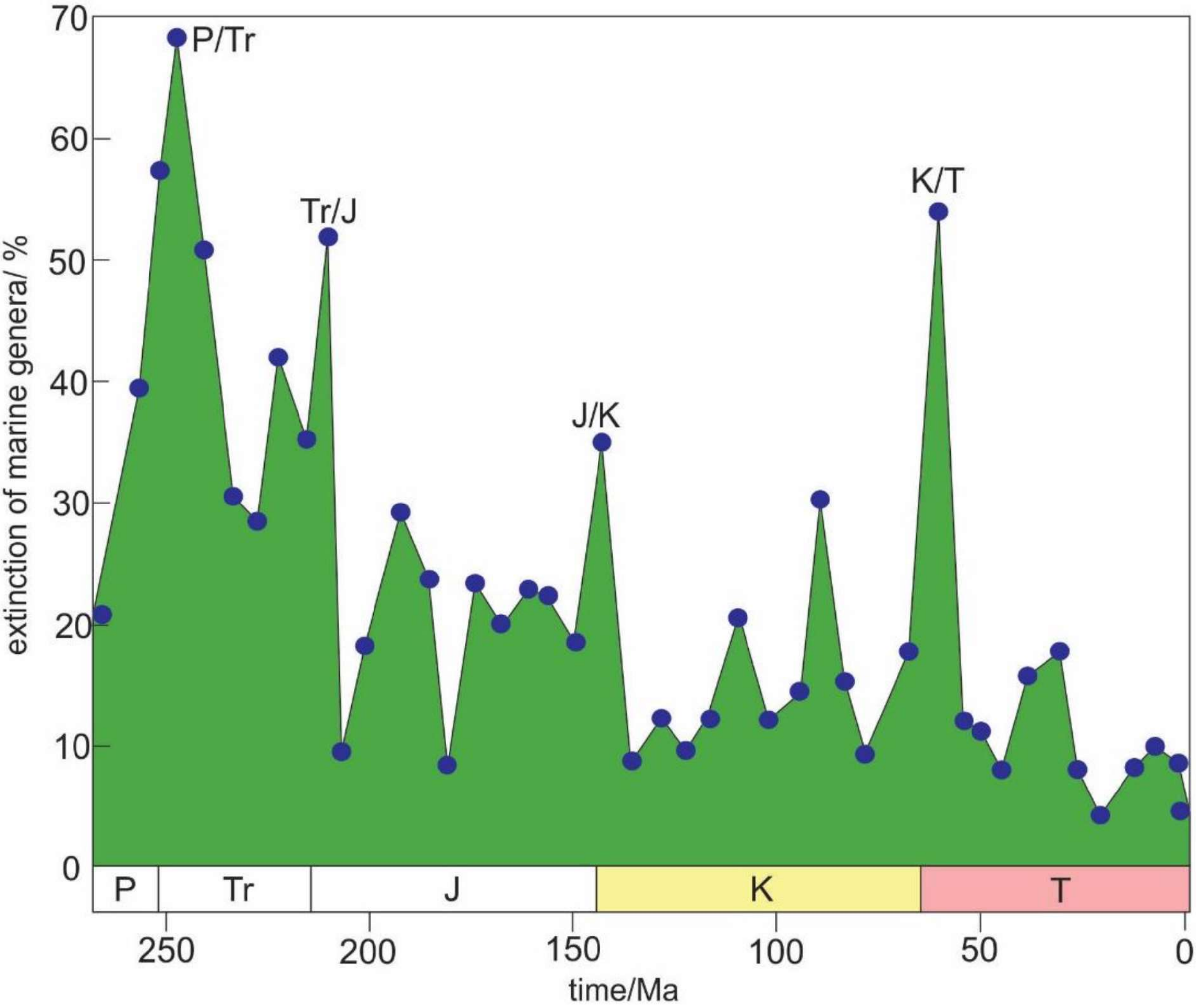


Figure 1.3 Extinction percentages of marine genera since last 270 Ma. The total number of genera is 10,383, of which 6350 are extinct (Sepkoski, 1990).

Modeling by Caldeira and Rampino (1990) suggests that the Late Cretaceous Deccan Trap eruption increased CO_2 concentrations in the ocean and atmosphere, creating a greenhouse effect and increasing global temperature and rainfall. Still, the warming due to CO_2 raised the earth temperature to 1°C and was an effect that did not cause K/T boundary extinction. The cause of K/T boundary extinction is a controversy to date. At most of the K/T boundary sections, a thin clay layer enriched in Iridium, a rare element in the earth's crust, is found. The element was found to occur with shocked minerals suggesting an asteroid impact. However, an abundance of the element can also be found in mantle-derived volcanics. Also, the huge craters required to create the implications are rarely seen on the earth. According to McLean (1985), the extinction at the K/T boundary during Deccan volcanism was not catastrophic but was gradual and selective. The sluggish marine circulation (Berger, 1979) and warmer deep oceans (14-15°C) during the Deccan volcanism led to a reduced accumulation of CO_2. The CO_2 was eventually stored in the mixed layer of the ocean and the atmosphere. The storage of CO_2 in the mixed layer lowered the pH of water, severely affecting $CaCO_3$ production and photosynthesis.

The Cenomanian-Turonian boundary (approximately 93.9 Ma, Cohen et al.., 2013) witnessed disappearance and drop in diversity of mollusks, dinoflagellates, and foraminifera (Hart and Ball, 1986; Kuhnt et al., 1986) and is defined as an extinction event in the Cretaceous (Raup and Sepkoski, 1984, 1986). Kuhnt et al. (1986) suggested the Cenomanian-Turonian extinction was caused by anoxia and affected mainly the midwater and shelf species. Also reported is the major terminal Cretaceous extinction event at Maastrichtian, which is used to mark the boundary between Mesozoic and Cenozoic, Hauterivian (Raup and Sepkoski, 1984), Aptian-Albian (Schlanger and Jenkyns, 1976) also known as OAE1, Barremian-Aptian-Albian and to a lesser extent Coniacian-Santonian (Jenkyns, 1980) known as OAE3 in Cretaceous.

Globally, the Cenomanian-Turonian oceanic anoxic events also known as OAE2 or Bonarelli Event (Tiskos et al., 2004) is represented by deposition of black shale facies globally in the oceanic, shelf, and epicontinental sediments and suggest global bottom water anoxic or dysoxic conditions (Hart and Ball, 1986; Schlanger and Jenkyns, 1976, Hart and Leary, 1989; Sinton and Duncan, 1997; Jenkyns, 2010), low O_2 concentration and a positive shift in the carbon isotope values of the marine carbonate and marine terrestrial organic matter (Arthur et al., 1988, Hasegawa, 1997), related to the excess burial of organic carbon (Jenkyns, 1980; Scholle and Arthur, 1980, Jenkyns et al., 1994; Pratt and Threlkeld, 1984). Modeling by Flögel et al. (2011) proves the role of emplacement of large igneous provinces during the Cenomanian-

Turonian to be the cause of an increase in CO_2 in the atmosphere and the OAE2. The Cenomanian-Turonian oceanic anoxic event coincides with the global thermal maximum (Jenkyns et al., 1994) and transgressions (Jenkyns, 1980, Schlanger and Jenkyns, 1976). The OAE2 had globally distributed occurrences across the Cenomanian-Turonian boundary at 93.6 Ma (Ogg et al., 2008) and lasted for about 500 kyr (Sageman et al., 2006; Voigt et al., 2008). It is argued that the high burial rates of organic carbon during this time led to the drawdown of atmospheric CO_2, which cooled the climate (Arthur et al., 1988; Freeman and Hayes, 1992; Kuypers et al., 1999).

1.3 CONCEPT OF THE STUDY

The conceptual section elaborates on stratigraphy aspects, emphasizing lithostratigraphy and sequence stratigraphy, sedimentary facies, ichnology, and its application to sequence stratigraphy. The various terminologies used in the present work are briefly described here.

1.3.1 STRATIGRAPHY

The word stratigraphy is derived from *stratum* (Latin) and graphia (Greek), which means studying rock succession and correlating geological events and processes in time and space. Stratigraphy is considered the fundamental discipline that helps reconstruct the events on earth and understand the evolution of life.

Stratigraphy *is defined as thescience related to studying of the rock strata, their succession, lithology, the process of deposition, fossil contents, physical evidence of the global and regional events, position in time and distribution of economic resources.*

It is important to discuss a few principles that form the foundation of present-day studies. The significant contribution to the field of stratigraphy in the eighteenth/nineteenth century comes from the work of William Smith and Nicolas Steno. Nicolas Steno postulated four principles in the 17^{th} century, which became crucial for understanding the formation of strata and fossils, and it earned him the title of “Father of stratigraphy.”

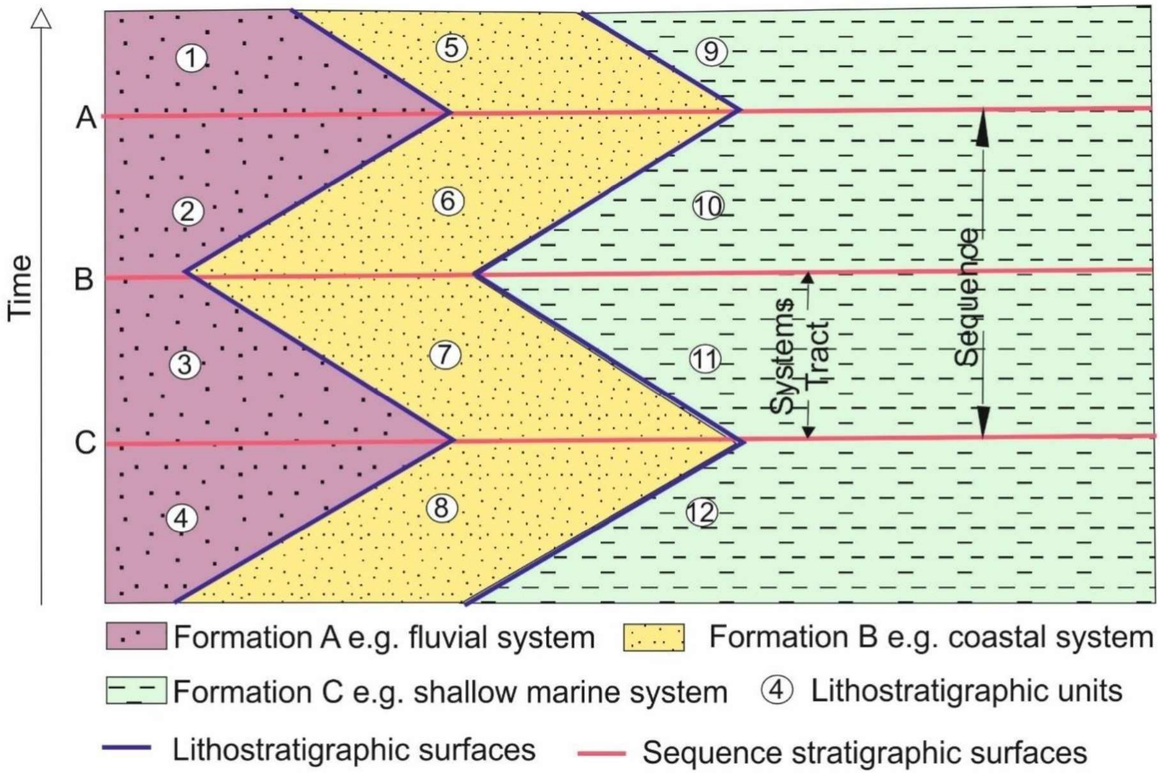


Figure 1.4 Conceptual contrast between lithostratigraphy and sequence stratigraphy (Emery and Myers, 1996 and Catuneanu, 2006).

A lithostratigraphic correlation would correlate units 1, 2, 3, and 4 of Formation A; units 5, 6, 7, and 8 of Formation B and units 9, 10, 11, and 12 Formation C, whereas a sequence stratigraphic correlation would correlate timelines A-A', B-B' and C-C' (Fig. 1.4). The changes in depositional trend (progradation, retrogradation, and aggradation) are marked by sequence stratigraphic changes which are events significant with timings controlled by turnaround points between transgression and regression (example A-A', B-B' and C-C' in this case). *Each system tract comprises three depositional systems and is defined by depositional trends:* progradational in 4, 8, and 12; *retrogradational* in 3, 7, and 11.

A sequence constitutes a complete cycle of base-level changes. The sequence stratigraphic boundaries cross the formation boundaries. *Sequence stratigraphy integrates time and relative sea-level changes to track the migration of facies.*

One of the principles is the law of superposition which states that the rock layers are arranged chronologically, with the oldest at the bottom and youngest towards the top unless some processes disturb it. He also postulated the principle of original horizontality (originally, all the rocks are deposited horizontally, filling the irregularities of the bottom), the principle of original lateral continuity (any strata deposited is continuous over the surface of earth unless there is some barrier preventing it from the spread) and cross-cutting relationships (a geological feature which cuts another is younger to the feature). William Smith postulated the principle of faunal succession, which states that the sedimentary layers contain fauna and flora deposited over each other in a specific order that can be traced to vast distances. This principle has been significantly applied to date to know the age of rocks and their fossils.

Based on the property types, the stratigraphic disciplines identified are allostratigraphy, biostratigraphy, chemostratigraphy, chronostratigraphy, lithostratigraphy, magnetostratigraphy, seismic stratigraphy, and sequence stratigraphy (Catuneanu, 2002). Lithostratigraphy deals with the strata organization into units based on lithic characteristics and stratigraphic position. Biostratigraphy deals with the correlation of rocks and assigns age to them based on the fossil assemblages. Allostratigraphy is the recognition of rock units based on the discontinuities bounding them. Sequence stratigraphy involves the subdivision and linkage of sedimentary deposits into unconformity bounded units that emerge from the interplay of sediment supply and variations in the rate of change in accommodation. Magnetostratigraphy deals with stratigraphic divisions of sedimentary rocks and layered volcanic rocks based on their magnetic properties. Chemostratigraphy is the correlation of rock units based on geochemical traits. Seismic stratigraphy is the study of stratigraphic and depositional facies as interpreted from seismic data. Chronostratigraphy deals with studying all rock strata formed with respect to time. The present study deals with the sequence stratigraphy and lithostratigraphy branches of stratigraphy in detail for the analysis of the Bagh Group of rocks.

1.3.1.1 Lithostratigraphy

The first edition of the International stratigraphic Guide -A guide to stratigraphic classification, terminology, and procedure by International Subcommission on Stratigraphic Classification (ISSC) was published in 1976 and edited by Hollis D. Hedberg. Later the second edition of the International Stratigraphic Guide was published in 1994 and edited by Amos Salvador with a more detailed description of igneous and metamorphic rocks, the addition of new chapters, and revision to the lithostratigraphy. To overcome the problem of access to the second edition of the guide, a third edition i.e., the abridged version of the International Stratigraphic Guide by ISSC, was published in 1999 and edited by Murphy and Salvador. This guide was proposed to promote the international agreement on stratigraphic classifications principles and develop internationally acceptable terminologies and procedures of stratigraphic classification. It is not a revised version of the International Stratigraphic Guide (1976, 1994) but its brief version omitting the history, glossary, explanatory text, examples of stratigraphic procedures, the extensive bibliography of stratigraphic classification, terminology, and procedures.

The publication of the International Stratigraphic Guide in 1976 draws attention to some shortcomings of the American Stratigraphic Code of 1961 and its revised form of 1970. The commission chose to rewrite the code. The North American Stratigraphic code, 1983 was prepared under the auspices of the North American Code of Stratigraphic Nomenclature (NACSN) and, to a large extent, is similar to the North American Stratigraphic Code, 2005 except for the revised biostratigraphic part. For areas outside North America, the International Stratigraphic Guide (Salvador, 1994) or its abridged version (Murphy and Salvador, 1999) is to be followed.

Thus, for the lithostratigraphic classification of Cretaceous rocks in the Lower Narmada Valley, the present study follows the International Stratigraphic Guide. The guide has laid a set of procedures for establishing and revising the stratigraphic units, which are briefly stated below:
a. Nomenclature: The geographic name of the unit should be derived from a permanent or an artificial feature near the unit and should be spotted in the standard published maps. The name is

combined with the rank in case of group and formation whereas for nomenclature of members. The name of formation also can be derived by combining the geographic location with the dominant lithology. The name of the member consists of a geographic name combined with the lithology and rank (member); this clearly differentiates the status of a unit either as formation or rank; however, the term member can be dropped if the distinction is not essential or if it is not necessary for clarity of meaning (Weller, 1960). The geographic name should be unique, and its spelling, once established, should not be changed; however, the associated rank and lithology can be changed. Multiple names assigned to a unit can be reduced if the correlation is established, prioritizing the earlier proposed name. The ISSC emphasizes retaining traditional well-established names and clarifies that the disappearance of the geographic name does not imply establishing a new name.

Synonymy: A stratigraphic unit can be recognized by two different names given at other places or times; however, if synonymy exists and to stabilize the units' priority is given to the widely used name and not necessarily the oldest name.

Homonymy: Using the same name formore than one stratigraphic unit creates homonymy and is not permissible.

<u>b. Intent and utility:</u> According to ISSC, revision or redefinition of an established unit without changing its name requires a strong justification and utility. The unit's rank can be changed, keeping its original definition, geographic name, and boundaries unchanged. A statement of intention is required to introduce a new unit.

<u>c. Stratotype:</u> The stratigraphic units must be well developed and exposed at the locality, where they are defined for their identification. Stratotype (type section) serves as a standard reference for the definition and /or characterization of a layered stratigraphic sequence is known as unit-stratotype. When it contains a specific point establishing a boundary between the two units, it is known as Boundary-Stratotype. The unit stratotypes, when combined, are known as Composite-Stratotype. The type locality is where the unit was originally described and/or named. The type area constitutes both the stratotype and type locality. Holo-, para-, neo-, lecto-, and hypostratotypes are various stratotypes. Holostratotype is the original stratotype designated by

the original author when proposing the stratigraphic unit or boundary. Parastratotype is a supplementary stratotype used in the original author's definition to demonstrate variability or some important feature not seen in the holostratotype. Neostratotype is the new stratotype proposed to replace the older one, which is not preserved or is inaccessible. Lectostratotype is a stratotype for a previously described stratigraphic unit and is chosen later due to the absence of a sufficiently designated holostratotype. Hypostratotype is proposed after the original designation of the holostratotype (and parastratotype) to extend knowledge of the unit or boundary to other geographic areas as an additional example of unit usually in other areas and is subordinate to the holostratotype.

d. Description of the unit at stratotype or type locality: The stratotype should be described in detail both geologically and geographically. The unit- and boundary-stratotype should be marked at a permanent geographic and geological feature. The study should provide an accessible stratotype and should ensure its preservation.

e. Unit Description: It includes the extent of the unit, its geomorphic expression, thickness, lateral lithological variation, stratigraphic relation, relation to other units, dimension, shape, distinctive or identifying features that can be used to extend the unit away from its stratotype and boundary-stratotypes. The details like measured sections, well logs, and maps are also included in the description of the new unit.

f. Geologic age: Other than the chronostratigraphic units, the age is not mandatory in the definition of the lithostratigraphic units but should be given wherever possible.

g. Depositional environment: It includes interpretation of the origin and environmental facies.

h. References to the literature: A complete historical background of the unit is desirable.

Apart from the above-stated norms, establishing a revised lithostratigraphy requires publication in a recognized scientific medium that is regularly published and readily available. The publication of revised lithostratigraphy in abstracts, field trip guidebooks, dissertation reports, company reports, etc., is unacceptable. The newly proposed proper names have a priority but do not justify replacing the well-established name because it is not well-known or is rarely used, nor does the priority justify the preservation of inadequately established names.

1.3.1.1.1 Lithostratigraphic units

According to Weller (1960), there is no absolute distinction between a group, formation, and member; however, a group, in general, is composed of two more formations. With decreasing rank, the units become more homogeneous and thinner. The same unit can be designated as a group, formation, or member in the same area or different area or at different times. Thus a unit originally recognized as a formation may become a group in another area and be divided into new formations. Similarly, a member recognized in one place may become formation in another area and be divided into new members. The formation is considered the fundamental lithostratigraphic unit formed under uniform conditions or under alternating conditions generating heterogeneous units, which in itself constitutes a unity.

Common geologic features	Mass properties	Contained peculiarities	Physical properties	Interpretative distinctions
Lithologic characters	Chemical composition	Characteristic fossils	Color	Genesis
Vertical continuity of deposition	Mineralogical composition	Pebbles, oolites, chert concretions, etc	Degree of consolodation	Age and time value
Lateral continuity of similar strata		Direction of cross-bedding, ripple marks, joints	Resistance to weathering & erosion	
Unconformable contacts or other boundaries		Size and type of granular constituents	Topographic expression	
Abrupt changes in lithology		Heavy minerals	Nature of residual soil	
Sequential relations to other formations		Varieties of clay minerals	Porosity and permeability	
Presence and persistence of key beds		Insoluble residues	Electric properties	
Cyclic repetition of strata		Trace elements	Magnetic properties	
		Concretion and chemistry of brines	Transmission of seismic waves	
			Radioactivity	
			Thermoluminescence	

Table 1.1 Various characteristics used to define formation or distinguish them from each other (Weller, 1960).

The criterion used for recognizing a formation are similarity in lithological composition, genesis, vertical relations to other formations, depositional time, and practicality in mapping; however, the concept of similarity in genesis is essential but cannot be considered as a firm basis for the definition of formations (Table 1.1). The characteristics used to define or distinguish formation from one another are grouped into common geologic features, mass properties, contained peculiarities, physical properties, and interpretative distinctions. However, they do not hold an equal value, and not all of them are used to recognize a formation but are used for correlation purposes. The formation is characterized by two most important characteristics- mappability and a unique gross lithology different from the adjacent formations. The boundaries of formations should be ideally unconformable, marking a break in the deposition or at least with contrasting lithological assemblage marked with an uneven contact surface, making the recognition sharper and clearer. Moreover, transitional formations or formations characterized by key beds or paleontological characteristics are less desirable than formations characterized by unconformities or sharp contrasted lithological units (Weller, 1960).

The following principles are suggested for defining a formation by Weller (1960).

1. It is a fundamental unit- two or more formations make a group, and a formation is not necessarily subdivided into members.
2. They should be recognized as practical rock units.
3. No limits are set for the thickness of the formation, but very thick and thin formations are undesirable; they should be mappable.
4. It should be defined by lithological characteristics and if possible, have a unique gross lithology.
5. Structural and paleontological characteristics may supplement lithological characteristics.
6. If these structural and faunal characteristics take precedence over lithologic, they should be clear and unequivocal.
7. Formations should be constituted such that their boundaries are very sharp and distinct.
8. If key beds are used as boundaries, they should be persistent and easily recognizable.
9. The same age of formation throughout their extent is desirable, but no time limits should be set.
10. Formations should not be redefined, or their boundaries changed without an important reason, and the redefinition, if any, should make them more distinct and practicable units than before.
11. Unless a much clearer and more practical stratigraphic classification are substituted, well-established formations should not be abandoned even if they violate the above-stated principles.

The recognition of groups has originated due to synthetic (combing formations due to similarity of lithologies and closely related fossils or occurrence of unconformity) or analytic (elevating the rank of an old formation and its splitting into constituents formations) ways. The synthetic groups are commonly combined based on fossil content and laterally pass into biostratigraphic and time-rock units (which should be considered stages) and are often confused with them. In contrast, the analytic groups have more distinct lithologic properties, and the constituent formation is likely to share the lithological similarities; these groups are not confused with the time-rock units.

The comparatively less essential and local lithological units within the formation are recognized as members, they can be named, but a formation need not be necessarily subdivided into members. The part of the formation of particular interest can be designated as a member, and the member need not be successive and adjacent (Weller, 1960). A bed is the smallest stratigraphic unit, and its plural may be equivalent to a member.

The lithostratigraphic boundaries are places at positions of lithic change. In intertonguing strata, they are arbitrarily placed within vertical or lateral lithologic gradation zones. The lithostratigraphic boundaries cross the time planes and the fossil ranges (Fig. 1.4).

The principles suggested for defining limits of formation by Weller (1960):

1. A formation should not be recognized beyond a point where lateral lithological changes occur, and the strata lose the characteristic features used to identify it at its type section.
2. The rock units should not be identified or extended solely based on paleontological characteristics.
3. Extension of units should be avoided beyond a single basin of deposition or into remotely separated regions.

1.3.1.1.2 Correlation

According to Weller (1960), correlation is the process of establishing mutual relations, and in stratigraphy, it is used to establish equivalent relations with respect to time. Correlation of the stratigraphic units or the facies is at times challenging because the rates of sedimentation have greatly varied from place to place during the same or different time intervals. The evidence used for correlation is grouped into two broad categories- physical and paleontological evidence. The physical evidence includes lithologic similarity, continuity of strata, position in a stratigraphic sequence, orderly variation in lithology, electric characters, unconformable relations, structural development, metamorphism, and radioactivity and is employed for short-range correlation. Still, its reliability decreases with an increase in distance between the outcrops. The paleontological evidence includes index fossils, paleontological sequences, paleontological similarity, and evolutionary development. The lithological similarity is considered to be a precise indicator of similar genesis rather than coeval distribution. After correlation, some units serve as reference units and forms bases for correlating the other units. Difficulties arise when the strata lack uniformity in the lithological characteristics and cannot be traced for a long distance, but if a major unconformity does not intervene in the sequence, the strata lying above and below the reference strata can be correlated irrespective of their lithological differences. The evidence of uniform lithology, continuity of strata, and its stratigraphic position are generally used for stratigraphic correlation. The orderly variations in lithology include the variations in grain size distribution.

1.3.1.2 Sequence stratigraphy

Sequence stratigraphy is a new method in stratigraphic analysis that has an application in the industry for the exploration and production of petroleum, academicians to study the genesis, history of evolution and internal architecture of the sedimentary basin fills, and to the government for mapping and correlation of the basins (Catuneanu, 2009; Fig 1.5a).

The flow chart depicting sequence stratigraphic analysis (Fig. 1.5b) involves preliminary data collection from outcrop/core and facies construction (Dalrymple, 2010). The facies are interpreted for depositional processes and are later merged for facies associations which are further interpreted for systems tract, and a sequence stratigraphic model is constructed. Sedimentology and facies analysis form the basis of sequence stratigraphy. According to Catuneanu et al. (2009), sequence stratigraphy focuses on analyzing facies variation, changes in the geometric character of the strata, and identification of key boundaries and surfaces, which further helps in understanding the order of basin fill and erosion. The system tracts are interpreted based on a stratal stacking pattern, its position within the sequence, and the types of bounding surfaces. The stratal stacking patterns define the particular type of genetic deposit, namely transgressive, normal regressive, and forced regressive, and respond to the interplay of changes in the rate of sedimentation and base level.

The advantage of sequence stratigraphy is that concepts are independent of scale; they can be applied to features produced in hours to millions of years. According to Catuneanu (2006),

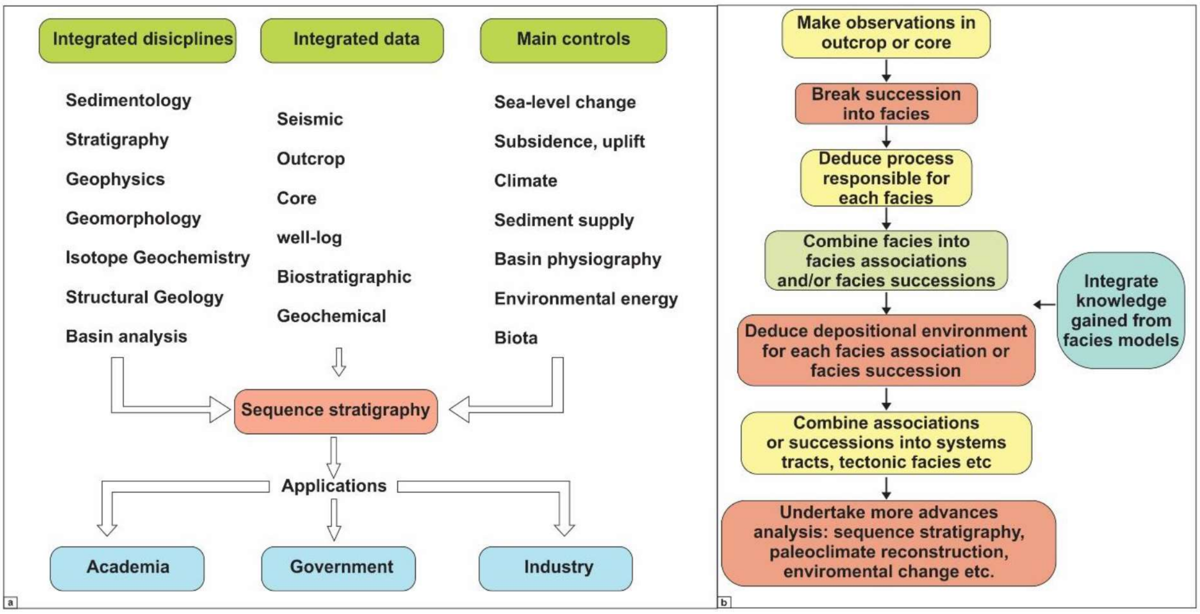


Figure 1.5 a. Flow chart explaining the progression of data assemblage for depositional environment interpretation and construction of sequence stratigraphic model followed in the present study (Dalrymple, 2010). b. Applications, controls, integrated disciplines, and data of sequence stratigraphy (Catuneanu et al., 2009).

lithostratigraphy and sequence stratigraphy both analyze the sedimentary sequence, but the lithostratigraphy mainly studies the organization of strata based on their lithological properties. In contrast, sequence stratigraphy focuses on the correlation of coeval strata irrespective of the facies (lithological) variation. The sequence stratigraphic surfaces are interpreted based on the nature of the contact (conformable or unconformable) and the facies in contact across each surface.

1.3.2 SEDIMENTARY FACIES

The common meaning of facies is general appearance. The term 'facies' was first introduced by Gressley in 1838 and later described by Teichert (1958), Krumbein and Sloss (1963), Middleton (1973; 1978), Reading (1978), and Miall (1984). The widely used and acceptable definition of facies is by Middleton (1978), who defines it as *"The more common (modern) usage is exemplified by De Raaf et al. (1965) who subdivided a group of three formations into a cyclical repetition of a number of facies distinguished by lithological, structural and organic aspects detectable in the field. The facies may be given informal designations (facies A, etc.) or brief descriptive designations (e.g., laminated siltstone facies), and it is understood that they are units that will ultimately be given an environmental interpretation; but the facies definition is quite objective and based on the total field aspect of the rocks themselves. The key to the interpretation of facies is to combine observations made on their spatial relations and internal characteristics (lithology and sedimentary structures) with comparative information from other well-studied stratigraphic units and particularly from studies of modern sedimentary environments".*

The difference in properties of grain size, sorting, physical structures, fossil content, and composition of syndepositional authigenic minerals forms the base of the creation of facies. In contrast, diagenetic and weathering characteristics such as color and type of cement are less important. According to Weller (1960), facies can be defined from a scale of individual beds to large scale bodies comparable to lithostratigraphic units, depending on study’s objective. In the stratigraphic literature, the term facies have been identified in different ways and the diagnostic features utilized are: lithologic characters (lithologic facies), metamorphic alteration (lithologic facies), biologic composition (biological assemblages or biologic facies), stratigraphic relations (stratigraphic facies which includes lithologic facies, biologic facies, and temporal facies), temporal sequence (temporal facies), structural form (structural facies, e.g., bioherms), environmental influences (environmental facies related to lithologic, biologic and tectonic environments, e.g., littoral facies, molluscan facies, geosynclinals facies, and bioherms), tectonic control, genetic interpretation (genetic facies based on process rather than conditions, e.g., bioherms and turbidity current deposits), geographic occurrence (geographic facies based on the geographical location), etc. The criterion of time-equivalent nature of stratigraphic facies poses a challenge in correlating these facies, and any deviation from the time-equivalence results in erroneous interpretation because the formations or horizons here are used as boundaries of stratigraphic facies, and the stratigraphic facies extend beyond the lateral limits of a formation. Also, the time-equivalent nature of facies (stratigraphic facies) is of less interest in the paleogeographic interpretation or the oil-producing region than the continuous lithostratigraphic units; the stratigraphic facies would correlate the heterogeneous lithological rock units based on their similar time of deposition. However, a detailed discussion on the stratigraphic facies is beyond the scope of the study.

Lithological facies are the most important types of facies in stratigraphy and form the basis for interpretation and include the criterion of color, bedding, composition, petrographic and faunal details. The lithological facies can be constructed in three ways- as variations in vertical sequence, as lateral variations, or irrespective of their relations with each other. Accordingly, rocks of similar composition and appearance are considered one facies regardless of their occurrence and relation to other rocks. This helps correlate similar rocks exposed in different areas, whereas the lateral and vertical variations are considered for stratigraphy. The term lithofacies is applied to characterize rock units and indirectly to the environment; however, the biological characters are not excluded since the fossils contained in the rock are essential for knowing the composition and imparting color to the rocks. The lithofacies concept is based on the criterion of appearance or composition used to differentiate them in contrast to stratigraphic facies, which use the form, nature of boundaries, and mutual relations. The lithofacies are further subdivided into two categories; the Class A type of facies are less heterogeneous and unrelated to their form or occurrence, e.g., shale facies, peloidal limestone facies. Large bodies characterize the Class B type of facies with no definite form, mutual relations and are restricted to certain areas or parts of the stratigraphic section; thus, there can be facies for each rock body, e.g., red-bed facies, evaporate facies, geosynclinals facies.

The term lithofacies is more commonly used for the lithologic stratigraphic facies; therefore, it is advised to correlate the temporally equivalent facies to reconstruct paleogeographic and geological history. The lateral facies variation of time-rock units can be compared whose boundaries correspond to the time planes. The lateral facies variation encountered in the stratigraphic facies boundaries can be located based on the qualitative distinction of two rock types or quantitative distinction, which involves the determination of lithology in percentage values. For intertonguing bodies, the concept of lithosome is used to demarcate the boundaries. The term lithofacies refers to a particular kind of rock whose relation to others was not specified. It forms a lateral subdivision of a stratigraphic unit differentiated from the adjacent subdivisions by its lithologic character. The boundaries of lithofacies correspond to the limits of some stratigraphic units. Lithofacies may be separated laterally in three ways- (1) Qualitative separation based on lithologic differences and naming them based on geographic location and the formation name e.g., Sagar Lithofacies of the Lameta Formation, (2) Statistical separation based on single or a combination of lithologic characters that can be expressed numerically e.g. percentage, (3) Irregular lithologic contacts of contrasting stratigraphic bodies (intertonguing units) showing transgressive or regressive mutual relations. Comparison of the successive set of facies reveals the changes in the depositional environment concerning the time at a particular locality, comparison of the time-equivalent facies throughout a region provides bases for paleogeographic relations and interpreting the lateral facies variation (i.e., sequential sets of time-equivalent facies) throughout time provides bases for the reconstruction of geological history.

Dalrymple (2010) defines *facies analysis* and *environmental interpretation* as dependent on observing sedimentary structure, texture, or fossil produced by the physical, biological, and chemical processes. These observable features are used to infer the process responsible for it and from the assemblage of processes, and thus, a depositional environment can be inferred. Therefore, ***facies****is a body or rock characterized by particular physical, chemical, and biological properties that make it differ from the rock lying above, below, or adjacent to it* (Dalrymple, 2010). In stratigraphy, the facies concept implies (1) the appearance of the body of a rock, (2) its composition, (3) the rock body itself as identified by its appearance or composition, and (4) the environment recoded by it. The ***facies model*** is a summary of the depositional system based on examples from recent and ancient deposits and is not to be inferred for an individual deposit. In contrast, ***facies succession*** is a vertical succession characterized by a change in attributes of grain size, bed thickness, sedimentary structures, or faunal composition. ***Facies association*** is a group of genetically-related facies with environmental significance (Collinson, 1969).

1.3.2.1 Microfacies

The microfacies concept was applied earlier to only the petrographic and paleontologic observations in thin sections; however, today, the concept is used for all sedimentological and paleontological data described from thin sections, rock samples or polished slabs (Flügel, 2010). Microfacies can be used for defining depositional models and recognizing facies zone for interpreting paleoenvironmental conditions. It can also be used for identifying sequence boundaries, sea-level changes, and systems tracts in sequence stratigraphy. The field data for microfacies analysis includes observation on lithology, texture, colors, bedding, and stratification (boundary planes and bedding surfaces, bed thickness, composition, and internal structure and vertical bed sequences), sedimentary structures, diagenetic features, fossils, biogenic structures, field logs, and compositional logs. The laboratory methods for microfacies analysis include slices, peels, thin sections, cast, etching, staining, petrographic microscopy, stereoscan microscopy, fluorescence, cathodoluminescence, and fluid inclusion microscopy, mineralogical, geochemical, trace elements, and stable isotope analysis. Further, based on the allochthonous or autochthonous nature of carbonate samples and the proportion of siliciclastic and carbonates in the mixed siliciclastic-carbonate rocks, classifications are proposed by Flügel (2010) for the nomenclature of microfacies.

1.3.3 ICHNOFACIES

Trace fossils straddle the boundary between sedimentology and paleontology (McIlRoy, 2004); although the trace fossils destroy the primary sedimentary structures but reveal paleoenvironmental information at a very high resolution compared with the primary physical sedimentary structures. Ichnofossils are the biogenic sedimentary structures comprising burrows, tracks, trails, borings, and other traces of organisms. Ichnology envelopes a wide range of organisms, their behavior, and habitat, not the actual body parts, which differentiate them from the body fossils (Frey, 2012). Ichnology applies to paleontology, archaeology, sedimentology, stratigraphy, geochemistry, and reservoir characterization. Trace fossils are generally observed in outcrops. Other techniques are coring, peeling, and casting of trace fossils. These days, the coring technique has gained momentum and is essential when no other source of information is available, especially for the chalk deposits that lack the bedding surface. The scanner-imaging technique is used for core analysis (Buatois and Mángano, 2011).

Ichnofacies is a combination of organism behavior (MacEachern et al., 2007) that recurs in time and space and directly reflects environmental conditions (Bromley, 1996). The ichnofacies concept helps understand the salinity, oxygenation, sedimentation rate, food supply, waves and currents energy, and substrate consistency. Recently, it was realized that ichnology could be a significant tool for interpreting rock records and thus crucial for the petroleum industry. Trace fossils are sensitive to the paleoenvironmental changes due to sea-level fluctuations but have been overlooked in the sequence stratigraphic studies (Savrda, 1991).

Seilacher (1967) introduced the ichnofacies concept, which emphasized marine succession and was originally based on recurring associations of trace fossils linked with the recognition that the factors controlling the distribution of marine trace makers that change with increasing distance from the paleocoast. This contribution of Seilacher was a significant revolution in the field of ichnology.

Ichnofacies is defined as the ethological grouping of distinctive, recurring (both in space and time) trace fossils, reflecting specific combinations of the organism response to environmental conditions (MacEachern et al., 2007). Seilacher (1967) established six archetypal ichnofacies, *Skolithos, Cruziana, Zoophycos, Nereites, Glossifungites,* and *Scoyenia* ichnofacies, based on the characteristic ichnogenera. Later five new ichnofacies were erected, namely *Trypanites* (Frey and Seilacher, 1980), *Teredolites* (Bromley et al., 1984), *Psilonichnus* (Frey and Pemberton, 1987), *Mermia* (Buatois and Mángano, 1995), and *Coprinispheira* (Genise et al., 2000). The above ichnofacies can be put into categories of soft ground ichnofacies (*Skolithos, Cruziana, Zoophycos, Psilonichnus, and Nereites*), substrate controlled ichnofacies (*Glossifungites, Teredolites, Trypanites*), and continental ichnofacies (*Scoyenia, Mermia, Coprinispheira, Termitichnus, Celliforma, Octopodichnus-Entradichnus*). The ichnofacies are briefly described below based on McILRoy (2004). The *Skolithos* ichnofacies is characterized by vertical traces made by suspension feeders deposited above a fair-weather wave base. *Cruziana* ichnofacies consist of horizontal and vertical traces made by deposit feeders between fair-weather and storm wave bases. *Zoophycos* Ichnofacies is made by pervasive deposit feeders suggesting shelf and slope bathymetry below storm wave base. *Nereites* ichnofacies are characterized by shallow burrows with complex morphologies made on the basin floor with turbidites. *Glossifungites* ichnofacies are traces preserving scratches of suspension feeders and are made on firm facies with incipient submarine lithification. *Scoyenia*is the non-marine ichnofacies made in freshwater conditions. *Mermia* ichnofacies consist of horizontal to subhorizontal grazing, feeding, and locomotion structures made in freshwater low-energy conditions. *Coprinispheira* ichnofacies for the permanently subaerially exposed continental setting found in paleosol. *Psilonichnus* ichnofacies represent marine, marginal-marine, and freshwater conditions in beach backshore, coastal dunes, washover fans, and supratidal flats. *Teredolites* ichnofacies constitute borings made in woody/xylic substrates. *Trypanites* ichnofacies encompass dwelling borings made in fully lithified marine substrates.

Ichnoassemblageis a group of trace fossils preserved in a single rock unit irrespective of its time of emplacement or recurrence in the stratigraphic record i.e., it may have been emplaced simultaneously as a single ecologically-related group or may represent several overprinted events of bioturbation (Bromley, 1996).

Together the ichnofacies and lithofacies data are analyzed for the depositional environment of the Bagh Group rocks in the WLNV and further analysis of the sequence boundaries, surfaces, systems tract, and improved broad-scale facies interpretation.

1.3.3.1 Application of Ichnology to Sequence stratigraphy

Pemberton et al. (2000) stated the long temporal range, narrow facies range, no secondary displacement, occurrence in unfossiliferous rocks, and creation by soft-bodied organisms are advantages of trace fossils in interpreting the ancient rock record and also useful in recognizing the stratigraphic surfaces. Extensive data have been collected to date, suggesting the association of substrate-controlled trace fossils with the sequence stratigraphic surfaces. According to Catuneanu (2006), the two broad groups of ichnofacies are softground and hardground suggesting conformity and unconformity, respectively. The softground ichnofacies suggest active sedimentation on subaqueous depositional surfaces except for the *Termitichnus* Ichnofacies, typical of subaerial conditions. The *Glossifungites* (firmground) ichnofacies develop on firm, unlithified dewatered muds and are subjected to erosion. The facies is related to scouring surfaces made by tidal currents and waves during transgression (Catuneanu, 2006). The *Trypanites* (hardground) ichnofacies form on fully lithified surfaces and are thus crucial for delineating unconformities in the sequence. The generation of lithified surfaces may occur in any environment, but their colonization suggests transgression and hence tidal or wave- ravinement surfaces or maximum flooding surfaces (Catuneanu, 2006). *Teredolites* ichnofacies are characteristics of woody substrates (woodground); it may or may not require exhumation before colonization but has colonizing organisms different from the freshwater settings. The ichnofacies occur below the transgressive tidal or wave-ravinement surfaces.

1.4 STUDY AREA

The study area is located on the western margin of the Indian plate in the Lower Narmada Valley (LNV), comprising the Bagh Group rocks exposed in patches. Although the study area is restricted to Narmada, ChhotaUdepur, and Rajpipla districts (Western Lower Narmada Valley) of Gujarat state, field check and laboratory studies of samples from Eastern Lower Narmada Valley also have been carried out for correlation and lateral facies variation. The study area is situated between latitude 22° 30' 00" and 21° 44' 38"; longitude 73° 34' 00" and 74° 06' 00". The present study is carried out in the following 36 localities, namely (1) Songir, (2) Ghantoli, (3) Chosulpura, (4) Chametha, (5) Vajeriya, (6) Agar, (7) Naswadi, (8) Devaliya, (9) Uchad, (10) Sultanpura, (11) Bilthana, (12) Bhekhadiya, (13) Bhadarwa, (14) Navagam, (15) Gulvani, (16) Mathsar, (17) Karvi, (18) Ambadongar, (19) Vajepur, (20) Mogra, (21) Chikhli, (22) Galesar, (23) Mohanfort, (WLNV) (24) Sejagaon, (25) Rampura, (26) Naingaon, (27) Jaminyapura, (28) Risawala, (29) Sitapuri, (30) Avral, (31) Badiya, (32) Chakdud, (33) Atarsuma, (34) Dhursal, (35) Borghata, and (36) Jeerabad (ELNV).

1.5 AIMS AND OBJECTIVES

The study aimed to investigate the Bagh group sequence of the WLNV on sedimentological and ichnological aspects astratigraphy of succession Lower Narmada Valley (Gujarat) using data. The objectives of this investigation therefore included:

1. To formalize the lithostratigraphy and analyze the sedimentological characteristics.
2. To document the trace fossils and analyze for paleoecological parameters.
3. To integrate sedimentological and ichnological data to delineate the sequence stratigraphic (boundaries, surfaces, and system tracts) and reconstruct the sequence architecture of Bagh Group rocks of Lower Narmada Valley of Gujarat.

1.6 METHODOLOGY

The Cretaceous Bagh Group rocks range in age from Berriasian? (Neocomian) to Coniacian is divided into Songir Formation, Vajepur Formation, Nodular Limestone, Bilthana Oyster Formation, and Uchad Formation (Shitole et al., 2021). The outcrops exposing Bagh Group rocks were studied at various localities of Gujarat and Madhya Pradesh (Fig. 1.6). Field studies form an integral component for the interpreting of the depositional environment, lithostratigraphy, sequence stratigraphy, palaeoecological conditions based on trace fossils. The interpretation of the depositional environment of rocks based on the field studies combined with thin-section is emphasized by several workers. To analyze the Cretaceous succession of Western

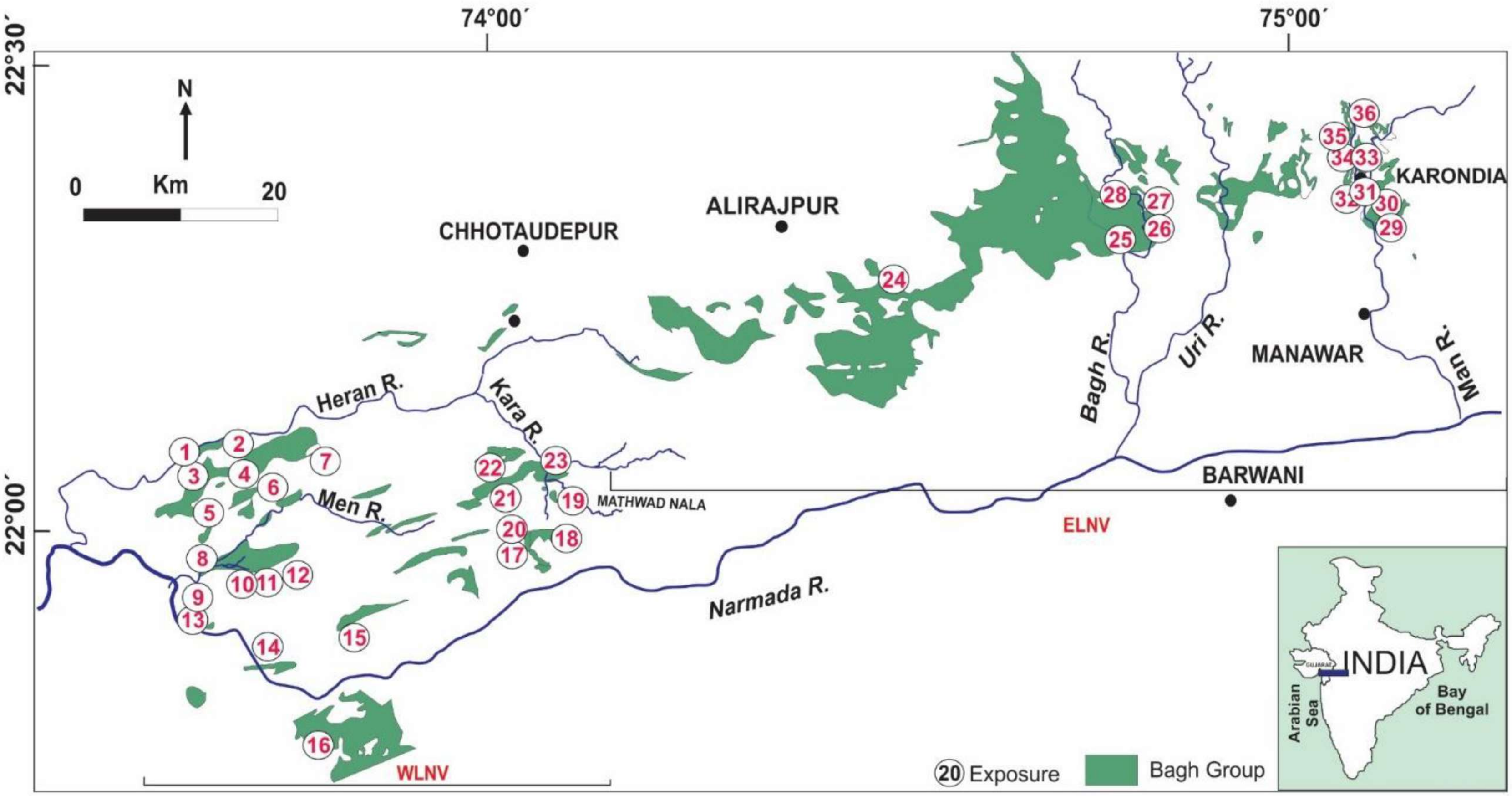


Figure 1.6 Map showing the studied sections of the Bagh Group of WLNV (location no. 1-23) and ELNV (location no. 24-36).

India, field studies were carried out at around 23 sections (Fig. 1.6). The lithofacies were assigned to rocks based on similar composition and appearance irrespective of their occurrence and relation to other rocks, which helps correlate similar rocks exposed in different areas. Microfacies analysis was done for carbonate rocks; they are further used to define the depositional environment, recognize facies zone, and identify sequence boundaries, sea-level changes, and systems tracts. The International Stratigraphic Guide was used to classify Cretaceous rocks in the Lower Narmada Valley for the lithostratigraphic classification. The characteristics like uniform lithology, continuity of strata, and its stratigraphic position are used for stratigraphic correlation in the study area.

To achieve the objectives following methodologies have been adopted:

- Stratigraphic sections have been measured at different localities, and lithologs were prepared.
- Systematic sample collection and documentation of sedimentary structures (physical and biological) was done.
- Petrographic study of the samples was done for textural parameters and mineralogical composition.
- Based on field observations and laboratory studies and the observed vertical and lateral lithological variations, lithostratigraphy is revised as per the International Subcommission on Stratigraphic Classification.
- Lithofacies analysis has been done based on field and laboratory data.
- Trace fossils were identified at the ichnospecies level, and their stratigraphic position was marked.
- Density and diversity of the trace fosssils were observed; ethological, ichnoassemblage, and ichnofacies analysis was done to interpret the palaeoecological parameters.
- Based on ichnological and sedimentological data, various sequence stratigraphic surfaces, boundaries, and system tracts are evaluated; a sequence stratigraphic model was constructed.
- The sequence of the WLNV was compared with the pervasive Tethyan basins to understand the various geological events.

CHAPTER 2
GENERAL GEOLOGY

2.1 INTRODUCTION

The Narmada Basin is an intracratonic rift basin and has the most complete record of the Cretaceous Period from Berriasian? (Shitole et al., 2021) to Maastrichtian (Prasad et al., 2017) comprising the rocks of Bagh Group, Lameta Group, and the Deccan Traps. The Narmada Basin is bounded by a several strike-slip faults and formed due to the reactivation of the Narmada Son Lineament during Early Cretaceous (Biswas, 1987). The Cretaceous Bagh Group rocks are exposed in the Lower Narmada Valley and unconformably overlie the Precambrian rocks. They are overlain by the rocks of Lameta Group, Deccan Traps, and Quaternary sediments. The chapter gives an overview of the tectonic history, evolution, and geology of the Narmada Basin.

2.2 GEOLOGY OF THE WESTERN LOWER NARMADA BASIN

Narmada rift basin extends from the western margin to the interior of the Indian peninsular and comprises Precambrian, Mesozoic, and Tertiary rocks, which are overlain by Quaternary sediments. Narmada and Tapti Rivers originate in Amarkantak (Anuppur district) and Satpura range in the Gawligarh hills of the Deccan plateau (Betul district) in Madhya Pradesh, respectively, are the two main rivers in the study area with course close to the Son-Narmada-Tapti (SONATA) lineament. Most of the area between the Narmada and Tapti River is covered by the Deccan Traps. The Cretaceous sedimentary rocks (Bagh Group and Lameta Group) underlie the Deccan Traps and occur as isolated patches over the Precambrian basement (Fig. 2.1). The Narmada valley is divided into two, eastern and western parts along its strike, and the divide is around Barwaha in Madhya Pradesh (Ghosh, 1976). The Bagh Group rocks are limited to the western part of the Narmada Valley (also referred to as Lower Narmada Valley). The Narmada River flows through Deccan Traps, Bagh Group rocks, and Quaternary deposits in the western part. In contrast, in the eastern part, it cuts the Gondwana, Vindhyan, Bijawar, and Archean rocks. The generalized stratigraphic succession observed in the study area is given in Table 2.1. The Narmada Son Lineament (NSL) is the conspicuous feature in the Indian Subcontinent (Tewari et al., 2001). West (1962) pointed out that Gondwana's are restricted to the south of NSL and Vindhyans to the north. In the central part/ELNV, both Vindhyans and Deccan Trap are exposed to the north and south of NSL.

2.2.1 PRECAMBRIAN

The Precambrian rocks in the Lower Narmada Valley comprise Archean unclassified granites and gneisses, Proterozoic metasedimentaries, Bijawars, and Vindhyan Supergroup. The Precambrian rocks observed in the Western Lower Narmada Valley can be categorized into the Pre-Champaner unclassified granites and gneisses, Aravalli Supergroup, and Post-Delhi igneous intrusive. Jambusaria (1970) suggested the unconformable relation of the overlying Champaner Group of rocks with the granites and gneisses and considered it the basement. The Aravalli Supergroup consists of Jharol, Rakhabdev Ultramafic suite, Lunawada, and Champaner; however, only the Lunawada and Champaner groups are exposed in the study area (Merh, 1995). The rocks of Lunawada and Champaner groups are considered an extension of the southern Aravalli Mountain Belt (SAMB) and comprise metasedimentaries. The Lunawada Group is divided into Kalinjara, Wagidora, Bhawanpura, Chandanwara, Bhukia, and Kadana formations in ascending order. It consists of mainly phyllites, mica schists, chlorite schists, meta-siltstones, meta-semipelites, meta-protoquartzites, petromict meta-conglomerate, manganiferous phyllite, dolomitic limestone, and phosphatic algal dolomite (Gupta et al., 1980, 1992). Only Kadana Formation represents the Lunawada Group in Gujarat. Recent geochemical studies of the calc-silicate rocks occurring in the Kadana Formation of Lunawada Group suggest calcareous sandstone with minor clay as the protolith and a low-moderate weathering of the source rocks in cold and arid climatic conditions (Akolkar and Limaye, 2020). Studies of Mamtani (1998) suggest that rocks of Lunawada Group have undergone metamorphism up to lower amphibolite facies.

The overlying Champaner Group of rocks occurs as isolated patches but has gained attention due to manganese and phosphorite deposits in it. The manganese deposits occur in the Shivrajpur Formation and the phosphorite deposits in the Khandia Formation. The metasedimentary rocks of the ChampanerGroup are folded and consist of dolomites, quartzites, phyllites, metaconglomerate, metagraywacke, mica schist, and dolomitic limestones. Studies of Jambusaria and Merh (1967); Das et al. (2009) suggest that Champaner Group rocks are metamorphosed up to green-schist facies. Only the Godhra Granite is exposed in the study area of the Post-Delhi igneous intrusive. The age of the Aravalli Supergroup is bracketed between 2000-2500 Ma,whereas the Godhra granite is dated 955±20 Ma (Gopalan et al., 1979).

2.2.2 BAGH GROUP

'Bagh Beds' is named after the type locality in Bagh town of Dhar district, Madhya Pradesh. The area is famous for its rock-cut monument-PanchPandoo caves, also known as Bagh caves. The caves are carved in the basal sandstone-dominated unit of the Bagh Group by the Buddhists during the 4^{th} -6^{th} century AD (Fig. 2.2). The first mention of the lithology of the caves can be found in the work of Captain Dangerfield in 1818, which describes the sandstone having an argillaceous cement intervened by layers of claystone at the top and a six feet thick claystone unit overlying this at the top. Later Stewart (1821) described the lithology encountered on the route from Mhow in Madhya Pradesh to Baroda in Gujarat via Dhar, Tila, Parrah (Para), and Rajpur. Impey (1856) described the Bagh caves and the rocks in them. Based on fossils contained in the rocks, Carter (1857) and Keatinge (1856) assigned the rocks Neocomian and Cretaceous age, respectively. Later Duncan (1865) correlated the fauna of Bagh Group with the European Upper Greensand and Lower Chalk fauna. Blanford, in 1869, was the first to systematically study the rocks belonging to formations of Lametas, Coralline Limestone, Deola and Chirakhan Marl, Nodular Limestone, Nimar Sandstone, and Mahadeva and were assigned as "Bagh beds." Later, Medlicott (1875) showed the Mahadevas belonging to Gondwana Supergroup. Bose (1884) resurveyed the area between Nimawar and Kawant and gave a detailed account of the Geology of the Lower Narmada Valley based on the primary database of Blanford (1869). The study area was split into Nimawur-Barwai, Bag Malesar, and Rajpur-ChotaUdepur and divided the Upper Cretaceous rocks into three units, namely Nodular Limestone, Deola and

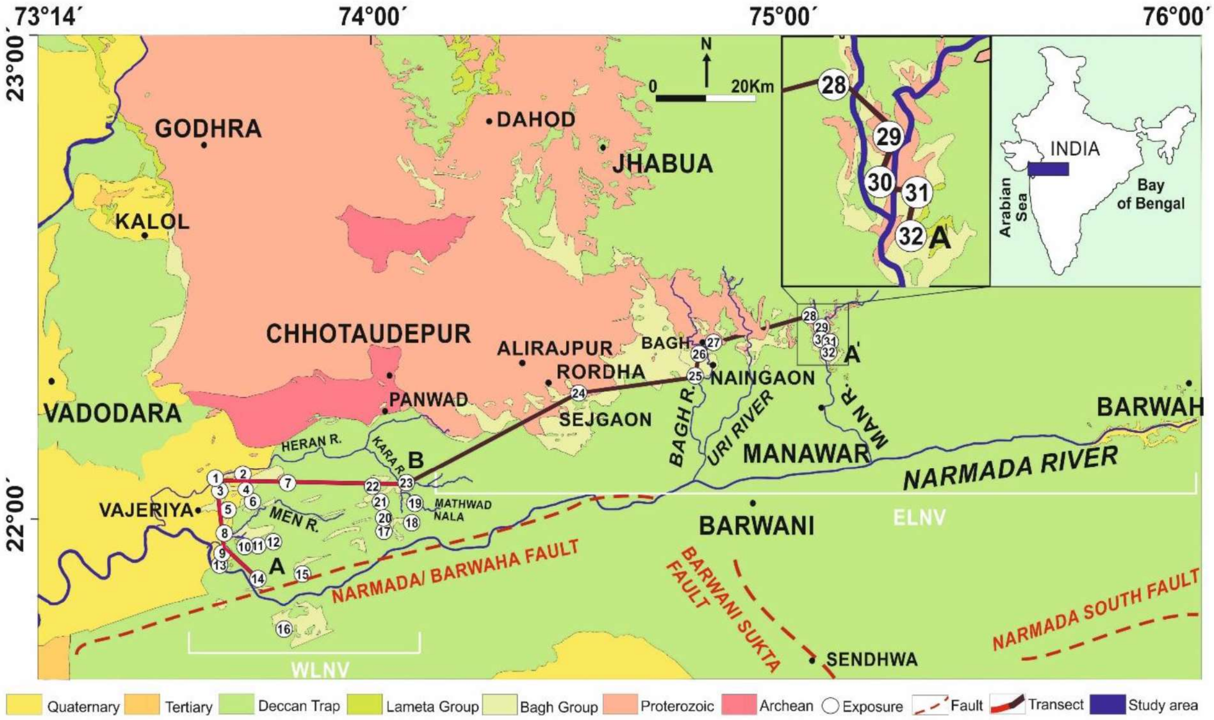


Figure 2.1 Geological and Tectonic map of the Lower Narmada Valley (Shitole et al., 2021; Abdul Azeez et al., 2013 and Jain et al., 1995) with studied localities of the Bagh Group: 1. Songir, 2. Ghantoli, 3. Chosalpura, 4. Chametha, 5. Vajeria, 6. Agar, 7. Naswadi, 8. Devaliya, 9. Uchad, 10. Sultanpura, 11. Bilthana, 12. Bhekhadiya, 13. Bhadarwa, 14. Navagam, 15. Gulvani, 16. Mathsar, 17. Karvi, 18. Ambadongar, 19. Vajepur, 20. Mogra, 21. Chikhli, 22. Galesar, 23. Mohanfort, 24. Sejagaon, 25. Rampura, 26. Risawala/Gayatri Temple, 27. Bagh Section (SE Bagh Town), 28. Borghata/ Ratitalai, 29. Dhursal, 30. Badia-Karondia, 31. Avral, 32. Sitapuri. Abbreviations: WLNV, Western Lower Narmada Valley; ELNV, Eastern Lower Narmada Valley; R, River. Localities no. 28 to 32 are shown in an enlarged view. A-B-A′ represents section lines across the Narmada Basin.

Chirakhan Marl, and Coralline Limestone. The occurrence of igneous, metamorphic, Bijawars, Vindhyans, Gondwanas, Lower Cretaceous Nimars, Upper Cretaceous (Nodular Limestone, Deola and Chirakhan marl, Coralline Limestone, and Lametas are described in detail in all three areas.

The Bagh Group rocks are exposed from Barwah (Madhya Pradesh) in the east to Vajeriya- Songir-Chosalpura (Gujarat) in the west (Fig. 2.1) along the Narmada-Son Lineament. The Bagh Group rocks of WLNV are mostly exposed to the north of the Narmada River, but few exposures are also observed southward at Mathsar, Vandri, and Kanji villages of the Gujarat and Maharashtra states. The Bagh Group rocks rest unconformably over the Precambrian rocks (Tripathi and Lahiri, 2000) and are capped by the Lameta and/or Deccan Trap formations. The exposures of the Bagh Group of ELNV are more or less continuous while they are patchy in WLNV, covered mainly by Deccan Traps (Fig. 2.1). The rocks overlie the Precambrian Bijawars in the ELNV (Bhattacharya and Jha, 2014), whereas in the WLNV, the rocks overlie quartzites and phyllites of the Precambrian Aravalli Supergroup. The propagation of the Narmada rift progressively advanced to the east, depositing the thickest sediments in the WLNV. The Cretaceous succession of WLNV comprises a fluvio-marine sequence. The Bagh Group in the ELNV can be grouped into Nimar Sandstone, Nodular Limestone, and Coralline Limestone, whereas in the WLNV, the rocks are, till date, informally grouped as Songir Formation, Calcareous Sandstone, Bilthana Oyster Bed, and Navagam Limestone. The Deola-Chirkahan Marl and Coralline Limestone of ELNV disappear towards the west, and the Bilthana Formation becomes a distinct unit. The basal unit, also known as Nimar Sandstone/ Nimar Formation/ Songir Formation, comprises conglomerate and sandstone-dominated rocks with siliciclastics derived from older Precambrian rocks. The lower part of the clastic sequence is deposited in a fluvial environment during the Early Cretaceous, whereas the upper part represents estuarine facies (Tandon, 2000). The basal clastic-dominated unit is derived from a cratonic source of low-grade metamorphic origin (Madhavraju et al., 2004). The marine Late Cretaceous (Turonian) succession, also known as Nodular Limestone/Navagam Limestone/Bilthana Oyster Bed, is dominated by mixed siliciclastic-carbonate rocks with sandstones, shales, and limestones. These rock types show lateral variation except the Nodular Limestone, a persistent unit in the basin with variable thickness. These transgressive deposits are overlaid by sandstones and mudstone of the Coniacian age, having a significant hiatus at the top represented by an unconformable contact with the Lameta Formation and the Deccan Traps of Maastrichtian age. According to Biswas (1982), the basin has a short geological history limited to Cretaceous with the basal Nimar Formation deposited in fluvial conditions deposited by a river flowing along the Narmada lineament grades to deltaic facies towards the western margin of the basin. The valley later opened into a rift basin and deposited the marine sediments in the Late Cretaceous, which was abruptly terminated with regional uplift followed by Deccan volcanism.

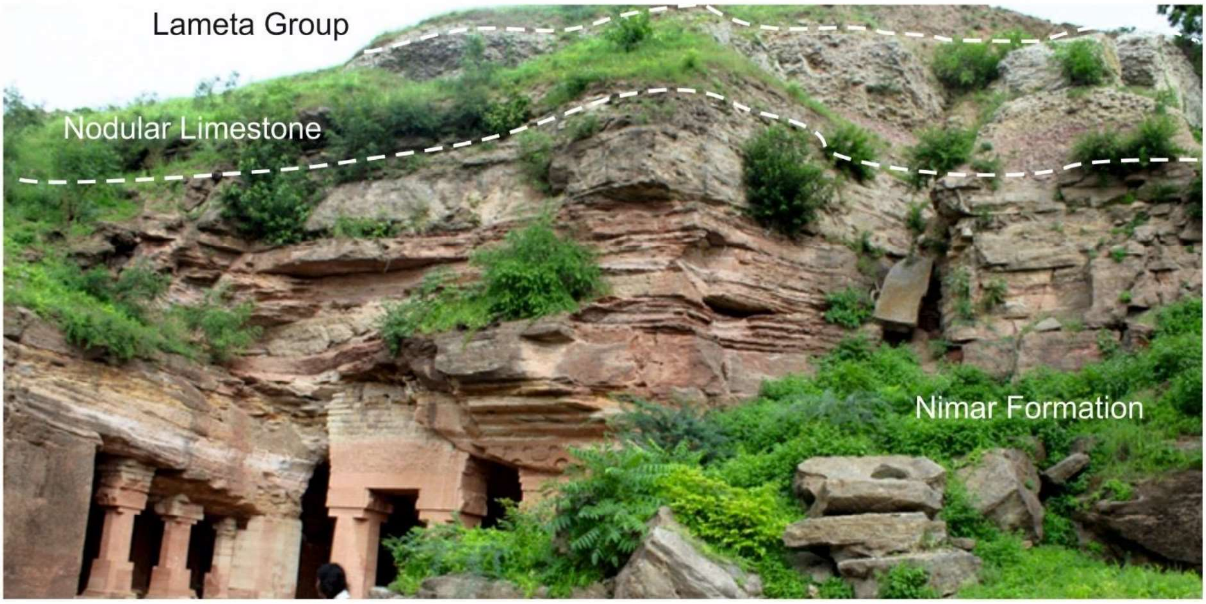


Figure 2.2 An almost complete sequence of the Bagh Group (ELNV) exposing the basal Nimar Formation and Nodular Limestone capped by the younger Lameta Group. Note: Buddhist caves in the Nimar Sandstone at Bagh village, Dhar district of Madhya Pradesh.

2.2.3 LAMETA GROUP

Lameta Group of rocks occurs as isolated patches in Gujarat, Madhya Pradesh, and Maharashtra states of India and is famous for the containing dinosaur fossils. The Lameta Group of rocks is extensively studied for the paleontological evidence of the K-T boundary extinction event. Along with dinosaurian eggs and bones, several other animal and plant fossils, like crocodile bones, algae, lizard eggs, fish remain, frogs, and palynomorphs, are also reported from the unit, which strongly points towards the Maastrichtian age. Recently, Prasad et al. (2017) elevated the status of the Lameta Formation to the group and divided the sequence into two formations, namely Hatini Limestone and Katkut Sandstone. The Hatini Limestone comprises calcareous sandstone, limestone with chert concretions, and dinosaur fossils. The Katkut

Sandstone is characterized by ferruginous red sandstone and chert with wood logs. In WLNV, the Lameta Group of rocks is found lying unconformably over the Men Nadi Limestone Member of Uchad Formation (Shitole et al., 2021) in localities like Bhekhadiya, Vajepur, and Bhadarwa, whereas in ELNV, they unconformably overlie the Coralline Limestone. At the Rampura section in ELNV, the Coralline Limestone of Bagh Group is found conformably passing into the Cherty limestones of Lameta Group. The Hatini Limestone and Katkut Sandstone are characterized by friable ferruginous sandstone with silty clays and calcareous sandstone with chert replacement, respectively. Abundant dinosaurian fossils are recovered from the unit, both from the eastern and western sectors of the Lower Narmada Valley. Sauropod dinosaurian bones of *Antarctosaursseptentrionalis*and theropod dinosaurian bones *Rajasaurusnarmadensis* (Jain and Bandhopadhya, 1997; Wilson and Upchurh, 2003; Wilson et al., 2003, see Mankar and Srivastava, 2019) and nesting sites of *Megaloolithuscylindricus, M. jabalpurensis, M. megadermus* and *Fusioolithusbaghensis* (Dwivedi et al., 1982; Mohabey, 1983, 1991; Sahni, 1995; Loyal et al., 1999; Vianey-Liaud et al., 2003; Fernández and Khosla, 2015, see Mankar and Srivastava, 2019) are reported from the Balasinor and Rayoli of Kheda district in WLNV. It is considered to be deposited in fluvio-lacustrine environment during the end-Cretaceous.

2.2.4 DECCAN TRAP

According to Merh (1995), the outpour of huge volumes of Deccan basalt marks the Cretaceous-Tertiary boundary, and it was the time when the Indian plate was moving northward at a fast rate, the breakup of Madagascar (80 MY) and Seychelles (65-60 MY) from India and the early collision of Indian plate with Eurasia is the plate tectonic events coinciding with the stages of Deccan volcanism. The Deccan Trap represents the most significant episode of continental flood basalt volcanism in the Phanerozoic releasing 5×10^{17} moles of CO_2 in the atmosphere, disturbing the carbon cycle of the atmosphere and a likely trigger of the Iridium anomaly and K-T boundary extinction (McLean, 1985).

It covers about 5,00,000 sq. Km. of the Indian subcontinent comprising mainly of tholeiitic basalts. The magmas in decreasing order of abundance in the WLNV are tholeiitic, rhyolitic, alkali-olivine basaltic magma, carbonatite-alkalic, and ultrabasic dykes representing the

Age	Super Group	Group	Formation	Member
Quaternary	Quaternary sediments			
Paleogene	Deccan Trap			
Maastraichtian		Lameta	Hatini Limestone	
			Katkut Sandstone	
Coniacian-Berriasian		Bagh	Rajpipla Limestone	
			Oyster Bed	
			Calcareous sandstone (Upper Nimars)	
			Nimar Sandstone	
Neoproterozoic	Post-Delhi Igneous intrusive	Godhra Granite		
Paleoproterozoic	Aravalli	Champaner	Rajgarh	
			Shivrajpur	
			Jaban	
			Narukot	
			Khandia	
			Lambia	
		Lunawada	Kadana	

Table 2.1 Lithostratigraphy of the Western Lower Narmada Valley (Gupta et al., 1992; Merh, 1995; Godbole et al., 1996; Gopalan et al., 1979; Dassarma and Sinha, 1975; Prasad et al., 2017).

final phase of Deccan volcanism (Merh, 1995). In WLNV, the Deccan Trap occurs as hills, plateaus, inliers, and outliers. According to Gwalani et al. (1993), the late stage of Deccan volcanism was accompanied by alkaline magmas, and the occurrences of igneous rocks in the WLNV can be divided into 1. Phenai Mata in the northern part of the study area comprises alkaline rocks associated with layered tholeiitic gabbro-anorthosite- granophyre intrusive complex 2. Lamprophyres and tinguaites characterize the Panwad-Kawantsubprovince lying east of Phenai Mata. 3. Bakhatgarh-Phulmahalsubprovince east of Panwad-Kawant consisting of ultrabasic dykes 4. Siriwasan-Dughasubprovince lying south of Kawant consists of trachytic rocks. 5. Amba Dongar lying south of Siriwasan and north of Narmada River, is characterized by a carbonatite ring complex. The Ambadongar Carbonatite Ring Complex (ACRC) is located within the Narmada Rift Zone and is the most voluminous alkaline intrusion in the LNV, yielding economic mineral deposits like fluorite and REE's. The Bagh Group rocks are deformed and uplifted due to emplacement of the ACRC. The ENE-WSW trending dikes dominate the Narmada and Tapti valleys with subordinate NE-SW and NW—SE trends (Nair et al., 1985). The Paleogene to Neogene rocks of the adjacent Cambay Basin is exposed in the WLNV, which comprises Olpad, Cambay Shale, Kadi, Kalol, Tarapur, Babaguru, Kand, and Jhagadia formations in ascending order.

According to Raju et al. (1971), Deccan Traps forms the floor to the oil-bearing Paleogene rocks in the Cambay Basin, located on the western margin of the Indian shield suggesting the formation of Paleogene-Neogene Cambay basin post-Deccan lava eruption. The courses of Narmada and Tapti Rivers represent fault trends and are parallel to the Satpura lineament.

2.2.5 QUATERNARY DEPOSITS

The Narmada basin to the north and Tapti-Purna basin to the south form the two depocenters for quaternary sedimentation in the Son-Narmada-Tapti (SONATA) lineament. The Deccan basalts and Tertiary rocks are exposed south of the Narmada-Son Fault (NSF), whereas north of it, the sediments lie in the subsurface and are overlain by Quaternary sediments (Chamyal et al., 2002). The NSF remained active since the Late Cretaceous, and the continued subsidence deposited Cenozoic sediments (Biswas, 1987). Chamyal et al. (2002) divide the Lower Narmada valley into upland consisting of Basalt and Bagh Group rocks, lowland consisting of Tertiary rocks, alluvial plains, and coastal zone consisting of mudflats. The glacio-eustasy and paleoclimate factors played a combined role in controlling and preserving the Quaternary sediments in Gujarat (Merh and Chamyal, 1997). About 350 and 400m of alluvium is recorded from the Narmada and Tapti valley borehole data, respectively (Nair et al., 1985). The east-west trending Jhagadia-Rajpipla seismic profile shot south of Narmada River suggests 3500m Quaternary sediments at Jhagadia in the west, decreasing gradually towards the east, attaining a thickness of about 150m at Rajpipla (Murty et al., 2011). The north-south Sinor-Valod seismic profile across the Narmada and Tapti Rivers suggests the occurrence of 600-700m of Quaternary sediments near Sinor, north of Narmada River pinches towards Valod in the south. East-west trending Panoli-Junamasda seismic profile lying between the Narmada and Tapti Rivers suggests the occurrence of about 1200m Quaternary sediments at Panoli, pinching towards the east (Murty et al., 2014). Merh (1995) referred to the Quaternary sediments deposited in the Cambay and Narmada graben of fluvio-marine, fluvial and Aeolian origin as 'Gujarat Alluvium.'

2.3 TECTONIC HISTORY AND EVOLUTION OF NARMADA BASIN

The crustal stretching prior to the continental breakup cuts the pre-rift succession, and the crystalline basement forms elongated crustal depression bounded normal faults called rift basins (Holz et al., 2017). The Late Triassic breakup of Pangea resulted in the development of rifts that propagated southwards between Africa and India-Madagascar and between India and Australia, thus starting the breakup of Gondwanaland (Royer et al., 1992). India, along with Africa, occupied a central position within Gondwanaland until its separation from the joint landmass of Antarctica and Australia at 130 Ma (Besse and Courtillot, 1988; Krishna, 2017; Powell et al., 1988; Veevers and McElhinny, 1976), and from Madagascar in the Late Cretaceous due to spreading in the Mascarene Basin (Storey et al., 1995). During Early Cretaceous (~132 Ma), India-Madagascar separated from Australia-Antarctica (Powell et al., 1988; Brown et al., 2003; Fig. 2.3). India-Seychelles separated from Madagascar during Late Cretaceous at around 90-85 Ma, (Storey et al., 1995; Torsvik et al., 2000), and western India witnessed a regional uplift. This separation of India from Gondwana in the Cretaceous period played a major role in reactivating the Precambrian ENE-WSW trending Satpura lineament and gave rise to extensional events.

According to Biswas (1982), the reactivated movements along the Precambrian trends and development of western marginal basins (Kachchh, Saurashtra, Cambay, and Narmada) in the Indian subcontinent are closely related to the drifting of the Indian subcontinent.The Saurashtra arch subsided in the Early Cretaceous along the eastern margin fault of Cambay Basin and formed and formed a depositional platform in continuation with the Kachchh shelf and Narmada region on which thick deltaic sequence was deposited (Biswas, 1987).

The rifting progressively developed from north to south, opening the Kachchh Basin during the Early Jurassic along the E-W trending Delhi trend, the Early Cretaceous Cambay Basin along the NNW-SSE Dharwar trend, and finally the Narmada Basin in Late Cretaceous along the ENE-WSW trending Satpura lineament (Biswas, 1982).The Narmada rift basin opened due to the tension created by the counterclockwise drift of the Indian plate (Biswas, 1982, 1987). Rifting along thePrecambrian lineament created a series ofsub-basins, in which the Bagh Group sediments got deposited. This was when the encroachment of anarm of Palaeo- Tethys Sea laid down a thick marine sequence (Biswas, 1987). Western India's Narmada basin and other pericontinental basins (Kachchh, Cambay and Saurashtra) evolved during Jurassic-Cretaceous deposition time of the Late Gondwana (Biswas, 1999).

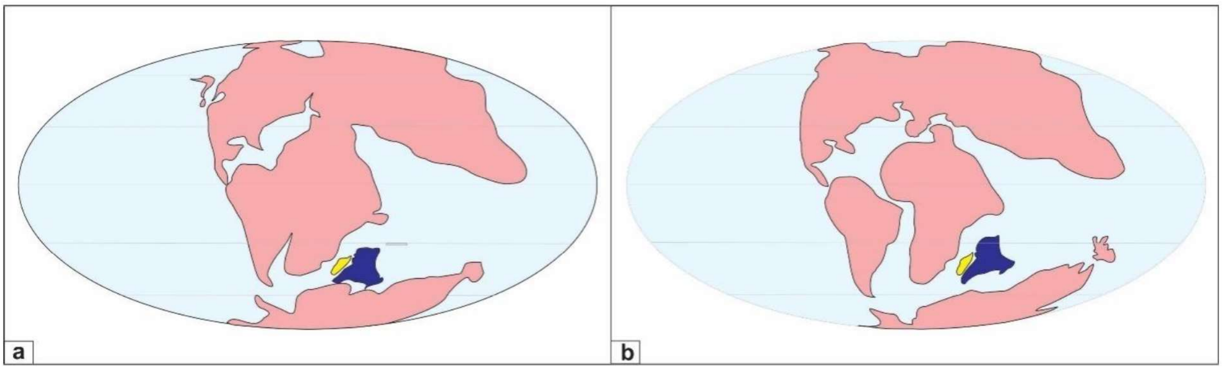


Figure 2.3 Cretaceous paleogeography highlighting the position of India (blue) and Madagascar (yellow) during a. Berriasian-Aptian and b. Albian-Turonian (Boucot et al., 2013).

The Narmada Basin, lying on the western margin of the Indian Peninsula, is an example of crustal stretching and preserves imprints of Cretaceous Gondwana breakup, its passage over the Réunion hotspot, sea-level rise, and an extinction event preserving in its rock record. The propagation of the Narmada rift progressively advanced to the east with deposition of the thickest sediments in the WLNV and created a series of sub-basins, in which the Bagh Group sediments were deposited. Tripathi (1995) identified three linear belts as sub-basins, in which the Cretaceous marine rocks were deposited, namely Bagh-Zirabad, Jobat-Dahod, and Kawant. The Narmada basin extended offshore towards the south of Saurashtra, the anticlockwise movement of India created extensional faulting, which opened the western part of the lineament. In contrast, the strike-slip movement along the lineament created compressive stress in the eastern part (Biswas, 1999). During Late Cretaceous, the uplift of the Gondwana basin in the eastern part of the Narmada-Son Fault ended the sedimentation while the transgression in the western part of the basin was initiated. The basins occupy the grabens, which are bounded by faults and open seaward.

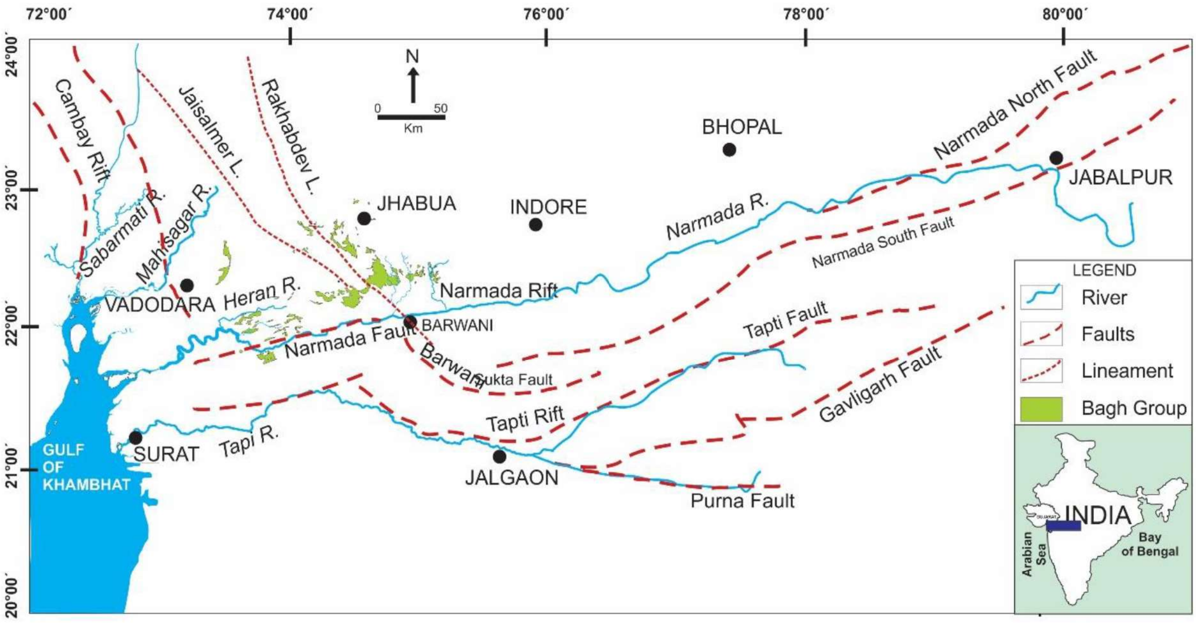


Figure 2.4 Tectonic Map of west-central India showing major faults, lineaments, and exposures of the Bagh Group, Narmada Basin (modified after Abdul Azeez et al., 2013; Jha et al., 2016).

The Bagh Group rocks rest unconformably on the Precambrian rocks (Tripathi andLahiri, 2000) and are exposed in Barwah (Madhya Pradesh) in the east to Vajeriya-Songir-Chosalpura (Gujarat) in the west (Fig.2.1) along the Narmada-Son Lineament. This Narmada-Son Lineament (Choubey, 1971) is a northern part of the Central Indian Tectonic Zone (Acharyyaand Roy, 2000).The Narmada rifting initiated in Early Cretaceous time along the ENE-WSW Satpura lineament divides the Indian shield into southern and northern foreland blocks (Biswas, 1982, 1987). The Narmada Son Lineament (NSL) is an ancient feature trending ENE-WSW located in central India along a paleo-rift and is intermittently active due to the tectonic movements (Choubey, 1971). The NSL is also considered a zone of crustal upwarping through which lava intruded (Auden, 1949). It is bounded by the active Son-Narmada North Fault (SNNF) to its north and the Son Narmada South Fault (SNSF) to its south. The region between SNNF and SNSF consists of Archaean greenstone. The SNNF further extends from Hoshangabad in the west to Markundi in the east (Jain et al., 1995). The Narmada Fault (Abdul Azeez et al., 2013) was referred to as the Barwaha Lineament and considered a possible extension of the SNNF by Jain et al. (1995). The Narmada-Son geofracture has a big role in the evolution of Gondwana rift basins (Biswas, 1999). The Son-Narmada and Tapti valleys exhibit a horst graben-horst structure between 20°-25° latitudes in the Indian sub-continent (Nair et al., 1985). Patro et al. (2005) suggested that north of Narmada River is a highly disturbed zone with faults trending E-W/ ENE-WSW whereas, between the Narmada, and Tapti Rivers, the BarwaniSukta Fault, South Narmada Fault, Gavligarh Fault and Tapti Fault (Fig. 2.4) are recorded.

CHAPTER 3
REVIEW OF STRATIGRAPHY

3.1 INTRODUCTION

The lithostratigraphy of Cretaceous rocks of the Lower Narmada Valley has been debated for more than 150 years. Since the middle nineteenth century, several authors have proposed and revised the lithostratigraphy of the Bagh Group rocks from the ELNV or/and WLNV (Table 3.1). Most lithostratigraphy is proposed, emphasizing the local lithological variation, and thus end up in variable names of the units. The new units are erected based on the local lithological variation observed and not following the standard norms of nomenclature resulting in synonymy and homonymy in the nomenclature; hence most of the studies have not been able to bracket the age of the units precisely. Several authors have proposed a separate lithostratigraphic classification for the Cretaceous rocks of ELNV and WLNV, while some workers have proposed a single lithostratigraphic classification for the ELNV and WLNV deposits. Initially, the Cretaceous LNV deposits were referred to as Bagh Beds (Blanford, 1869; Bose, 1884; Rode and Chiplonkar, 1935 and are now considered Group (Ruidas et al., 2018). A detailed review of the stratigraphy of the Cretaceous rocks in ELNV and WLNV is discussed below.

3.1.1 LITHOSTRATIGRAPHY OF ELNV

Since the middle nineteenth century, several authors have worked on the stratigraphical, sedimentological, and paleontological aspects of the Cretaceous rocks exposed in ELNV. A brief review of the lithostratigraphic succession of the Cretaceous rocks described by the workers is given below.

Blanford, in 1869 for the first time, systematically studied the rocks exposed in the Tapti and the Lower Narmada valley ranging from Precambrian to Quaternary. The area was mapped, and the western and eastern limits of the rocks were accurately marked at Baroda (Vadodara) and Barwah, respectively. The rocks were assigned the Cretaceous age, and the term 'Bagh Beds' as described by earlier workers was retained. The Bagh Beds section at Chirakhan (ELNV) was described as sandstone and conglomerate, unfossiliferous Nodular Limestone, Fossiliferous argillaceous limestone abounding in echinoderms, and Coralline limestone in ascending order (Table 3.1a). However, Bose (1884) considered Lametas a part of the Bagh Beds, and the lower sandstone unit was correlated with the Mahadevas of Gondwana Supergroup.

Bose (1884) resurveyed the rocks and separated the Lower Cretaceous sandstone dominated series as Nimar Sandstone. In contrast, the Upper Cretaceous marine series was considered Bagh Beds and divided into three units Nodular Limestone, Deola and Chirakhan Marl, and Coralline Limestone in ascending order (Table 3.1a). He renamed the fossiliferous argillaceous limestone abounding in the echinoderms unit described by Blanford in 1869 as Deola-Chirakhan Marl occurring between the Nodular Limestone and the Coralline Limestone.

Wadia (1919), in his book Geology of India, suggested the extension of the marine Bagh Beds up to Kathiawar in the west and Gwalior in the east. The Bagh Beds were divided into unfossiliferous sandstone and conglomerate (Nimar Sandstone), Nodular Limestone, Deola Marl and Coralline Limestone, and the whole succession was assigned the Cenomanian age (Table 3.1a) based on the occurrence of echinoids, bivalves, polyzoan, corals, and gastropods. The author rightly pointed out that fossiliferous Deola Marl and the Coralline Limestone do not extend westward. The unfossiliferous Songir Sandstone exposed at Baroda (WLNV) was considered to underlie the Bagh Beds, separated from it, and correlated with the Ahmednagar sandstones of Idar state (WLNV).

Rode and Chiplonkar, in 1935, considered Barwah and Wadhwan as the eastern and western limits of the Bagh Beds, respectively. The authors observed the occurrence of the Bryozoan Limestone bed in the Chirakhan area and traced it at many other localities in the ELNV occurring between Nodular Limestone and the Deola-Chirakhan Marl. The new unit was named Lower Coralline Limestone, separated from the upper Coralline Limestone by Deola Marl. The lower Coralline Limestone was observed to pinch out, and the marl occurring between the two

Coralline limestone beds was eroded, often leading to the juxtaposition of the two beds. The Bagh beds were divided into five units, Nimar Sandstone, Nodular Limestone, Lower Coralline Limestone, Deola-Chirakhan Marl, and the Upper Coralline Limestone (Table 3.1a).

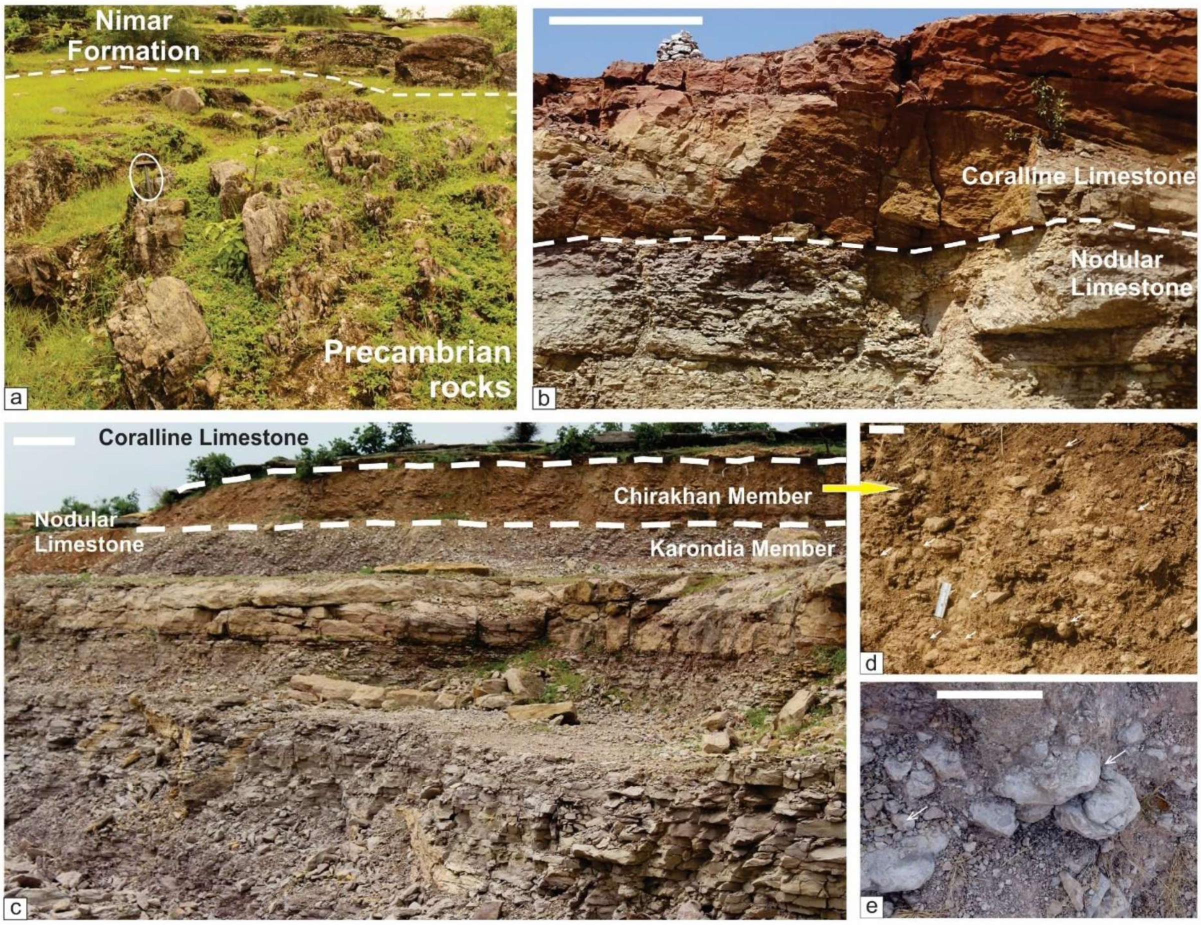


Plate 3.1 Field photographs of the ELNV sections. a. Angular contact between the Nimar Formation and the Precambrian rocks (length of hammer= 32 cm). Sharp contact between the Nodular Limestone and the Coralline Limestone at b. Borghata/Ratitalai village (scale bar= 2 m). and c. Sitapuri village (scale bar= 2 m). d. Echinoderms in Chirakhan Member (white arrows), Sitapuri village (scale bar= 5 cm). e. Ammonites in Nodular Limestone (white arrows), Risawala village/ Gayatri Temple (scale bar= 10 cm).

Pascoe (1959), in his book 'Manual of Geology of India and Burma', defined the western and eastern limits of the Bagh Beds at Rajpipla and Barwah respectively and divided the Bagh Beds of Central India into Oyster Bed, Nodular Limestone, Deola-Chirakhan Marl, and Coralline Limestone in ascending order (Table 3.1a). The Nimar Sandstone exposed in the eastern part of the basin is considered part of the Gondwana Supergroup. In contrast, in the western part, the Bagh Beds sequence is considered to unconformably overlie the Nimar Sandstone, thus separating it from the Bagh Beds. The important observation in the work of Pascoe was the occurrence of the Oyster Bed, which was considered the basal unit of the Bagh Beds based on the field and paleontological evidence; the age of Bagh Beds was bracketed between Middle Cenomanian to Campanian (Senonian).

Roy-Chowdhary and Sastri (1962) considered the Bagh Beds to be the Cretaceous and divided it into Nimar Sandstone with Oyster Bed at the top, Nodular Limestone, and Coralline Limestone (Table 3.1a). The Deola-Chirakhan Marl was considered a part of the Nodular Limestone and ruled out its status as a separate unit in the stratigraphy of Bagh as proposed by Bose (1884).

Murty et al. (1963) proposed new lithostratigraphic units for the Bagh Beds exposed in Jhabua (ELNV). He was the first to elevate the rank of Bagh Beds to Group and divided the sequence into Nimar Group and Bagh Group. The Nimar Group was subdivided into Nimar Sandstone (plant fossils at the base) and Umrali Flagstone. In contrast, the Bagh Group was subdivided into Amlipura Oyster Bed, Kanasgali Grit, and Sejagaon Limestone (Table 3.1a). The Amlipura Oyster Bed was considered doubtfully Neocomian, whereas the age of Kansagali Grit and the Sejagaon Limestone was bracketed between Senonian to Aptian. Murty et al. (1963) recovered plant fossils *Ptilophyllumcutchense*, *Ptilophyllumacutifolium*, *Peltate,* and *Sphenopteris* sp. from the lower carbonaceous clay-bearing unit of the Nimar Sandstone and based on the assemblage suggested fixed the upper age of the unit as Hauterivian, and the Nimar Group was thus tentatively assigned Lower Cretaceous age.

Poddar (1964) proposed separate lithostratigraphic classification for the eastern and western parts of the Lower Narmada Valley. In ELNV, the Cretaceous rocks were divided into the Nimar Group and the Bagh Group. The Nimar Group was further subdivided into Nimar Sandstone and Umrali Flagstone, separated by a disconformity. The age of the Nimar Group was bracketed between Upper Jurassic to Lower Aptian. The Bagh Group was subdivided into Amlipura Oyster Bed, Kanasgali Grit, Sejagaon Limestone, and Bagh Formation, extending from Middle Aptian-Turonian (Table 3.1a).

Sahni and Jain (1966) revised the lithostratigraphy of the Bagh Beds and divided it into Nimar Sandstone, Oyster Bed, Nodular Limestone, and Coralline Limestone (Table 3.1a). The authors supported the view of Roy-Chowdhary and Sastri (1954) and suggested that Deola-Chirakhan Marl lacks occurrence as a distinct horizon and is absent in most places. They remarked that Deola-Chirakhan Marl is a combined weathered product of the Nodular Limestone and the Coralline Limestone, and the Bagh Beds were deposited in the marine environment during the Cretaceous period.

Verma (1965), based on the collection of shark teeth from the Ambadongar region of WLNV, assigned the Oyster Bed (also known as Bilthana Oyster Bed) Cenomanian-Senonian age, and the age of Bagh Beds was considered to be Cenomanian to Maastrichtian. Verma in 1968 proposed a new lithostratigraphic division of the Bagh Beds (as cited in Verma, 1969), dividing the sequence into Nimar Sandstones (Lower Cretaceous), Oyster Bed (Cenomanian-Turonian), Nodular Limestone (Turonian-Santonian), and Coralline Limestone (Campanian-Lower Maastrichtian) (Table 3.1a). Later Verma, in 1969, based on the fossil shark fauna discovered from the Oyster Bed near Kawant (WLNV), assigned the Bagh Beds Cenomanian-Maastrichtian age and also suggested it to range from Turonian to Lower Maastrichtian but not older than Cenomanian. However, in the correlation chart with the Cretaceous rocks of South India, Verma (1969) assigned the Bagh Beds is Lower Cretaceous-Maastrichtian in age.

Pal (1970) revised the lithostratigraphy of the Cretaceous sequence and divided it into Nimar Sandstone, Lower Coralline Limestone, Nodular Limestone, Upper Coralline Limestone. Pal in 1971, re-revised the units as the Ajantar Bryozoan Limestone (equivalent to the Lower Coralline Limestone), Cave Nodular Limestone (equivalent to the Nodular Limestone), DeolaMarl, Mohanpura Marl, and Barwah Bryozoan Limestone (Table 3.1a). The Nimar Sandstone was assigned Valanginian to lower Aptian age.

Sastry and Mamgain (1971) proposed a separate division for the Bagh Beds exposed in the ELNV and WLNV. The authors divided the Cretaceous sequence into the Lower Cretaceous Nimar Sandstone with plant fossils overlaid by Cenomanian-Turonian Calcareous Sandstone, Nodular Limestone, and Coralline Limestone (Table 3.1b). Based on fossils, the authors considered the carbonate sequence of WLNV to be much younger than the ELNV.

Jain (1971) marked the eastern and western limits of the Bagh Beds at Indore and Rajpipla, respectively, and divided it into Nimar Sandstone, Nodular Limestone, and Coralline Limestone (Table 3.1b). Based on the occurrence of Turonian ammonites in the Nodular Limestone and the conformable relationship of the underlying Nimar Sandstone, the Nimar sandstone was assigned upper Turonian age, and Coralline Limestone was considered not younger than Coniacian.

Gupta (1975) has revised the status of Bagh Beds to Formation and divided it into Nimar Sandstone, Nodular Limestone, Deola-Chirakhan Marl, and Coralline Limestone without bracketing its age (Table 3.1b).

Dassarma and Sinha (1975) have proposed separate lithostratigraphy for the ELNV and WLNV. The eastern and western limits of the Cretaceous rocks of Lower Narmada Valley were marked at Barwah and Rajpipla, respectively. In the revised lithostratigraphy, Nimar Sandstone was separated from the Bagh Beds and assigned Lower Cretaceous age. The overlying sequence was considered as Bagh Beds. It was divided into Calcareous Sandstones locally with a cluster of Oysters (Upper Nimars), Nodular Limestone, and Coralline Limestone and assigned Cenomanian-Turonian age (Table 3.1b).

Guha (1976) divided the Bagh Group into Nimar Sandstone, Karondia Limestone, and Chirakhan Limestone (Table 3.1b). The name Nodular Limestone was replaced with Karondia Limestone, whereas the Deola-Chirakhan Marl and Coralline Limestone were renamed Chirakhan Limestone, which later became highly debatable.

Singh and Srivastava (1981) studied the Cretaceous sedimentary sequence between Chikli and Barwah and renamed it the Narbada Group to include the Nimar Formation in the Bagh Formation. Narbada Group was divided into Nimar Formation and Bagh Beds (Formation). The Bagh Beds were further subdivided into Nodular Limestone Member, Deola-Chirakhan Marl Member, Lower Coralline Limestone (pinching), and Upper Coralline Limestone Member/Hatini Sandstone Member (Table 3.1b). The authors rightly pointed out that the Nimar Sandstone shows variable lithological properties and interpreted its lower part to be deposited in a fluvial environment, whereas the upper part showed marine influence. However, the authors correlated the Bagh Formation with the Lameta Formation based on the lithology, trace fossils, and stratigraphic position of the Nodular Limestone (Bagh Formation) with the Mottled Nodular Formation (Lametas).

Badve (1987) reassessed the stratigraphy of the Bagh Beds exposed in the Barwah area (Madhya Pradesh) and divided it into Nimar Sandstone with Oyster Bed at the top, Nodular Limestone, Deola and Chirakhan Marl and Coralline Limestone (Table 3.1b). The Nimar Sandstone was considered Lower Cretaceous (Neocomian), whereas the younger series was considered Upper Cretaceous. Based on the occurrence of trace fossils in the upper part of Nimar Sandstone, the author suggested a shallow sublittoral depositional environment with low to moderate energy.

Kumar (1994) studied the Cretaceous rocks of Narmada valley exposed in the Jhabua area (Madhya Pradesh). The author followed the lithostratigraphy proposed by Singh and Srivastava (1981) and divided the Narbada Group into Nimar Formation and Bagh Formation (Table 3.1c). However, the age of Nimar Formation was revised to Late Jurassic based on palynoflora and non-availability of the Early Cretaceous palynofossils and did not comment on the retention of Maastrichtian age for the Coralline Limestone as proposed by Singh and Srivastava (1981). Based on the palynofossils, the author suggested freshwater, warm, humid, swampy depositional environment of the Nimar Formation.

Taylor and Badve (1995) divided the Bagh Group into Nimar Sandstone Formation, Nodular Limestone Formation, and Chirakhan Limestone Formation and bracketed its age between Neocomian and Turonian (Table 3.1c) considering the previous literature. Based on the occurrence of *Chiplonkarina*in the Upper Tal Shale Limestone (Uttar Pradesh), and the Coralline Limestone (Madhya Pradesh), the authors assigned the Cenomanian-Turonian age to the bryozoan bearing Bagh Group. The authors subdivided the Chirakhan Limestone Formation into Deola-Chirakhan Marl Member and Coralline Limestone Member to separate the marly facies from the coralline limestone. The authors discarded the Barwaha Bryozoan Limestone unit proposed by Pal (1971), stating that it does not occur in the vicinity of Barwaha.

Rajshekhar reported the foraminifera from the Bagh Group in 1991 and 1995 and followed the stratigraphy given by Chiplonkar et al. (1977) and Guha (1976), respectively. Rajshekhar in 1997 observed a different generalized stratigraphic sequence comprising of Nimar Sandstone, Oyster Bed, Nodular Limestone, and Rajpipla Limestone. The Rajpipla Limestone was considered to be younger than the Nodular Limestone (Table 3.1c). Rajshekhar (1997), based on the occurrence of echinoids, foraminifers, bivalves, and gastropods from the Navagam Limestone, suggested a shallow-water depositional environment of the unit.

Akhtar and Khan (1997), based on the studies in Zeerabad and Jobat town of ELNV, divided the Cretaceous rocks into Bagh and Lameta Groups. According to their lithostratigraphic table (Table 3.1c), Bagh Group rocks are overlaid by Lower Deccan Trap (first effusive activity) of Lower Turonian age, Lameta Group, and Upper (main) Deccan Trap in ascending order. Moreover, the Songir Sandstone and Navagam Limestone of WLNV were considered part of the Lameta Group, younger than Bagh Group rocks. The Bagh Group was divided into Nimar Sandstone and Karondia Limestone, and its age was bracketed between Albian-Cenomanian (Table 3.1c). The authors suggested a tidal island model for deposition of the carbonates of Karondia (Nodular) Limestone based on facies variation attributed to shifting islands separated by subtidal areas.

Kumar et al. (1999) have grouped the Bagh Beds into Nimar Sandstone, Bagh Formation, and Lameta Formation; the Bagh Formation is further subdivided into Nodular Limestone, Deola-Chirakhan Marl, and the Coralline Limestone (possible members of the Bagh Formation), whereas the Lameta Formation constitutes of Calcareous Sandstone (Table 3.1c). The Nimar

Formation is considered Early Cretaceous in age and deposited in an estuarine and freshwater environment. The Bagh and Lameta formations are Late Cretaceous in age, deposited in marine and estuarine-freshwater environments, respectively.

Nayak (2000b, 2004) followed the amended classification proposed by Chiplonkar et al. (1977) and Taylor and Badve (1995). Accordingly, the Bagh Group is divided into three formations: Nimar Sandstone, Nodular Limestone, and Coralline Limestone (Table 3.1c). The Nimar Sandstone Formation was subdivided into Oyster Bed, trace fossils horizon, Oyster Bed with shark teeth, ammonoids, and *Jhabotrigonia-Turritella* bed. The overlying Coralline Limestone Formation was further subdivided into Deola-Chirakhan Marl and Coralline Limestone members. The whole Bagh Group sequence was bracketed between Upper Albian and Turonian. Nayak (2000b) studied ostracods of the Nimar Formation (Bagh Group) and suggested its deposition in the warm, shallow water of normal salinity during Cenomanian-Turonian. Based on trace fossils recovered from the Nimar Sandstone, Nayak (2004) suggested shallow sublittoral depositional conditions with moderate to low energy.

Vaidyanathan and Ramakrishnan (2010), in their book 'Geology of India', modified the lithostratigraphic classification proposed by Merh (1995) and followed the classification proposed by Bose (1884) and Chiplonkar et al. (1972-not seen, 1977), whereas the age of the units was revised significantly. The precise age of the upper and lower was not mentioned, and the status of Lameta is also not clear (Chiplonkar et al., 1972-not seen, 1977). The age of Nimar Sandstone with Oyster Bed at top originally considered Valanginian to Albian by Bose (1884) was revised to Valanginian to Aptian, and Nodular Limestone was assigned Aptian age whereas, the age of overlying Deola-Chirakhan Marl and Coralline Limestone was revised to Cenomanian-Turonian and Coniacian-Campanian respectively (Table 3.1d).

Gangopadhyay and Maiti (2012) studied the gastropods and bivalves of the Nodular Limestone exposed in Zeerabad and divided the Cretaceous rocks of ELNV into Nimar and Bagh groups. The Bagh Group was further subdivided into the Nodular Limestone and Bryozoan Limestone formations (Table 3.1d). The authors suggested that the Coralline Limestone name of the topmost unit of the Bagh Group is a misnomer and is devoid of corals but is characterized by abundant bryozoans in it. The authors proposed to rename the unit as Bryozoan Limestone Formation. Based on the bipolar arrangement of the gastropod shells and convex down position of the bivalve shell, a nearshore beach depositional environment was suggested.

Jaitly and Ajane (2013) divided the Bagh Group into Nimar Sandstone, Nodular Limestone, and Coralline Limestone formations. The Nodular Limestone Formation was further subdivided into Karondia and Chirakhan members (Table 3.1d). Jaitly and Ajane (2013) followed the lithostratigraphic classification scheme of Tripathi (2006); however, no further subdivisions were made to the Nimar Sandstone Formation. The authors too, believed Coralline Limestone's notion to of being a misnomer but suggested retaining it because it is deeply entrenched in the literature. Based on the ammonite *Placenticeras mintoi* collected from different levels in the Nodular Limestone, the authors assigned it Turonian age. The Coralline Limestone was assigned Coniacian age based on the studies of Gangopadhyay and Bardhan (1998) reporting *Barroisiceras onilahyense* from the Coralline Limestone. The Nimar Sandstone was assigned Cenomanian age after the studies of Chiplonkar et al. (1977).

Jha et al. (2016) modified the stratigraphy of Singh and Srivastava (1981) and divided the Bagh Group rocks into Nimar Sandstone, Nodular Limestone, and Coralline Limestone (Table 3.1d) belonging to Cenomanian, Turonian, and Coniacian age respectively, which is similar to the lithostratigraphy proposed by Jaitly and Ajane (2013). However, the authors avoided further subdividing the Nodular Limestone into Karondia Member and Chirakhan Member. Based on the presence of seismites in the Nimar Sandstone Formation, reactivation of the Son-Narmada South Fault during the Cenomanian was suggested, which led to basin subsidence and deposition of marine sediments.

Kumar et al. (2016) followed the stratigraphic unit of the Bagh Group rocks proposed by Jaitly and Ajane (2013) with modification of ages. The Bagh Group was divided into the Cenomanian Nimar Sandstone, Turonian Nodular Limestone, and Coniacian Coralline Limestone (Table 3.1d). The Nodular Limestone was subdivided into Karondia and Chirakhan members, similar to Jaitly and Ajane (2013). However, Karondia and Chirakhan members' age was revised to early-middle Turonian and late Turonian, respectively. Kumar et al. (2016)

recovered suspension-feeding bivalves from the Turonian Nodular Limestone of Bagh Group and suggested availability deposition in a protected lagoonal to the subtidal environment.

Prasad et al. (2017) followed the stratigraphy of Tripathi (2006) and Jaitly and Ajane (2013) and divided the Bagh Group into the Cenomanian Nimar Sandstone, Turonian Nodular Limestone, Coniacian Coralline Limestone and Green Sandstone (Table 3.1d). The authors identified Green Sandstone as a new unit overlying the Coralline Limestone, which yielded abundant shallow littoral shark teeth (*Ptychodus* sp., *Scapanorhynchus* sp. aff. *S. raphiodon*, *Cretodus* sp. aff. *C.crassidens*, *Cretalamna* sp., *Squalicorax* sp. aff. *S. falcatus*), and suggested deposition in the nearshore environment.

3.1.2 LITHOSTRATIGRAPHY OF ELNV-WLNV

Chiplonkar et al. (1977) described the stratigraphy of the Cretaceous rocks of LNV in detail and divided the Bagh Group into Nimar Sandstone consisting of trace fossils horizon and Oyster Bed overlaid by Oyster Bed with shark teeth and ammonoid, *Jhabotrigonia-Turritella* bed, Nodular Limestone with lower *Inoceramus* bed at the top, Lower Coralline Limestone, Deola and Chirakhan Marl with *Hemiaster*, Upper *Inoceramus* bed and Upper Coralline Limestone with Oyster Bed at the top (Table 3.1b). Several authors, including Nayak (2000a), followed the lithostratigraphic scheme of Chiplonkar et al. (1977). Although the authors have strongly criticized the workers who have separated the lithostratigraphy of the eastern and western part of the basin, the units proposed in their study were erected solely based on the lithological and paleontological properties observed in the eastern part of the basin and lacked a description of the western part. Moreover, the absence of Deola-Chirakhan Marl and the Coralline Limestone in the west part of the basin was completely neglected.

Biswas and Deshpande (1983) divided the sequence into the Nimar Group and Bagh Group in ELNV. The Nimar Group of ELNV was correlated with the Songir Group of WLNV, whereas the Bagh Group in ELNV was correlated with the Navagam Group in WLNV. The authors proposed Nimar Sandstone and Umrali Flagstone as the new subdivisions of the Lower Cretaceous Nimar Group, whereas the Upper Cretaceous Bagh Group was divided into Nodular Limestone, Coralline Limestone, and Lameta Formation (Table 3.1b).

Ramasamy and Madhavaraju (1993) studied the Bagh Group rocks of Madhya Pradesh and revised the lithostratigraphy based on the detailed petrographic analysis. The authors divided the Bagh Group into Nimar Sandstone, Karondia Limestone, and Bryozoan Limestone (Table 3.1c) and discussed the nomenclature, contact, thickness, paleontology, lithology, geographic extension, stratotypes, and age of the lithostratigraphic units in detail.

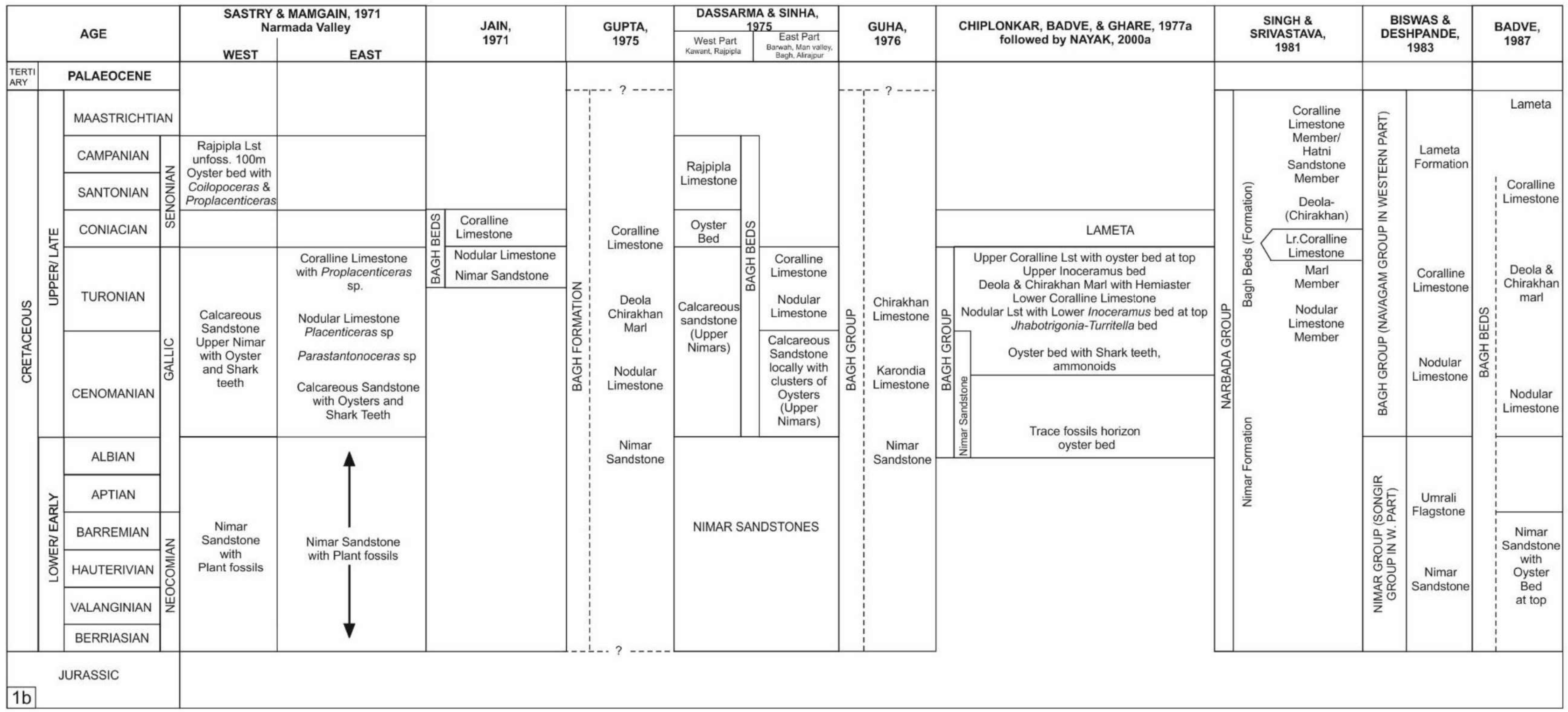
Tripathi (1995) suggested the deposition of the Bagh Group rocks in three sub-basins, namely Zeerabad-Bagh, Jobat-Bhabhra, and Kawant, indicating a south/southwest slope of the basins with occasional basin highs. The author divided the Bagh Group into Nimar Sandstone, Nodular Limestone, and Coralline Limestone formations (Table 3.1c) and proposed Bagh Cave and Bariya members as the new subdivisions of the Nimar Sandstone Formation; the Nodular Limestone Formation was further subdivided into Karaundia Member and Chirakhan Member.

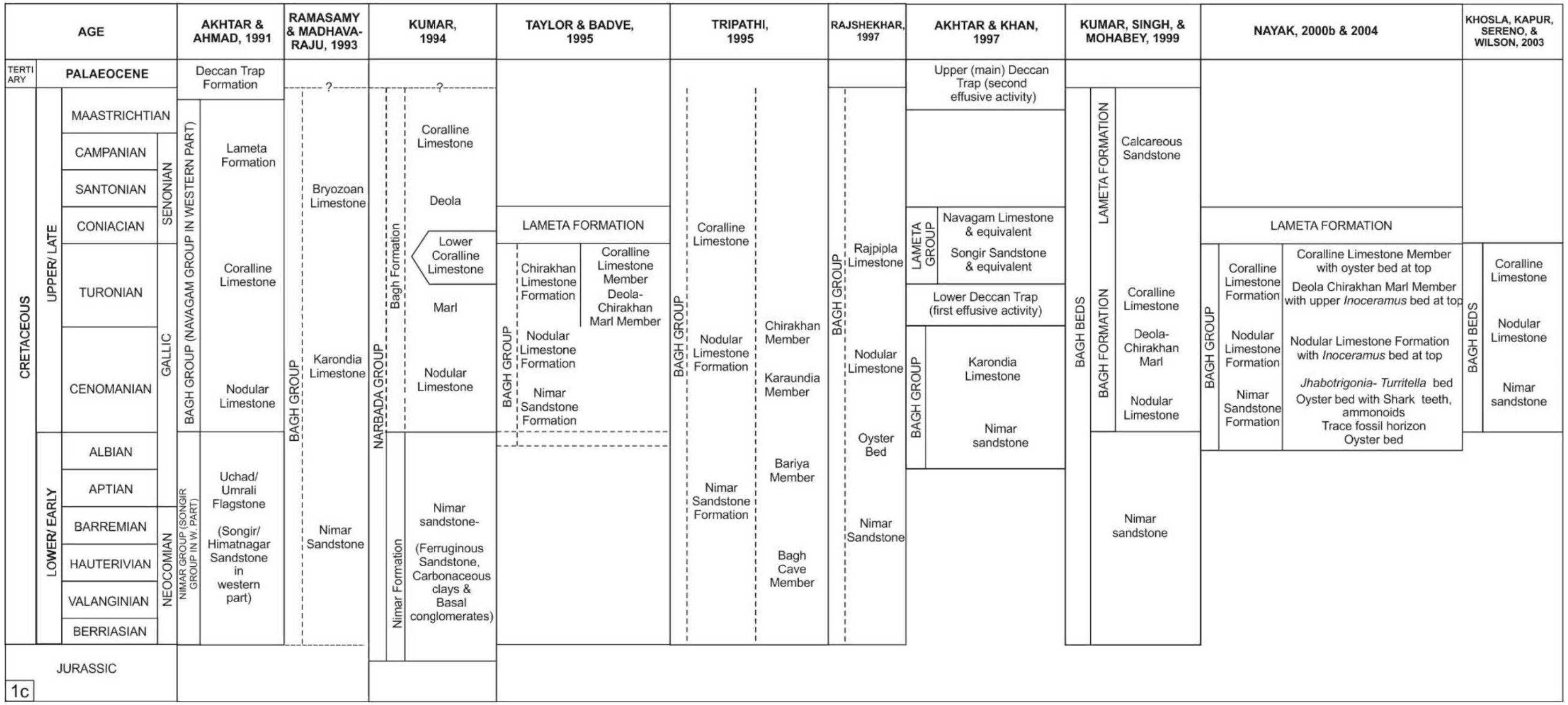
Tripathi, in 2006, revised the stratigraphy of the Bagh Group and divided it into Nodular Limestone and Coralline Limestone. The Bagh Cave Member and Bariya Member subdivisions of the Nimar Sandstone Formation and the Karondia Member and Chirakhan Member subdivisions of the Nodular Limestone from his 1995 classification scheme were retained (Table 3.1d). A hard ground separated the two formations; however, the author proposed to separate the Nimar Sandstone Formation from the Bagh Group. The Nodular Limestone in ELNV was suggested to be deposited in a shallow, open, and slowly sinking basin. In contrast, the Nodular Limestone in Kawant was considered to be deposited in a reducing environment of a deep and stable basin.

Racey et al. (2016) proposed a single classification for the Bagh Group deposited in ELNV and WLNV. The Cretaceous rocks were grouped into the Nimar group and the Bagh Group; the Bagh Group was divided into Nimar Sandstone and Upper Nimar, whereas Nodular Limestone and Coralline Limestone formations as the earlier subdivisions of the Bagh Group were retained (Table 3.1d). The authors suggested separating the lower siliciclastic unit from the rest of the marine deposits and assigned it Nimar Group. The Nimar Sandstonewas assigned Hauterivian to Aptian age, whereas the Upper Nimars was assigned Albian-Cenomanian age, while the Nodular Limestone Formation and Coralline Limestone Formation were assigned Turonian age.

AGE				BLANFORD, 1869	BOSE, 1884	WADIA, 1919	RODE & CHIPLONKAR, 1935	PASCOE, 1959	ROY-CHOWDHARY & SASTRI,1962	MURTY, RAO, DHOKARIKAR, & VARMA, 1963	MURTY, RAO, DHOKARIKAR, & VARMA, 1963: Equivalent in type area of P. N. Bose	PODDAR, 1964 Narmada Valley WEST	PODDAR, 1964 Narmada Valley EAST	SAHNI & JAIN, 1966	VERMA, 1968	PAL (1970 & 1971, as cited in CHIPLONKAR, BADVE, & GHARE, 1977a) 1970	PAL 1971
				BAGH BEDS	BAGH BEDS		BAGH BEDS	BAGH BEDS	BAGH BEDS	BAGH GROUP / NIMAR GROUP		NAVAGAM GROUP / SONGIR GROUP	BAGH GROUP / NIMAR GROUP	BAGH BEDS	BAGH BEDS		
TERTIARY	PALAEOCENE																Barwaha Bryozoan Limestone
CRETACEOUS	UPPER/ LATE	MAASTRICHTIAN														Upper Bagh	
CRETACEOUS	UPPER/ LATE	CAMPANIAN	SENONIAN	Lameta	Lameta			Coralline Limestone							Coralline Limestone		Mohanpura Marl
CRETACEOUS	UPPER/ LATE	SANTONIAN	SENONIAN	Coralline Limestone	Coralline Limestone		Upper Coralline Limestone								Nodular Limestone	Upper Coralline Limestone	Deola Marl
CRETACEOUS	UPPER/ LATE	CONIACIAN	SENONIAN					Deola & Chirakhan Marl									
CRETACEOUS	UPPER/ LATE	TURONIAN	GALLIC	Fossiliferous argillaceous Limestone abounding in echinoderms (Hemiaster)	Deola & Chirakhan Marl		Deola & Chirakhan Marl	Nodular Limestone	Coralline Limestone	Sejagaon Limestone	Coralline Limestone Deola/ Chirakhan Marl	Gulvani Limestone	Bagh Formation	Coralline Limestone			
CRETACEOUS	UPPER/ LATE	CENOMANIAN	GALLIC	Unfossiliferous Nodular Limestone	Nodular Limestone	Coralline Limestone Deola Marl Nodular Limestone (argillaceous limestone) Unfossiliferous sandstone & Conglomerate (Nimar Sandstone)	Lower Coralline Limestone Nodular Limestone	Oyster Bed	Nodular Limestone	Kanasgali Grit	Nodular Limestone	Navagam Limestone	Sejagaon Limestone Kanasgali Grit	Nodular Limestone	Oyster Bed	Nodular Limestone	Cave Nodular Limestone
CRETACEOUS	LOWER/ EARLY	ALBIAN												Oyster Bed			
CRETACEOUS	LOWER/ EARLY	APTIAN		Sandstone and Conglomerate	Nimar Sandstone with Oyster Bed At top		Nimar Sandstone					Bilthana Oyster bed	Amlipura Oyster Bed	Nimar Sandstone	Nimar Sandstone	Lower Coralline Limestone	Ajantar Bryozoan Limestone
CRETACEOUS	LOWER/ EARLY	BARREMIAN	NEOCOMIAN						Nimar Sandstone with Oyster Bed At top	Amlipura Oyster Bed	Oyster Bed	Uchad Flagstone	Umrali Flagstone				
CRETACEOUS	LOWER/ EARLY	HAUTERIVIAN	NEOCOMIAN							Umrali Flagstone			Disconformity			Nimar Sandstone	
CRETACEOUS	LOWER/ EARLY	VALANGINIAN	NEOCOMIAN							Nimar Sandstone (Plant fossils at the Base)	Nimar Sandstone	Songir Sandstone	Nimar Sandstone				
CRETACEOUS	LOWER/ EARLY	BERRIASIAN	NEOCOMIAN														
JURASSIC												Extending down into Upper Jurassic	Extending into Upper Jurassic				

1a


AGE
SASTRY & MAMGAIN, 1971 Narmada Valley
WEST
EAST
JAIN, 1971
GUPTA, 1975
DASSARMA & SINHA, 1975
West Part Kawant, Rajpipla
East Part Barwah, Man valley, Bagh, Alirajpur
GUHA, 1976
CHIPLONKAR, BADVE, & GHARE, 1977a followed by NAYAK, 2000a
SINGH & SRIVASTAVA, 1981
BISWAS & DESHPANDE, 1983
BADVE, 1987
TERTIARY
PALAEOCENE
CRETACEOUS
UPPER/ LATE
LOWER/ EARLY
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
SENONIAN
GALLIC
NEOCOMIAN
JURASSIC
Rajpipla Lst unfoss. 100m Oyster bed with Coilopoceras & Proplacenticeras
Calcareous Sandstone Upper Nimar with Oyster and Shark teeth
Nimar Sandstone with Plant fossils
Coralline Limestone with Proplacenticeras sp.
Nodular Limestone Placenticeras sp
Parastantonoceras sp
Calcareous Sandstone with Oysters and Shark Teeth
Nimar Sandstone with Plant fossils
BAGH BEDS
Coralline Limestone
Nodular Limestone
Nimar Sandstone
BAGH FORMATION
?
Coralline Limestone
Deola Chirakhan Marl
Nodular Limestone
Nimar Sandstone
Rajpipla Limestone
Oyster Bed
Calcareous sandstone (Upper Nimars)
BAGH BEDS
Coralline Limestone
Nodular Limestone
Calcareous Sandstone locally with clusters of Oysters (Upper Nimars)
NIMAR SANDSTONES
BAGH GROUP
Chirakhan Limestone
Karondia Limestone
Nimar Sandstone
LAMETA
BAGH GROUP
Upper Coralline Lst with oyster bed at top
Upper Inoceramus bed
Deola & Chirakhan Marl with Hemiaster
Lower Coralline Limestone
Nodular Lst with Lower Inoceramus bed at top
Jhabotrigonia-Turritella bed
Oyster bed with Shark teeth, ammonoids
Nimar Sandstone
Trace fossils horizon oyster bed
NARBADA GROUP
Bagh Beds (Formation)
Nimar Formation
Coralline Limestone Member/ Hatni Sandstone Member
Deola- (Chirakhan)
Lr.Coralline Limestone
Marl Member
Nodular Limestone Member
BAGH GROUP (NAVAGAM GROUP IN WESTERN PART)
Lameta Formation
Coralline Limestone
Nodular Limestone
NIMAR GROUP (SONGIR GROUP IN W. PART)
Umrali Flagstone
Nimar Sandstone
BAGH BEDS
Lameta
Coralline Limestone
Deola & Chirakhan marl
Nodular Limestone
Nimar Sandstone with Oyster Bed at top
1b


AGE
TERTIARY
PALAEOCENE
CRETACEOUS
UPPER/ LATE
LOWER/ EARLY
SENONIAN
GALLIC
NEOCOMIAN
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
JURASSIC
1c
AKHTAR & AHMAD, 1991
Deccan Trap Formation
BAGH GROUP (NAVAGAM GROUP IN WESTERN PART)
Lameta Formation
Coralline Limestone
Nodular Limestone
NIMAR GROUP (SONGIR GROUP IN W. PART)
Uchad/ Umrali Flagstone
(Songir/ Himatnagar Sandstone in western part)
RAMASAMY & MADHAVA-RAJU, 1993
?
BAGH GROUP
Bryozoan Limestone
Karondia Limestone
Nimar Sandstone
KUMAR, 1994
?
NARBADA GROUP
Bagh Formation
Coralline Limestone
Deola
Lower Coralline Limestone
Marl
Nodular Limestone
Nimar Formation
Nimar sandstone- (Ferruginous Sandstone, Carbonaceous clays & Basal conglomerates)
TAYLOR & BADVE, 1995
LAMETA FORMATION
BAGH GROUP
Chirakhan Limestone Formation
Coralline Limestone Member
Deola-Chirakhan Marl Member
Nodular Limestone Formation
Nimar Sandstone Formation
TRIPATHI, 1995
BAGH GROUP
Coralline Limestone
Nodular Limestone Formation
Nimar Sandstone Formation
Chirakhan Member
Karaundia Member
Bariya Member
Bagh Cave Member
RAJSHEKHAR, 1997
BAGH GROUP
Rajpipla Limestone
Nodular Limestone
Oyster Bed
Nimar Sandstone
AKHTAR & KHAN, 1997
Upper (main) Deccan Trap (second effusive activity)
LAMETA GROUP
Navagam Limestone & equivalent
Songir Sandstone & equivalent
Lower Deccan Trap (first effusive activity)
BAGH GROUP
Karondia Limestone
Nimar sandstone
KUMAR, SINGH, & MOHABEY, 1999
BAGH BEDS
LAMETA FORMATION
Calcareous Sandstone
BAGH FORMATION
Coralline Limestone
Deola-Chirakhan Marl
Nodular Limestone
Nimar sandstone
NAYAK, 2000b & 2004
LAMETA FORMATION
BAGH GROUP
Coralline Limestone Formation
Coralline Limestone Member with oyster bed at top
Deola Chirakhan Marl Member with upper *Inoceramus* bed at top
Nodular Limestone Formation
Nodular Limestone Formation with *Inoceramus* bed at top
Nimar Sandstone Formation
Jhabotrigonia- Turritella bed
Oyster bed with Shark teeth, ammonoids
Trace fossil horizon
Oyster bed
KHOSLA, KAPUR, SERENO, & WILSON, 2003
BAGH BEDS
Coralline Limestone
Nodular Limestone
Nimar sandstone

AGE		TRIPATHI, 2006	VAIDYANADHAN & RAMAKRISHNAN, 2010 modified after Merh, 1995 — Bose (1884)	VAIDYANADHAN & RAMAKRISHNAN — Chiplonkar, Badve and Ghare 1972, 1974 (not seen)	GANGOPADHYAY & MAITI, 2012	JAITLY & AJANE, 2013 followed by KUMAR, PATHAK, PANDEY, JAITLY, & GAUTAM, 2018; BHATTACHARYA, JHA & MONDAL, 2020	JHA, BHATTACHARYA & NANDWANI, 2016	KUMAR, GAUTAM, PANDEY, PATHAK, & JAITLY, 2016	RACEY, FISHER, BAILEY, & ROY, 2016	PRASAD, VERMA, SAHNI, LOUREMBAM, & RAJKUMARI 2017	RUIDAS, PAUL, & GANGOPADHYAY, 2018	BORKAR & KULKARNI, 2021
TERTIARY	PALAEOCENE				?							
CRETACEOUS — UPPER/ LATE — SENONIAN	MAASTRICHTIAN	LAMETA GROUP: Hatini Lst Formation; Katkut Sst Formation			NIMAR GROUP					LAMETA GROUP: Hatini Lst Formation; Katkut Sst Formation		
	CAMPANIAN		Coralline Limestone	LAMETA								
	SANTONIAN				?							
	CONIACIAN			Upper Coralline Limestone with Oyster bed at top	BAGH GROUP: Bryozoan Limestone Formation	BAGH GROUP: Coralline Limestone Formation	BAGH GROUP: Coralline Limestone	BAGH GROUP: Coralline Limestone Formation		BAGH GROUP: Shark tooth yieding Green Sandstone Coralline Limestone	BAGH GROUP: Bryozoan Lst Formation; Member 3	
UPPER/ LATE — GALLIC	TURONIAN	BAGH GROUP: Coralline Limestone Formation	Deola and Chirakhan Marl	Upper *Inoceramus* bed; Deola & Chirakhan Marl with Hemiaster	Nodular Limestone; ?	Nodular Limestone Formation; Chirakhan Member; Karondia Member	Nodular Limestone/ Nodular Limestone Fm.	Nodular Limestone Formation; Chirakhan Member; Karondia Member	BAGH GROUP: Coralline Limestone Formation; Nodular Limestone Formation	Nodular Limestone; Chirakhan Member; Karondia Member	Nodular Limestone; Member 2; Member 1; Nimar sandstone	BAGH GFORMATION: Sitapuri Bryozoan Limestone Member; Deola Chirakhan Marl Member; Nodular Limestone Member; Nimar Sandstone Member
	CENOMANIAN	Nodular Limestone Formation; Chirakhan Member; Karondia Member		Lower Coralline Limestone; Lower *Inoceramus* bed; nodular limestone		Nimar Sandstone Formation	Nimar Sandstone	Nimar Sandstone Formation; Baria Member; Bagh Cave Member	NIMAR GROUP: Upper Nimars	Nimar Sandstone		
	ALBIAN		Nodular Limestone	Astarte-Turritella bed								
LOWER/ EARLY	APTIAN		Nimar Sandstone with oyster bed at top	Oyster bed with Shark teeth								
LOWER/ EARLY — NEOCOMIAN	BARREMIAN	Nimar Sandstone Formation; Bariya Member							Nimar Sandstone			
	HAUTERIVIAN			Trace fossils horizon Lower portion of Nimar Sandstone with oyster bed								
	VALANGINIAN											
	BERRIASIAN	Bagh Cave Member			?							
JURASSIC												

1d

Table 3.1 Correlation of the lithostratigraphic units proposed by different workers for the Cretaceous sequence of the Lower Narmada Valley.

Recently, Borkar and Kulkarni (2021) revised the lithostratigraphy of the upper Bagh Group, and the Coralline Limestone Member was replaced by Sitapuri Bryozoan Limestone (Member) considering the composition of the rocks (Table 3.1d).

3.1.3 LITHOSTRATIGRAPHY OF WLNV

Poddar (1964) has treated the Bagh Group rocks exposed in the WLNV and ELNV separately and revised the lithostratigraphy of the Bagh Group rocks. The WLNV sequence was divided into Songir Group and Navagam Group. The Songir Group was assigned Jurassic to Lower Aptian age and was further subdivided into Songir Sandstone and Uchad Flagstone. The Navagam Group was subdivided into Bilthana Oyster Bed, Navagam Limestone, and Gulvani Limestone (Table 3.1a). The age of the Navagam Group was bracketed between Middle Aptian to Turonian. The WLNV and ELNV sequence was considered to be contemporaneous. However, the studies lacked a description of the unit, age, depositional environment, assignment of stratotype, boundaries, justification for renaming the old nomenclature, and erecting the new units. The proposed units invalidate the ICSN norms for nomenclature and erection of new units.

Sastry and Mamgain (1971) divided the Cretaceous deposits of the WLNV into Nimar Sandstone with plant fossils, Calcareous Sandstone, Upper Nimar with Oyster, and shark teeth, Oyster Bed with *Coilopoceras* and *Proplacenticeras* and Rajpipla Limestone. The authors divided the lower siliciclastic unit into Nimar Sandstone and Calcareous Sandstone Upper Nimar in the WLNV (Table 3.1b). The Oyster bed and Rajpipla Limestone were considered to be Santonian-Campanian in age. However, Chiplonkar et al. (1977a) have strongly criticized the placement of the two units at a much higher stratigraphic level and the separation of the Oyster Bed from the Calcareous Sandstone.

Dassarma and Sinha (1975) followed the lithostratigraphy of Sastry and Mamgain (1971) and separated the Bagh Group into eastern and western parts. The basal unit, namely Nimar Sandstone, was considered a separate unit, and the Bagh Beds was divided into Calcareous sandstone (Upper Nimars), Oyster Bed, and Rajpipla Limestone (Table 3.1b) however, the ages of the lithounits were revised based on the collection of bivalves, gastropods, ammonites, echinoids, and fish remains.

3.2 SUMMARY

The Cretaceous Bagh Group rocks have been classified by several authors using variable names for the same unit or the same name for different units leading to synonymy and homonymy, which in turn complicates the correlation process. Same units with different names are proposed based on the local lithological variations observed, and thus several units are inadequately established. In addition, the lithostratigraphic classifications are published in field guides, conference volumes, reports lacking availability, and publication in a scientific medium which has led to the proposal of more classification schemes. Considerable debate continues till date over the validity of some lithostratigraphic units (Deola-Chirakhan Marl of Bose (1884); the Lower Coralline Limestone and the Upper Coralline Limestone of Rode and Chiplonkar (1935) and Pal (1970); the Nimar Group and the Bagh Group of Murty et al. (1963), Poddar (1964), Biswas and Deshpande (1983) and Gangopadhyay and Maiti (2012); the Navagam Group and the Navagam Limestone, the Songir Group and the Songir Sandstone of Poddar (1964); the Ajantar Bryozoan Limestone, the Cave Nodular Limestone, the Mohanpura Marl, the Deola Marl and the Barwaha Bryozoan Limestone of Pal (1971); the Karondia Limestone of Guha (1976); the Sejagaon Limestone (Murty et al., 1963; Poddar, 1964); the Bryozoan Limestone Formation of Gangopadhyay and Maiti (2012)).

In ELNV, the basal non-marine sandstone unit, Nimar Group, is separated from the overlying marine unit, Bagh Group (Murty et al., 1963; Poddar, 1964; Biswas and Deshpande, 1983; Gangopadhyay and Maiti, 2012; Racey et al., 2016), similarly it is referred as Songir Group and the Navagam Group in the WLNV (Poddar, 1964; Biswas and Deshpande, 1983) (Table 3.1). However, the usage of the same name for units and their subunits (Nimar Formation in the Nimar Group and the Navagam Formation in the Navagam Group) in the lithostratigraphic schemes by Poddar (1964) and Biswas and Deshpande (1983) invalidates the stratigraphic norms. The earlier studies lack the assignment of formal units to the upper and lower part of the Nimar Group/Formation. Moreover, based on conformable contact of the basal siliciclastic-dominated unit (Nimar Sandstone) with the overlying carbonate-dominated unit, Bose (1884) and Chiplonkar (1983) argued against their separation into different groups. Also, informal stratigraphic names were used for the Bagh Group sequence based on the local lithic characteristics and were described as different groups and formations by various workers (Table 3.1). The locally proposed names complicate the correlation process; for example, the Nodular Limestone is described as Navagam Limestone, Gulvani Limestone, and Rajpipla Limestone at an even higher stratigraphic level are coeval. Moreover, the lithostratigraphic units overlying the Nodular Limestone in WLNV have a distinct lithological composition compared to the coeval Coralline Limestone in ELNV and have been overlooked until now. Most of the classifications proposed for the Cretaceous sequence of WLNV lacked appraisal of the lateral lithological variation. Some authors who worked in the eastern and western parts of the basin have proposed a separate lithostratigraphic classification. However, a review of the lithostratigraphic classification in the WLNV revealed a lack of assignment of stratotypes to the units and a large number of informal units. To resolve the long-standing controversy of nomenclature of the units, amended lithostratigraphy of the Bagh Group sedimentary succession of Western Lower Narmada Valley was proposed by Shitole et al. in 2021 following the standard stratigraphic norms of the International Subcommission on Stratigraphic Classification (ISSC) and is dealt in the next chapter.

CHAPTER 4
LITHOSTRATIGRAPHY OF THE STUDY AREA

4.1INTRODUCTION

Several workers proposed theseparate lithostratigraphic classification of Lower Narmada Valley forthe Eastern Lower Narmada Valley and Western Lower Narmada Valley (WLNV) (Dassarmaand Sinha, 1975; Poddar, 1964; Sastry andMamgain, 1971); the same viewpoint for a lithostratigraphy for both parts of the basin is also supported by the Shitole et al. (2021).Poddar (1964), is the first worker who has proposed two separate groups for the Cretaceous sequence of WLNV, the lower Songir and the upper Navagam. However, a gradational contact has been observed between the lower siliciclastic dominated, and the upper carbonate dominated unit (Shitole et al., 2021; Chiplonkar et al., 1977a). Further, Navagam Limestone (Albian-Cenomanian) and Gulvani Limestone (Turonian) of Navagam Group were described at a different stratigraphic level (Poddar, 1964), and the Rajpipla Limestone (Sastry and Mamgain, 1971; Dassarma and Sinha, 1975) was described much younger (Santonian-Campanian) (Table 3.1), although field check of these three units revealed them to be isochronous deposits (Shitole et al. 2021). The Late Cretaceous fluvio-marine sequence was considered Bagh Group (ELNV), with age ranging from Cenomanian to Coniacian (Jaitly and Ajane, 2013; Kumar et al., 2016; Prasad et al., 2017).

Considering the earlier view, field and laboratory study, and the ISSC (1994) norms, the lithostratigraphy for WLNV is amended, and the name 'Bagh,' well-established and deeply entrenched in the Indian geological literature, is retained. The Cretaceous fluvio-marine sequence of the WLNV is revised and upgraded as to 'Bagh Group'. The constituent units differ in the WLNV compared with the ELNV; however, priority was given to retaining the old names. The retention of existing units and the establishment of new units were emphasized wherever necessary; stratotypes are also defined following all the stratigraphic norms.

The revision of lithostratigraphy of the Bagh Group rocks is done on extensive fieldwork, intensive regional mapping, measurement of sections, and a systematic sampling carried out at 23 locations in the WLNV and 9 locations in ELNV. The detailed sedimentological, stratigraphical, and paleontological dataare acquired and correlated, which have helped in describing and erecting the new lithostratigraphic units (Table 4.1) for the Cretaceous sequence of the Western Lower Narmada Valley.

4.2 STRATIGRAPHIC NORMS

The lithostratigraphy of the WLNV, the Bagh Group, is amended based on the ISSC norms, which has laid a set of procedures for establishing and revising the stratigraphic units, which are briefly stated below:

Name: The geographic name of the unit should be derived from a permanent or an artificial feature near the unit and should be spotted in the standard published maps. The name is combined with the rank in the case of group and formation, whereas for nomenclature of members, the geographic name is to be combined with the lithology and the rank of the unit. The geographic name should be unique, and it's spelling once established, should not be changed; however, the associated rank and lithology can be changed. Multiple names assigned to a unit can be reduced if the correlation is established, prioritizing the earlier proposed name. The ISSC emphasizes retaining traditional well-established names and clarifies that the disappearance of the geographic name does not imply establishing a new name.

Intent and Utility: According to ISSC, a revision or redefinition of an established unit without changing its name requires a strong justification and utility. The unit's rank can be changed, keeping its original definition, geographic name, and boundaries the same.

Stratotype: The stratigraphic units must be well developed and exposed at the locality, where their identity is defined. Stratotype (type section), when serves as a standard reference for definition and /or characterization of a layered stratigraphic sequence, is known as unit-stratotype. When it contains a specific point establishing the boundary between the two units, is is known as Boundary-Stratotype. The unit stratotypes, when combined, are known as Composite-Stratotype. The type locality is where the unit was originally described and/or named. The type area constitutes both the stratotype and type locality.

Description of Unit at Stratotype or Type Locality: The stratotype should be described geologically and geographicallyin detail. The unit- and boundary-stratoypes should be marked at a permanent geographic and geological feature. The study should provide an accessible stratotype and should ensure its preservation.

Unit Description: It includes the extent of the unit, its geomorphic expression, thickness, lateral lithological variation, stratigraphic relation, relation to other units, dimension, shape, distinctive or identifying features that can be used to extend the unit away from its stratotype and boundary-stratotypes. The details like measured sections, well logs, and maps in the description of the new unit.

Geologic Age: Other than the chronostratigraphic units, the age is not compulsory in the definition of the lithostratigraphic units but should be given wherever possible.

Depositional Environment: Discussion on the depositional environment includes interpretation of the origin and environmental facies.

4.3 LITHOSTRATIGRAPHY

The Bagh Group Bagh Group of the WLNV is characterized by rudaceous and arenaceous rocks in the lower part, while the upper part comprises shales, limestones, and mixed siliciclastic-carbonate rocks (Plate3.2) andis divided into five formations- Songir, Vajepur, Bilthana, Nodular Limestone, and Uchad; the Uchad Formation is further subdivided into the Narmada Sandstone Member and the Men Nadi Limestone Member (Table 4.1).

According to Shitole et al. (2021), the Bagh group sequence of WLNV is comparable with the ELNV, but its lower limit is extended up to Albian (Chiplonkar et al., 1977; Chiplonkar, 1983) and Hautervian based on plant fossils (Murty et al., 1963). The Western part of the Lower Narmada valley (WLNV) preserves the fluvio-marine sequence and allows studying the older sequence of Bagh Group spanning in age from Berriasain? to Coniacian as compared to its eastern counterparts.

Age	Group	Formation	Member	Lithology
Coniacian	Bagh	Uchad	Men Nadi Limestone (7m)	Mudstone, Muddy micrite, Shale
			Narmada Sandstone (50m)	Micritic sandstone, Calcareous sandstone, Sandy micrite, Shale, Quartz arenite, Gravelly sandstone
Turonian		Nodular Limestone (80m)		Mudstone, Sandy micrite, Muddy micrite, Wackestone
Cenomanian - Turonian		Bilthana (9m)		Shale, Sandy allochemic limestone, Muddy micrite, Wackestone, Grainstone, Mudstone, Calcareous sandstone, Siltstone
Albian-Cenomanian		Vajepur (46m)		Calcareous sandstone, Micritic sandstone, Quartz arenite, Shale, Siltstone
Berriasian? (Neocomian) - Aptian		Songir (127m)		Conglomerate, Gravelly sandstone, Quartz arenite

Table 4.1 Lithostratigraphy of the Bagh Group sedimentary succession, Western Lower Narmada Valley (Shitole et al., 2021).

4.3.1 BAGH GROUP

Historical background: Dangerfield (1818) first introduced the word 'Bagh' in the literature, which discussed the lithology of the sandstone near Bagh Town, Madhya Pradesh (Fig 3.1a). Later Blanford (1869) named them Bagh Beds based on a systematic survey of the Cretaceous rocks of the Narmada Valley. Subsequently, the word 'Bagh Beds' was used by many workers for the marine sequence of the Narmada Valley in their lithostratigraphic classifications (Bose, 1884; Rode and Chiplonkar, 1935; Roy-Chowdhary and Sastri, 1962). Murty et al. (1963) elevated the rank and considered it the Bagh Group, which was later followed by Biswas and Deshpande (1983) and Poddar (1964) for the marine succession.

Intent and Utility: Murty et al. (1963) divided the ELNV Cretaceous succession of the Jhabua district into the Nimar Group (comprising Umrali Flagstone and Nimar Sandstone) and Bagh Group (comprising Amlipura Oyster Bed, Sejagaon Limestone, and Kanasgali Grit). Later, Poddar (1964) divided the Cretaceous sequence of ELNV into the lower Nimar Group (comprising Nimar Sandstone and Umrali Flagstone) disconformably overlain by the Bagh Group. The Bagh Group is comprised of Amlipura Oyster Bed, Kanasgali Grit, Sejagaon Limestone, and Bagh Formation in the ELNV. A similar explanation was provided for the separation of the Songir Group (comprising the Songir Sandstone, the Uchad Flagstone) and the Navagam Group (comprising the Bilthana Oyster Bed, the Navagam Limestone, and the Gulvani Limestone) in the WLNV. However, according to Chiplonkar et al. (1977a) and based on field investigation by Shitole et al. (2021), it was inferred that the Cretaceous sequence of LNV showed a single episode of deposition with a conformable contact between the two groups. Hence, the separation of the sequence into two groups is unwarranted according to the lithostratigraphic norms. Also, the name “Bagh” (Dangerfield, 1818) has been deeply entrenched in Indian literature for more than two centuries, and it would not be appropriate to replace it. Hence, owing to the invalidity of Poddar’s proposed groups and considering the strong historical background and usage of the term ‘Bagh Group’ for the Cretaceous sequence of ELNV (Jaitly and Ajane, 2013; Prasad et al., 2017), the term “Bagh Group” was formalized for WLNV with variable component formations by Shitole et al. (2021).

According to the ISSC (1994) norms, formations making up a group need not necessarily be the same everywhere. The lower sandstone unit was found to wedge out towards the southern side and the upper carbonate towards the northern side of the basin. Hence, their study justifies the reduction of the rank of the Songir Group to the Songir Formation and the Navagam Group to the Nodular Limestone.

Designation: The unit was previously referred to as Bagh Beds, Nimar Group, Songir Group, Navagam Group, Bagh Group, and Nimar Sandstone (Table 3.1a-d) in the WLNV, and its status is considered as Bagh Group.

Boundary. The lower boundary of the Bagh Group is unconformable with the Precambrian (Plate 4.1a), and the upper boundary is unconformable with the Lameta Group /Deccan Trap Formation, respectively.

Age: Berriasian? (Neocomian) to Coniacian (Gangopadhyay and Bardhan, 1998; Jana et al., 2013).

Depositional environment: The lower part of the Bagh Group comprises conglomerates of sediment gravity flow (Plate 4.1b-d) which progressively grade into gravelly sandstones to sandstones deposits of probably channel lag and braided bar (Plates 4.1e-f, 4.2a). Medium- to coarse-grained cross-bedded sandstone suggests vertical accretion of channel sand bars, and carbonaceous shale indicates the floodplains and back swamps/marshy conditions. Marine influence is observed in the sequence marked by the mixed siliciclastic-carbonate deposits of the marginal marine environment, further overlain by shallow marine carbonate rocks (Plates 4.3-4.4).

4.3.1.1 Songir Formation

Historical background: Foote (1898) referred to the marine Cretaceous rocks exposed in Gujarat State as Bagh Beds and, for the first time, assigned the slabby cross-bedded sandstone exposed near Songir village a term 'Songir Sandstone,' where they were extensively quarried. Earlier reports described the unit also as the Nimar Sandstone in the Narmada Basin; later, the Nimar Sandstone and the Songir Formation were used for sandstone exposures in the eastern and western part of the LNV sequence, respectively (Biswas and Deshpande, 1983; Poddar, 1964). The Songir Formation occurs as a consistent sandstone-dominated unit extending laterally from the Barwah in Madhya Pradesh westwards to the Songir-Chosalpura villages in Gujarat (Plates 2.1, 4.1, 4.2a). The lower sandstone-dominated unit was widely referred to as Songir Sandstone Formation (Bhatt et al., 2016), Songir Sandstone (Bhosle et al., 2019; Foote, 1898; Merh, 1995; Poddar, 1964), and Songir Group (Biswas and Deshpande, 1983; Poddar, 1964; Racey et al., 2016) in the WLNV. Merh (1995) correlated the Songir Sandstone of Vadodara with the Himmatnagar Sandstone, Nimar Sandstone of Nimar Valley (Madhya Pradesh), Dhrangadhra Formation of Saurashtra, and Bhuj Formation of Kachchh.

Intent and Utility: The Nimar Formation was termed for the lower part of the Bagh Group and was considered a single lithological unit by many authors; Chiplonkar et al. (1977a) extended it to include the overlying oyster limestone bed. Poddar (1964) considered the Nimar Sandstone of ELNV equivalent to the Songir Sandstone of the WLNV. Dassarma and Sinha (1975) and Sastry and Mamgain (1971) classified the lower sandstone-dominated unit in the WLNV as Nimar Sandstone and Calcareous Sandstone (Upper Nimar), whereas Poddar (1964) classified into as upper Uchad Flagstone and lower Songir Sandstone. It was classified as upper Umrali Flagstone and lower Nimar Sandstone in ELNV by Biswas and Deshpande (1984), Murty et al. (1963), and Poddar (1964). The Nimar Sandstone Formation was recently classified as lower Bagh Cave Member and upper Baria/Bariya Member in the ELNV by Kumar et al. (2016) and Tripathi (2006). Singh and Dayal (1979) also supported the division of Nimar Sandstone into lower fresh water and upper marine unit. Thus, the lower part of the sandstone-dominated unit in the WLNV has already been separated from its upper part by previous workers, and the separation was also proposed for the ELNV (Table 3.1a-d). Several workers have designated this lower part of the sandstone-dominated unit as a formation or group. It is widely recognized as Songir in the WLNV (Bhosle et al., 2019; Biswas and Deshpande, 1983; Foote, 1898; Merh, 1995; Poddar, 1964; Racey et al., 2016). However, its status as a formation or group is still unclear. It was considered as Songir Formation, utilizing the name 'Songir" from the earlier works (Shitole et al., 2021). However, the suffix 'sandstone' as described in Foote (1898) and Poddar (1964) was removed to acknowledge the dominance of conglomerate and gravelly sandstone in the unit. Murtyet al. (1963) and Sastry and Mamgain (1971) described this unit as Nimar Sandstone in WLNV. However, no stratotype or boundaries were assigned.

Designation: Formation

Stratotype: The unit was earlier described as Songir Sandstone (Foote, 1898; Poddar, 1964) for the rocks exposed around Songir village without designating a type section. The stratotype for this formation is well exposed at Songir-Chosalpura villages of the Chhota Udepur District of Gujarat (N 22°05'01" E 73°38'00") and attains a thickness of approximately 127 m. It exhibits a distinct rock assemblage of conglomerates at the base, followed upward by gravelly and coarse-grained sandstones (Plates 4.1, 4.2a). This formation is also well exposed around Ghantoli, Mohanfort, Chametha, Vajeriya, Agar, Naswadi, and Sinhada villages (Plate 4.1, 4.2b).

Plate 4.1 Outcrop view of the Songir Formation showing a. Angular contact of sandstones with the Precambrian rocks, Ghantoli village. b. Cobble-rich (clasts impression) conglomerate; Songir village (length of hammer = 32 cm). c. Gravelly sandstone with interbedded conglomerate; Vajeriya village (length of hammer = 34.5 cm). d. Matrix-supported conglomerate, Ghantoli village. e. Large-scale planar cross-stratification in gravelly sandstone; Songir village (length of hammer = 32 cm). f. Planar cross-bedding in

coarse-grained sandstone at Mohanfort section (length of hammer = 32 cm). Scale bar represents 1m.

Description of unit: The Songir Formation (WLNV) rests unconformably over the Precambrian rocks and comprises a thick, coarse clastic sequence, as compared to its ELNV counterpart, the Nimar Sandstone. It is characterized by predominately arenaceous rocks with a subordinate amount of rudaceous deposits (Plates 4.1, 4.2a). The lower part of the formation consists of clast/matrix-supported oligomictic/polymictic conglomerate, gravelly sandstone, fine- to coarse-grained horizontally-bedded and cross-bedded sandstones (Plate 4.1c-d). The conglomerate is poorly sorted and consists of subangular to subrounded granules, pebbles, and cobbles of quartz, jasper, and feldspar minerals. The conglomerates at Songir are about 5 m thick. The sequence grades into gravelly sandstone and coarse- to very coarse-grained sandstone, where the former is frequently repeated in the sequence. The upper part of the unit is dominated by cross-bedded gravelly sandstone (Plate 4.1e), which are discontinuous and pinch out at a very short distance, while the overlying coarse-grained sandstones are horizontally bedded (Plate 4.2a) and cross-stratified (Plate 4.1f) with occasional occurrence of conglomerate (Plate 4.1b).The sandstones are white, yellow, reddish-brown and consist of small gravels scattered throughout the sequence. Petrographically, they are mature sandstones and consist of more than 97% quartz grains, which are poorly sorted, angular to subangular, bounded by a siliceous cement, and show evidence of pressure solution and overgrowth.

Boundaries: The lower boundary of the formation has an unconformable contact with the Precambrian igneous (granite) and metamorphic rocks (phyllites, quartzites, and gneiss) (Plate 4.1a) and is best seen around Agar, Naswadi, Sinhada, Ghantoli, and Vajeriya villages of Narmada and Chhota Udepur districts of Gujarat. The upper boundary is conformable with the overlying calcareous sandstone of the Vajepur Formation, observed at Vajepur village.

Age: Bose (1884) suggested the siliciclastic-dominated sequence beneath the Nodular Limestone from the Ambadongar and surrounding regions (WLNV) to be of Neocomian age. Plant fossils have been recorded by Murthy et al. (1963) from the lower fluvial portion of the Songir Formation (Nimar Group) of Jhabua district, Madhya Pradesh which suggests a Hauterivian age (Early Cretaceous). Kumar (1994) recorded palynomorphs from the carbonaceous clays of the lower part of the fluvial portion of the Nimar Sandstone (Songir

Formation) at Umrali village (Jhabua District), suggesting a broad age range of Late Jurassic–Early Cretaceous. Recently, Jana et al. (2013), based on a plant fossil assemblage *Allocladus–Brachyphyllum–Pagiophyllum* assemblage [zone 9], reported from the Gardeshwar Formation assigned it an Early Cretaceous age. Rajanikanth and Chinnappa (2016) correlated the Gardeshwar Formation (Narmada district, WLNV) with the Dhrangadhra (Saurashtra) and Bhuj formations (Kachchh) and assigned a Neocomian to Aptian age. Based on floral evidence and thick sandy conglomeratic sequence, the Songir Formation's age is considered Berriasian? (Neocomian) to Aptian (Early Cretaceous).

Depositional environment: The lower part of the Songir Formation is characterized by coarse-grained clastic materials of channel gravels and sand bar deposits, characteristic of a braided river. Conglomerates at the base of the sequence characterized by a variable proportion of clast/matrix ratio suggest sediment gravity flows of a fluvial environment. The overlying strata are characterized by thick sandstone; the massive sandstone bodies observed generally at the bottom of the sequence suggest short-lived debris-flow deposits. The occurrence of planar and trough cross-stratification indicates the migration of subaqueous dunes in the lower flow regime of channels. The planar stratified sand bodies intervened by gravel deposits are interpreted as bar deposits. The lithological properties of the rocks in the Songir Formation suggest high bedload and fluctuating discharge characteristics of a braided river environment (Shitole et al., 2021) and debris flow deposits of the alluvial fan.

4.3.1.2 Vajepur Formation

Historical Background: The formation is named after the Vajepur village of Chhota Udepur district, situated at the confluence of Kara River and its tributary, Mathwad Nala. It is well exposed in the Kara River section under the bridge and its E-W trending tributary near Vajepur village (Plate 4.2b, e). Poddar (1964) divided the Songir Group into the Songir Formation and the Uchad Flagstone and incorporated the sandstone-shale unit as part of the Songir Formation, while the Upper Calcareous Sandstone unit was referred to as Uchad Flagstone, also described as Calcareous Sandstone/Upper Nimar by Dassarma and Sinha (1975) and Sastry and Mamgain (1971) in the WLNV. In the ELNV, the upper calcareous sandstone unit is described as Umrali Flagstone (Biswas and Deshpande, 1983; Poddar, 1964), the Upper Nimar Formation (Dassarma and Sinha, 1975; Racey et al., 2016; Sastry and Mamgain, 1971), the Nimar Formation (Jaitly and Ajane, 2013; Prasad et al., 2017) and Bariya Member (Kumar et al., 2016; Tripathi, 2006).

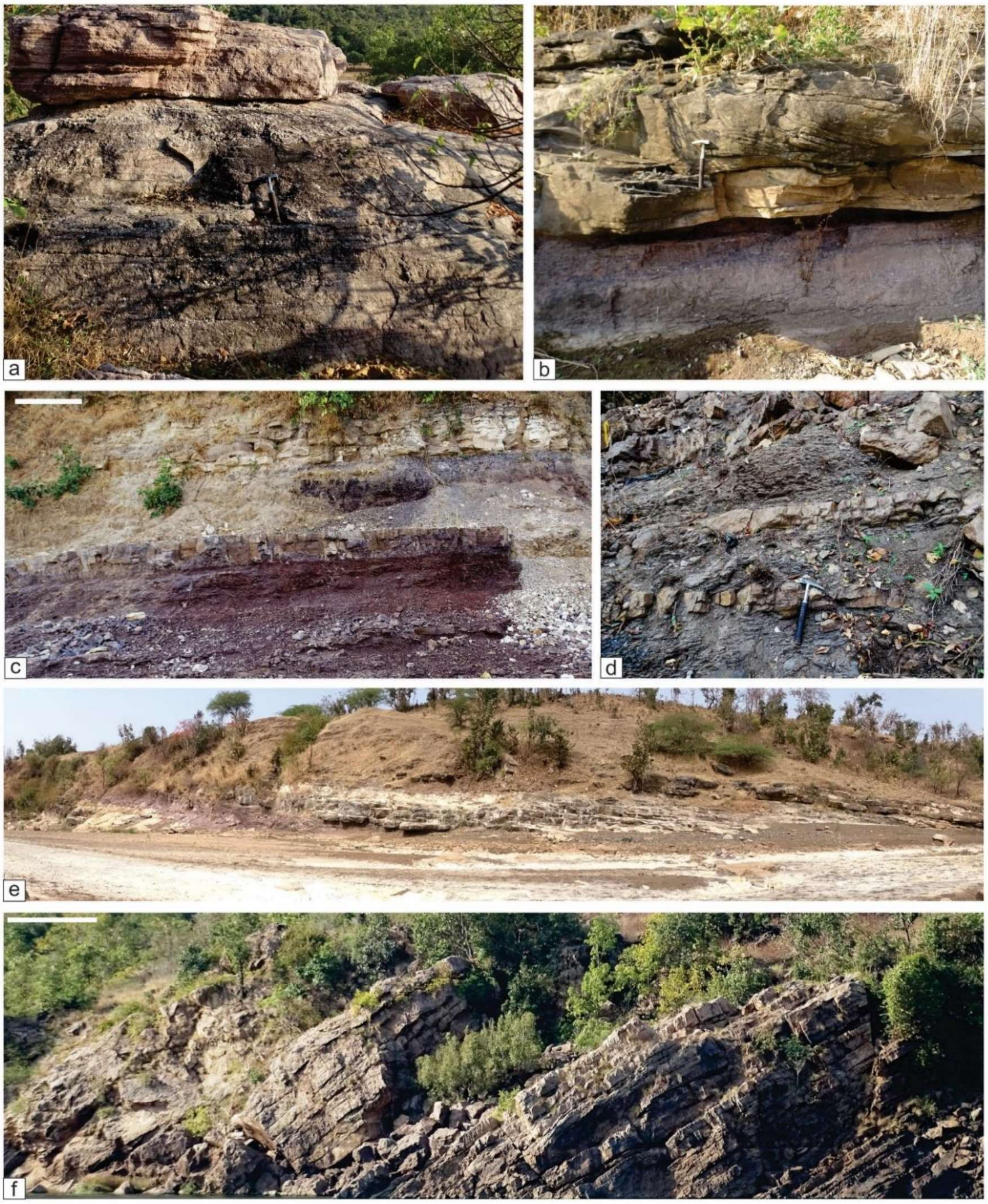


Plate 4.2 Outcrop view of Songir and Vajepur formations. a. Horizontally-bedded coarse-grained sandstone with granules and pebbles, Songir Formation, Songir village. b. Cross-bedded sandstone and shale of the Vajepur Formation, Vajepur village. Sandstone-shale intercalation of Vajepur Formation exposed at c. Sultanpura-Devaliya village (Scale bar = 1 m) and d. Navagam village. e. The basal sandstone-shale sequence of the Vajepur Formation,

Mathwad Nala, a tributary of Kara River near Vajepur village. f. Thickly-bedded sandstones; Vajepur Formation, Navagam village (Scale bar= 5 m). Length of hammer = 32 cm.

Intent and Utility: Poddar (1964) informally used the term Uchad flagstone, the thinly-bedded rippled sandstone that overlies the Songir Formation, wherein neither the type sections nor the formal description of the unit was given. Field investigation in the studies of Shitole et al. (2021) revealed at least a 40 m-thick intercalated sandstone-shale succession and rippled sandstone which is sandwiched between the Uchad flagstone as described by Poddar (1964) and the underlying Songir Formation, which is exposed in the Navagam, Vajepur, Uchad, Devaliya, Bilthana and Sultanpura sections (Plate 4.2b-e). Therefore, a new lithostratigraphic unit, 'Vajepur Formation' was introduced to formalize the aforesaid unit and encompass the additional thick sedimentary package, which has laterally consistent lithological characteristics. The new unit Vajepur Formation has a different lithological assemblage and bed geometry and therefore differs from the underlying Songir Formation.

Designation: The unit was earlier referred to as Uchad Flagstone, Calcareous Sandstone Upper Nimar with oyster and shark teeth, Calcareous Sandstone (Upper Nimars), and Upper Nimar in the WLNV (Table 3.1a-d). It is considered herein as the Vajepur Formation (Shitole et al., 2021).

Stratotype: The stratotype for this formation was selected for rocks exposed near Vajepur village (Plate 4.2e) of Chhota Udepur district (N 22° 03'31" E 74°05'10"). It has gradational contacts, the lower contact exposed in Kara River east of the Mohan Fort section. The upper contact is exposed near Vajepur village in the Mathwad Nala. It is 46 m thick and comprises white to grey colored sandstone and purple shale sequence capped by rippled sandstone.

Description of unit: The Vajepur Formation comprises of intercalated thickly-bedded sandstone and shale succession in its lower part (Plate 4.2b-e), thickly-bedded sandstone in the middle part (Plate 4.2f), which further grades to flaggy and rippled calcareous sandstone in the upper part (Plate 4.3a-b). The maximum formation thickness (180 m) is observed in the Navagam section. The sandstone bands show the presence of planar, trough, and hummocky cross-stratifications. The calcareous sandstones in the upper part are fine- to medium-grained, flaggy in nature, characterized by ripple marks on each bed, bioturbated, and fossiliferous. Several fossils viz., algae (Badve and Nayak, 1984; Kundal and Sangarwar, 1998a), bivalves (Chiplonkar and Badve, 1976; Dassarma and Sinha, 1975; Nayak, 2000a), foraminifera

(Nayak, 1987; Rajshekhar, 1991), gastropods (Gangopadhyay and Maiti, 2012) and trace fossils (Badve, 1987; Chiplonkar and Badve, 1972; Ghare and Badve, 1980; Kundal and Sanganwar, 1998b, 2000; Nayak, 2000b, Patel et al., 2018; Sanganwar and Kundal, 1997; Singh and Dayal, 1979) were reported from the different sections. Abundant burrows of sea anemones (*Conichnus* and *Conostichnus*) were observed in the uppermost part of the unit (Patel et al., 2018). Petrographically, it is composed of more than 70% fine- to coarse-grained angular quartz grains and subordinate polycrystalline quartz grains with plagioclase feldspar, microcline, chert, glauconite, and ooids. The unit is also observed around Sultanpura, Bilthana, Mathsar-Kanji, Gulvani, Uchad, Navagam, and Karvi villages, Men River section near Devaliya, and fringes of Ambadongar Carbonatite Ring Complex (Shitole et al., 2021).

Boundaries: The upper and lower boundaries of the Vajepur Formation are gradational; coarse-grained pebbly sandstones of the Songir Formation grade upwards to the fine- to coarse-grained quartz arenite and calcareous sandstone of Vajepur Formation in the Kara River section. The upper boundary of the Vajepur Formation grades to the shale of the overlying Bilthana Formation (Plate 4.3b), which is well exposed on either side of the Mathwad Nala near Vajepur village and also observed at Uchad, Sultanpura, Navagam, Karvi, and Gulvani villages.

Age: The Upper Nimar (equivalent to Vajepur Formation) was considered Cenomanian-Turonian in age based on bivalves and calcareous algae (Dassarma and Sinha, 1975; Kundal and Sanganwar, 1998a; Nayak, 2000a). Chiplonkar et al. (1977a) observed placenterid ammonites in the overlying Nodular Limestone and Coralline limestone and assigned the basal Nimar Formation as Albian to Cenomanian. Chiplonkar (1982), based on trace fossils, oysters, and other fossils such as the gastropod *Turritella*, bivalve *Astarte*, and ammonoids *Baghiceras* and *Malwiceras* from the upper part of the Nimar sandstone, suggested its Cenomanian age, based on foraminifera from the calcareous top of the Nimar sandstone unit assigned the Albian-Cenomanian age (Nayak, 1987). Later, Rajshekhar (1995) examined Nayak's collection and found some characteristic forms such as *Miliannina manitovensis, Gavelinella plummerae,* and *G. intermedia* supporting an Albian to Cenomanian age. Based on the above-mentioned fossil evidence, the age of the Vajepur Formation was considered Albian to Cenomanian (Shitole et al., 2021).

Depositional environment: Rocks of the Vajepur Formation are calcareous in nature and contain marine fossils (Dassarma and Sinha, 1975; Murty et al., 1963; Poddar, 1964; Sastry and Mamgain, 1971; Tripathi, 2006). Marine signatures reported from the ELNV and WLNV were tidal evidence (Bhattacharya and Jha, 2014; Dassarma and Sinha, 1975; Sarkar, 1973), sedimentary structures (Bose and Das, 1986), microfossils (Jafar, 1982; Nayak, 1987; Rajshekhar, 1991); calcareous algae (Badve and Nayak, 1984; Kundal and Sanganwar, 1998a); bivalves (Bose, 1884; Chiplonkar and Badve, 1976; Dassarma and Sinha, 1975; Nayak, 2000a) and trace fossils (Chiplonkar and Badve, 1980; Ghare and Badve, 1980; Kundal and Sanganwar, 1998b; Nayak, 2000b; Patel et al., 2018; Sanganwar and Kundal, 1997). Sedimentological and paleontological evidence indicates that the rocks were deposited in a marginal marine to shallow marine environment.

4.3.1.3 Bilthana Formation

Historical background: Poddar (1964) proposed the name 'Bilthana' for the first time for the oyster embedded limestone in WLNV. The calcareous sandstone and oyster bed with shark teeth was designated as Upper Nimar (Jaitly and Ajane, 2013; Racey et al., 2016; Sastry and Mamgain, 1971; Tripathi, 2006) or Bariya Member (Tripathi, 2006); while the oyster bed was recognized as a separate unit by Murty et al. (1963), Poddar (1964), and Verma (1968). Dassarma and Sinha (1975) separated the Bagh beds into three units, Calcareous Sandstones, Oyster Bed, and Rajpipla Limestone; the last two units were placed at higher stratigraphic levels i.e., Coniacian and Senonian, respectively. The oyster-bearing bands were variously named as Oyster Bed (Bose, 1884; Roy-Chowdhary and Sastri, 1962; Verma, 1968) and Amlipura Oyster Bed (Murty et al., 1963; Poddar, 1964) in ELNV, whereas they are recognized as Bilthana Oyster Bed (Poddar, 1964) and Oyster Bed (Dassarma and Sinha, 1975) in WLNV. The Bilthana Oyster Bed was considered equivalent to the Amlipura Oyster Bed of ELNV by Poddar (1964).

Intent and Utility: The unit is characterized by different lithological and paleontological characteristics compared to the underlying unit (Vajepur Formation) and the overlying unit (Nodular Limestone). This unit possesses a degree of internal lithic homogeneity and distinctive lithic features, i.e. intercalation of oyster limestone and shales (Plate 4.3b). Previously, it was described as the Bilthana Oyster Bed (Poddar, 1964) and the Oyster Bed (Dassarma and Sinha, 1975).

Designation: The formation was earlier referred to as Bilthana Oyster Bed, Calcareous Sandstone Upper Nimar (oyster and shark teeth), and Oyster Bed in WLNV. It was formalized as Bilthana Formation (Shitole et al., 2021).
Stratotype: The stratotype of this unit is well exposed in the tributary of Men River, near Sultanpura village, ~500 m east of Bilthana village (N 21° 57’52” E 73° 39’57”). The stratotype section is 9 m thick and comprises about nine oyster-bearing limestone bands intercalated with shale. The maximum thickness of an oyster limestone band is ~20 cm, while the intervening shale bands are relatively thick, and their thickness varies from 30 to 80 cm (Shitole et al., 2021).

Description of unit: The Bilthana Formation consists of an intercalated sequence of oyster limestone and shale (Plate 4.3b-c). The oyster bands are hard, yellow in color, and pinch out at a short distance. The limestone bands are usually centimeters thick, but the exposed band’s maximum thickness (20 cm) is observed in the type locality. The intervening shale is grey to dull yellow, fissile, with variable thickness, and the maximum thickness is 80 cm. It is a highly fossiliferous unit and consists of abundant oyster species *Bosostrea* (Chiplonkar and Badve, 1976) with shark teeth (Dassarma and Sinha, 1975; Verma, 1965), gastropods, foraminifers, and ostracods. It is also highly bioturbated (Ghare and Badve, 1980) and mainly consists of *Thalassinoides* and plug-shaped (*Bergaueria, Conichnus, Conostichnus*) burrows (Patel et al., 2018, Shitole et al., 2019). Oysters are also observed at a higher stratigraphic level i.e., on the top of the Nodular Limestone; however, the occurrence is localized. Petrographically, the Bilthana Formation is composed of abundant shell fragments of oysters with echinoderms, foraminifers, ostracodes with subordinate quartz, and plagioclase feldspar grains embedded in a micritic matrix.

Boundaries: The Bilthana Formation shows a gradational contact with the underlying sandstones of the Vajepur Formation (Plate 4.3b), while the upper boundary of shale grades to the Nodular Limestone. Both the upper and lower contacts of the unit are well exposed at Bilthana, Sultanpura, Uchad, Mathsar, Kanji, Chikhli, Karvi, Gulvani, and Vajepur sections.
Age: Verma (1965) reported shark teeth from the Oyster bed of the Ambadongar area (WLNV) and assigned a Cenomanian-Senonian age to it; later, in 1969, Verma revised the age to Cenomanian-Turonian. Dassarma and Sinha (1966, 1975) reported *Ostrea, Turritella,* and shark teeth from the Oyster Bed of Alirajpur area (ELNV) and assigned a Cenomanian

age. Sastry and Mamgain (1971) in WLNV merged the Oyster Bed in the Calcareous Sandstone Upper Nimar and assigned a Cenomanian-Turonian age based on the fossils contained in it.

The Oyster beds are observed at two different stratigraphic levels in the Bagh Group. The upper oyster bed is observed at the top of the Nodular Limestone and is localized in nature. The lower oyster beds occur above the flaggy sandstone of the Vajepur Formation and consist of abundant species of *Bosostrea* (Badve and Ghare, 1978; Chiplonkar and Badve, 1978). Chiplonkar et al. (1977a) considered the oyster bed of the Ambadongar region in WLNV equivalent to the oyster bed of Amlipura, Phata, and Bagh of ELNV, based on ammonites and shark teeth. The shark species *Onchopritis indicus* collected from the Oyster Bed of Ambadongar region in WLNV showed affinities to the *Onchopritis* sp. from the Sahara of Albian-Cenomanian age (Chiplonkar et al., 1977a). The overlying conformable horizon consisting of *Astarte-Turritella* with *Cardium* was assigned a Cenomanian-Turonian age. These authors assigned the Cenomanian-Turonian age for the upper part of Nimar Sandstone (Oyster Beds) till the Upper Coralline Limestone, whereas the Albian age was suggested for the lower part of the Nimar Sandstone (Table 3.1b). The Bilthana Formation shows similar fossil affinities with ELNV and is considered Cenomanian-Turonian in age.

Depositional environment: The formation is characterized by intercalated oyster limestone–shale sequence, with the basal part comprising argillaceous sedimentary rocks. It is immediately overlain by a bed of sandy allochemic limestone containing abundant molluscan shells (marine bivalves), echinoids, and trace fossils. The shell beds suggest deposition in shallow marine conditions. The increase in carbonate content, concentrations of oysters, and argillaceous intervals suggest an increase in water depths compared with the underlying calcareous sandstone of the Vajepur Formation. The increase in the shell fragments towards the top of the oyster limestone bands i.e., from sandy allochemic limestones to bioclastic grainstone/packstone, suggests high-energy conditions. The sedimentological and paleontological evidence suggests that the sequence was developed in low- to high-energy conditions of a transgressive shallow marine environment.

4.3.1.4 Nodular Limestone

Historical background: The name 'Nodular Limestone' was first proposed by Bose (1884) and subsequently followed by several workers in the LNV (Table 3.1a-d). Bose (1884) observed the uniform nodular appearance of the lithology in the LNV, except in the eastern and western

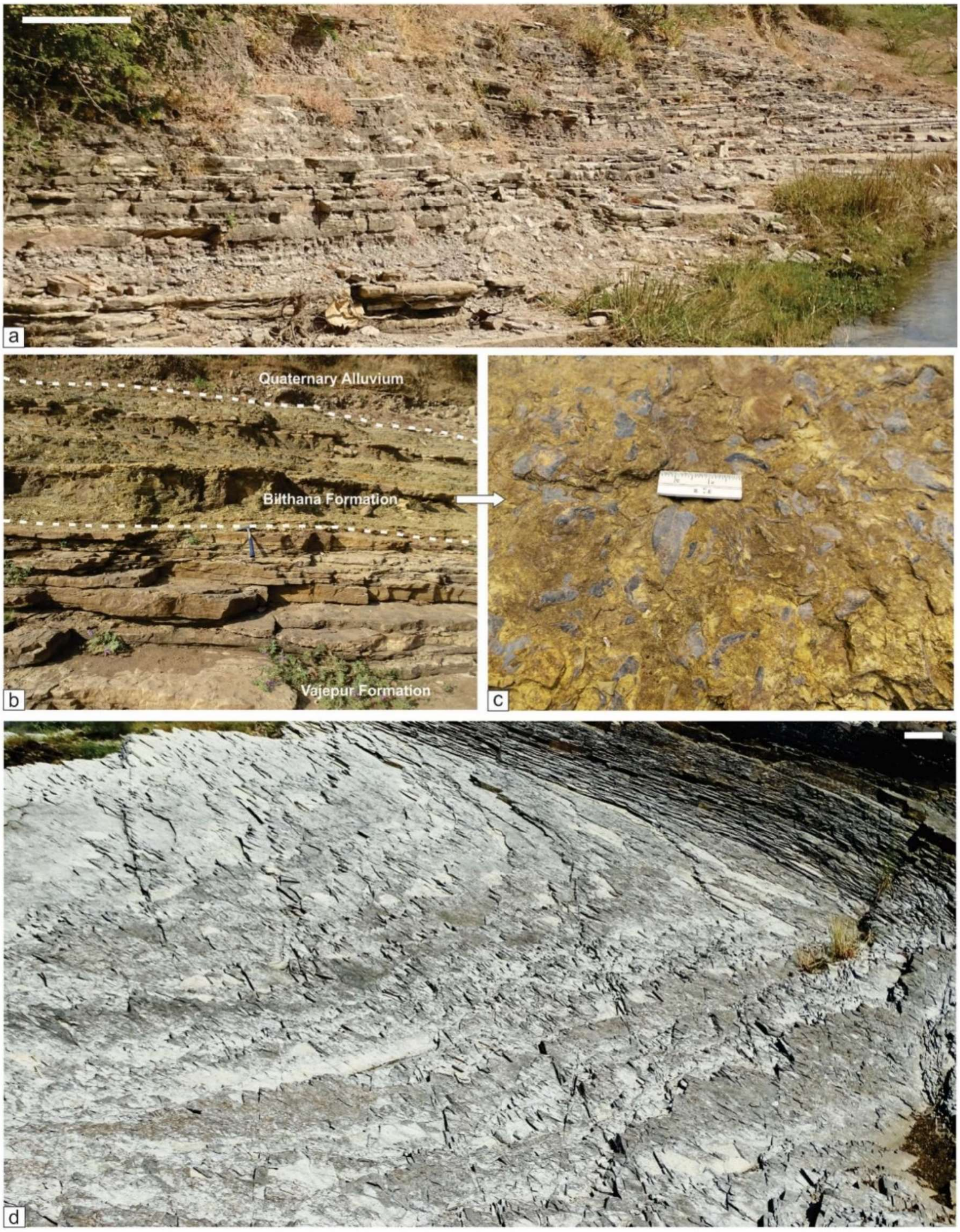


Plate 4.3 Outcrop view of Vajepur Formation, Bilthana Formation, and Nodular Limestone. a. Flaggy, rippled calcareous sandstone, top of the Vajepur Formation exposed in the tributary of Men River, Sultanpura village. b. Contact of flaggy rippled calcareous sandstone of the Vajepur Formation with the overlying sandy allochemic limestone of Bilthana Formation, Uchad village (length of hammer = 32 cm). c. Close-up view of the fossiliferous limestone bands of the Bilthana Formation showing disarticulated oyster shells. d. Thinly-bedded Nodular Limestone, Narmada River, Navagam village. Scale bar represents 1m.

extremities of Barwah, and Kawant, respectively. Bose (1884) suggested the name owing to a lack of towns or features of importance to give a geographic name. Nodular Limestone is the most consistent lithounit observed in the Narmada Basin (Blanford, 1869; Bose, 1884; Chiplonkar, 1982; Rajshekhar and Aptalkar, 1995). The unit was referred to as Sejagaon Limestone in Jhabua district, Madhya Pradesh by Murty et al. (1963) and correlated it with the Nodular Limestone in ELNV. Poddar (1964) assigned it 'Navagam' name and the status of a group as well as formation.

This unit is variably described as Gulvani Limestone and Navagam Limestone (Poddar, 1964), Rajpipla Limestone (Sastry and Mamgain, 1971 and Dassarma and Sinha, 1975), and the Rajpipla Limestone and Nodular Limestone (Rajshekhar, 1997) in WLNV and as Sejagaon Limestone (Murty et al., 1963; Poddar, 1964), Cave Nodular Limestone (Pal, 1971), Karondia Limestone (Akhtar and Khan, 1997; Guha, 1976), Nodular Limestone Member (Singh and Srivastava, 1981), Karaundia Member (Tripathi, 1995), Nodular Limestone Formation and Karondia Member (Jaitly and Ajane, 2013; Kumar et al., 2016; Ruidas et al., 2018; Tripathi, 2006), Lower *Inoceramus* Bed, Nodular Limestone (Vaidyanathan and Ramakrishnan, 2010), Nodular Limestone Formation (Racey et al., 2016) and Nodular Limestone (Karondia Member) (Prasad et al., 2017) in the ELNV. Later, the unit was redefined as Rajpipla Limestone in the WLNV and considered the youngest unit of the Bagh Group (Dassarma and Sinha, 1975; Sastry and Mamgain, 1971). Biswas and Deshpande (1983) revised the stratigraphy and considered it Nodular Limestone for the entire Lower Narmada Basin. Field investigation of the WLNV succession revealed isochronous deposits and is considered Nodular Limestone (Shitole et al., 2021).

Intent and Utility: The unit has been named variably in the literature and bears many synonyms and homonyms. The Navagam Limestone was first proposed by Poddar (1964) as part of the Navagam Group for the Cretaceous marine sequence of the WLNV and divided the group into three units, Bilthana Oyster Bed, Navagam Limestone, and Gulvani Limestone. The Navagam Limestone within the Navagam Group are homonyms and lead to confusion. The Navagam Group, which was separated from the rest of the Bagh Group, showed a gradational contact with the underlying Bilthana Formation and was therefore incorporated in the Bagh Group (Shitole et al., 2021). Pascoe (1959) also observed that the Oyster bed would grade into the overlying Nodular Limestone. This Nodular Limestone is laterally traceable and mappable in the LNV and has characteristic lithological features different from the underlying Bilthana Formation and the overlying Narmada Sandstone Member of the Uchad Formation. Limestone exposed in the Narmada River and south of it lacked the typical nodular structure and was described as Rajpipla Limestone (Dassarma and Sinha, 1975; Pascoe, 1959; Sastry and Mamgain, 1971). Biswas and Deshpande (1983) described it as the Nodular Limestone, a part of the Navagam Group. Rajshekhar (1995), based on the field and microfaunal evidence, suggested that although different stratigraphic nomenclatures are used for the Nodular Limestone of the Bilthana (WLNV) and Man River sections (ELNV), both are equivalent. Rajshekhar and Aptalkar (1995) suggested that the Navagam Limestone of Poddar (1964) and the Rajpipla Limestone of Dassarma and Sinha (1975) are equivalents. Also, field investigations of all the proposed units revealed them to be stratigraphically and compositionally similar and have been variably named based on local observations. Blanford (1869), Bose (1884), and Rajshekhar and Aptalkar (1995) suggested that the nodular appearance was not uniform in the basin, and the name Nodular Limestone was open to objection, but the name Nodular Limestone was entrenched in the literature since the past century and was extensively used in the LNV. Therefore, to avoid multiplicity in the nomenclature, the name of the formation was retained in the WLNV, and the names Gulvani Limestone, Navagam Limestone, and Rajpipla Limestone were abandoned (Shitole et al., 2021).

Designation: Previous studies recognized this unit as Gulvani Limestone, Navagam Limestone, Rajpipla Limestone, and Nodular Limestone Formation in the WLNV (Table 3.1a-b, d). The name Nodular Limestone is retained in the present study, and the unit is designated as a formation.

Stratotype: The stratotype for the Nodular Limestone is chosen inthe Narmada River Channel (Plates 4.3d, 4.4a) near Statue of Unity, Navagam village, Narmada district of Gujarat (N 21° 50’52” E 73° 42’18”). The stratotype section comprises 80 m of grey limestone, which grades upward to shaly limestone. It is thinly-bedded; however, the hard bands show a nodular appearance towards the top. The lower and upper contact of the formation grades from the Bilthana Formation and the Uchad Formation, respectively (Plate 4.4a-b). The Nodular Limestone is also exposed in Uchad, Sultanpura, Bilthana, Bhadarwa, Vajepur, Gulvani, Galesar, Mogra, Chikhli, Karvi, Mathsar, and Kanji villages of Gujarat.

Description of unit: This Nodular Limestone is mainly comprised of thick carbonate-dominated rocks with shaly limestone and attains a maximum thickness of ~80 m in the Narmada River channel (Plate 4.3d). The formation is of variable thickness at many localities. It is characterized by black-colored mudstone and sandy micrite rocks. The type section lacks the nodular feature (Plates 4.3e, 4.4a), but it is observed at other localities (Plate 4.4b). The upper part of the formation, which has a typical nodular appearance, occasionally shows the presence of oyster shells. The sparse occurrence of the oyster shells is also observed at different levels in the type section. Sporadic occurrence of ammonites, bivalves, ostracods, foraminifers, echinoid species, and *Thalassinoides* burrows are also observed. Petrographically, the formation is composed mainly of micrite with a subordinate amount of quartz and allochems.

Boundaries: The Nodular Limestone conformably overlies the Bilthana Formation and is overlain by calcareous sandstone of the Narmada Sandstone Member of the Uchad Formation (Plate 4.4a-b). The upper and lower contacts of the units are well exposed at localities such as Uchad, Sultanpura, Bilthana, Vajepur, Gulvani, Galesar, Chikhli, Karvi, Mathsar, and Kanji villages of Gujarat.

Age: Several ammonite species have been reported from the Nodular Limestone in the ELNV viz. *Placenticeras mintoi, Prinocyclus germari,* and *Placenticeras kaffarium* (Bose, 1884; Chiplonkar and Ghare, 1976; Dassarma and Sinha, 1975; Ganguly and Bardhan, 1993; Jaitly and Ajane, 2013; Kennedy et al., 2003; Vredenburg, 1907). *Namadoceras* described from Bagh by Vredenburg (1907) was later considered similar to *Coilopoceras* Hyatt, 1903of Middle to Late Turonian in age (Chancellor et al., 1994; Cobban and Hook 1980; Pervinquière, 1910). *Prinocyclus germari* recorded from the Upper Nodular Limestone was dated Late Turonian (Kennedy et al., 2003). Sastry and Mamgain (1971), based on ammonites from the WLNV, assigned the Rajpipla Limestone (Nodular Limestone) and Oyster Bed with *Coilopoceras* and *Proplacenticeras* a Santonian-Campanian age. However, Chiplonkar et al. (1977a) suggested a Turonian age based on megafossils.

Smith (2010) collected abundant species of echinoderms from the upper part of the Nodular Limestone, the Coralline Limestone, and the lower part of the Deola-Chirakhan Marl and suggested the age of the Coralline Limestone and upper part of the Nodular Limestone be Turonian. The echinoid species *Mecaster mutabilis* reported from the Nodular Limestone of the Bilthana village in WLNV (Srivastava et al., 2011) and also from the upper part of the Nodular Limestone, Man-Sukar Nala rivers region to the south of Zeerabad in ELNV (Smith, 2010) was assigned a Cenomanian-Turonian age. Jaitly and Ajane (2013) collected abundant specimens of *Placenticeras mintoi* from different levels of the Nodular Limestone and assigned a Turonian age. The ammonoids *Prinocyclus germari* (Kennedy et al., 2003) and*Placenticeras kaffarium* (Bardhan et al., 2002) are considered to be an ecophenotypic variation of *Placenticeras mintoi*. Bardhan et al. (2002) recorded *Placenticeras kaffarium* and the inoceramid bivalve *Volviceras involutus* from the middle and upper part of the Nodular Limestone and assigned it an Early-Middle Coniacian age. Recently Ruidas et al. (2018) reassessed the *Placenticeras kaffarium* and *Volviceras involutus* from the Nodular Limestone and bracketed its age from upper Turonian-lower Middle Coniacian. Two poorly preserved ammonite specimens were collected from this unit near the Uchad village are apparently identical to the genus *Placenticeras*. The stratigraphic position, lithological and paleontological characteristics of the Nodular Limestone of WLNV are identical to ELNV, hence considered a coeval deposit and assigned a Turonian age.

Depositional environment: The sequence of the type area mainly consists of bedded limestone with fissile shaly limestone, usually unfossiliferous, except for the top layers, which consist of abundant oysters (Fig. 4.1). The limestone bands are compositionally homogeneous and chiefly comprise micrite, while shaly limestone consists of silt-size quartz particles. The accumulation of limestone bands marks the episodes of shallow shelf starvation from terrigenous sediment, but the presence of fine-grained quartz suggests the intervening agitative phases. Rajshekhar (1991), based on the high frequency of agglutinated foraminifera from the Nodular Limestone of Ambadongar region (WLNV), suggested a reducing depositional environment. The presence of pyrite minerals in the Nodular Limestone suggests euxinic conditions (Badve and Ghare, 1978). The limestone progressively grades upward to shaly limestone with thin bands of shale-oyster layers at the top, indicating a subtidal environment.

4.3.1.5 Uchad Formation

Historical background: The Uchad Formation is a newly defined unit based on the variable lithology encountered above the Nodular Limestone. It is the youngest formation of the Bagh Group. The name Uchad Formation is derived from Uchad village, situated on the confluence of the Men River and its unnamed tributary, where it is best developed and well exposed.

Intent and Utility: Up to now, the succession younger than the Nodular Limestone in the Bagh Group was not described in the WLNV. This lithostratigraphic unit is well developed near Uchad village and comprises micritic sandstone, calcareous sandstone, quartz arenite, mudstone, muddy micrite, and shale. Considering the distinctive physical appearance and composition of this lithounit compared to the underlying Nodular Limestone Formation, this sedimentary package can be considered as a separate lithounit. Thus, it is defined as a new separate stratigraphic unit, 'Uchad Formation.' This formation is further subdivided into a lower sandstone-dominated Narmada Sandstone Member and an upper carbonate-dominated Men Nadi Limestone Member. The formation differs from the Coralline Limestone (youngest unit in ELNV) by lack of bryozoan-rich assemblage.

Designation: The unit is designated herein as a formation.

Stratotype: The stratotype for the Uchad Formation was chosen at the NW-SE trending small tributary of Men River, north of Uchad village, Narmada district of Gujarat (N 21° 56'56" E 73° 38'10"). The stratotype section exposes yellow to brown-colored sandstones of Narmada Sandstone Member (Plate 4.4d) overlain by buff-colored shale, muddy micrite, and mudstone rocks of Men Nadi Limestone Member (Plate 4.4e).

Description of unit: The total thickness of the formation is 13 m at the type section. Arenaceous and calcareous rocks characterize the Uchad Formation. The lower part of the formation consists of coarse-grained siliciclastics showing wavy-bedding, cross-bedding, and graded-bedding. The upper part consists of carbonate-dominated rocks. The formation attains a thickness of ~50 m at the Navagam section consisting entirely of siliciclastics of the Narmada Sandstone Member.

Boundaries: The boundaries of the formation are well defined. The lower boundary is gradational at Bilthana, Navagam (Plate 4.4a), Vajepur, and Ambadongar, while sharp with the Nodular Limestone near Uchad village (Plate 4.4b). The upper boundary of the formation is unconformable with the Lameta Group exposed at Bhekhadiya and Bhadarwa.

Age: The Coralline Limestone rests conformably over the Nodular Limestone in ELNV (Plate 3.1b-c) and is assigned a Coniacian age (Jaitly and Ajane, 2013). Similarly, the Uchad Formation rests conformably over the Nodular Limestone in the WLNV. This unit shows a lateral lithological variation with the ELNV and is unfossiliferous, but it occurs at the same stratigraphic level and hence, is assigned a Coniacian age.

Depositional environment: The Uchad Formation comprises two distinctive types of lithology. The lower part is characterized by micritic sandstone and quartz arenite with different types of cross-bedding indicating a foreshore to shoreface environment. The upper part comprises muddy micrite and mudstone with occasional juvenile bivalve shell fragments suggesting a calm, low-energy shoreface environment.

4.3.1.5.1 Narmada Sandstone Member

Historical background: It is a newly defined unit based on the distinct lithological, stratigraphic position, and field characteristics observed. The name 'Narmada' is based on the Narmada River near Navagam village (WLNV), which exposes thick sandstone above the Nodular Limestone (Plate 4.4a, c). This sandstone forms a small hillock in the Narmada River channel over which recently the Statue of Unity was constructed.

Intent and Utility: The uppermost unit of the Bagh Group is well developed in ELNV and described as Coralline/Bryozoan Limestone (Biswas and Deshpande, 1983; Bose, 1884; Dassarma and Sinha, 1975; Gangopadhyay and Maiti,2012; Jaitly and Ajane, 2013; Murty et al., 1963; Prasad et al., 2017; Taylor and Badve, 1995; Tripathi, 2006; Sastry and Mamgain, 1971; Verma, 1968). The equivalent unit in the WLNV was overlooked by earlier workers who described the Bagh Group up to the Nodular (Rajpipla) Limestone (Dassarma and Sinha, 1975; Poddar, 1964; Sastry and Mamgain, 1971). The unit in the WLNV bears distinct lithological characteristics differentiating it from the underlying carbonate-dominated

Nodular Limestone. Thus, it was considered a separate unit from the underlying Nodular Limestone and named Narmada Sandstone Member (Shitole et al., 2021).

Designation: The unit is designated as a member.

Stratotype: The stratotype for this unit was chosen in the Narmada River channel (Plate 4.4a, c), near the Statue of Unity, Narmada district Gujarat (21°50' 34"N, 73° 42' 52"E). The section is 50 m thick and comprises micritic sandstone at its base, overlain by calcareous sandstone, gravelly sandstone, thinly-bedded quartz arenite (Plate 4.4c) characterized by planar, herringbone cross-stratification, and ripple marks, capped by the gravelly sandstone (Shitole et al., 2021).

Plate 4.4 Field photographs of Uchad Formation. a. Gradational contact of the Nodular Limestone with the overlying Narmada Sandstone Member of the Uchad Formation, Narmada River, Navagam village. b. Sharp contact of the Nodular Limestone with the Narmada Sandstone Member of Uchad Formation, Uchad village. c. Thinly-bedded, rippled sandstone occurring in the middle part of the Narmada Sandstone Member, Narmada River, Navagam village. d. Thickly-bedded Narmada Sandstone Member in the tributary of Men River, Uchad village. e. Men Nadi Limestone Member of the Uchad Formation in the tributary of Men River, Uchad village (length of hammer = 32 cm). Scale bar represents 1m.

Description of unit: The type section of the Narmada Sandstone Member consists of bioturbated micritic sandstone at the base containing abundant *Skolithos* tubes, which further grade into thinly- and thickly-bedded sandstones (Plate 4.4c) and gravelly sandstones. The thinly-bedded sandstones are characterized by ripple marks (Plate 4.4c), while the thickly-bedded sandstones show sedimentary structures such as cross-bedding and graded-bedding. Petrographically, it shows fine- to coarse-grained, moderate to poorly sorted quartz grains with subordinate microcline, plagioclase feldspar, and polycrystalline quartz grains bonded with ferruginous, siliceous, or calcareous cement (Shitole et al., 2021).

Boundaries: This member conformably overlies the Nodular Limestone (Plate 4.4a) and is unconformably overlain by the Deccan Traps. It is also well exposed near Uchad village, where the lower boundary is sharp and shows an erosional contact (Plate 4.4b), while the upper boundary grades to Men Nadi Limestone Member. The lower contact of the Narmada Sandstone Member is observed at Sultanpura, Navagam, Vajepur, and Ambadongar villages, while the upper contact with the Men Nadi Limestone Member is observed only at Uchad village.

Age: The stratigraphic position of the member is equivalent to the cross-bedded Coralline Limestone of Bose (1884) or Bryozoan Limestone Formation of Gangopadhyay and Maiti (2012) in the ELNV but differs in lithology. Gangopadhyay and Bardhan (1998) and Jaitly and Ajane (2013) assigned the Coniacian age to the Coralline Limestone based on its stratigraphic position and the presence of ammonite *Barroisiceras onilahyense* Basse, 1947. This unit has gradational contact with the underlying Nodular Limestone and lacks age-diagnostic fossils. Based on its stratigraphic position, the Narmada Sandstone Member was considered similar to the coralline limestone of ELNV and was assigned Coniacian age (Shitole et al., 2021).

Depositional environment: The unit has a sharp and conformable contact with the underlying Nodular Limestone. It grades upward into thinly-bedded rippled sandstone to planar and herringbone cross-stratified sandstone beds. The lithology changes from micritic sandstone, siliceous sandstones at the bottom, to gritty/gravelly sandstone towards the top of the unit, suggesting shallowing of the sea. With the lithology, bed geometry, sedimentary structures, and presence of the abundant vertical *Skolithos* burrows, a high-energy shoreface environment with tidal influence, was inferred for the unit (Shitole et al., 2021).

4.3.1.5.2 Men Nadi Limestone Member

Historical background: Name of the unit was derived from the Men River, a tributary of the Narmada River referred to as 'Men Nadi' in the Geological Survey of India toposheet no. 46G/9. The Men Nadi Limestone Member is the topmost unit of the Bagh Group and is newly defined. Srivastava et al. (2011) first reported a limestone band younger than the Nodular Limestone in the WLNV and referred to it as the Navagam/Rajpipla Limestone in WLNV. However, field investigations of the Uchad section revealed that the limestone band is younger than the Nodular Limestone and is separated from it by a 6-m-thick sandstone unit belonging to the Narmada Sandstone Member. Due to its distinct lithological characteristics and stratigraphic position, it was separated from the Narmada Sandstone Member and named Men Nadi Limestone Member (Shitole et al., 2021).

Intent and Utility: It is the youngest stratigraphic unit of the Bagh Group, resting conformably over the Narmada Sandstone Member. This member is a carbonate-dominated sedimentary unit that can be easily differentiated from the underlying sandstone-dominated Narmada Sandstone Member. It also differs from the Nodular Limestone of a lower stratigraphic level by its lack of nodularity (Plate 4.4e) and its stratigraphic position. This youngest unit of the Bagh Group in the WLNV was unreported. The Men Nadi Limestone Member is preserved in the tributary of Men River near Uchad village and at Bhekhdiya village. It was assigned the separate status of an upper member in the Uchad Formation of the Bagh Group succession based on its well-defined lithological characteristics.

Designation: Member.

Stratotype: The stratotype for the member lies in the NW-SE flowing tributary of Men River (Plate 4.4e), north of Uchad village (21°56' 52"N, 73° 38' 12"E).

Description of unit: The unit is yellowish-white colored, thickly-bedded mudstone in its upper part (Plate 4.4e), while it appears intercalated with shale in its lower part. It is 7 m thick and observed in the Uchad and Bhekhadiya villages of the Narmada district. Petrographically, the member consists of muddy micrite, which grades up into mudstone. The member is poorly fossiliferous; occasionally, a few delicate shell fragments are found in the mudstone. The top of the member is composed dominantly of micritic mud, while the base shows the presence of mixed siliciclastic-carbonate rocks wherein the fine-grained quartz grains are bounded in micritic cement.

Boundaries: The lower boundary of the unit is conformable with the Narmada Sandstone Member and is observed in the tributary of Men River near Uchad village. The Men Nadi Limestone Member is overlain by Quaternary alluvium and friable ferruginous sandstone and gravelly sandstones with chert replacement of the Maastrichtian Lameta Group near Uchad and Bhekhadiya villages.

Age: The Men Nadi Limestone Member of the WLNV and Coralline Limestone of ELNV are the youngest lithostratigraphic units of the Bagh Group. Gangopadhyay and Bardhan (1998) have reported the Late Turonian-Coniacian ammonite, *Barroisiceras onilahyense* Basse, 1947 from the top oyster-rich bed (Coralline Limestone) along with inoceramid bivalves have suggested a Coniacian age, which was subsequently followed by Jaitly and Ajane (2013) and Prasad et al. (2017).

Depositional environment: This member conformably overlies the thick Narmada Sandstone Member and is dominated by carbonate rocks. The lower part of the unit comprises muddy micrite, which progressively grades upward into mudstone. It is poorly fossiliferous and consists of rare, delicate bivalve shell fragments. Sedimentological and paleontological evidence suggests calm water, a carbonate-prone shoreface environment and marks a second transgression in the WLNV during the Late Cretaceous. The unit was previously informally recognized

4.4 SUMMARY

Several authors (Dassarma and Sinha, 1965; Poddar, 1964 and Sastry and Mamgain, 1971) who have worked in both parts of the basin have separated the lithostratigraphy of WLNV from the ELNV. Songir Formation consists of mappable coarse-grained clastic rocks which lie unconformably above the Precambrian rocks in the WLNV (Plate 4.1a) and is a well-established unit in the WLNV. The equivalent part of the Songir Formation is very thin in the ELNV and hence not recognized as a separate unit in the Nimar Sandstone (Fig. 4.1; Plate 3.1a). Shitole et al. (2021) have identified Vajepur Formation as a distinct unit with heterogeneous lithology, which differs from the underlying Songir Formation. Thus, it justifies a separate status of the Vajepur Formation.

The unit was previously informally recognized as Calcareous Sandstone (Dasarma and Sinha, 1975), Upper Nimar (Sastry and Mamgain, 1971), Uchad Flagstone (Poddar, 1964), and Umrali Flagstone (Murty et al., 1963; Poddar, 1964) in the WLNV and is correlated with the Nimar Sandstone (Bose, 1884), Nimar Sandstone Formation (Tripathi, 1995; Nayak, 2000b, 2004; Tripathi, 2006; Jaitly and Ajane, 2013), Calcareous Sandstone (Sastry and Mamgain, 1971; Dassarma and Sinha, 1975), and Upper Nimar (Dassarma and Sinha, 1975; Racey et al., 2016) in the ELNV (Table 3.1a-d). Moreover, the Nimar Sandstone of ELNV is equivalent to the Songir Formation and the Vajepur Formation of WLNV.

The overlying Bilthana Formation is recognized as Bilthana Oyster Bed and Oyster Bed in WLNV. It is very thinly developed in ELNV and informally referred to as Oyster Bed or Amlipura Oyster Bed (Murty et al., 1963), which is often merged with the Nimar Sandstone (Table 3.1a-d) (Bose, 1884; Sastry and Mamgain, 1971). This unit has distinct lithological and paleontological characteristics compared to Vajepur Formation in WLNV and Nimar Sandstone in ELNV and cannot be considered it's part; moreover, it is widely mappable in the WLNV. As per the lithostratigraphic nomenclatorial guideline, the name of the formation constitutes the geographic name combined either with the rank or the lithology and is not solely based on the paleontological characteristics. Therefore, only a minor part of the content of the originally established unit and its rank and the original geographic name 'Bilthana' is retained.

Since the name Nodular Limestone is deeply entrenched in the literature and shows lateral continuity with an identical lithology in ELNV and WLNV, its name is retained. The ammonite- and echinoderm-bearing Nodular Limestone (Fig. 4.1; Plate 3.1e) is overlain by cross-bedded Coralline/Bryozoan Limestone in the ELNV (Fig. 4.1; Plate 3.1b-c), whereas in the WLNV, it is overlain by a sandstone-dominated unit (Fig. 4.1; Plate 4.4a-b). The Coralline/Bryozoan Limestone of ELNV (Plate 3.1c-d) lacks mappability in the WLNV (Plate 3.2). In the same way, units overlying the Nodular Limestone in WLNV also lack mappability in the eastern counterpart. The Uchad Formation is the youngest unit of the WLNV

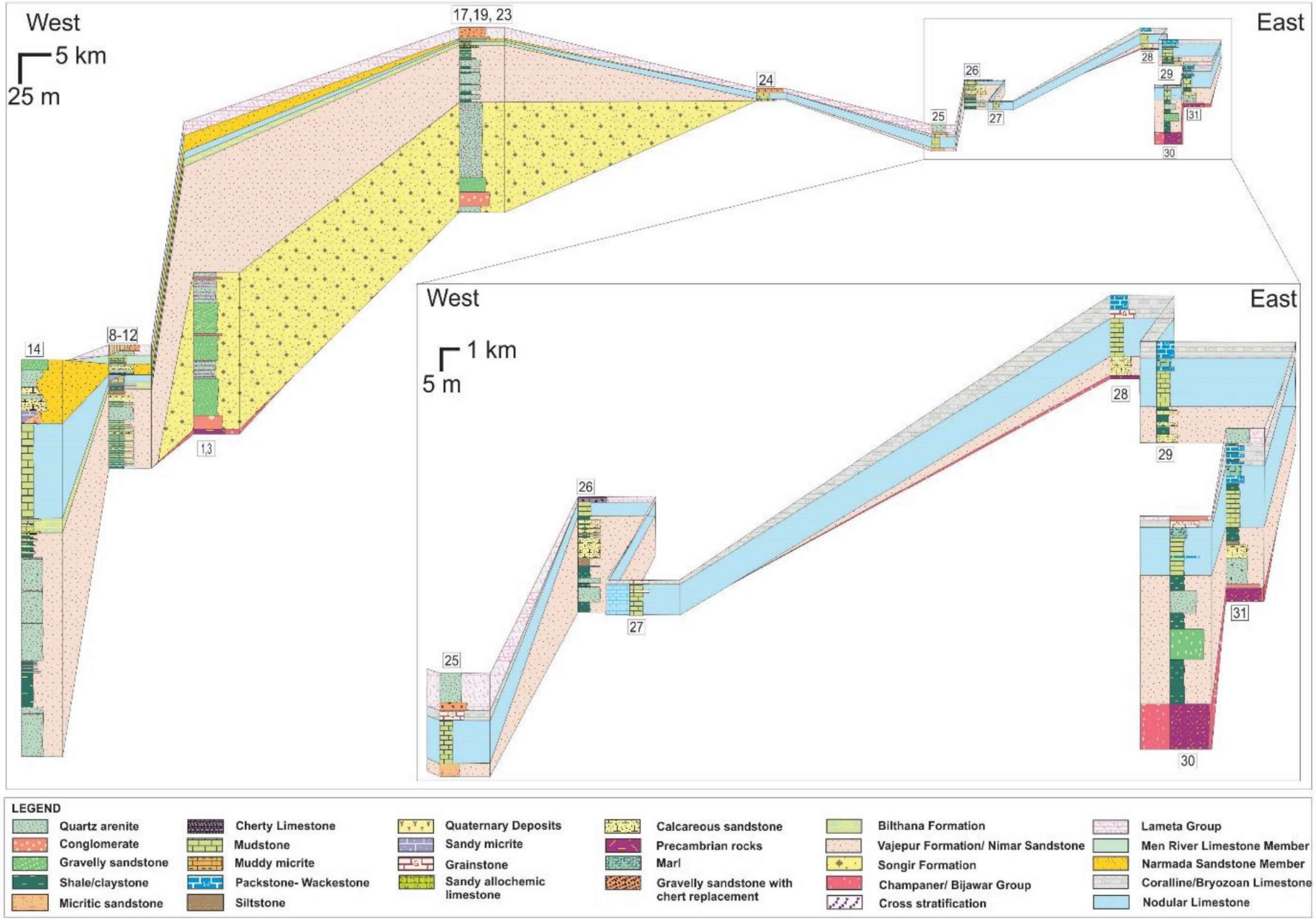


Figure 4.1 Stratigraphic correlation of the Cretaceous Bagh Group rocks sections along the profile A-A′ (Figure 2.1) in the Lower Narmada Valley; Men River Valley (8-12) and Mohanfort-Vajepur (17, 19, 23) are the composite profiles (Shitole et al., 2021).

which overlies the carbonate-dominated Nodular Limestone.It is newly introduced in the lithostratigraphic succession of the WLNV due to its distinct sedimentary characteristics, which is further subdivided into two members, Lower Narmada Sandstone and upper Men Nadi Limestone. The Late Cretaceous Lameta Group caps the Coralline Limestone in ELNV and the Uchad Formation in WLNV. The succession of WLNV is characterized by distinct gross lithology compared to its eastern counterparts, which do not fit into the earlier proposed lithostratigraphic schemes. Finally, the author has been able to discriminate lithological succession of ELNV and WLNV, maintain the status of both considering the geographic limits, amend the lithostratigraphy of the WLNV discussed herein, and published (Shitole et al., 2021).

CHAPTER 5
SEDIMENTARY FACIES

5.1 INTRODUCTION

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

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

5.2 DESCRIPTION OF THE FACIES

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

5.2.1 FLUVIAL FACIES

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

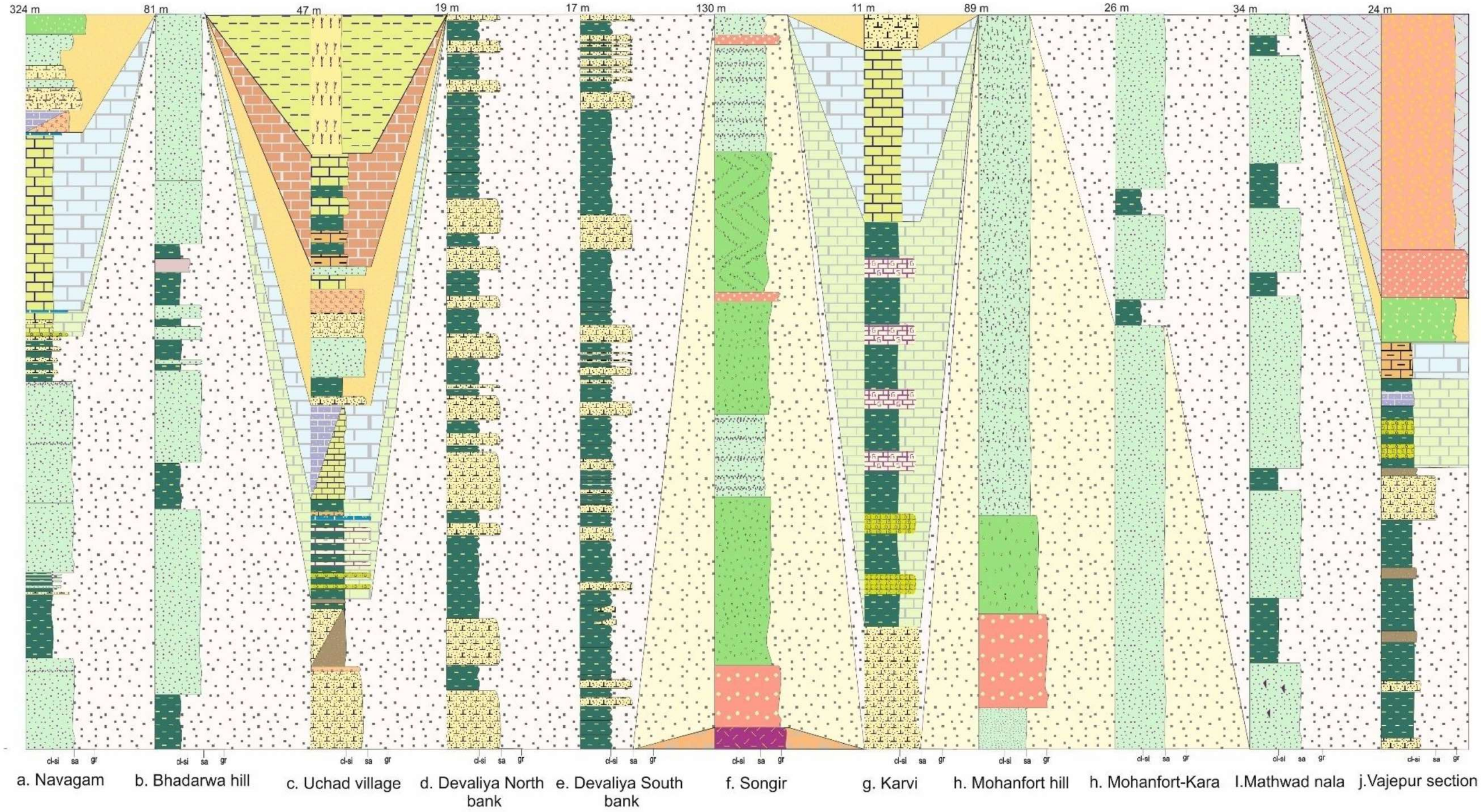
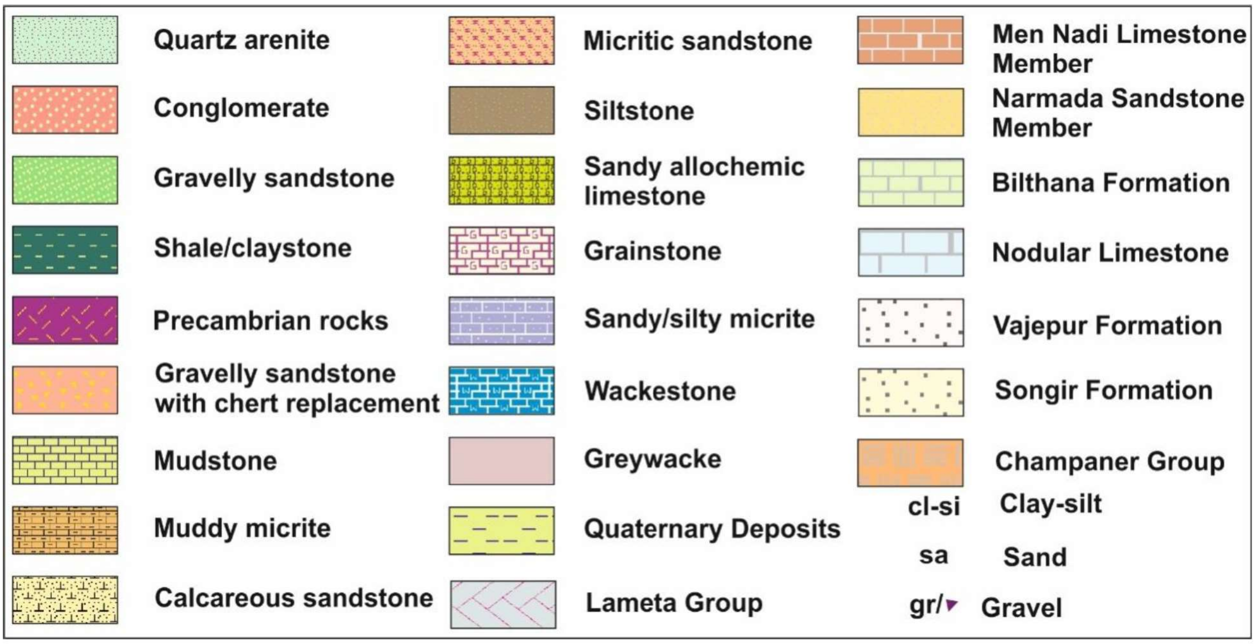


Figure 5.1 Two-dimensional strip log correlation of the WLNV sections.



Legend represents the symbols used in the present study.

5.2.1.1 Conglomerate facies

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

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

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

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

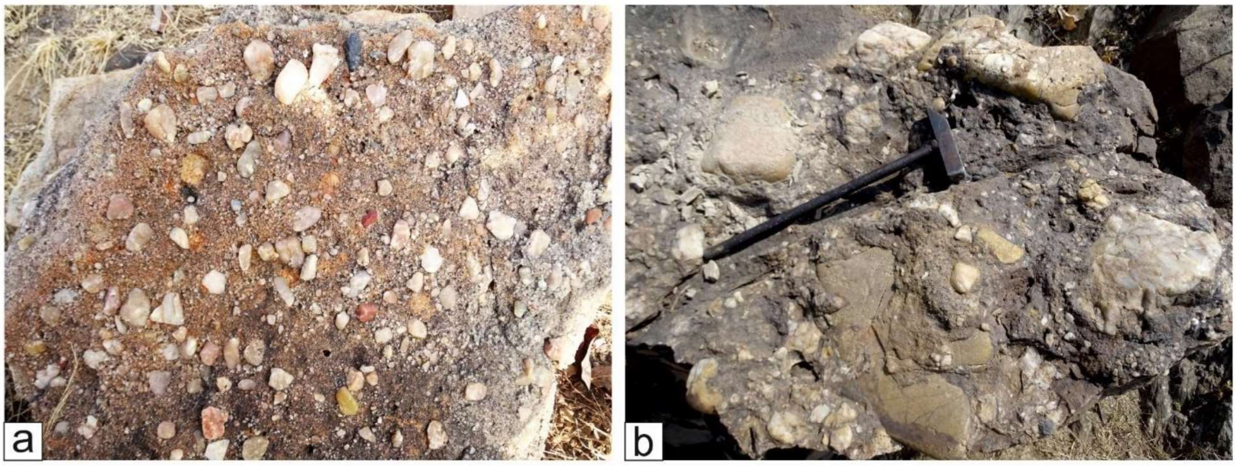


Plate 5.2 Field photographs of the matrix-supported conglomerate. a. Conglomerate with angular to subangular clasts, Mohanfort section. b. Conglomerate containing boulder to pebble-sized angular to subrounded clasts, Ghantoli section.

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

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

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

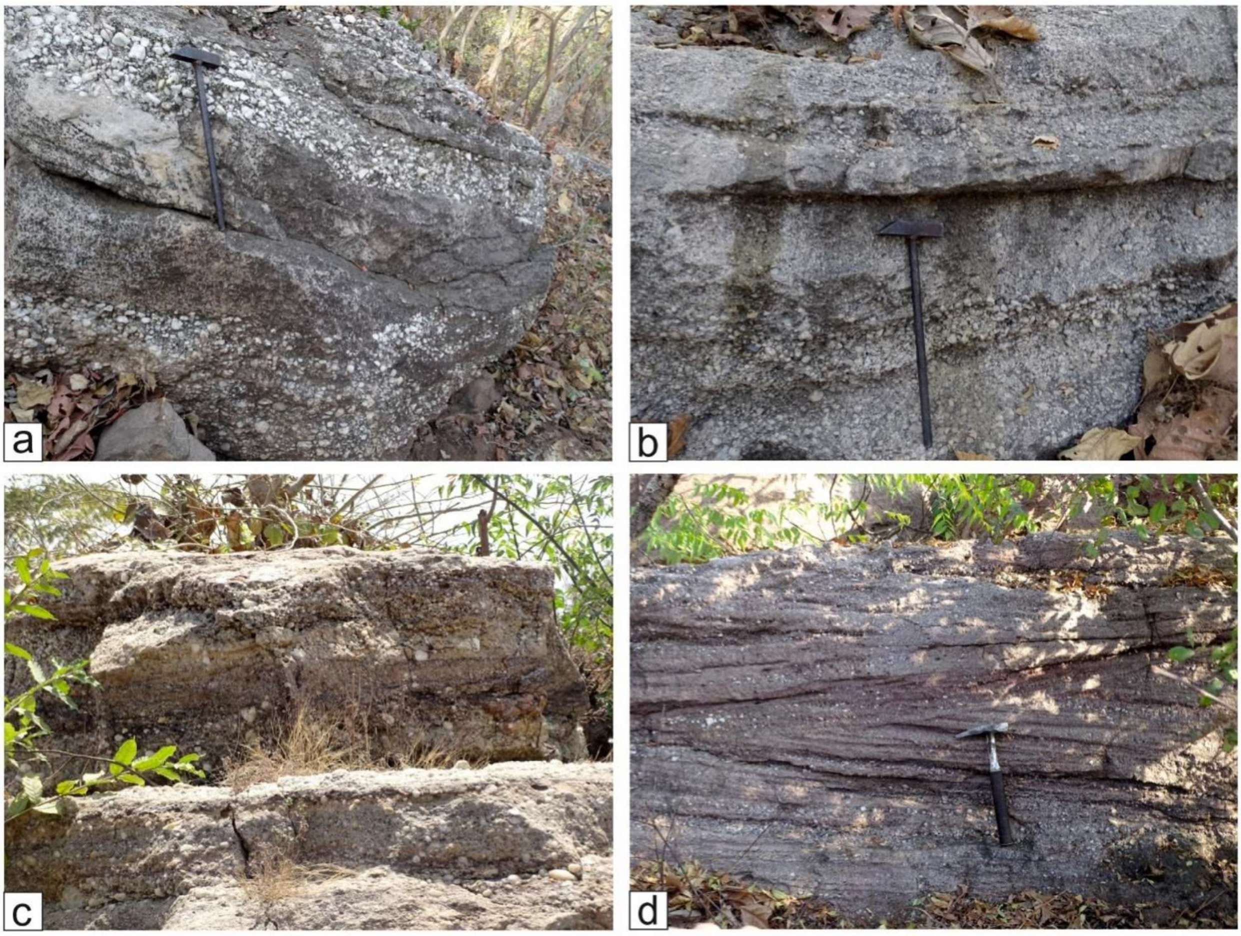


Plate 5.3 Field photographs showing conglomerate interbedded with sandstone and cross-stratified gravels. a-b. Clast-supported massive pebble conglomerate interbedded with trough cross-stratified sandstone, Vajeriya section. c. Fine pebbly matrix-supported conglomerate, Ghantoli section. d. Planar-stratified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

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

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

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

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

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

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

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

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

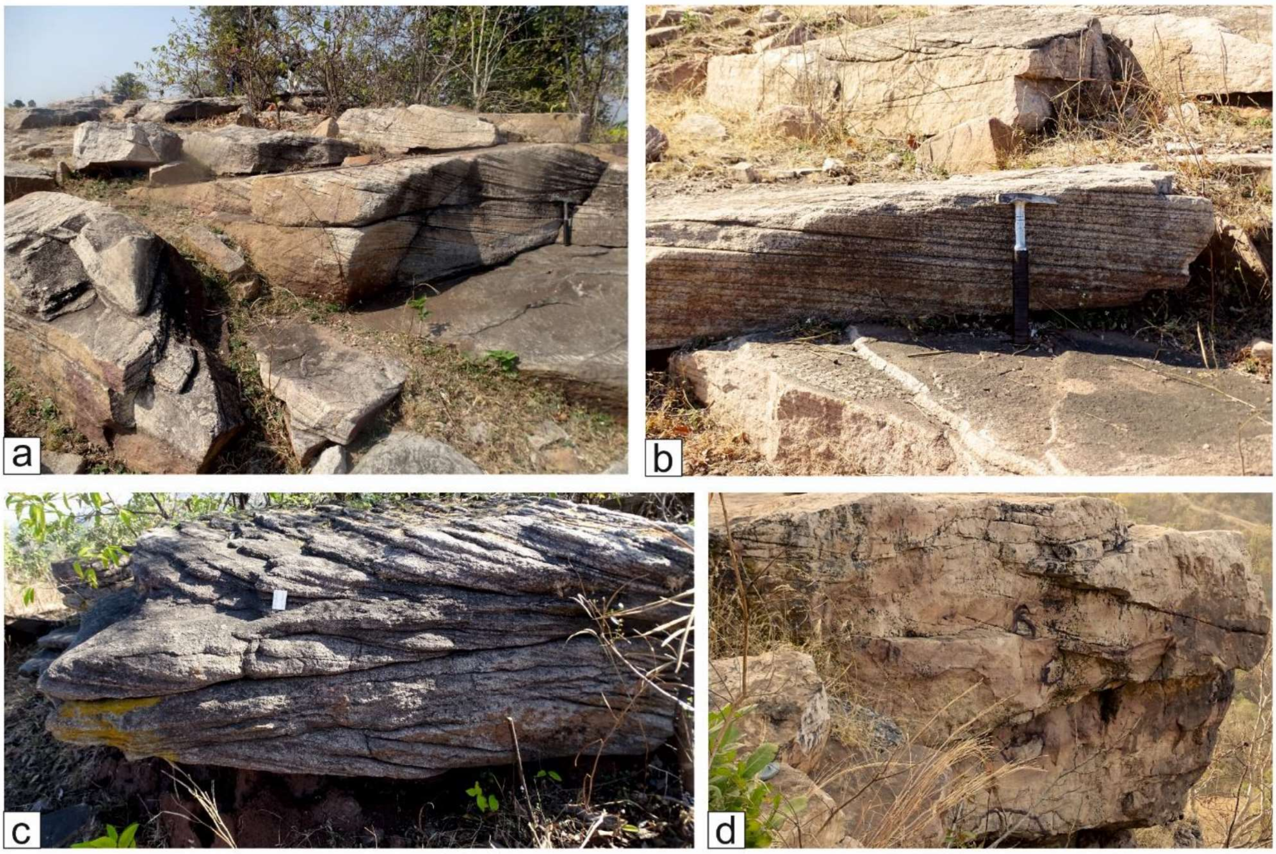


Plate 5.4 Field photographs of planar cross-stratified sandstone. a. Large-scale cross-stratification, Kara River section. b. Large scale cross-stratification, Kara River section. c. Coarse-grained cross-stratified sandstone with gravels; Mohanfort section. d. Trough cross-stratified sandstones; Songir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

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

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

5.2.1.3 Horizontal-thinly Bedded Sandstone Facies (Sh)

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

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

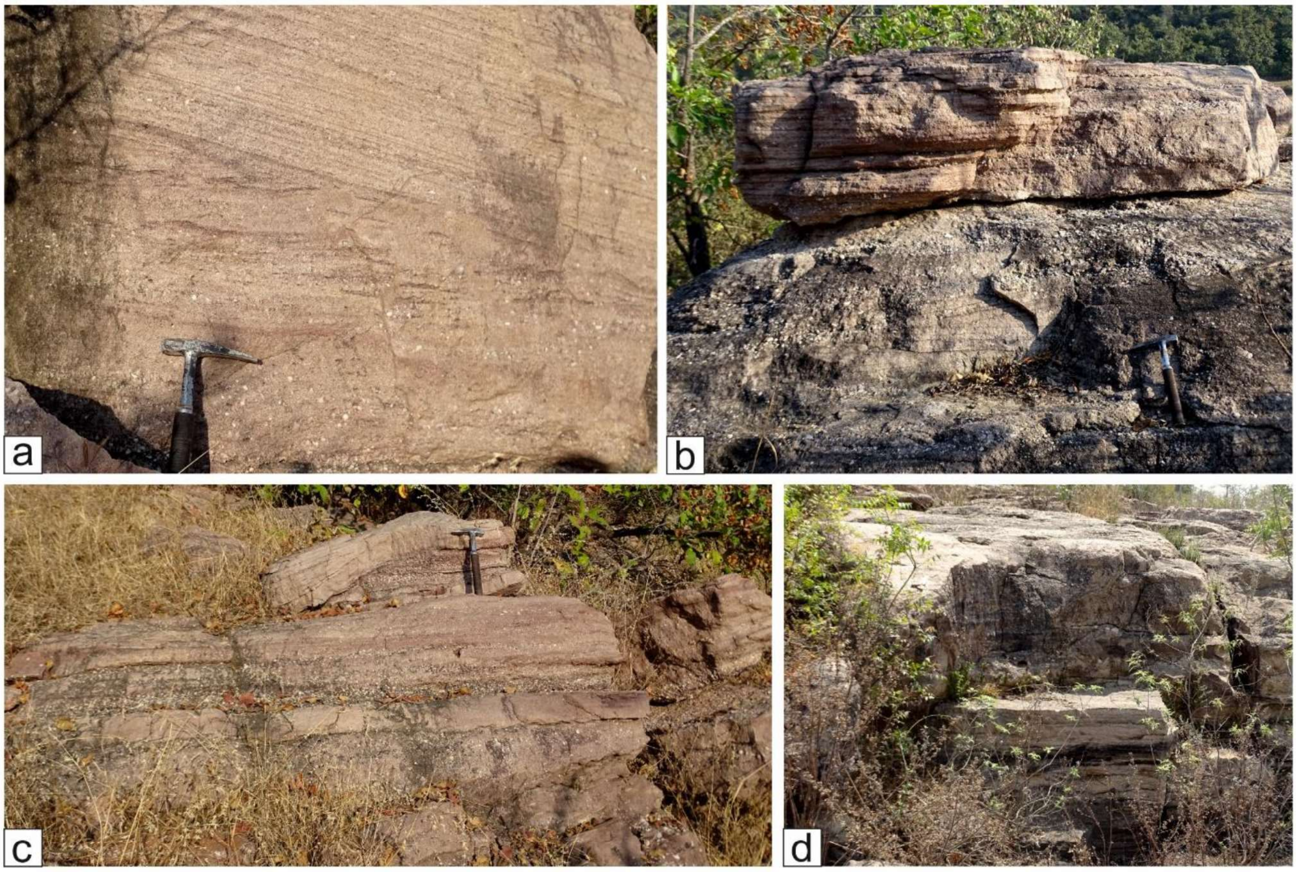


Plate 5.5 Field photographs of horizontally bedded sandstone facies. a. Thinly bedded sandstones with scattered fine pebbles, Songir Formation, Chametha-Chosalpura section. b. Coarse-grained sandstones with gravels; Songir Formation, Chametha-Chosalpura section. c. Laminated coarse-grained sandstones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

5.2.1.4 Massive sandstone facies

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

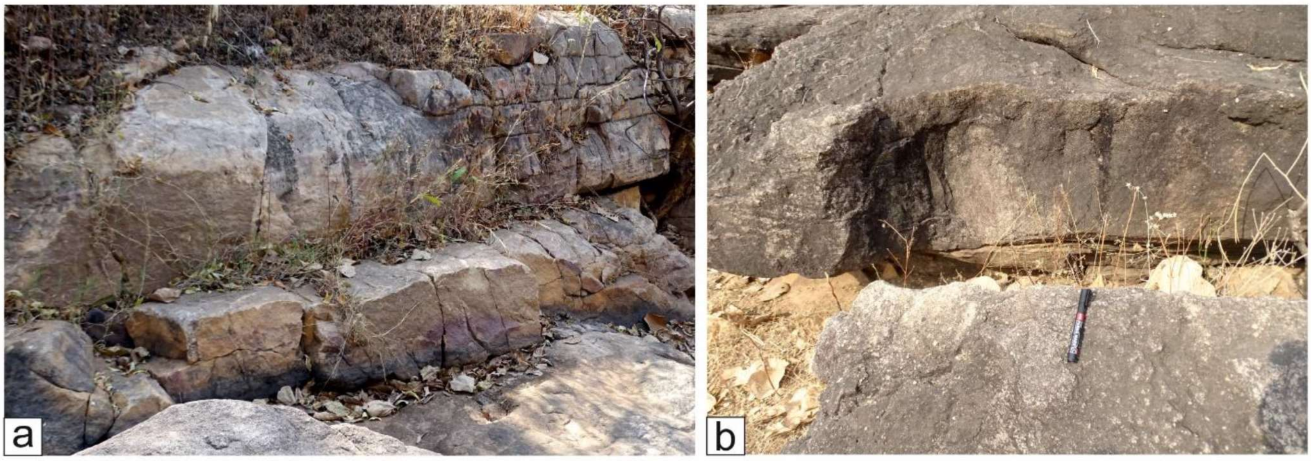


Plate 5.6 Field photographs of massive sandstone facies (Sm). a and b. fine to coarse-grained sandstone, Songir Formation, Mohanfort section.

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

5.2.2 MARINE-MARGINAL TO MARINE FACIES

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

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

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

5.2.2.1 Bedded Quartz Arenite Facies

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

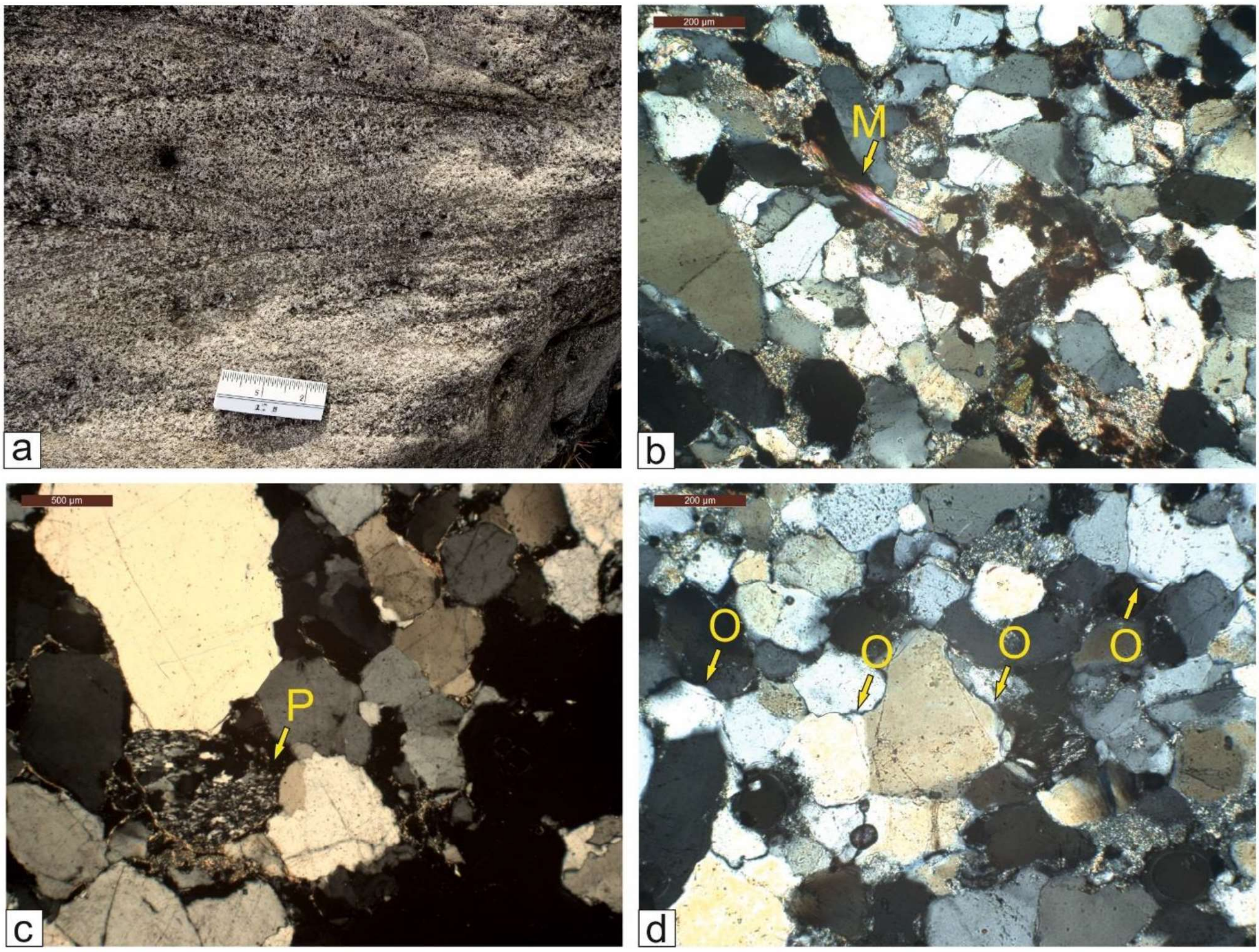


Plate 5.8 Field and photomicrographs of the bedded-quartz arenite facies. a. Herringbone cross-stratification; Narmada Sandstone Member; Navagam section. b. Fine to medium-grained quartz grains with argillaceous cement and Muscovite (M) in the herringbone cross-stratified sandstone; Narmada Sandstone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

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

5.2.2.2 Shale facies

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

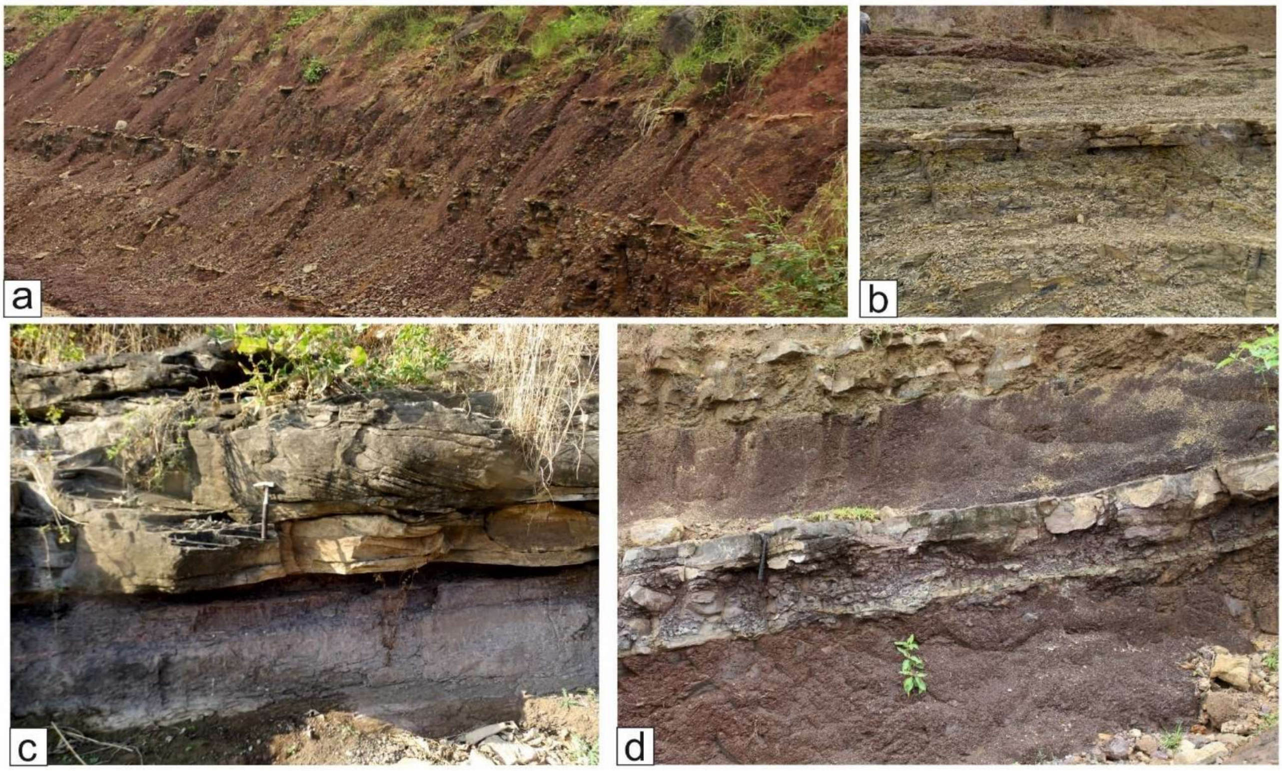


Plate 5.9 Field photographs of the shale facies. a. Reddish shale intercalated with oyster beds, Bilthana Formation, Sultanpura-Bilthana section. b. Greenish-yellow shale intercalated with oyster beds; Bilthana Formation, Uchad section. c. Purple shale underlying cross-stratified sandstone; Vajepur Formation,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

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

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

5.2.2.3 Calcareous Sandstone facies

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

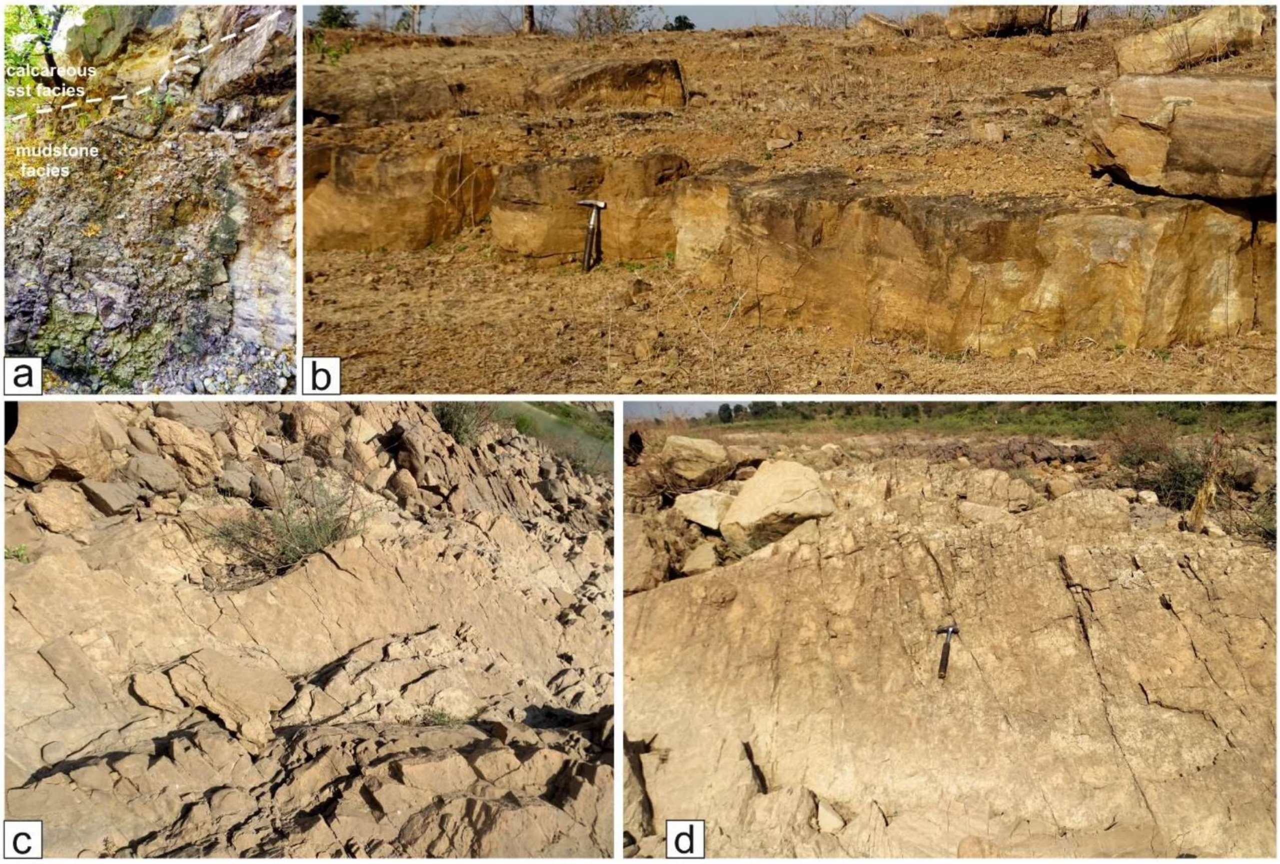


Plate 5.10 Field photographs of the calcareous sandstone facies. a. Thickly-bedded sandstone; Narmada Sandstone Member, Bilthana section. b. Thickly-bedded, cross-stratified sandstones; Vajepur Formation, Vajepur section. c. Thinly-bedded, rippled calcareous sandstones and d. Gently inclined bed surface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

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

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

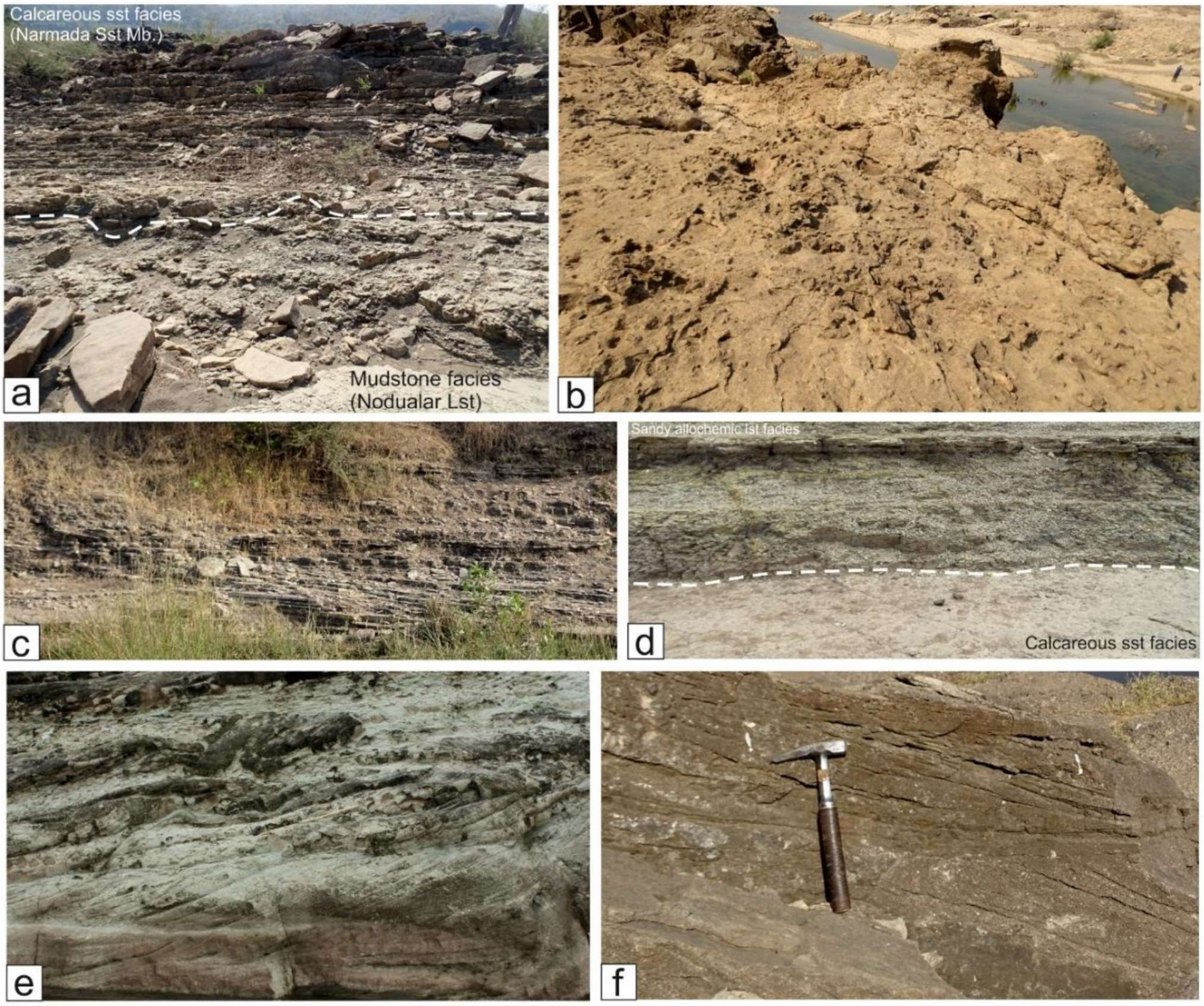


Plate 5.11 Field photographs of the calcareous sandstone facies. a. Conformable contact of mudstone facies (Nodular Limestone) with overlying thinly bedded, calcareous sandstone facies (Narmada Sandstone Member), Navagam section. b. Bioturbated calcareous sandstones; Narmada Sandstone Member, Navagam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

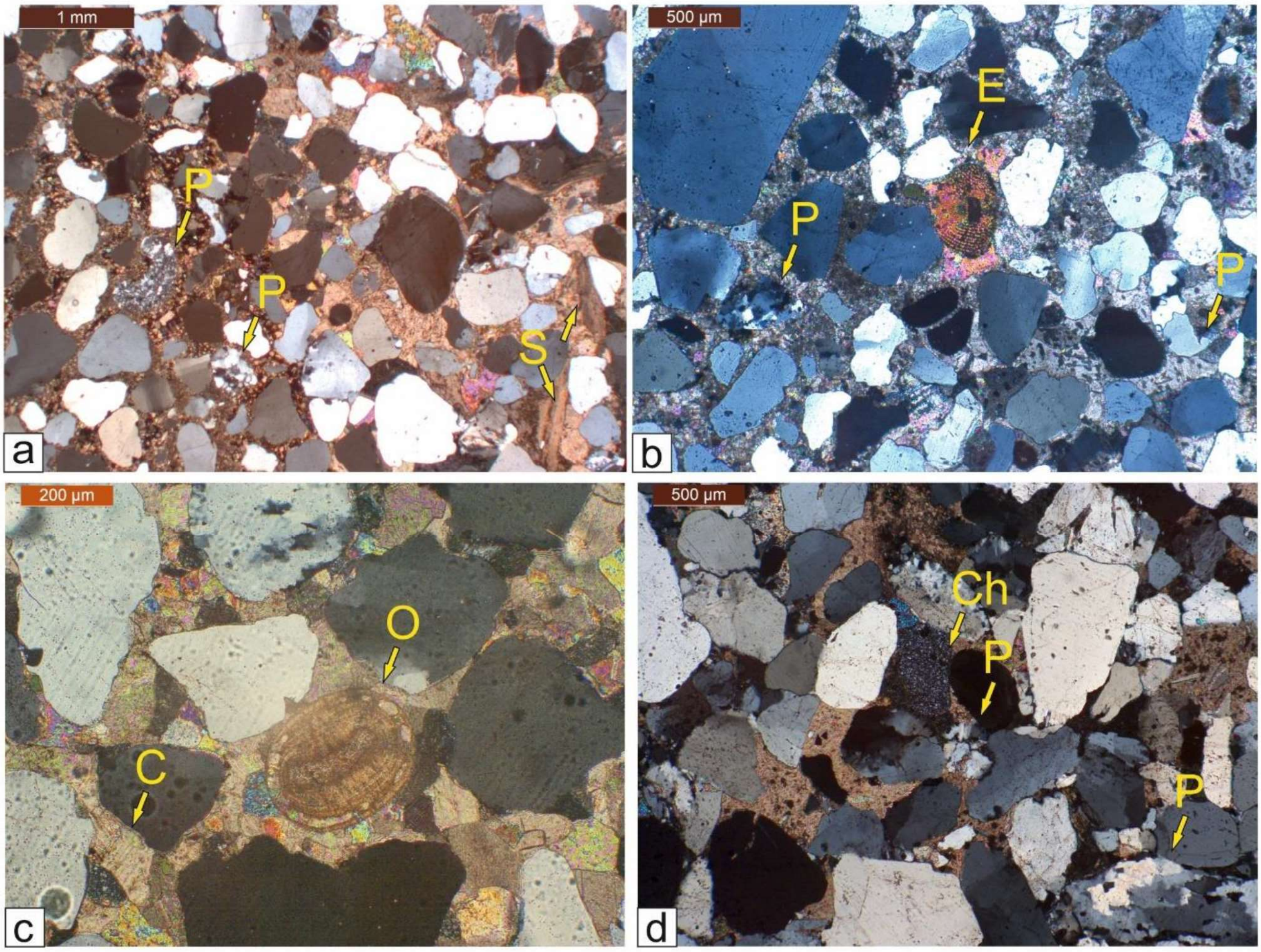


Plate 5.12 Photomicrographs of calcareous sandstone facies showing textural and compositional variations. a. Subangular to subrounded quartz grains, polycrystalline (P) quartz grains, and shell fragments are bounded by calcareous cement; Vajepur Formation, Sultanpura section. b. Poorly sorted quartz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

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

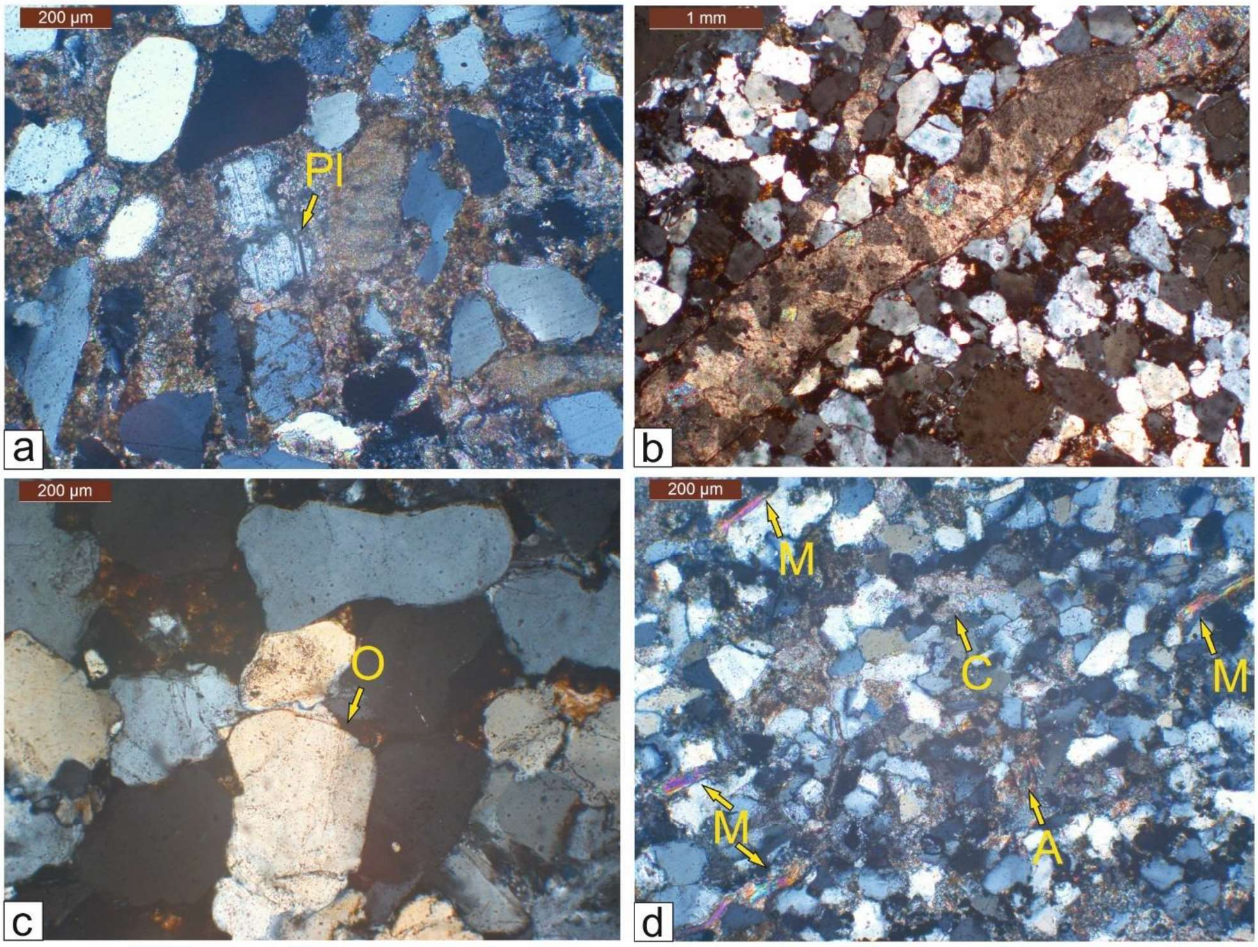


Plate 5.13 Photomicrographs of calcareous sandstone facies. a. Plagioclase feldspar (Pl) surrounded by patches of argillaceous cement; Narmada Sandstone Member, Sultanpura-Bilthana section. b. Microburrow filled with sparry calcite; Vajepur Formation, Vajepur section. c. Overgrowth (O) cementation on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

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

5.2.2.4 Micritic Sandstone Facies

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

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

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

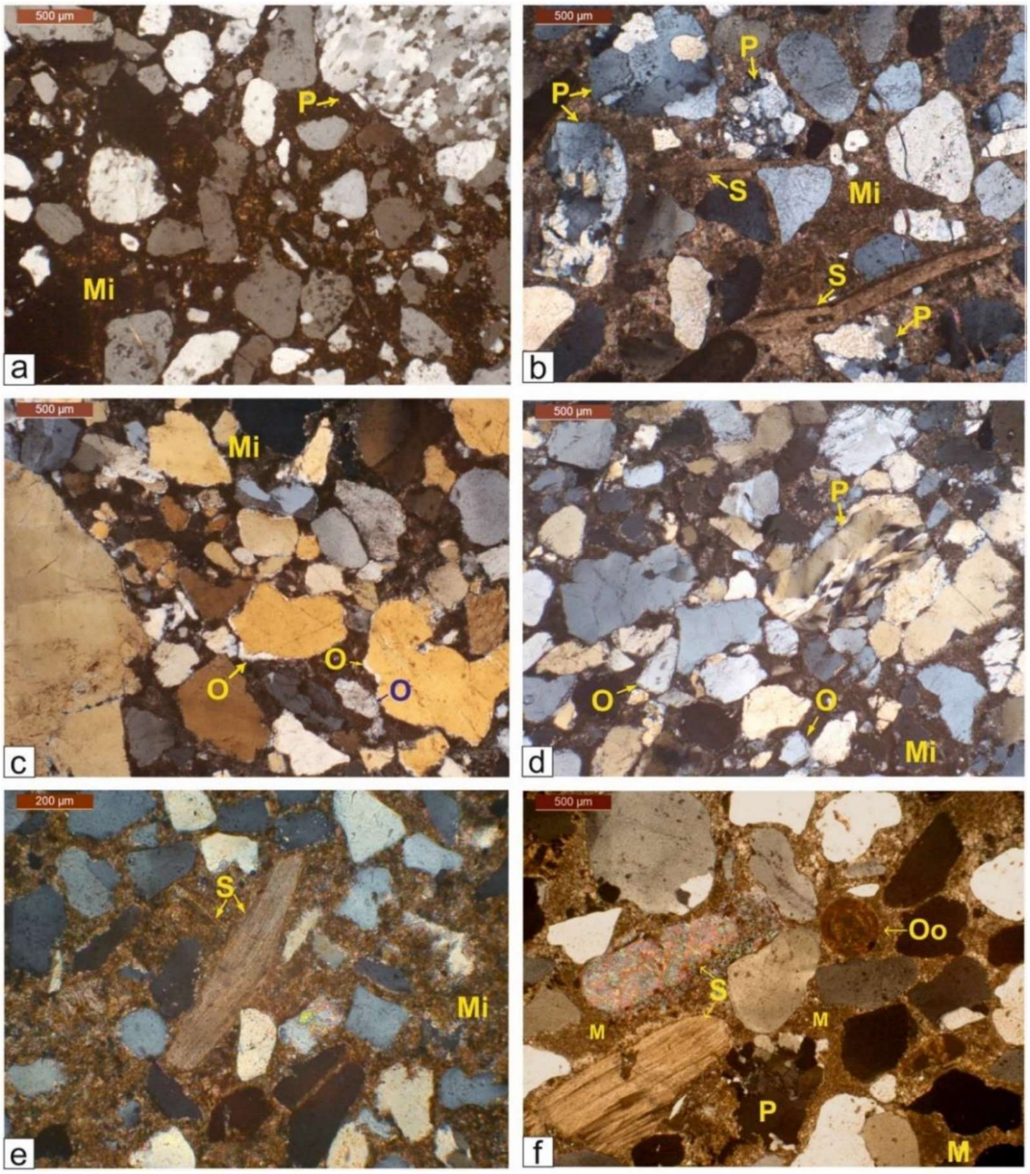


Plate 5.15 Photomicrographs of the micritic sandstone facies. a. Subangular to subrounded grains and polycrystalline (P) quartz grain in the micritic matrix (Mi); Narmada Sandstone Member, Navagam section. b. Polycrystalline (P) quartz grains, bivalve shell fragments (S), and subangular to subrounded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

5.2.2.5 Sandstone- Siltstone-Shale Facies

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

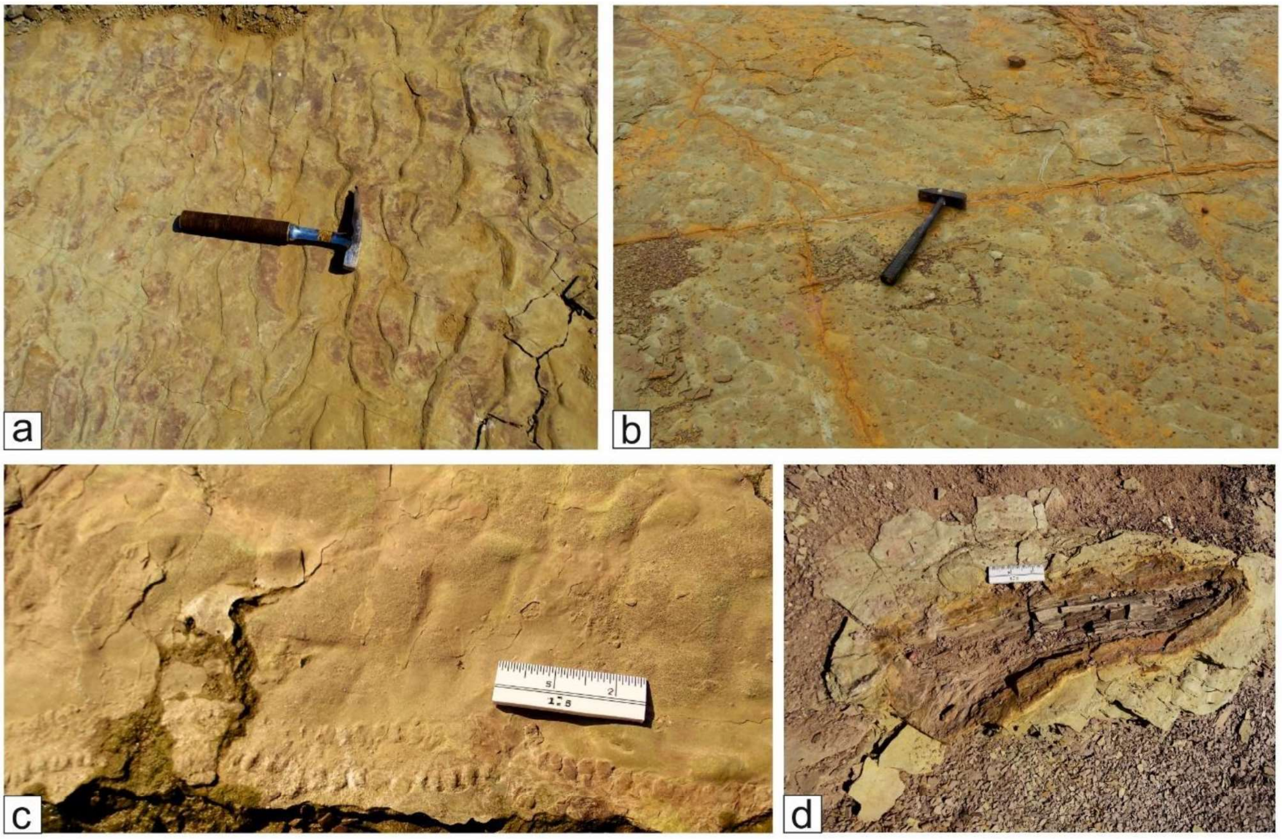


Plate 5.16 Field photographs of the sandstone-siltstone-shale facies. a. Bifurcating current ripples observed at Sultanpura section. b. Current ripples; Vajepur Formation, Bhekhadiya section. c. *Oniscoidichnus* trace fossil as epirelief on the silty micrite bed at Bhekhadiya section. d. Fossil wood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

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

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

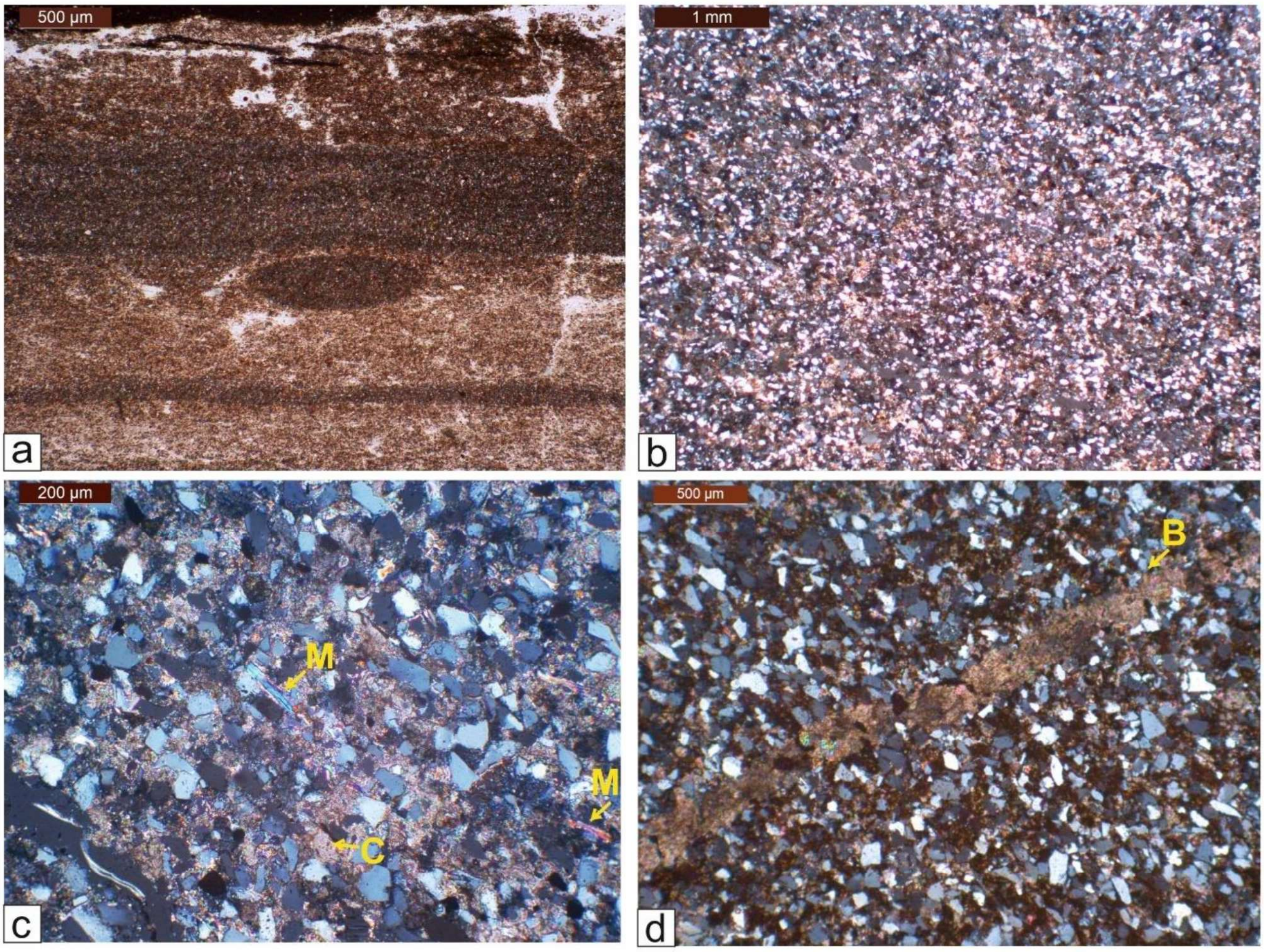


Plate 5.17 Photomicrographs of sandstone-siltstone-shale facies. a. Laminations in Vajepur Formation exposed at Bhekhadiya section. b. Predominance of silt-sized quartz grains exposed in Sultanpura section. c. Presence of angular quartz grains and undeformed mica grains (M) bounded by calcareous cement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

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

5.2.2.6 Sandy/Silty Allochemic LimestoneFacies (SAL)

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

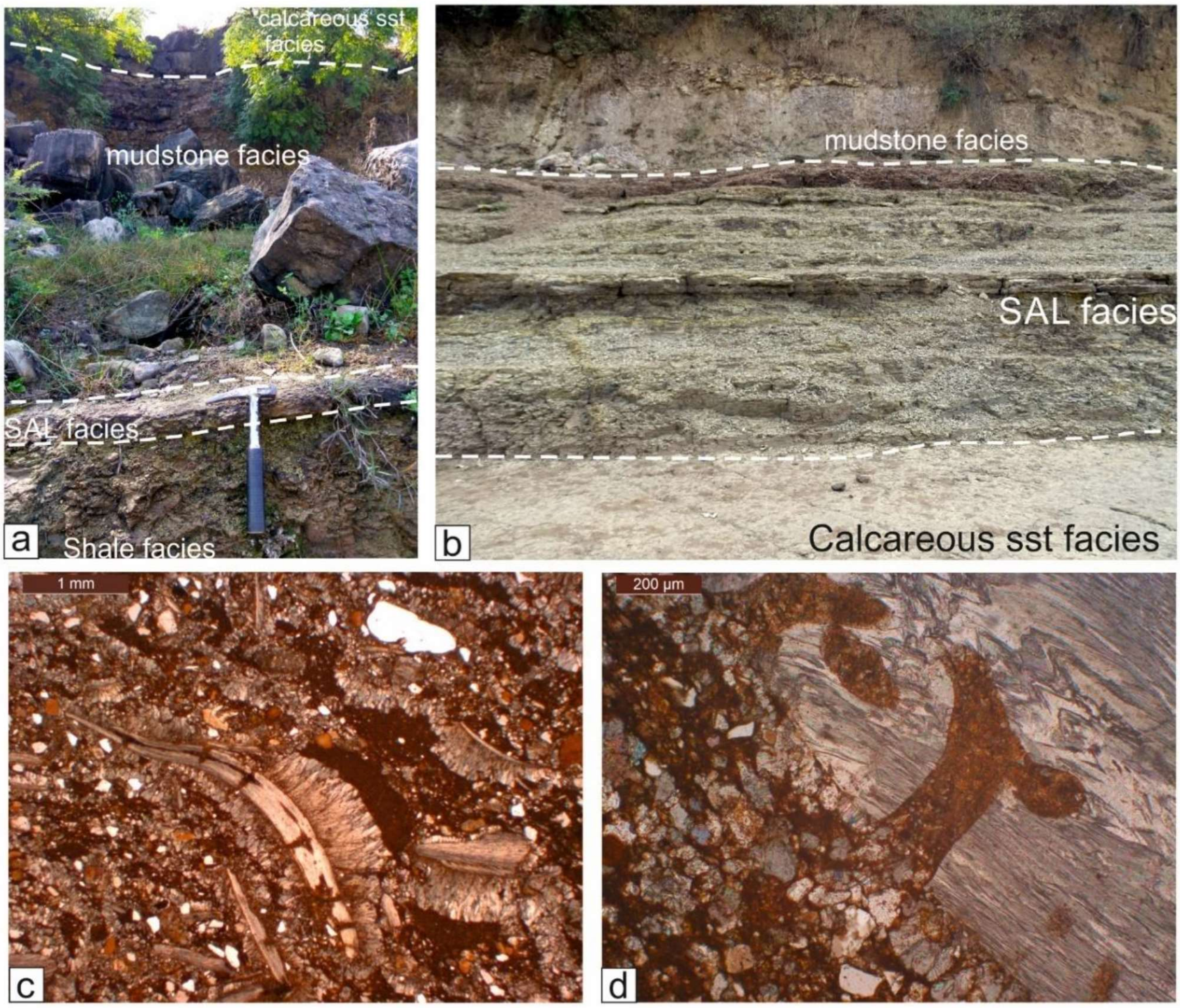


Plate 5.18 Field and photomicrographs of the sandy allochemic limestone facies showing compositional and textural variations. a. Photograph showing shale, sandy allochemic limestone (Bilthana Formation), mudstone (Nodular Limestone), and calcareous sandstone (Narmada Sandstone Member) facies, large blocks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

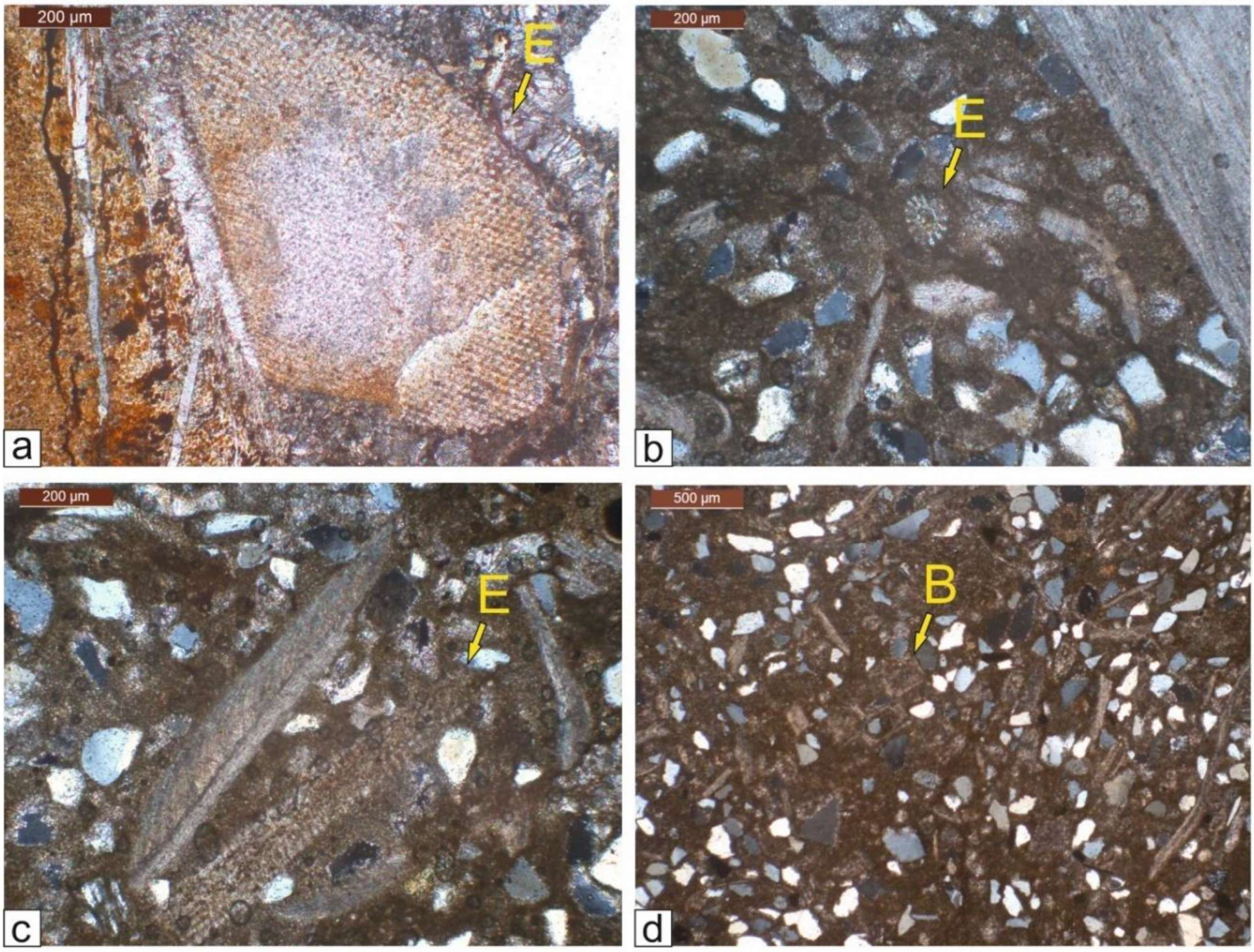


Plate 5.19 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation. a. Echinoderm recognized by a regular pattern of internal pores and singly crystal extinction, Bhekhadiya section. b. Oyster shells and echinoderm (E) in the micritic matrix; Uchad section. c. Angular quartz grains,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

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

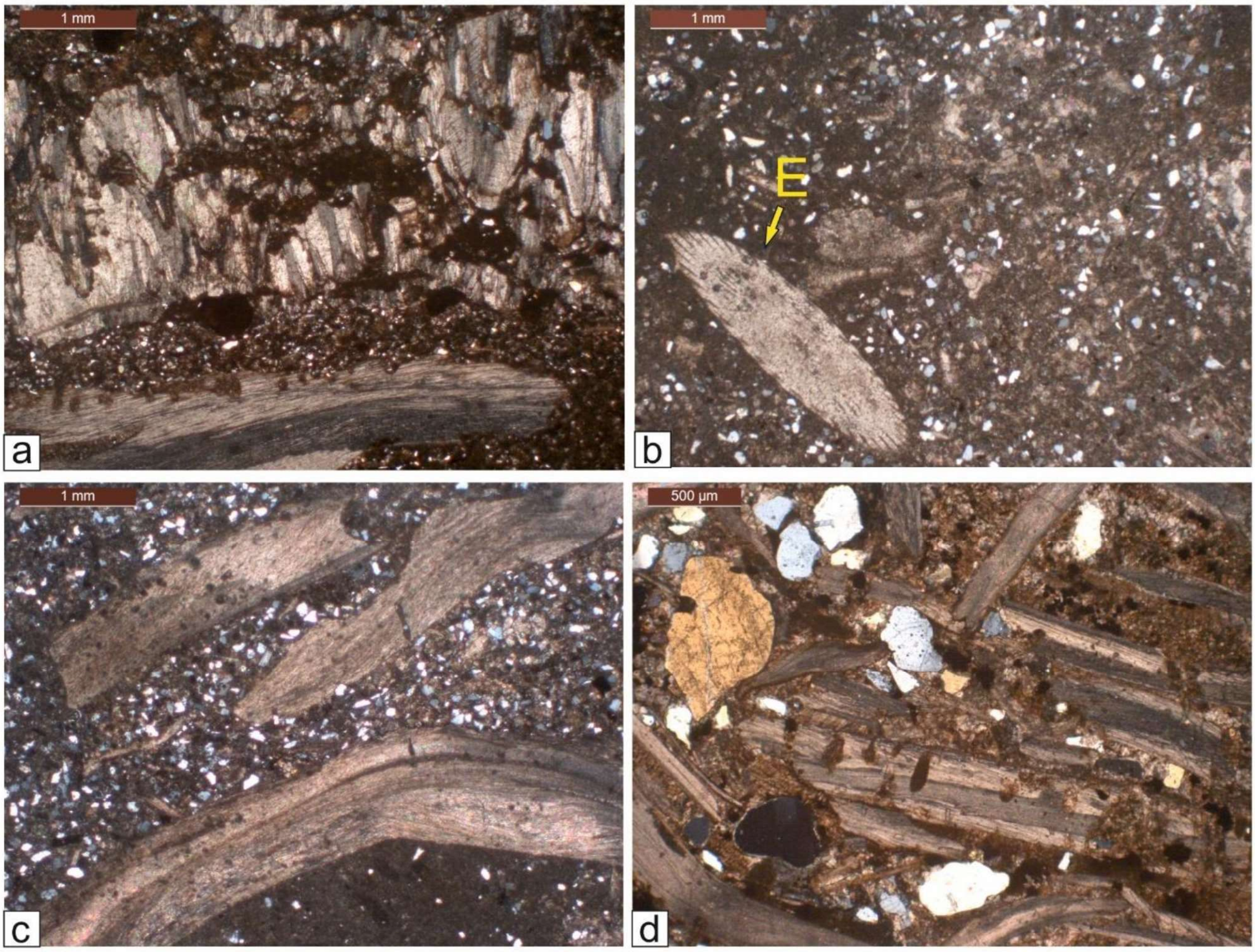


Plate 5.20 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation showing compositional and textural variations. a. Silt-sized quartz grains, foliated and bored oyster at the bottom and prismatic in the center in the top band of oyster; Uchad section. b. Silt-sized quartz grains,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

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

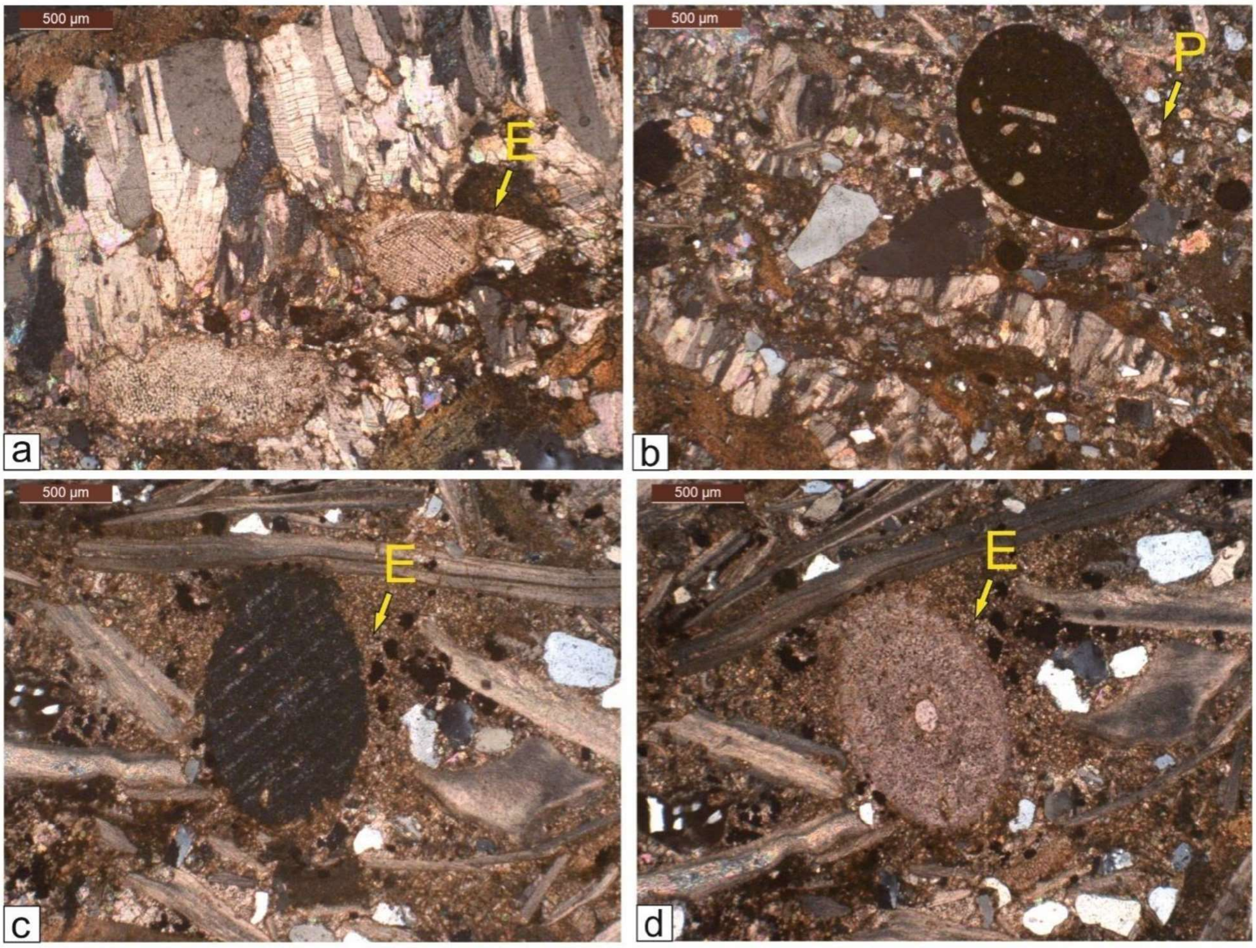


Plate 5.21 Photomicrographs of the sandy allochemic limestone facies of Bilthana Formation, Uchad section. a. Recrystallized (calcitic) prismatic oyster shells and echinoderm fragments (E). b. Disintegrated prismatic shell fragment, which forms the matrix and pellet? (P) in the top right corner. c-d.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

5.2.2.7 Fossiliferous Limestone facies (FL)

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

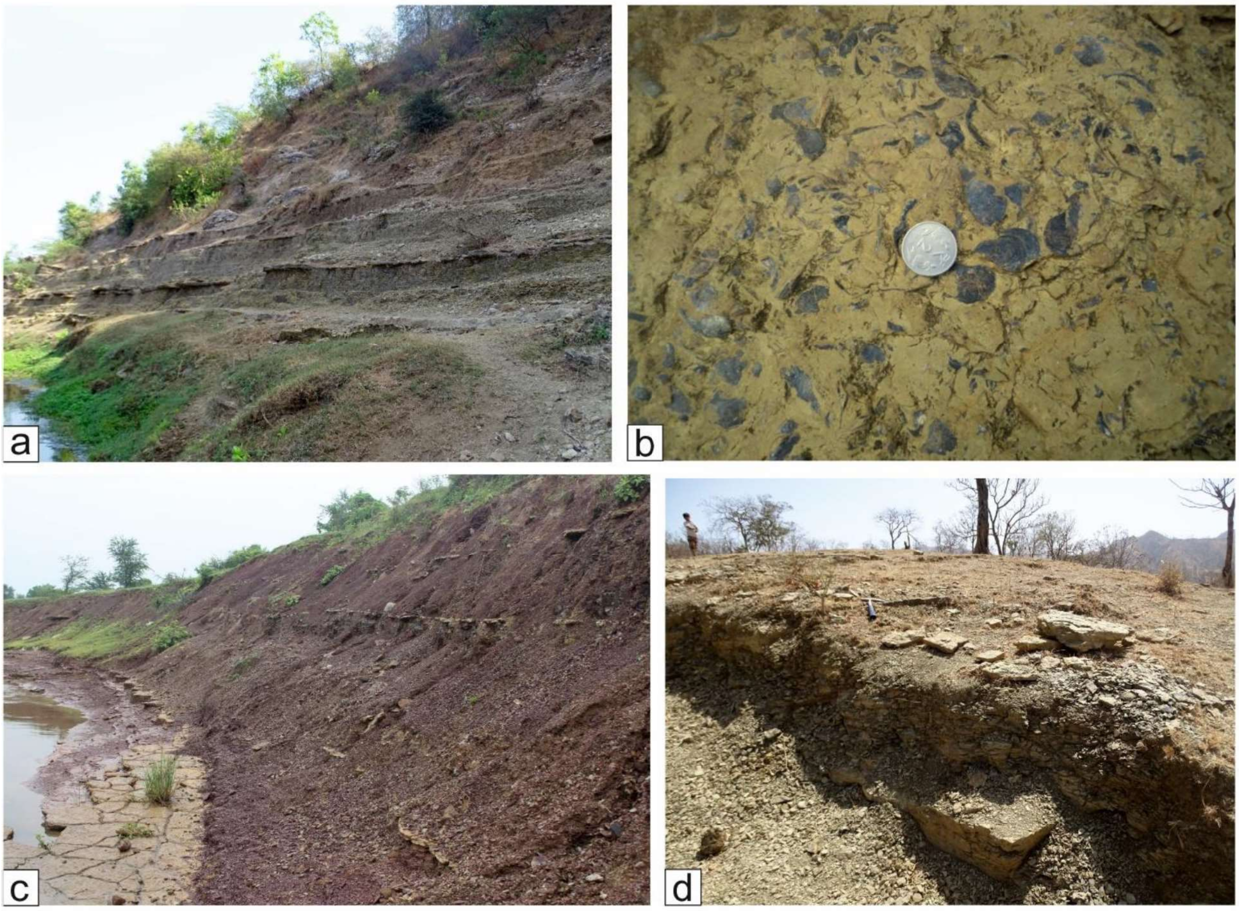


Plate 5.22 Field photographs of fossiliferous limestone facies of Bilthana Formation. a. Panoramic view of the oyster beds intercalated with yellow shale; Uchad section. b. Close-up of the oyster bed; note the disarticulated oysters in convex-up and -down positions; Uchad section (diameter of coin =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

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

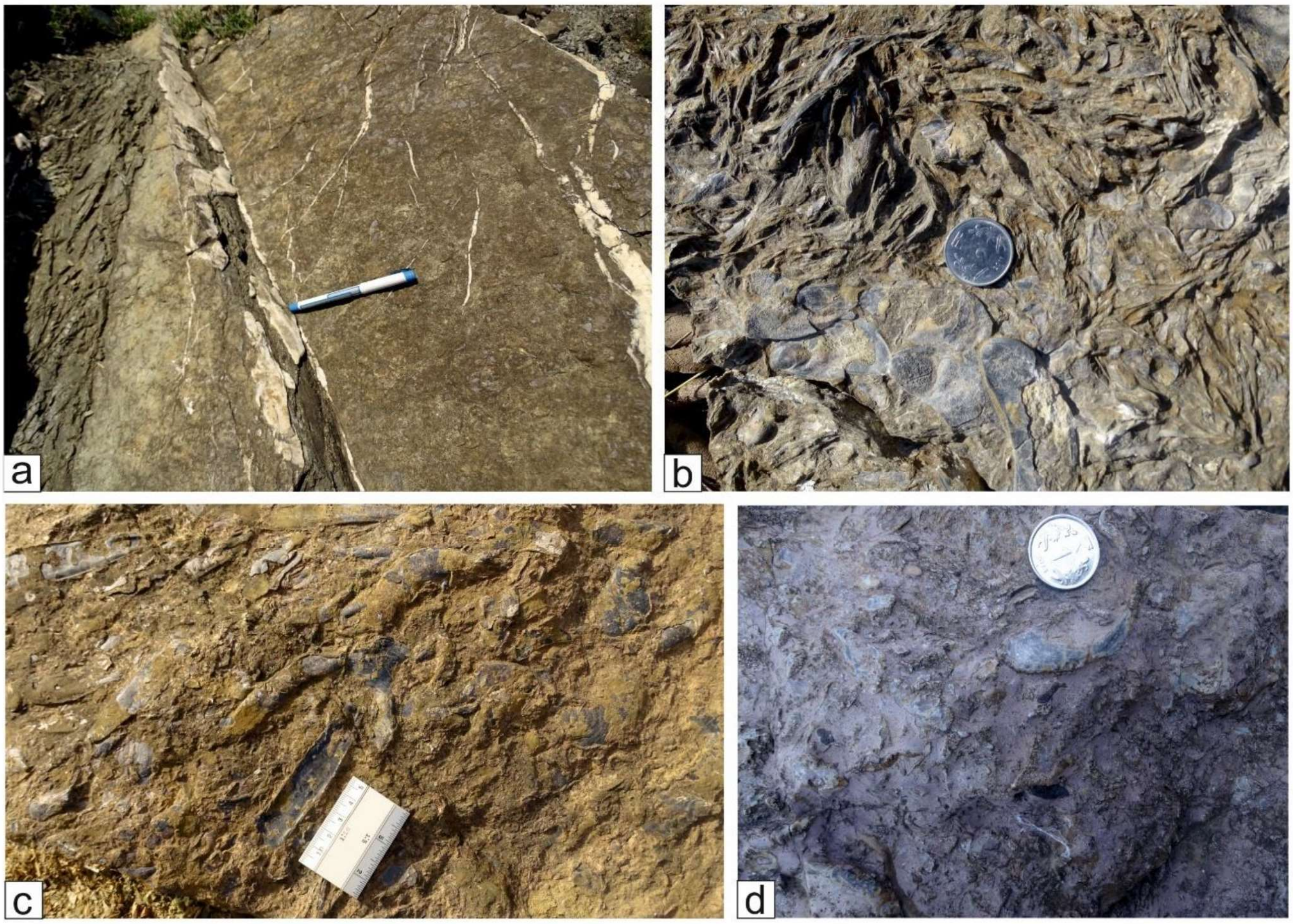


Plate 5.23 Field photographs of fossiliferous limestone facies. a. Oyster slab of the Bilthana Formation, Navagam section. b. Close-up view of the crowded oysters in the fossiliferous slab of Bilthana Formation, Karvi section (diameter of coin = 23 mm). c. Close-up view of the broken oyster slab of the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

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

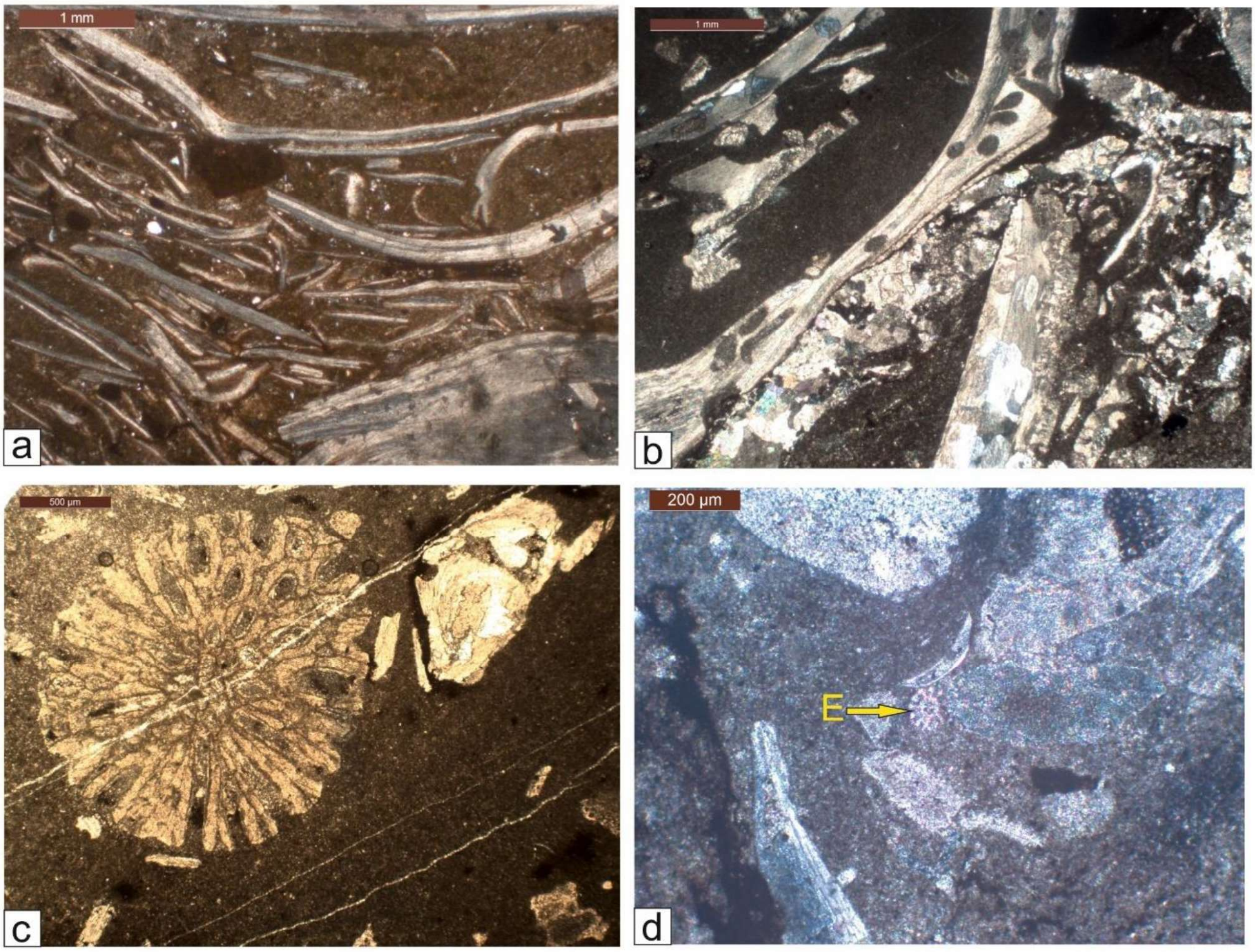


Plate 5.24 Photomicrographs of the fossiliferous limestone facies showing textural and compositional variations. a. Abundant oyster fragments showing growth lines cemented in the micritic matrix; Bilthana Formation, Gulvani section. b. Bored and partly dolomitized oyster shells in micritic matrix suggesting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

5.2.2.7. 1 Bioclastic Grainstone microfacies (BGm)

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

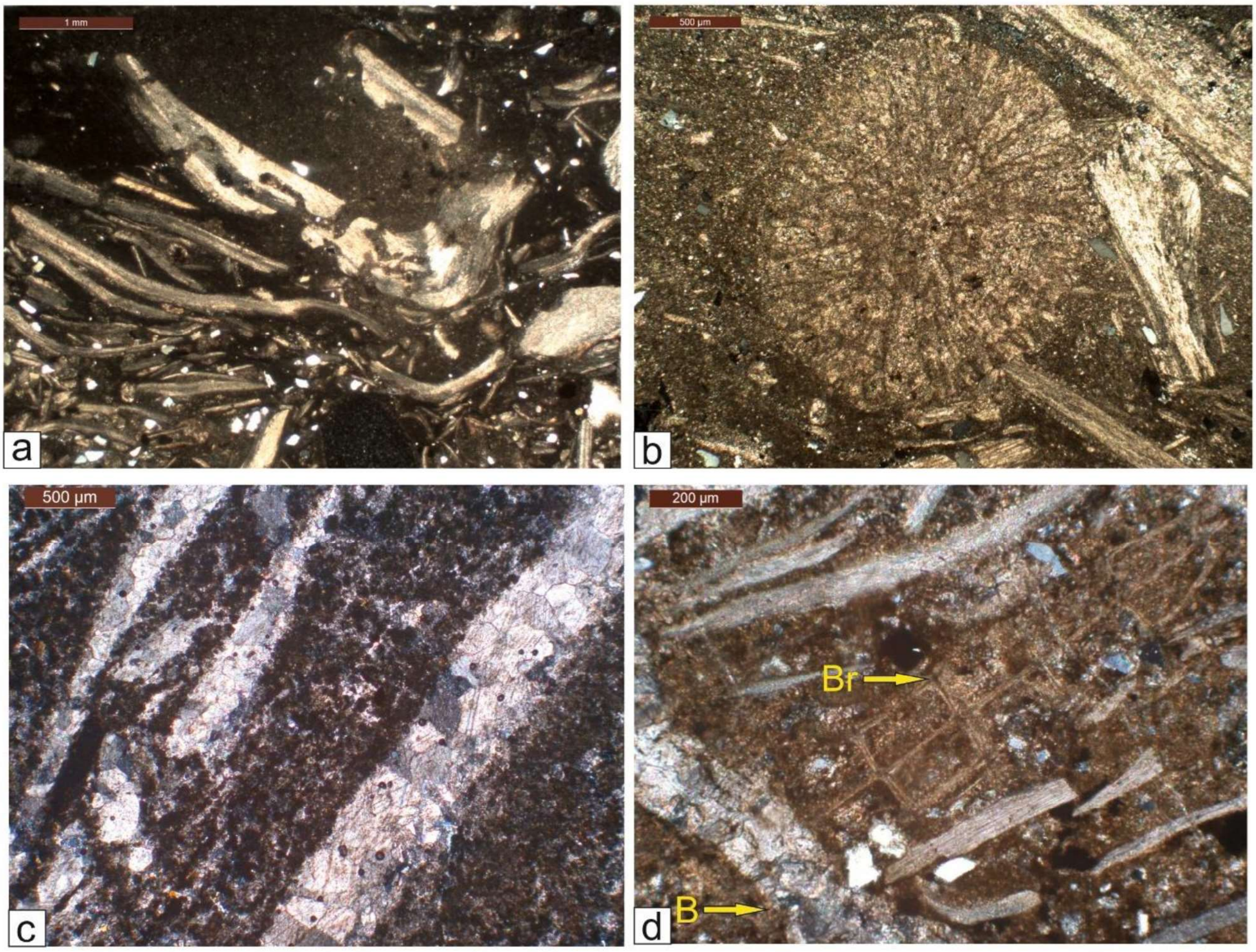


Plate 5.25 Photomicrographs of the fossiliferous limestone facies of the Bithana Formation. a. Heavily bored oyster shells with growth lines and few silt-sized quartz grains in the micritic matrix; Navagam section. b. Micritised shell fragments of echinoderm? and oyster in the micritic matrix; Navagam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

5.2.2.7.2 Bioclastic Packstone-wackestone microfacies (BPm)

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

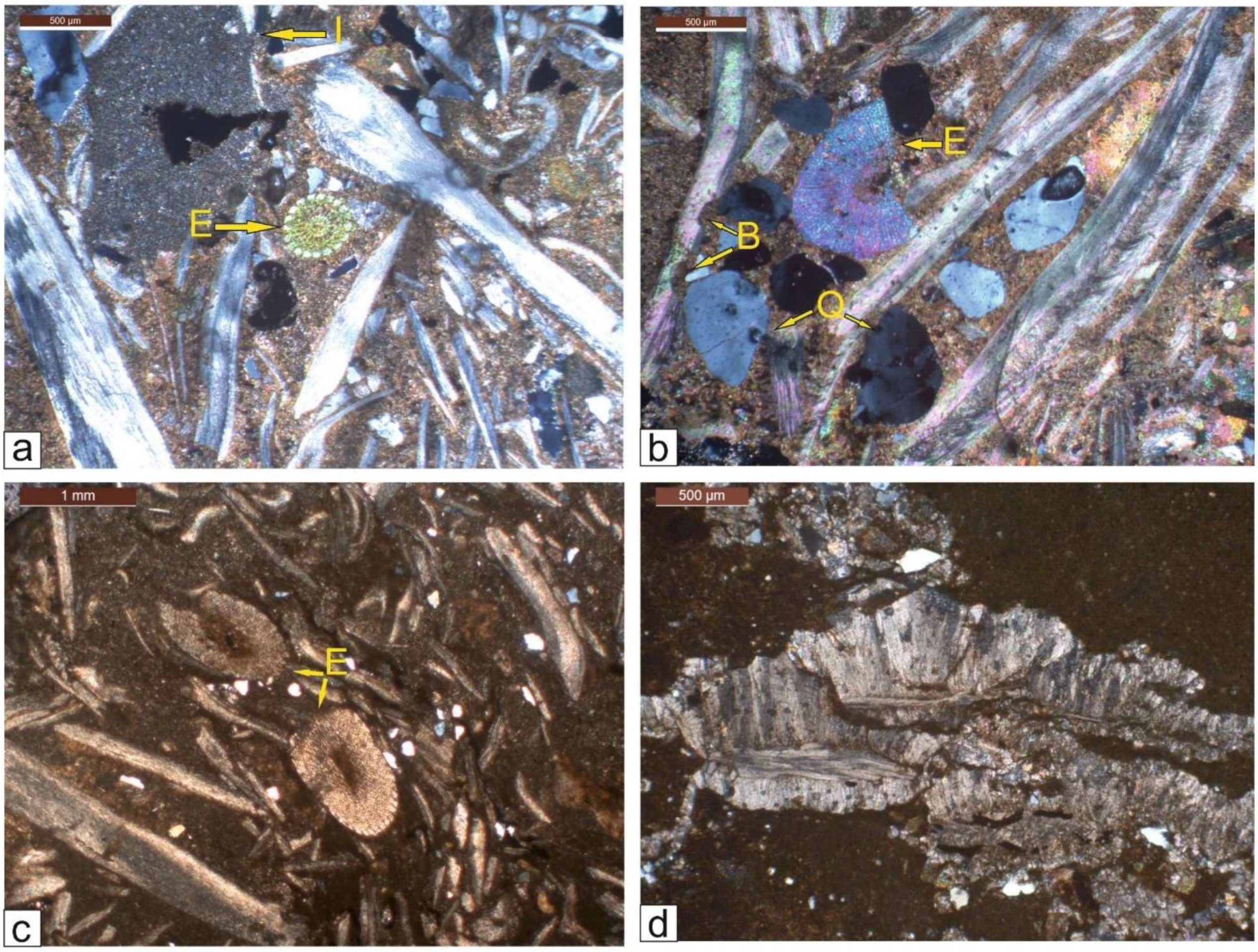


Plate 5.26 Photomicrographs of fossiliferous limestone facies of Bilthana Formation showing textural and compositional variations. a. Grainstone consisting of oyster fragments showing growth lines, transverse section of echinoderm spine (E), intraclasts (I), and scattered silt-sized quartz grains in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

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

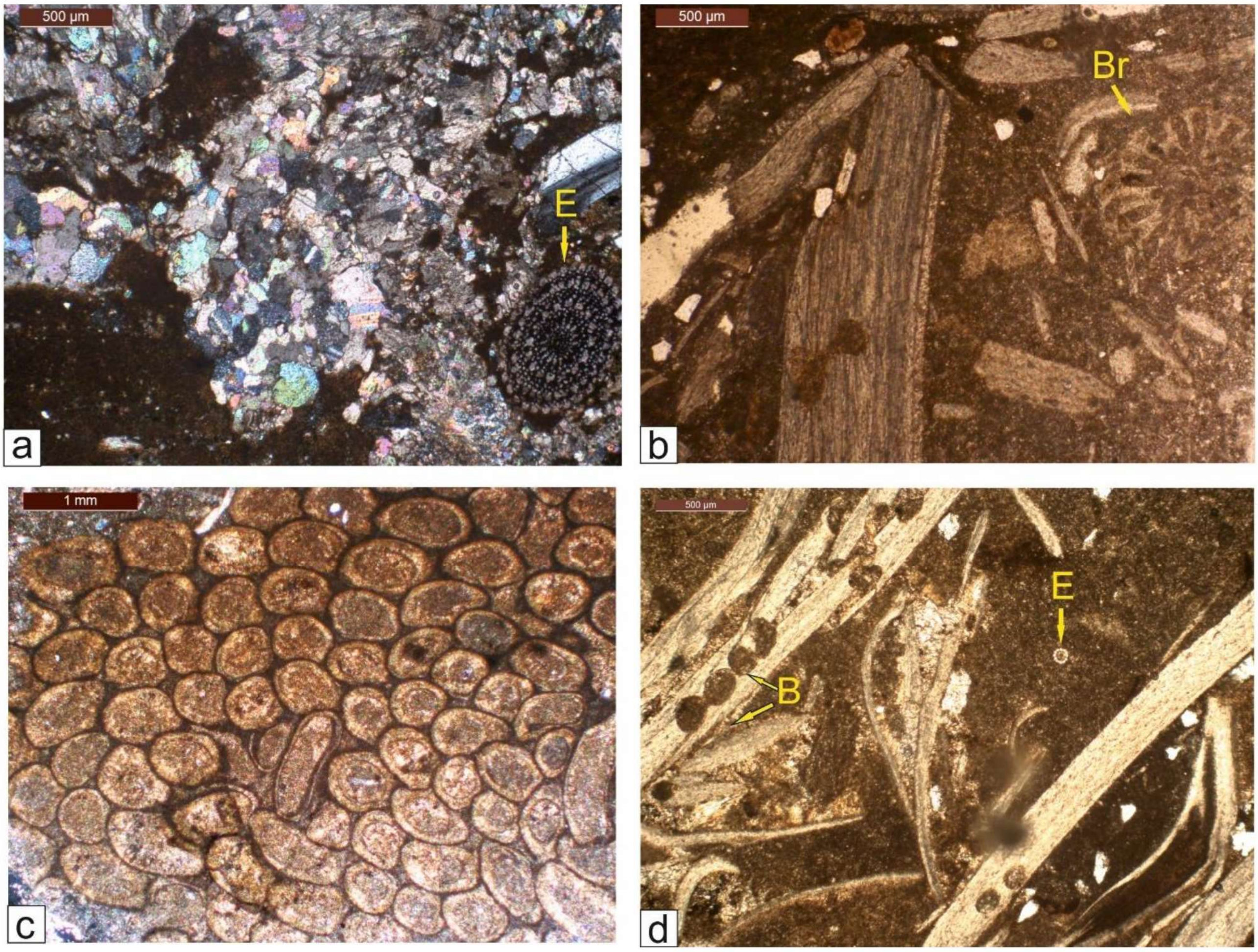


Plate 5.27 Photomicrographs of fossiliferous limestone facies of the Bilthana Formation. a. Recrystallized bivalves shell fragments formed cleavable calcite crystals and transverse section of echinoderm spine (E) in the micritic matrix (black); Uchad section. b. Bored oyster shell with bryozoan (Br);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

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

5.2.2.8 Sandy/silty micrite facies

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

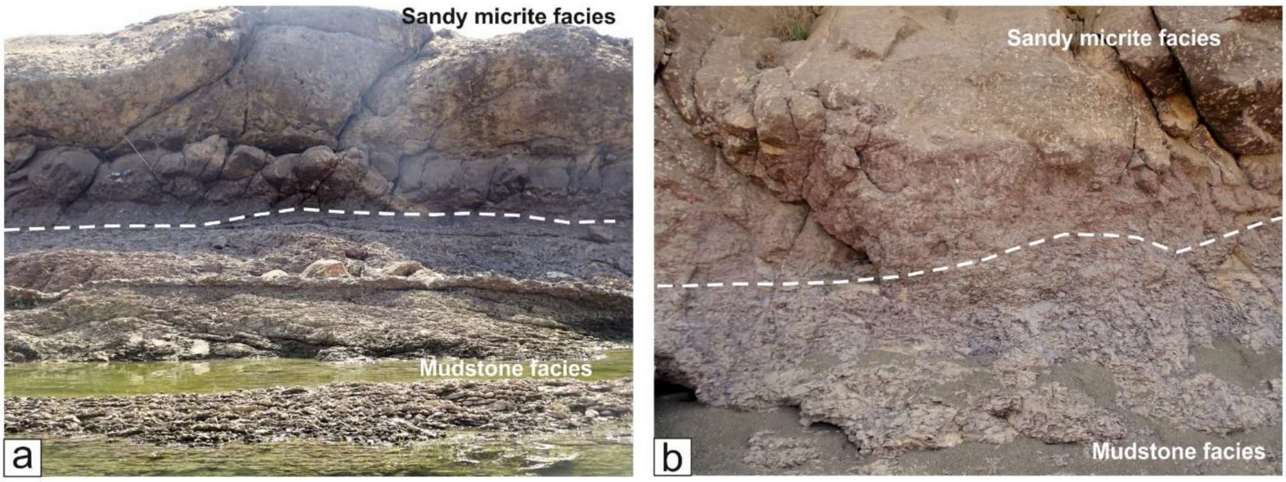


Plate 5.28 Field photographs of the sandy micrite facies. a. Thickly-bedded sandy micrite facies of Narmada Sandstone Member overlying the mudstone facies of the Nodular Limestone, Navagam section. b. Close-up view of a. note the gradational contact between the two lithostratigraphic units.

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

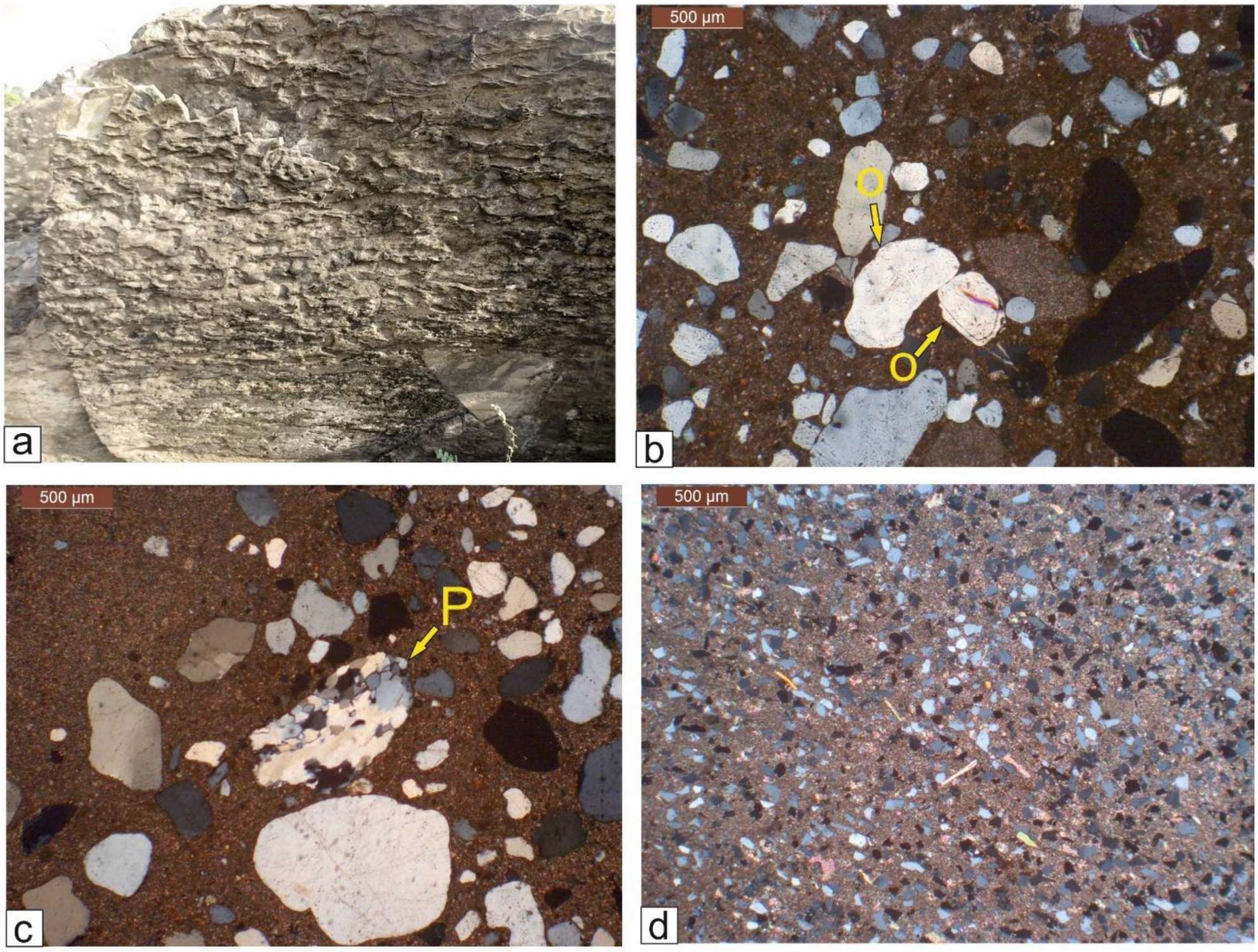


Plate 5.29 Field photographs and photomicrographs of the sandy/silty micrite facies. a. Silty micrite facies; Nodular Limestone, Uchad section. b. Subangular to subrounded, poorly sorted quartz grains in the micritic matrix; quartz grains showing the presence of overgrowth (O); Narmada Sandstone Member,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

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

5.2.2.9 Mudstone facies

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

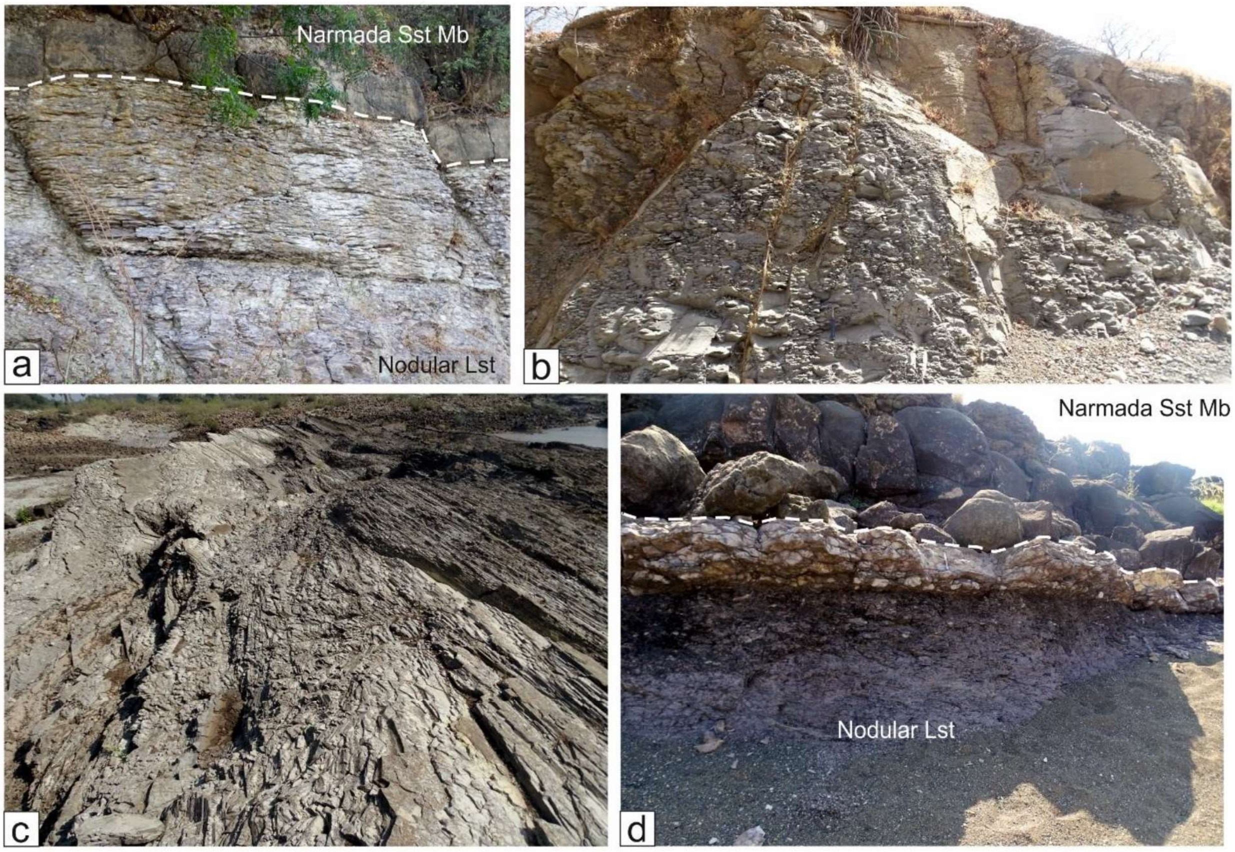


Plate 5.30 Field photographs of mudstone facies. a. Mudstone of Nodular Limestone showing bedded appearance in contact with the overlying Narmada Sandstone Member; Uchad section. b. Mudstone exhibiting nodular appearance; Nodular Limestone, around Mathsar village. c. Extensively fractured thinly-bedded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

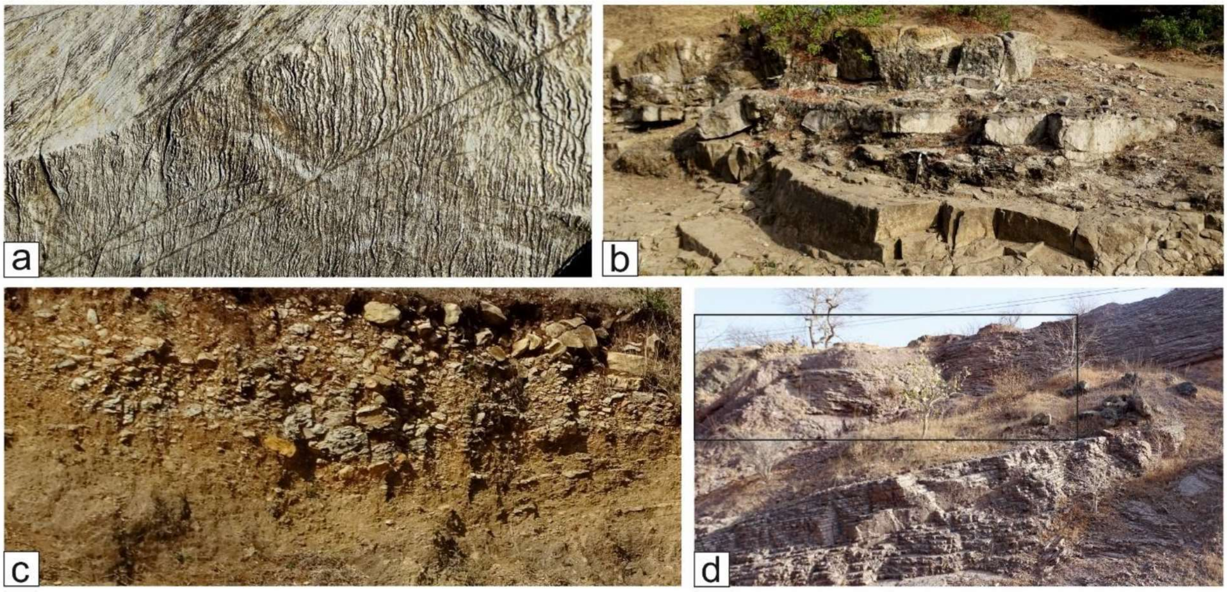


Plate 5.31 Field photographs of the mudstone facies. a. Intense chemical weathering marks on the limestone surface; Nodular Limestone, Navagam section. b. Thickly-bedded mudstone of the Men Nadi Limestone Member, Uchad Formation; Uchad section. c. Mudstone exhibiting nodular appearance; Nodular Limestone;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

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

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

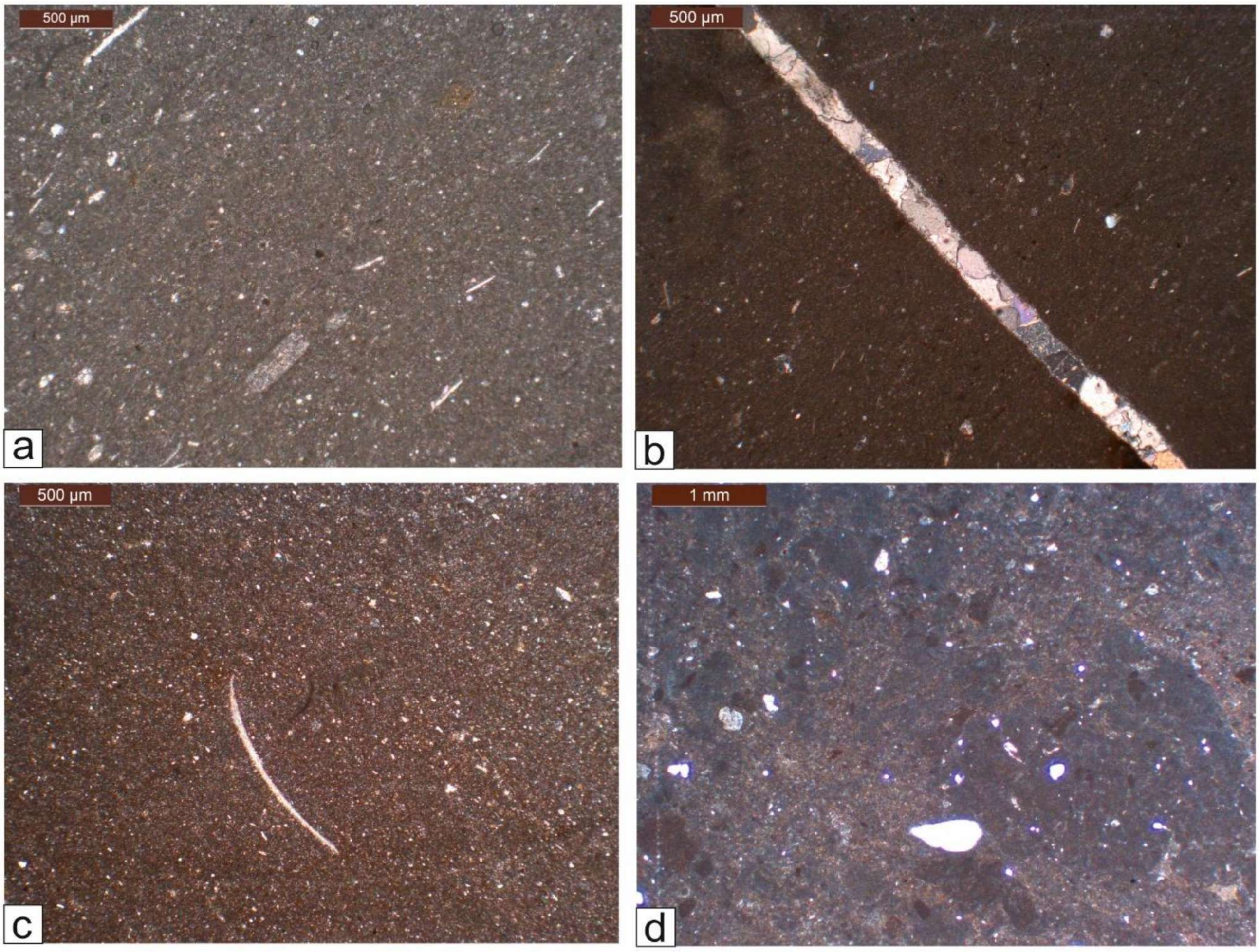


Plate 5.32 Photomicrographs of mudstone facies showing compositional and textural variations at the Uchad section. a. Mudstone consisting of delicate shell fragments with scattered fine quartz grains; Nodular Limestone. b. A calcitic vein in mudstone possibly due to fracturing during burial process;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

5.2.2.10 Muddy micrite facies (MM)

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

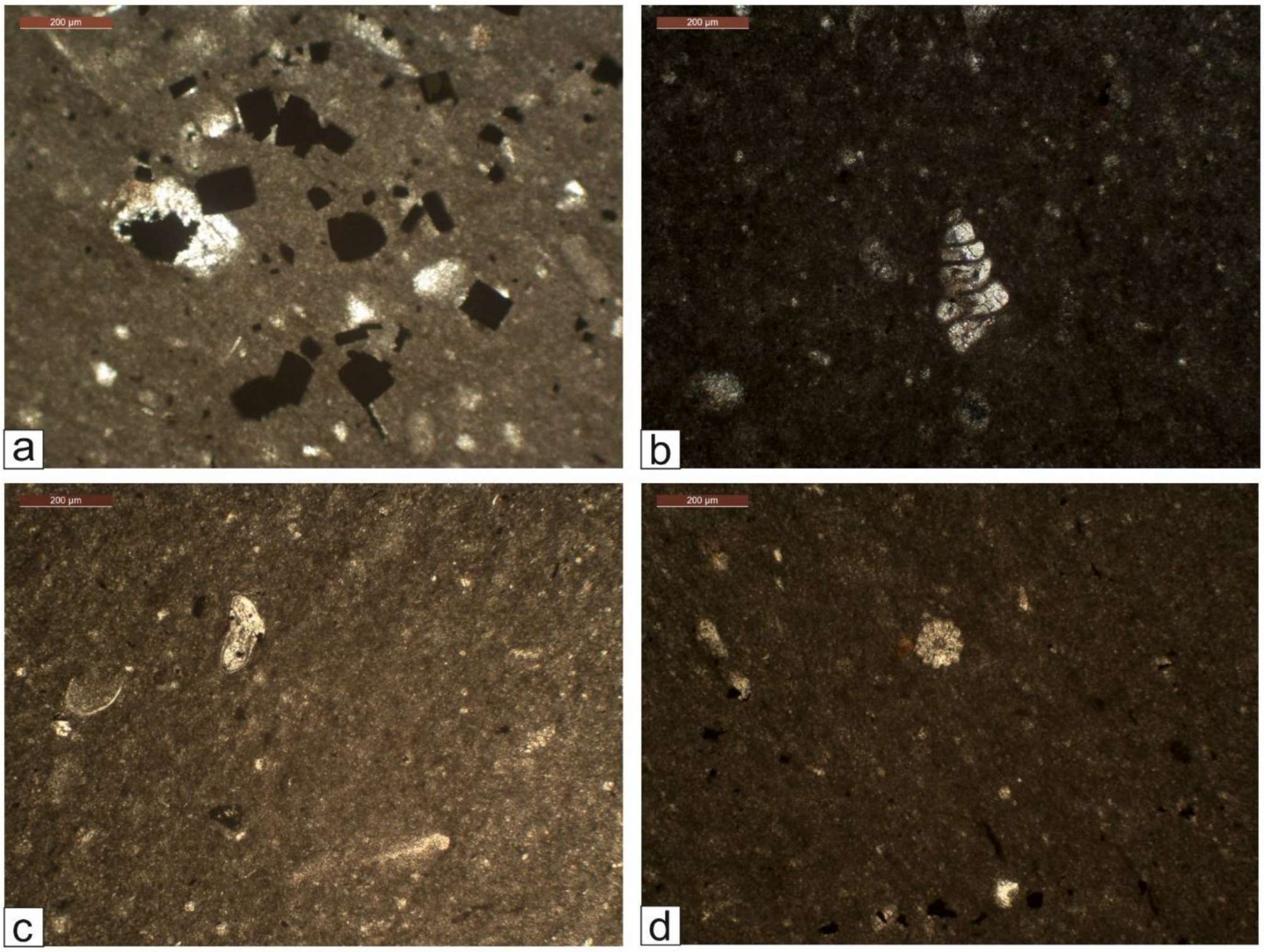


Plate 5.33 Photomicrographs of the mudstone facies; Nodular Limestone. a. euhedral, isotropic, pyrite grains in micritic matrix. b. Calcitised helicoid gastropod in micritic cement. c. Ostracod carapace? in the micritic matrix. d. Transverse section of echinoid spine and fecal pellets? in the micritic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

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

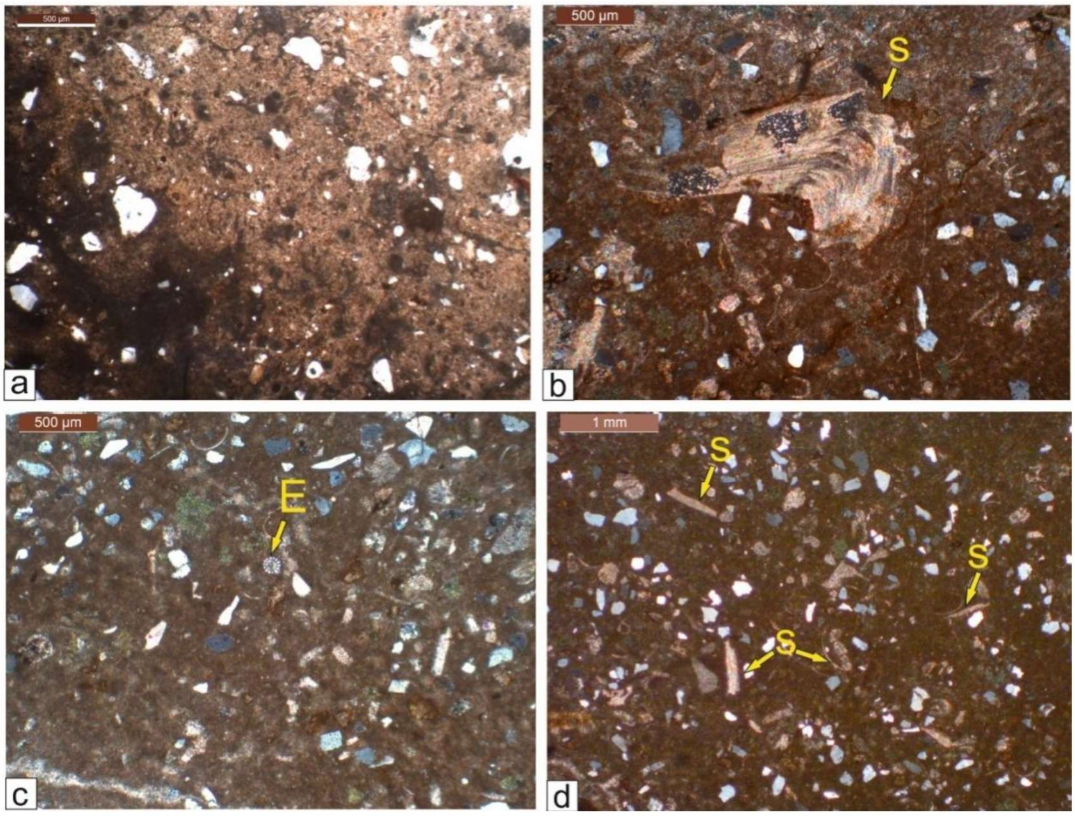


Plate 5.35 Photomicrographs of the muddy micrite facies. a. Subangular to subrounded silt to medium-sized quartz grains floating in the micritic matrix; Men Nadi Limestone Member, Uchad section. b. Silt-fine grained quartz grains and fecal pellets? in the micritic matrix and shell fragment showing growth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

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

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

CHAPTER 6
ICHNOLOGY

6.1 INTRODUCTION

Trace fossils are autochthonous in nature and intimately related to the depositional environment; they are significant in interpreting the various geological and biological processes. They have been recorded since the Neoproterozoic Era, and their abundance and diversity have increased throughout the Phanerozoic Eon. The Mesozoic Era witnessed the Gondwanaland break up and inundation of the sea on the continent during the Jurassic-Cretaceous Period. The encroachment of the sea on the Indian continent resulted in the deposition of thick marine sedimentary rocks, including the Narmada Basin. The global sea-level rise during the Cenomanian- Turonian time invited a variety of fauna evidenced by diverse trace fossils in the Lower Narmada Valley. The Western Lower Narmada Valley is characterized by various rock types, including fine and coarse clastics, nonclastics, and mixed siliciclastic-carbonate sediments, bioturbated to varying degrees. Trace fossils are mainly reported from moderately bioturbated Vajepur Formation, intensely bioturbated Bilthana Formation, Nodular Limestone, and Narmada sandstone Member of Uchad Formation. The Bagh Group rocks in the WLNV possess diverse trace fossils and variability in its sedimentary record. There have been several advancements in the study of trace fossils taxonomy; several old ichnogenera and species are merged, renamed, replaced, or invalidated. In the present study, the Cretaceous trace fossil record of the Indian Tethyan basins is discussed, emphasizing their taxonomic status. The study aims to revive the status of the earlier reported and the newly proposed ichnogenera and ichnospecies from the Cretaceous Period of India and understand the depositional conditions in Cretaceous basins based on the trace fossil record. To derive the information on the depositional environment of the Cretaceous basins in India, the data is synthesized, re-evaluated, and corrections are made to the old invalid names. Also, the present status of the ichnogeneric and ichnospecies name and their potential synonyms is reviewed.

To date, most of the ichnological studies of the Bagh Group rocks were carried out in the eastern part of the Lower Narmada Valley- ELNV (Chiplonkar and Badve, 1969, 1970, 1972;

Chiplonkar and Ghare, 1975a and b; Singh and Dayal, 1979; Ghare and Badve, 1980, Singh, 1982; Badve, 1987, Sanganwar and Kundal, 1997; Kundal and Sanganwar, 1998b, 2000; Nayak, 2000) and very few studies in the western part of the Lower Narmada Valley- WLNV (Verma, 1970; Chiplonkar and Badve, 1972; Badve and Ghare, 1980; Patel et al., 2017 and Shitole et al., 2019). However, studies reporting trace fossils from the WLNV and interpreting them from a paleoecological point of view are scarce. Based on occurrence, preservation style, ethology, trophic type, and distribution of the trace fossils, ichnoassemblages and ichnofacies have been identified. Quality exposures and abundant well-preserved trace fossils in the study area make ichnology an ideal tool for studying paleodepth, oxygen, salinity, food supply, and organisms flourishing in the transgressive Cretaceous Palaeo-Tethys Sea.

6.2 TRACE FOSSILS DESCRIPTION

Treatise of InvertertebratePaleontology was the first compilation of valid invertebrate trace fossils done by Häntzschel (1975). Knaust (2012) updated the original version of the treatise and proposed a nomenclature key based on the hierarchy of diagnostic features (ichnotaxobases like orientation, presence or absence of branching, shape, and presence or absence of lining). Buatois et al. (2017) categorized the 523 ichnogenera into seventy-nine architectural designs based on morphological characters. The concept of ichnodisparity is similar ichnotaxonomy since both involve morphological studies and ethological interpretation. However, the concept differs from ichnodiversity since it merges the minor behavioral variants within a single morphological plan, whereas it may lead to a high ichnodiversity interpretation. Ichnodisparity identifies the number of architectural design categories, whereas ichnodiversity measures the number of ichnogenera. The application of ichnodiversity lies in analyzing environmental stress (viz., low ichnodiversity suggests a more stressful environment), stability in facies interpretation, reconstructing evolution history, and evaluating species richness in different depositional settings geological times (Buatois and Mángano, 2013). Taphonomy has a huge impact on the ichnodiversity viz. the low diversity can be interpreted in terms of stressed environmental conditions, or it can reflect stable conditions giving rise to deep-tier climax communities and thus has a taphonomic origin, i.e., produced due to intense bioturbation of deep tier organisms and does not reflect environment stability (Buatois and Mángano, 2013). This suggests low ichnodiversity cannot always be attributed to stressful environmental conditions. Buatois and Mángano (2013) suggest that ichnodiversity is essential in the information provided for the otherwise unfossiliferous rocks. Still, their comparison with the actual diversity of organisms is equivocal because ichnodiversity is the outcome of organism-substrate interaction and is unrelated to the factors which control species or body fossil diversity, i.e., contrasting substrate conditions can produce different biogenic structures. A single organism shows variable behavior; therefore, several ichnogenera can result from the same producer.

The previous literature is the primary backbone and forms a strong foundation for any research investigation. Trace fossils are the fossil record of biological activity; although more common than body fossils, they are not so readily discernible in the field. In the present study, historical record of the Cretaceous ichnology in the Narmada Basin is compiled (Table 6.3) to ensure that they do not escape records of their occurrence and can be used in a purposeful manner. The study describes the present status of the ichnogeneric and species names, and a broader interpretation is derived regarding the Cretaceous depositional environment in the basins of the Indian subcontinent based on the occurrences of trace fossils. The history of invertebrate ichnology in India has been divided into three periods: 1800-1960 involving a report of trace fossils; 1960-2000 report, erection of new ichnotaxa and palaeoecological interpretations and 2000 to present involving new ethological interpretations, demonstration of trace fossils, and combining sedimentological and ichnological studies for demonstrating the sea-level changes and the evolutionary change in trace fossils. Studies on invertebrate ichnology as a separate field started in 1800, but it was not until 1960 that it began to bloom worldwide (Cadée and Goldring, 2007). However, ichnological studies in India gained popularity in early 1970. 1970-80 was a period of development in ichnological studies in India when many occurrences of ichnotaxa were reported, and the concept of ichnofacies was used enormously, which strengthened the paleontological and sedimentological interpretations (Figure 8.3). The period 1969-2000 in India witnessed intense ichnological research, during which many new ichnogenera and species were reported and preserved in the museums. The ichnological studies in India were initially started by Chiplonkar, Badve, and Ghare and later by Borkar, Patel, Kundal, Sanganwar, etc. Their studies substantially contributed to the development of ichnological studies in India during the early 1970 and culminated in many significant contributions, which is the foundation for the present investigation. Recently Knaust (2012) and Buatois et al. (2017) have made important contributions to the trace fossils systematics part by compiling the valid and invalid names of the ichnogenera and species and providing details and lists of the synonyms.

Chiplonkar and Badve (1969, 1970) reported two new genera, *Arthropodichnus*, *Diplopodomorpha* and twelve new species *Arthropodichnus indicus*, *Diplopodomorpha cretacea, Dreginozoum orientale, Nereites malwaensis, Oniscoidichnus communis, O. ampla, O. elegans, O* *robustus, Permichnium bosei, Taphrhelminthopsis subauricularis, Asterosoma spatulata* and *Phycodes gregarious* from the Bagh Group rocks LNV. *Arthropodichnus* (Chiplonkar and Badve, 1970) was also reported by Ghare and Badve (1980) from the Bagh Group, WLNV; Viglietti et al. (2020) from the Karoo Group, South Africa; Shibata and Varricchio (2020) from the Cretaceous of Two Medicine Formation, USA, and the Ordovician Welsh basin by Nicholls (2019) and was validated by Häntzschel (1975). However, *Arthropodichnus* was also proposed by Gevers et al. (1971) for paired parallel track impression; later, Gevers realized the name was already used for another ichnogenus and changed it to *Beaconichnus* in 1973. Bradshaw (1981) redescribed Gevers specimens and synonymized the ichnospecies with *Diplichnites gouldi*. The ichnogenus was recently considered nomina dubia by Buatois et al. (2017), lacking adequate description and unclear diagnostic characteristics. Ichnogenus *Permichnium* (Guthörl, 1934) is invalidated and regarded as a junior synonym of *Lithograptus* by Minter and Braddy (2009). Chiplonkar and Badve, (1970) erected new ichnospecies *Dreginozoum orientale*. The ichnogenus *Dreginozoum* (Marck, 1894), although reported by several authors (Cuerda et al., 1990; Nielsen et al., 2015) has been considered as ichnogenera with unclear taxonomic status by Knaust (2012) and is not much in usage. The ichnospecies *Fucusopsis cf. angulatus* (Vassoevich, 1932) was reported by Chiplonkar and Badve (1969, 1970) and by Saha et al. (2010) from the Narmada basin. The ichnogenus *Fucusopsis* and its three ichnospecies (*F. angulata, F. annulate,* and *F. striata*) were included in *Halopa* as its junior synonym by Uchman (1998). However, it was added to the list of valid ichnogenera but with an unclear taxonomic status by Knaust (2012). *Diplopodomorpha* was introduced as an ichnogenus with type species *D. cretacea* by Chiplonkar and Badve (1970). The ichnogenus was validated by Knaust (2012) but was considered nomina dubia by Buatois et al. (2017). The new ichnospecies *Nereites malwaensis, O. communis, O. ampla, O. robustus,* and *Asterosoma spatulata* erected by Chiplonkar and Badve (1970) are not found in usage but are also not invalidated. *O. elegans* is reported only from the Tertiary rocks of Bengal Basin by Bera (1996). Uchman (1995) included the ichnotaxa *Taphrhelminthopsis* and ichnospecies (*T. auricularis, T. plana, T. convolute, T. auricularis, T. vagans, T. sacco,* and *T. recta*) in *Scolicia strozzi* (Savi and Meneghini, 1850). However, the status of *Taphrhelminthopsis subauricularis* (Chiplonkar and Badve, 1970) was not made clear, but the revision of ichnogenus should be synonymized with *Scolicia*. The ichnospecies *Phycodes gregarious* (Chiplonkar and Badve, 1970) was regarded to be nomen dubium by Han and Pickerill (1994) because of its small size and was considered to be similar to *P. circinatus*.

Later in 1970, Chiplonkar and Badve erected one new ichnogenus *Discotomaculum* and two new ichnospecies *Discotomaculum variabilis, Protovirgularia mongraensis* from the Bagh Group rocks WLNV. The new ichnogenera *Discotomaculum* (Chiplonkar and Badve, 1972), although not much in usage, was considered to be a valid ichnogenus by Gutiérrez-Marco et al. (1984) and was also reported by Fraunfelter (1987) from the Cambrian Davis Formation of Missouri. *Protovirgularia mongraensis* was later considered a junior synonym of *P. dichotoma* (Han and Pickerill, 1994).

Verma (1970) reported one new ichnogenus *Baghichnus* and three new ichnospecies- *Baghichnusbosei, Laevicyclus mongraensis,* and *Pholeus robustus,* from the Bagh Group rocks exposed in the Ambadongar area, WLNV. Knaust (2012) considered *Baghichnus* to be nomen dubium and added it to the list of invalid ichnogenera. *Pholeus robustus* was removed from the ichnogenus *Pholeus* by Knaust (2002) in lack of oblique burrow and a small vertical burrow. *Laevicyclus mongraensis* is a valid ichnospecies reported from the Jurassic rocks of Kachchh basin (Desai et al., 2008; Joseph et al., 2020); Jurassic rocks of Jaisalmer basin (Desai and Saklani, 2014); Cretaceous rocks of Narmada basin (Chiplonkar and Badve, 1970; Sanganwar and Kundal, 1997; Kundal and Sanganwar, 1998); Cretaceous-Eocene of Julian basin (Tunis and Uchman, 1996); Tertiary rocks of Cambay basin (Mude, 2012a and b) and Surma Group (Tiwari et al., 2011). However, Alpert and Moore (1975) suggested its resemblance with *Dolopichnus*.

Chiplonkar and Tapaswi (1972) described new ichnospecies *Scalarituba indica* from the Cretaceous rocks of the Cauvery Basin. Uchman (1995) suggested that ichnogenus *Scalarituba* should be regarded as a junior synonym of *Nereites*. Later Mángano et al. (2002) suggested that the species *Scalaritubaindica* be removed from the *Nereites* Group and included in *Taenidium*.

Chiplonkar and Ghare (1975a) erected nine new ichnospecies, an ichnogenus from the Cretaceous Bagh Group rocks and a new ichnospecies from the Lameta Group rocks. Of the newly proposed ichnospecies, *Cosmorhaphe filiformis, Cylindricum curvosus, Eoclathrus subramanyami, Hirmeria khandluensis, Pelecypodichnus chikliensis, Phycodes mongraensis, Paleodictyon mongraensis,* and *Rhizocorallium mongraensis* are not in usage but also not invalidated. However, the ichnospecies *Rhizocorallium mongraensis* was reported by Kundal and Sanganwar from the Nimar Sandstone Formation of Bagh Group rocks, ELNV. The authors erected new ichnogenus *Arthrotelsonichnus namadicus*; the genus was recently considered nomen dubia by Buatois et al. (2017) based on lack of adequate description and unclear diagnostic characteristics. The ichnogenus *Pennatulites* reported by the authors was synonymized with *Protovirgularia* by Seilacher and Seilcher (1994). The newly erected ichnospecies *Spongeliomorpha reticulata* was invalidated by

Melchor et al. (2009) owing to its erection based on a single specimen, cylindrical structure, and lack of network. The authors proposed new ichnospecies *Granularia obliqua*; however, the ichnogenus *Granularia* was synonymized with *Ophiomorpha* (Pemberton and Frey, 1982) and invalidated by Uchman (1995, 1998).

Chiplonkar and Ghare (1975b) reported *Keckia annulata* and *Paleodictyon isp.* from the Bagh Group rocks, ELNV. The ichnospecies were also reported by Ghare and Badve (1980) and Nayak (2000) from the Bagh Group rocks. The status of specimens later described as *Keckia* is highly debated and not clear (see Uchman, 1998 and references therein; Knaust, 2012). The ichnogenus is considered nomen dubium (D'Alessandro and Bromley, 1987), and its usage is not recommended (Buatois et al., 2017). Uchman (1998) included *Keckia annulata* in *Protovirgularia;* thus, the status of *Keckia annulata* reported by Chiplonkar and Ghare (1975b) stands revised to *Protovirgularia*.

Singh and Dayal (1979) erected new ichnogenera *Striatolites* and ichnospecies *Striatolites bariaensis* from the Bagh Group rocks exposed between Avalda and Zeerabad villages, ELNV. The ichnogenus lacked usage and was regarded as a junior synonym of *Halopoa* (Buatois et al., 2017).

Badve and Ghare (1980) reported two new ichnogenera from the Bagh Group rocks exposed in Deva River, South of Narmada, Maharashtra, namely *Annetuba* and *Notocubichnia*. The authors also erected four new ichnospecies- *Annetuba chapdiensis, Imponoglyphus kevadiensis, Monomorphichnus crefacea,* and *Notocubichnia minuta*. The newly introduced ichnogenera *Annetuba* with typespecies *A. chapdiensis* (Badve and Ghare, 1980) was also reported by Kundal and Sanganwar (1998) from the Bagh Group rocks and was later considered to be the junior synonym of *Arenituba* verso (Knaust, 2015). The new ichnogenera *Notocubichnia* and ichnospecies *N. minuta* (Badve and Ghare, 1980) and ichnospecies *Imponoglyphus kevadiensis* (Badve and Ghare, 1980) are not in usage but are also not invalidated. The ichnospecies *I. kevadiensis* is reported from the Jurassic rocks of Jaisalmer Basin by Parihar et al. (2017) and Desai and Saklani (2014). However, Uchman (1998) suggested that *Imponoglyphus* is a preservational variant of Taenidium.

Ghare and Badve (1980) reported *Pennatulites* (de Stefani, 1885) from the Cretaceous Bagh Group rocks. *Pennatulites* has been regarded a junior synonym of *Protovirgularia* by Seilacher and Seilacher, 1994; Uchman (1998) and Buatois et al. (2017). However, Knaust (2012) added it to the list of valid ichnogenera.

The ichnogenus *Aulichnites* reported by Krishna (1987) from the Cretaceous of Kachchh basin and by Kundal and Sanganwar (2000) from the Cretaceous Bagh Group of Narmada basin are invalidated by Knaust (2012). The ichnotaxa is highly debated (Mángano and Rindsberg, 2003 and references therein) and was reported abundantly by several authors; later, it was found that the holotype of *Aulichnites* was a poorly preserved specimen of *Psammichnites* (Hakes, 1977; D'Alessandro and Bromley, 1987; Mángano and Rindsber, 2003). However, it is still used in the lack of ichnogeneric name for smooth, bilobate, tape-like, epirelief traces (Mikuláš et al., 2017).

Badve (1987) described two new species, *Palaeophycus annulatus,* and *Granularia velamensis,* from the Bagh Group rocks, Barwah area, ELNV. Badve also reported *Brookvalichnus obliquus* (Webby, 1970); the ichnogenus is not used but is considered a valid ichnogenus (Knaust, 2012). However, it has not been regarded as a trace fossil by Buatois et al. (2017). *Palaeophycus annulatus* (Badve, 1987) was considered to be a junior synonym of *Palaeophycus anulatus* (McCann and Pickerill, 1988) by Fillion and Pickerill (1990). McCann (1993) suggested using the name *Palaeophycus serratus,* considering the dilemma associated with the name *P. anulatus*. Later Buckman (1995) regarded *P. anulatus* as a homonym of *P. annulatus* and synonym of *P. serratus* and considered *P. serratus* nomen dubium. *P. annulatus* was also considered to be nomen dubium and invalidated by Buckman (1995) based on incomplete description and illustration and lack of sectioned material and suggested it should be referred informally. Buckman argued that the annulations seen on Badve's figure might be a taphonomic feature due to compaction or weathering; the annulation could be swelling as seen in the specimens of *Planolites tubularis*, or it could be the compartmentalized fill seen in *Taenidium* or *Eione*. Moreover, Buckman erected a new genus *P. crenulatus*, an annulated specimen differing from *P. annulatus* and *P. anulatus* based on the width of annuli and well-defined lining. The ichnogenus still stands valid and is widely used to describe the irregular annulated *Palaeophycus* specimens and is also used to describe similar specimens occurring in the study area. The Cretaceous occurrences of the ichnospecies in India are from the Narmada basin (Kundal and Sanganwar, 1998; Sanganwar and Kundal, 1997). The ichnogenus *Granularia* was synonymized with *Ophiomorpha* and invalidated by Uchman (1995, 1998). The ichnospecies *Granularia velamensis* described by Badve (1987) lacks resolution hence cannot be convincingly regarded as a synonym of *Ophiomorpha. Keckia annulata* reported by Chiplonkar and Ghare (1975), as discussed earlier, is revised to *Protovirgularia* (Uchman, 1998).

Sanganwar and Kundal (1997) identified new ichnospecies *Arthropodichnus chiplonkari, Rhizocorallium yelamensis* and reported *Uvaites catanus* (Badve and Ghare, 1978) from the Nimar

Sandstone Formation of Bagh Group, ELNV. The ichnogenus *Arthropodichnus* was recently invalidated by Buatois et al. (2017) in lack of adequate description and unclear diagnostic characteristics. The ichnospecies *Arthropodichnus chiplonkari* (Sanganwar and Kundal, 1997) is a poorly preserved specimen and can be tentatively assigned to *Protovirgularia*. The new ichnospecies *Rhizocorallium yelamensis* (Sanganwar and Kundal, 1997) reported from the Bagh Group rocks was recently synonymized with *Rhizocorallium commune* (Schmid, 1876) by Knaust (2013). The ichnogenus and ichnospecies *Uvaites catanus* erected by Badve and Ghare (1978) and reported by Sanganwar and Kundal (1997) is barely used but is also not invalidated.

Kundal and Sanganwar (1998) identified new ichnospecies *Palaeophycus intermediatus* from the Nimar Sandstone of Bagh Group rocks, ELNV. *Annetuba chapdiensis* (Badve and Ghare, 1980) was regarded to be the junior synonym of *Arenituba verso* (Knaust, 2015). The ichnospecies *Granularia yelamensis* (Badve, 1987) was reported by Kundal and Sanganwar (1998) from the Bagh Group rocks. However, the ichnogenus *Granularia* was synonymized with *Ophiomorpha*. Kundal and Sanganwar (1998) reported *Imponoglyphus kevadienesis* (Badve and Ghare, 1980), *Keckia annulata* (Glocker, 1841), and *Laevicyclus mongraensis* (Verma, 1970); their status of is already discussed above. *Palaeophycus intermediatus* (Kundal and Sanganwar, 1998) is not much in usage but also not invalidated.

Tewari et al. (1998) reported *Teredolites clavatus* and *Teredolites longissimus* from the Cauvery basin. However, the type species of *Teredolites* (*T. clavatus*) was regarded to be *Gastrochaenolites clavatus* (Leymerie, 1842) by Donovan and Ewin (2018) and *Teredolites longissimus* (Kelly and Bromley, 1984) is reclassified as the type ichnospecies of *Apectoichnus* (Donovan, 2018).

Kundal and Sanganwar (2000) reported *Corophioides luniformis* from the Bagh Group rocks. The ichnogenus *Corophioides* (Smith, 1893) has been regarded as a synonym of *Diplocraterion* (Torell, 1870) by Fürsich (1974) and is considered to be invalid by Knaust (2012). The new ichnospecies *Cylindrichnus karondiaensis* (Kundal and Sanganwar, 2000) from the Bagh Group rocks exposed in the Manawar area of ELNV is not in usage but also not invalidated. The status of *Granularia* and *Keckia annulata* is already discussed. *Rhizocorallium mongraensis* (Chiplonkar and Ghare, 1975), reported by Kundal and Sanganwar (2000), was recently synonymized with *Rhizocorallium commune* by Knaust (2013). The status of ichnogenus *Aulichnites* is specified above and is invalidated by Knaust (2012) but is still in usage.

Trace fossil		Orientation	Branching	Shape	Fill	Ichnogenus
I	**Burrows**	Subhorizontal	Unbranched	Cylindrical, ridge-like	Passive	*Palaeophycus*
					Active	*Planolites*
					Active/ Passive	*Ptychoplasma*
					Active	*Taenidium*
		Subvertical	Unbranched	Cylindrical	Passive	*Skolithos*
				Plug- shaped	Passive	*Bergaueria*
						Conichnus
						Conostichus
						Lockeia
				U- and bow-shaped	Passive	*?Arenicolites*
		Complex	-	Boxwork	Passive	*Thalassinoides*
II	**Trails**	Number of Lateral Elements	Unary	Straight or curved		*Archaeonassa*
					-	*Helminthoidichnites*
				Winding with loops	-	*Gordia*
			Binary	Straight or curved		*Didymaulichnus*
III	**Trackways**	-	Biserial	Bract-like-	-	*Oniscoidichnus*
IV	**Bioerosional**	-	Unbranched	Clavate	-	*Apectoichnus*

Table 6.1 Morphological classification of the trace fossils based on the hierarchy of ichnotaxobase (Knaust, 2012).

Nayak (2000) erected four new ichnospecies *Arenicolites phataensis, Monocraterion variabilis, Thalassinoides badvei,* and *Scalarituba kanwaraensis* from the Nimar Sandstone of Bagh Group exposed in the Jhabua area, ELNV. The ichnogenus *Scalarituba* (Weller, 1899) is also reported by Chiplonkar and Tapaswi, 1972 from the Cauvery basin and by Bhatt and Patel (2017) from the Kachchh basin. The ichnogenus is synonymized with *Nereites* by Uchman (1995). The ichnospecies *Arenicolites phataensis* (Nayak, 2000) is not in usage and based on the examination of the specimen, Kulkarni et al. (2008) regarded its ichnogeneric identification to be doubtful. *Keckiaannulata* (Glocker, 1841) was reported by Nayak (2000) from the Bagh Group rocks; its status is already discussed in the preceding paragraphs. The new ichnospecies *Monocraterion variabilis* and *Thalassinoides badvei* erected by Nayak (2000) are not in usage but also not invalidated.

Saha et al. (2010) reported several trace fossils from the Maastrichtian Lameta Group of the Narmada Basin. The ichnogenus *Calycraterion* (Karaszewski, 1971) is regarded as a junior synonym of *Laevicyclus* (Quenstedt, 1879) by Knaust (2012, 2015) and the ichnogenus *Stipsellus* (Howell, 1957) was put in synonym with *Skolithos* by Alpert (1974). However, several authors later reported it, and it is still in usage.

After the first compilation of trace fossils by Häntzschel (1975), several new ichnogenera were erected, synonymized, and invalidated. Therefore, in the present study, trace fossils are classified based on Buatois et al. (2017) and Knaust (2012), an updated treatise of trace fossils and would serve as a base for systematics. For trace fossil description, the preservational and ethological classification schemes proposed by Seilacher (1953, 1964) and Martinsson (1970) are adopted, and the nomenclature is done as per ICZN guidelines. Each trace fossil is further described, interpreted for the probable trace maker, and noted for its occurrence in the lithology (Table 6.1). Thus, trace fossils in the present study are described following five major approaches, i.e., descriptive, preservational, behavioral, organism, and taxonomic.

6.2.1 BURROWS

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, Ridge-like

Fill: Passive

Burrow Wall: Lined

Ichnogenus: *Palaeophycus* HALL, 1847

Diagnosis: Branched or unbranched, smooth or ornamented, lined, essentially cylindrical, predominantly horizontal burrows of variable diameter; infillings typically structureless, of the same lithology as host (Pemberton and Frey, 1982).

Ichnospecies: *Palaeophycus tubularis*, HALL, 1847

(Plate 6.1 a-b)

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

Description: Horizontal, epichnial, parallel to bedding, straight to gently curved, distinctly lined, smooth-walled, unbranched, cylindrical trace fossil, burrow fill same as host sediments. The maximum observed length in the Men River valley specimens is 7.59 cm, and its diameter is 1.12 cm. In contrast, the Gulvani specimen is about 25.46 cm long and has a diameter of 4.2 cm.

Interpretation: Thin wall of *Palaeophycus tubularis* distinguishes it from *Palaeophycus heberti.* It differs from similar-looking *Planolites* and other ichnospecies of *Palaeophycus* by prominent lining and fills identical to the host rock. It is distinguished from *P. striatus* by lack of parallel striations, *P. heberti* by its thinner wall, *P. sulcatus,* which has anastomosing striations, and *P. alternatus,* which possesses alternate striations (Pemberton and Frey, 1982). *Palaeophycus* is reported from the foreshore and lower shoreface-offshore environments and is more common in nearshore settings (Pemberton et al., 2001; Buatois and Mángano, 2011). Pemberton and Frey (1982) interpreted *Paleophycus* to be passively filled open burrows constructed for domicile purposes based on the identical fill of the host and type specimen and the "apparently hollow" observation of Hall (1847). *Paleophycus* is facies crossing form constructed by predaceous or suspension feeders (Pemberton and Frey, 1982) or by insects and arthropods in continental settings (Buatois and Mángano, 1993).

Occurrence: *Palaeophycus* occurs at bed junction as epichnia in the sandy allochemic limestone facies of Bilthana Formation and calcareous rippled sandstone of Vajpeur Formation, Men River valley.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, ridge-like

Fill: Active

Burrow wall: Unlined

Ichnogenus: *Planolites* NICHOLSON, 1873

Diagnosis: Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or annulated burrows, circular to elliptical in cross-section of variable dimensions and configurations; infillings essentially structureless, differing in lithology from the host (Pemberton and Frey, 1982).

Ichnospecies: *Planolites annularis* WALCOTT 1890

(Plate 6.1 c)

Diagnosis: Distinctly annulated, subcylindrical burrows.

Description: Horizontal, unbranched, slightly curved, unlined, elliptical in cross-section, transversely annulated, maximum length and diameter of the burrow is 4.81 cm and 0.63 cm, respectively. Burrow is parallel to the bedding and tapers at one end.

Interpretation: The lack of lining differentiates it from *Palaeophycus annulatus*. The specimen shows faint, transverse, irregularly spaced annulations, differentiating it from the other ichnospecies of *Planolites*. The annulation in *P. annularis* is interpreted to represent the peristaltic movement of the organism such that the prominence and spacing of rings are related to ease and efficiency of feeding (Pemberton and Frey, 1982).

Occurrence: It occurs at bed junction as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Ichnospecies: *Planolites beverleyensis* BILLINGS, 1862

(Plate 6.1 d)

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

Description: Burrows are cylindrical, elliptical in cross-section, unlined, unbranched to rarely branched, isolated or crowded and cross each other at some places, straight to gently curved, burrows horizontal to the bedding plane, show much variation in shape and diameter, length of burrow varies from 17 to 18 cm, and width ranges from 0.6 to 1.6 cm.

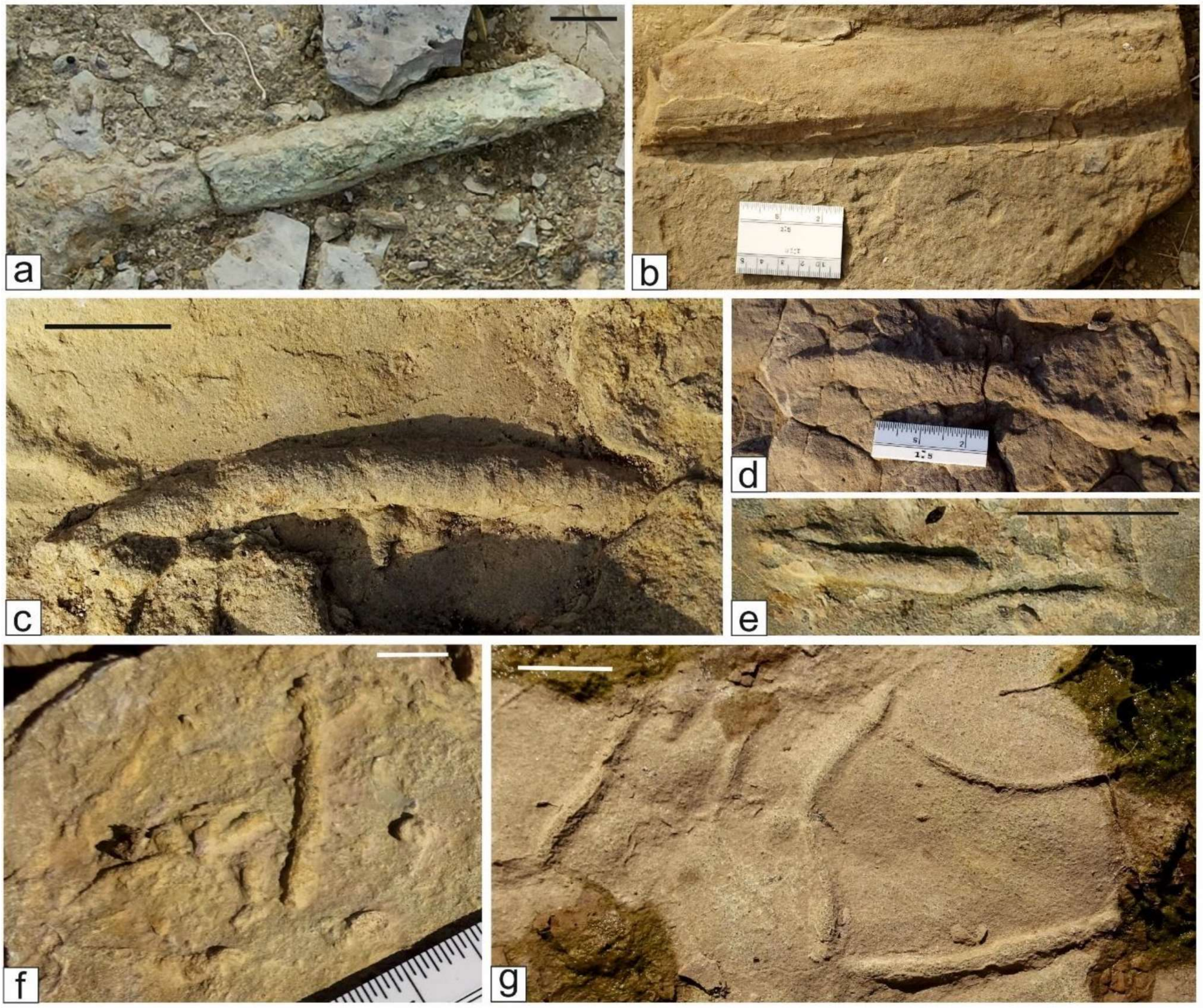


Plate 6.1 Passively filled horizontal burrows and simple actively filled (massive) horizontal to oblique structures. a. *Paleophycus tubularis* horizontal, lined burrow, sandy allochemic limestone facies, Bilthana Formation (Scale bar = 1 cm). b. *Paleophycus tubularis* horizontal, lined burrow, calcareous sandstone facies, Vajepur Formation, Gulvani village. c. *Planolites annularis* horizontal, lined burrow with annulations, sandy allochemic limestone facies, Bilthana Formation, Uchad village (Scale bar = 1 cm). d. *Planolites beverlyensis* in the calcareous sandstone facies, Vajepur Formation, Devaliya village. *Planolites montanus* in e. Calcareous sandstone facies of Vajepur Formation, Uchad section (Scale bar = 1 cm). f. Sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya (Scale bar =1 cm) and g. Sandstone-siltstone-shale facies, Bilthana Formation, Bhekhadiya village (Scale bar = 1 cm).

Interpretation: The absence of burrow lining results in the collapse of the burrow wall, suggests the semi-permanent nature of the burrows (Bromley, 1996). *Planolites* have a long stratigraphic range from Proterozoic to Recent (Häntzchel, 1962), also found in a wide range of facies. *Planolites beverleyens is* differs from *Palaeophycus* and other ichnospecies of *Planolites* by its long, straight, slightly curved, and unlined nature (Pemberton and Frey, 1982). The burrow is interpreted as a trace of an active backfilling mobile deposit feeding worms (Nicholson, 1873; Pemberton and Frey, 1982) or arthropods in a terrestrial environment (Buatois and Mángano, 1993). The present specimens show a smooth burrow surface and lack of any collapse structures favoring the active backfill, whereas *Palaeophycus* has irregular walls and shows collapse structures (Frey and Chowns, 1972). The diameter exceeding 0.5 cm and gently curved nature differentiate it from *Planolites montanus.*

Occurrence: This ichnospecies occurs at bed junction as epichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Ichnospecies: *Planolites montanus* RICHTER, 1937

(Plate 6.1 e-g)

Diagnosis: Relatively small, curved to contorted burrows (Pemberton and Frey, 1982).

Description: Cylindrical, circular to elliptical in cross-section, gently curved, parallel to bedding and preserved as epichnial ridges. The burrow population shows variable dimensions; diameters range from 0.22 to 0.38 cm, and length varies from 1.23 to 3.29 cm.

Interpretation: The small, curved nature of *P. montanus* with diameters less than 0.5 cm differentiates it from the large, gently curved burrows of *P. beverleyensis* characterized by diameters between 0.8-0.1 cm (Pemberton and Frey, 1982). It is made by deposit-feeding worms (Pemberton and Frey, 1982).

Occurrence: It occurred at bed junction and preserved as epichnia in the sandy allochemic limestone facies of Bilthana Formation, Uchad section, calcareous sandstone facies, Vajepur Formation, Bhekhadiya village, and sandstone-siltstone-shale facies, Bilthana Formation, Bhekhadiya village.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, Ridge-Like

Fill: Active/Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Ptychoplasma* FENTON AND FENTON, 1937a

Diagnosis: In hypichnial aspect, nearly smooth, undulating, continuous to discontinuous subhorizontal ridges that display a characteristically amygdaloid, carinate or blocky cross-section, little or no chevron sculpture, and commonly a straight, winding, irregularly meandering, or looping course (Uchman et al., 2011).

Ichnospecies: *Ptychoplasma vagans* KSIĄŻKIEWICZ, 1977

(Plate 6.2 a)

Diagnosis: In hypichnial view, an irregularly meandering or looping, discontinuous ridge containing a series of elongate mounds, carinate in cross-section, amygdaloid in outline, and pointed at both ends. The mounds are at least two and half times and commonly three or more times longer than their width. They are rarely preserved as relevant epichnial depressions (Uchman et al., 2011).

Description: Stright row of hypichnial mounds which does not overlap and are welded to the surface. The ridges are 0.9 cm long and 0.33 cm wide. The mounds are symmetrical, tear-shaped, and tapering at one end. The serial arrangement of the mounds resembles the ichnospecies *Lockeia serialis* proposed by Seilacher and Seilacher (1994) but which is now considered to be *nomen dubium* (Schlirf et al., 2001) due to lack of holotype. *L. serialis* is regarded to be *Ptychoplasma* which is further categorized into different species based on their continuity (Uchman et al., 2011). The present specimen occurs as discontinuous series of mounds. Thus, it differs from *P. excelsum,* a relatively continuous trace, and *P. conica,* a less welded form consisting of conical mounds (Uchman et al., 2011).

Interpretation: The present specimen resembles *Lockeia vagans;* however, Uchman et al. (2011) restricted *Lockeia* as a resting trace of the bivalve, isolated in nature. *Tuberculichnus vagans,* which is a locomotion trace similar to the present specimen, is considered to be *Ptychoplasma vagans* (Uchman et al., 2011). *Ptychoplasma* is common in shallow marine sandstones and is interpreted to be produced by wedge-foot bivalves (Uchman et al., 2011). The ichnospecies is also reported from the Jurassic rocks of the Jaisalmer basin by Paranjape et al. (2013).

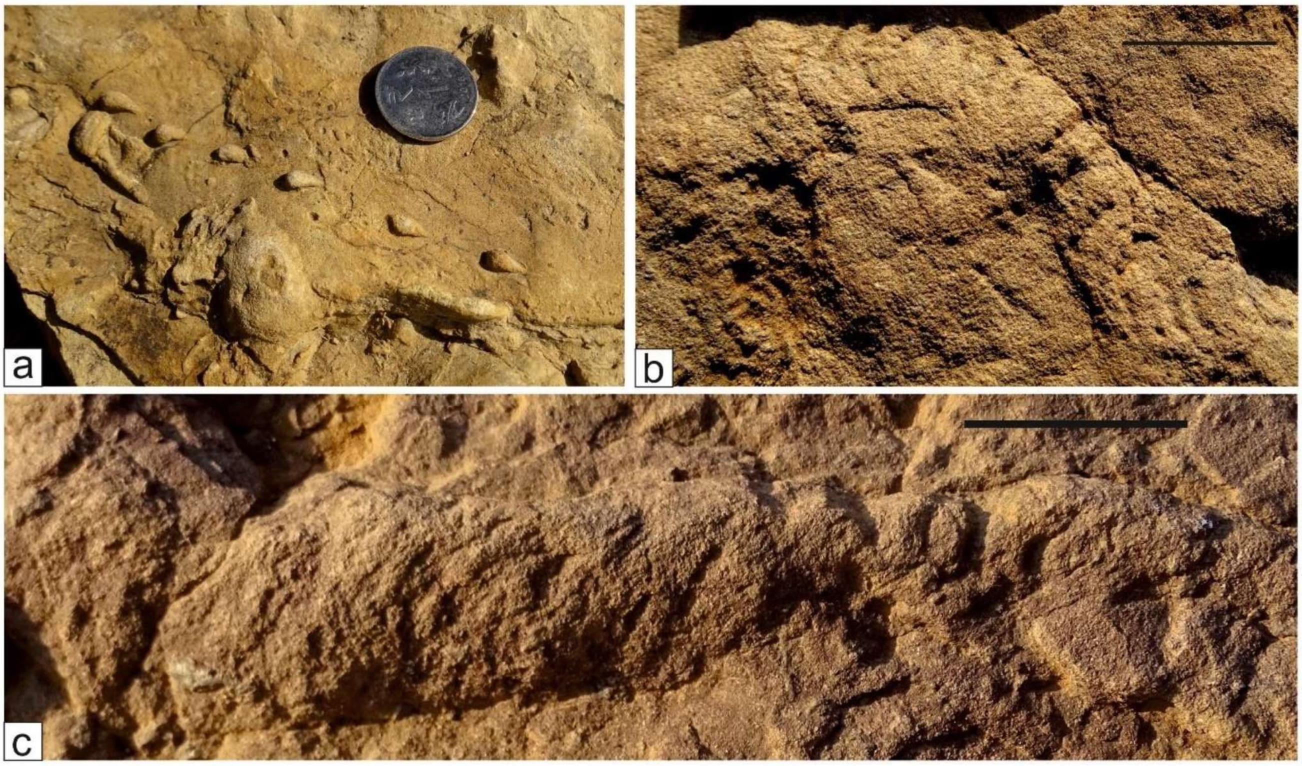


Plate 6.2 Cylindrical ridge-like active and/ or passively filled burrows. a. *Ptychoplasma vagans* hypichnion, stout, almond-shaped structures in sandstone-siltstone-shale facies, Vajepur Formation, Mogra village (coin diameter = 2.193 cm). b. *Taenidium serpentinum* serpentiform burrow with arcuate menisci in calcareous sandstone facies, Vajepur Formation, Devaliya village (Scale bar = 2 cm). c. *Taenidium barretti* unlined, unbranched, segmented cylindrical burrow in calcareous sandstone facies, Vajepur Formation, Devaliya village (Scale bar = 2 cm).

Occurrence: It occurs as hypichnia in the sandstone-siltstone-shale facies of Vajepur Formation, Mogra village.

Orientation: Subhorizontal

Branching: Unbranched

Shape: Cylindrical, ridge-like

Fill: Active

Burrow wall: Unlined

Ichnogenus: *Taenidium* HEER 1877

Diagnosis: Variably oriented, unlined or very thinly lined, unbranched, straight or sinuous cylindrical burrows consisting of segmented fill articulated by meniscus-shaped partings (D'Alessandro and Bromley, 1987) lack true branching, but secondary branching may occur (Keighley and Pickerill, 1994).

Ichnospecies: *Taenidium barretti* BRADSHAW, 1981

(Plate 6.2c)

Diagnosis: Straight to variably meandering, unbranched, unwalled, meniscate backfilled burrow. Menisci are commonly hemispherical or deeply arcuate, tightly packed or stacked, lacking compartmentalized backfill (Keighley and Pickerill, 1994).

Description: Horizontal, straight to curved, unbranched, unwalled, cylindrical meniscate burrow with irrregular boundary and preserved as endichnia. Menisci are diffuse, deeply arcuate, forming non-compartmentalized heterogeneous backfill. The width of the burrow range from 0.85 to 2.0 cm, and the length is about 9.2 cm. The burrow fill is homogeneous and similar to the host rock lacking fine-grained sediments and are less long and sinuous.

Interpretation: *Taenidium* differs from *Scoyenia* by lack of wall striations. D'Alessandro and Bromley (1987) originally recognized three ichnospecies, *T. serpentinum, T. cameronensis,* and *T. satanassi*. Forms initially considered to *Beaconites barretti* were later assigned to *Taenidiumbarretti* due to their unlined and unwalled nature (Keighley and Pickerill,1994). *Taenidium barretti* differs from other ichnospecies because of its uncompartmentalized nature and lack of distinct lining. The lack of well-spaced menisci, longer intermeniscate segments, and alternating meniscate of two sediment types distinguishes it from *T. serpentinum, T. cameronensis* and *T. satanassi* respectively. The meniscate fill is interpreted to be produced by ingestion and excretion of worm-like deposit-feeding organisms and compacting the sediment behind the body (Fürsich, 1974; see Díez-Canseco et al., 2016 and references therein) or by transport around the body during movement of the organism (Heinberg, 1974; Bromley and Asgaard, 1975) and with few ingestion evidence (Bradshaw, 1981) or by a combination of physical and ingestion process (Bromley and Asgaard, 1975; Pemberton and Frey, 1984). However, the fill resembling the host rock is non-ingested (D'Alessandro and Bromley, 1987), as observed in the present case. Keileigh and Pickerill (1994) suggested an external backfill process for the thinly and densely packed sediments. The trace maker of *Taenidium* is variable interpreted till date viz. burrows of less than 3 cm are assigned to variable trace makers, whereas burrows more than 3 cm wide are interpreted to be made by arthropods (Rolfe, 1980; Bradshaw, 1981; Pearson and Gooday, 2019)

Occurrence: It occurs as endichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Ichnospecies: *Taenidium serpentinum* HEER 1877

(Plate 6.2b)

Diagnosis: Serpentiform *Taenidium* having sharp boundary and well-spaced, arcuate menisci; distance between the menisci is equal to or less than the burrow width. External moulds may show slight annulations related to the menisci or wrinkling. Secondary branching and intersections occur (D'Alessandro and Bromley, 1987).

Description: Curved, unbranched burrows parallel to the bedding, preserved in positive epichnia with fill similar to the host rock. Menisci are arcuate, regular in shape and spacing; distances between the menisci are much less than the burrow's width. The burrow is 7.0 cm long, and its width is almost constant, about 1.07 cm to 1.1 cm.

Interpretation: The present specimen differs from other species of *Taenidium* in having a homogeneous fill and well-spaced, moderately curved menisci. The determination of trace maker of *Taenidium* has remained problematic; however, it is related with the insects/larvae in the terrestrial environment, worm-like organisms (Fürsich, 1974; see Díez-Canseco et al., 2016 and references therein) and arthropods (Rolfe, 1980; Bradshaw, 1981; Pearson and Gooday, 2019).

Occurrence: It occurs as hypichnia in the calcareous sandstone facies of Vajepur Formation, Devaliya village.

Orientation: Subvertical

Branching: Unbranched

Shape: Cylindrical

Fill: Passive

Burrow wall: Lined

Ichnogenus: *Skolithos* HALDEMAN, 1840

Diagnosis: Unbranched, vertical or steeply inclined, cylindrical or subcylindrical, lined or unlined burrows, with or without funnel shaped top. Wall distinct or indistinct, smooth to rough, possibly annulated; fill massive; burrow diameter may vary slightly along its length (Schlirf, 2000).

Ichnospecies: *Skolithos linearis*, HALDEMAN, 1840

(Plate 6.3 a-b)

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: Vertical, unbranched, cylindrical, isolated burrow, circular in cross-section; tubes straight to slightly inclined, unbranched, and unlined; oriented perpendicular to the bedding plane with a structureless fill identical to the host sediments. Burrow tubes lack funnel shape aperture, and tubes protrude on the surface (Plate 6.3b). The burrow wall is distinct and lacks ornamentation (Plate 6.3a). The Men River Valley specimen has a burrow length of 5.0 cm and a diameter of 1.24 cm. In contrast, the Navagam specimens are crowded on the surface (Plate 6.3b) and have a burrow tube diameter of 1.3 cm.

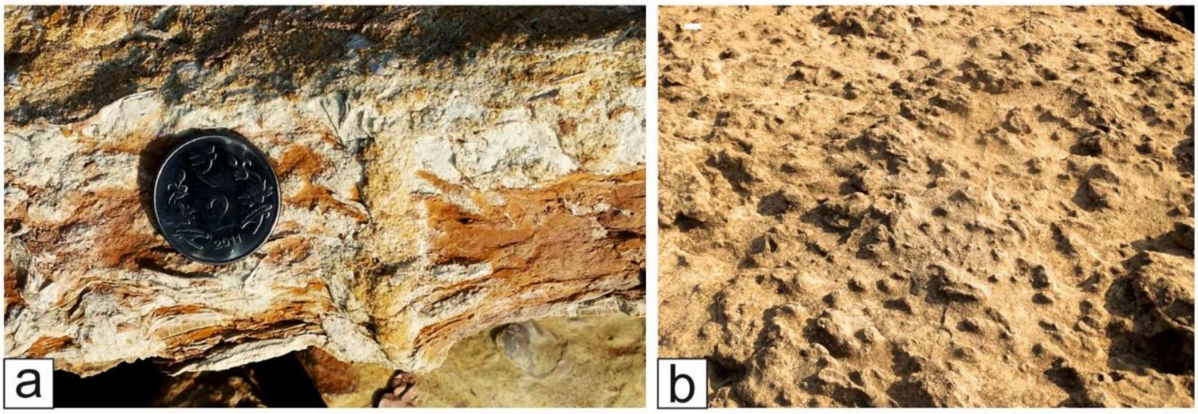


Plate 6.3 Vertical burrows of *Skolithos linearis.* a. Cylindrical, straight, unbranched burrows in fossiliferous limestone facies, Bilthana Formation, Bhekhadiya village(coin diameter = 2.7 cm)b. Top view of thickly-lined burrows in calcareous sandstone facies, Narmada Sandstone Member, Uchad Formation, Navagam village (Scale bar = 2 cm).

Interpretation: Ichnogenus *Skolithos* is characterized by a simple, cylindrical, circular aperture at the top of the bedding surface compared with funnel-shaped *Monocraterion*. Pemberton and Frey

(1984) suggested that *Skolithos* represent the dwelling burrows of suspension-feeding polychaete or phoroid in a marine environment (Alpert, 1974, Fürsich, 1974) or by insects and spiders in continental settings (Schlirf and Uchman, 2005 and references therein). *Skolithos* is typical of shallow marine high-energy settings and has a broad geographical and geological occurrence (Fillion and Pickerill, 1990).

Occurrence: It is preserved as full-relief in the wackestone of Bilthana Formation in Sultanpura and Bilthana village and the calcareous sandstone facies, Narmada Sandstone Member, Navagam village.

Orientation: Subvertical
Branching: Unbranched
Shape: Plug-shaped
Fill: Passive
Burrow wall: Unlined
Ichnogenus: *Bergaueria* PRANTL, 1945

Diagnosis: Cylindrical to hemispherical, vertical burrows with rounded base, lack ornamentation, circular to elliptical in cross-section, structureless fill, with or without central depression and radial ridges (Prantl, 1945).

Ichnospecies: *Bergaueria hemispherica* CRIMES, LEGG, MARCOS AND ARBOLEYA, 1977
(Plate 6.4 a-i)

Diagnosis: Bergauerians lack a shallow central depression (Crimes et al., 1977).

Description: Usually unornamented, vertical to inclined (35º–90º), cylindrical burrow with rounded base, preserved as hypichnia on the sole of sandy allochemic limestone facies (Plate 6.4b-i). The burrow fill is essentially structureless, and some specimens display faint, thin, equally spaced ring-like structures (Plate 6.4 c-d). The dimensions of 44 specimens have been measured (Table 6.2). The diameter (D) of the burrow ranges from 1.5 to 2.9 cm, and its height (H) varies from 0.5 to 4.0 cm. The measured specimen displayed variable D/H ratios; 29 specimens show D/H = 0.7–1.5, 11 specimens have D/H = 1.5–2 and, for 3 specimens, D/H exceeds 2.0 (Table 6.2).

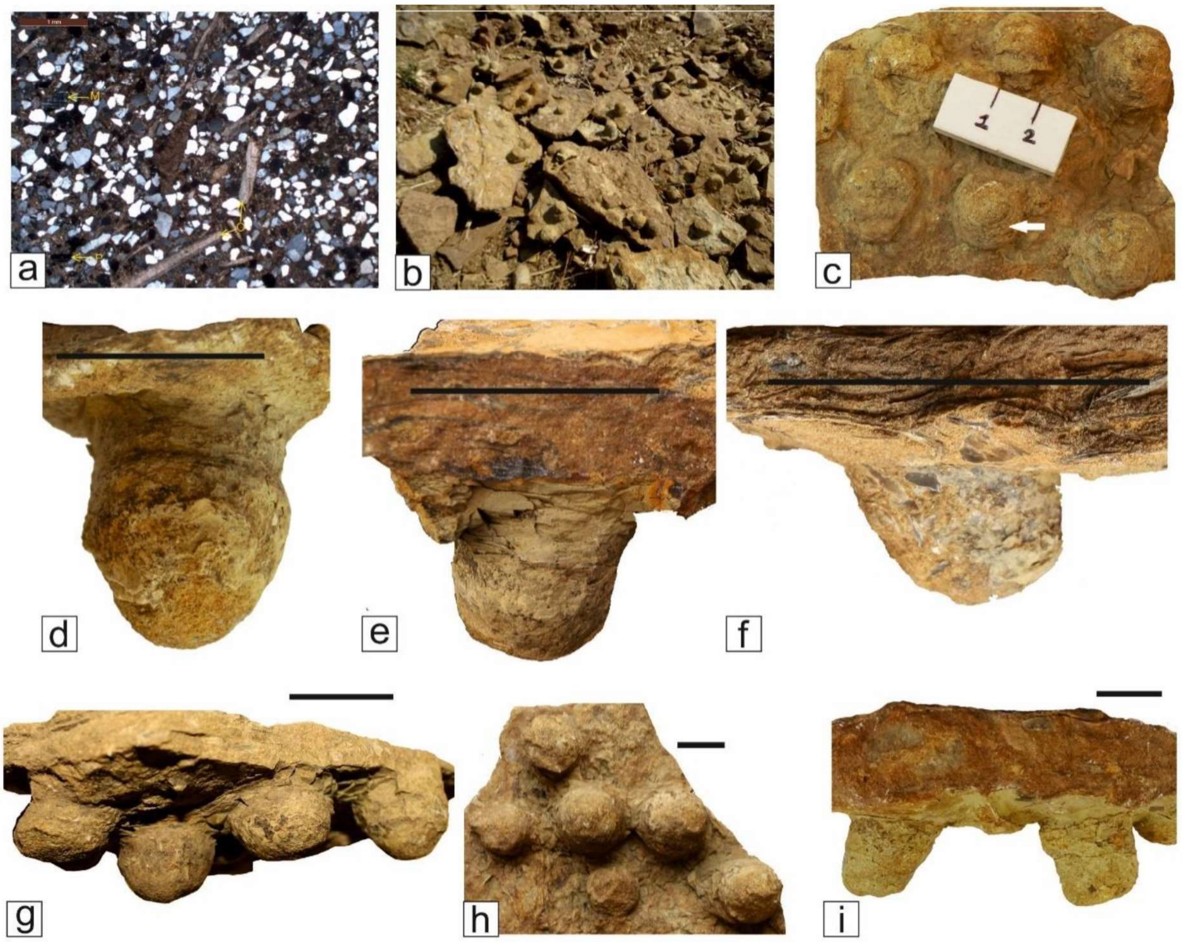


Plate 6.4 Photographs of burrow fill material and *Bergaueria hemispherica*. a. Photomicrograph of the burrow in 2.5× showing allochemic sandstone composition with microcline (M), plagioclase feldspar (F), and oyster shell fragments (O). b. Field photograph of inverted blocks of sandy allochemic limestone facies showing densely packed *B. hemispherica* burrows c. Close-up view of *B. hemispherica*. Note the overall size variation and the circular impressions (arrow) of circumferential muscles on the lower part of the burrow. Morphological variation of *B. hemispherica* showing d. Vertical burrow with subconical base and e. Slightly inclined burrow with rounded base showing contracted and relaxed state of muscles respectively. f. Inclined burrow showing infill of oyster shell fragments. g. Normal and h. Inverted view of vertical to sub-vertical burrows of different sizes, indicating different age groups of sea anemones; i. Normal view showing inclined burrows. Scale bar represents1.5 cm.

Interpretation: Based on morphological features such as thin wall lining and lack of ornamentation, the present specimens are identified as *B. hemispherica* (Crimes et al., 1977). The burrow occurs as hypichnia on the sole of oyster bearing sandy allochemic limestone facies within shale and is filled with allochemic sandstone and small bivalves shell fragments (Plate 6.4 a, f). The general shape is

Specimen No.	Diameter (D) cm	Height (H) cm	(D/H) Ratio
GEPBE01	2.32	2.3	1.01
GEPBE02	2.16	2	1.08
GEPBE03	1.68	0.9	1.87
GEPBE04	2.92	2.0	1.46
GEPBE05	2.35	2.4	0.98
GEPBE06	2.38	1.6	1.49
GEPBE07	1.78	0.9	1.98
GEPBE08	2.35	2.7	0.87
GEPBE09	1.9	1.7	1.10
GEPBE10	1.97	1.0	1.97
GEPBE11	2.32	2.1	1.10
GEPBE12	2.13	1.8	1.18
GEPBE13	1.93	1.3	1.48
GEPBE14	2.3	2.1	1.09
GEPBE15	2.1	1.1	1.90
GEPBE16	2.13	2.5	0.85
GEPBE17	2.03	1.0	2.03
GEPBE18	1.74	1.3	1.34
GEPBE19	2.25	1.4	1.61
GEPBE20	1.9	1.2	1.58
GEPBE21	2.57	1.3	1.98
GEPBE22	1.93	1.5	1.29
GEPBE23	2.13	2.7	0.79
GEPBE24	2.25	2.3	0.98
GEPBE25	1.87	1.0	1.87
GEPBE26	2.3	2.1	1.09
GEPBE27	1.78	1.5	1.19
GEPBE28	2.22	1.8	1.23
GEPBE29	1.84	1.0	1.84
GEPBE30	1.81	1.8	1.01
GEPBE31	2.06	2.0	1.03
GEPBE32	2.4	4.0	0.60
GEPBE33	2.54	3.2	0.79
GEPBE34	1.93	2.0	0.97
GEPBE35	1.81	2.3	0.79
GEPBE36	2.16	3.0	0.72
GEPBE37	1.9	2.5	0.76
GEPBE38	2.13	2.8	0.76
GEPBE39	1.49	0.5	2.98
GEPBE40	1.97	2.1	0.94
GEPBE41	1.62	1.0	1.62
GEPBE42	2.22	1.0	2.22
GEPBE43	2.16	1.7	1.27
GEPBE44	2.1	1.1	1.90

Table 6.2 Morphometry of the 44 specimens of *B. hemispherica*. Note: Height is highly variable as compared to diameter.

cylindrical to hemispherical, which resembles the ichnospecies *B. hemispherica* (Crimes et al., 1977). The holotype specimen described by Alpert (1973) shows a diameter of 5.5 and a depth of 1.4 cm, while the three specimens of *B. hemispherica* described by Hofmann et al. (1994) from the Cambrian of Arctic Canada are 2.5–5.0 cm wide and 1.0–2.7 cm long. The Late Cretaceous Bagh Group specimens show considerable variation in height, which causes variation in D/H compared to the type specimen. Pemberton et al. (1988) have noticed an overlap in diameter and height of plug-shaped burrows, but they evidenced consistency in the diameter/height (D/H) ratio; the considered *Bergaueria* has a diameter about twice the height. The numerical data (Table 6.2) of the 44 measured specimens of *B. hemispherica* reveals three specimens having diameters twice the height. In contrast, most specimens have diameters either less than or equal to the height. The specimens show significant variations in D/H but offer a high degree of similarity in morphological features, which have priority to consider as *B. hemispherica* (Crimes et al., 1977). The ichnogenus was also reported from the upper part of the Nimar Formation in ELNV by Singh (1982).

Occurrence: *B. hemispherica* is observed in the sandy allochemic limestone facies (oyster limestone) of the Bilthana Formation, Karvi village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Conichnus* MYANNIL, 1966

Diagnosis: Conical, amphora-like, or acuminated subcylindrical structures oriented perpendicular to bedding plane; base may be rounded or exhibit a distinct, papilla-like protuberance. Fillings may reveal patterned internal structures such as chevron laminae but not radial medusoid symmetry.

Ichnospecies: *Conichnus conicus* MYANNIL, 1966

(Plate 6.5 a-c)

Diagnosis: Indistinctly to thinly lined conichians tapering to a smooth, rounded, but distinctly basal apex.

Description: Short conical, filled burrows with unornamented vertical shaft, circular in a transverse section, gently tapering and terminating in a smooth, rounded base. The height of the specimen is 42 mm, and the diameter of 27 mm; the diameter/height ratio is 0.64. (Plate 6.5 a and b); and 55mm height and diameter of 45 mm with diameter/height ratio is 0.81 (Plate 6.5 c). Burrow fill is carbonate mud (Plate 6.5 a-b) and siltstone (Plate 6.5 c). The lining is very thin but marks a distinct boundary between the cone fillings and the adjacent rock. Basal part smooth and rounded, without apical protuberance.

Interpretation: Specimens of *Conichnus* have been interpreted as the dwelling burrow of an anemone-like organism (Frey and Howard, 1981). The nested internal laminae in *Conichnus* burrows suggest that the trace maker kept pace with sedimentation by periodically moving upward in an aggrading substrate (Curran and Frey, 1977). The burrow in sandstone-siltstone-shale facies and sandy allochemic limestone facies is different from the overlying nonclastic sediments suggesting passive filling in low-energy shallow marine environments (Patel et al., 2018).

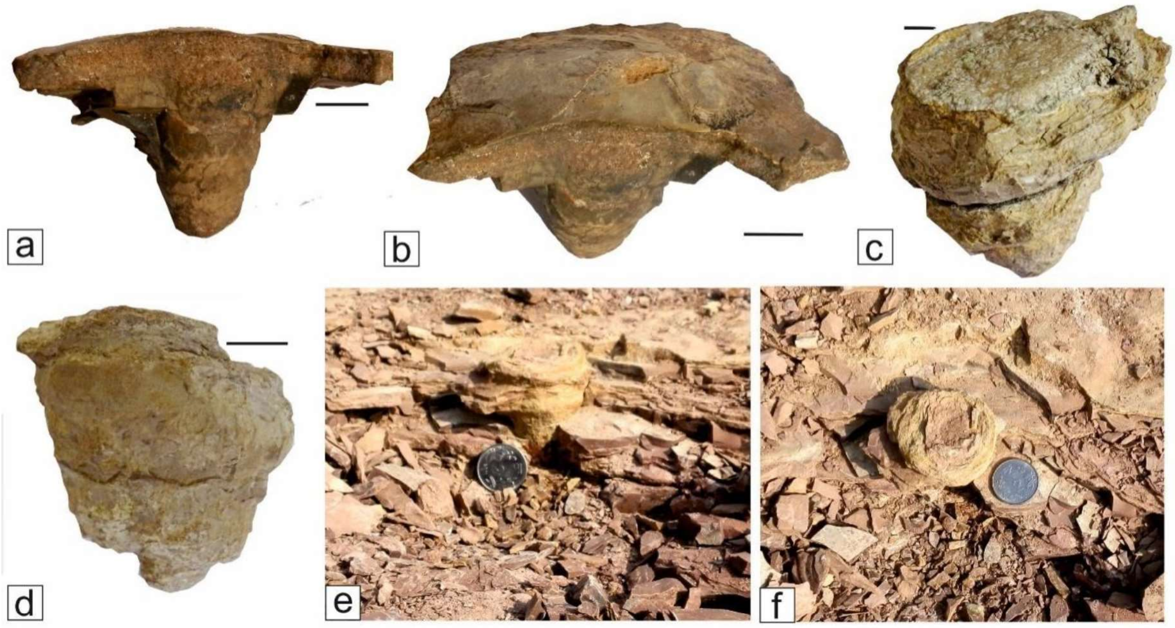


Plate 6.5 Photographs of plug-shaped burrows *Conichnus* and *Conostichus*. a. and b. Vertical view of *Conichnus conicus* displaying conical shape and passive filled burrow materials undiscerning the opening; c. Vertical view of *C. conicus* in rippled sandstone-siltstone-shale facies. d. Vertical view of *Conostichus broadheadi* with a prominent narrow apical protuberance in rippled sandstone-siltstone-shale facies. e. and f. Field photograph of *Conostichus stouti* in sandy allochemic limestone-shale facies. Scale bar represents 1 cm, and the coin’s diameter is 2.7 cm.

Occurrence: It is preserved as hypichnia with burrow fill different from host sediments. It occurs in sandstone-siltstone-shale facies of Vajepur Formation, Bhekhadiya village, and sandy allochemic limestone facies of Bilthana Formation, Uchad village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Unlined

Ichnogenus: *Conostichus* LESQUEREUX, 1876

Diagnosis: Conical to sub-conical, vertical burrows, most of which display a duodecimal symmetry on the apex sides. Most walls are fluted by transverse constrictions and longitudinal ridges, and furrows. Well-developed apical disc and central sub-cylindrical core may not be present. Burrow fills may be structureless or composed of concentric conical or subconical laminae.

Ichnospecies: *Conostichus broadheadi* LESQUEREUX, 1880

(Plate 6.5 d)

Diagnosis: Strongly conical conostichians having well-developed longitudinal fluting; the apical disc is narrow and short and does not display prominent septation.

Description: Burrow appears as a short cone and possesses weakly developed longitudinal furrows and apical disc. It consists of a distinct knob-like structure at the apex. The diameter of the burrow is 38 mm, and the length is 40 mm. Diameter/height ratio is 0.95. The apical disc is small and narrow and does not display any septation. Burrow fill sediments are different from the host sediments. According to Pemberton et al. (1988), *Conostichus broadheadi* is the most distinctive ichnospecies of *Conostichus* and is strongly conical in shape. *Conostichus broadheadi* of the Late Cretaceous of Bagh Group comprises of small apical disc distinguishing it from the other plug-shaped ichnospecies like *Conostichus typicus,* which is characterized by extremely broad and flat apical disc (Harrington, and Moore, 1955).

Interpretation: *Conostichus broadheadi* occur in the rippled sandstone-siltstone-shale facies and is characterized by an inclined burrow opening with a small apical disc that lies below the inclined surface rather than the center. The weakly developed apical disc of *C. broadheadi* indicates that the animal dug the soft clastic fine-grained sediments at a shallow depth to stabilize using its smaller appendages. Later on, it periodically pushed the appendages by swirling action till the animal fully stabilized itself (Pfefferkorn, 1971). However, the position of the apical disc indicates that the animal holdfast the sediments which prevented uproot against the currents. The trace maker was a suspension feeder which burrowed in fine-grained clastic sediments and vacated it during the deposition of mixed carbonate-siliciclastic sediments in a shallow marine environment.

Occurrence: It occurs as hypichnia in sandstone-siltstone-shale facies of Vajepur Formation, Bhekhadiya village.

Ichnospecies: *Conostichus stouti* BRANSON, 1961

(Plate 6.6 a-b)

Diagnosis: Conical to sub-conical conostichians having well-developed transverse constrictions and short longitudinal furrows near the apex; the small apical disc is planar to slightly hemispherical and displays very weak septation.

Description: Conical-shaped structure having circular to slightly oblong cross-section at the burrow entrance while later part subconical. The structures reflect the anteroventral features of the trace producer and clearly show the different parts of the organism like capitulum, scapus, and physa. The burrow fills show thick concentric laminae (Plate 6.5 e-f, 6.6a-b, d, f) at the entrance (capitulum part) but the latter part shows faintly developed longitudinal striations (Plate 6.6 c and e) exteriorly throughout the structures (scapus and physa parts). Prominent transverse constrictions are lacking in the conical part. Two specimens of *C. stouti* are recovered from the Bhekhadiya village. The height of specimen 1 (Plate 6.5 e-f, 6.6 a-c) is 92 mm, and it shows concentric structures from the top to up to 25 mm; diameter varies from 52 to 60 mm (diameter/height ratio- 0.65), and decreases downward from 40 mm to 26 mm and again increases at the bulbous structure (physa part); apical bulbous structure attached with the core of the apex with a flat inclined surface-displayed variable diameter ranging from 28 mm to 15 mm. Specimen 2 (Plate 6.6 d-f) shows variable dimension (height-60 mm, diameter-25 mm, diameter/height ratio-0.41) with faintly developed striations on apical side. The infill material of the burrows is lime mud or siltstone, which is different than the host i.e., fine clastic sediments.

Plate 6.6 Photographs of plug-shaped burrow *Conostichus.* a. Vertical view of *Conostichus stouti* displaying concentric laminae at the top. b. The top view of *C. stouti* shows concentric filling with the argillaceous sediments. c. Close-up view of *C. stouti* displaying longitudinal striations and bulbous apex. d. Field photograph of *C. stouti* in sandstone-siltstone-shale facies. e. Vertical view of *C. stouti* displaying faintly developed longitudinal striae at the lower end of the burrow. f. Top view of *C. stouti.* Scale bar = 1 cm.

Interpretation: Pemberton et al. (1988) examined numerous specimens of *Conostichus,* indicating its overall geometry, and recognized five ichnospecies. The Bagh specimen shows the diameter generally one-half to three-quarters the height, which differentiates it from the ichnospecies *C. ornatus* and *C. broadheadi* having a diameter equal to the height and double the height, respectively. Accordingly, the presence of a subconical burrow form also differentiates it from the strongly conical burrow form *C. broadheadi* and subcylindrical burrow form *C. wycherlyi*; and the small narrow apical disc having weak septation differentiates it from *C. ornatus* and *C. typicus*. The sea anemones might have required a muddy substrate favoring its consistency, found in alternating lithologies i.e., intercalated sandstone-siltstone-shale/sandy allochemic limestone facies. The column of *Conostichus* specimens constitutes a subcylindrical core, and the physa is represented by the bulbous base, which accounts for several behavioral aspects of the burrowing anemones. The animal body parts, capitulum, scapus, and physa are reflected in the burrow structure.

Occurrence: It is preserved as hypichnia in the sandstone-siltstone-shale facies of Vajepur Formation and the sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya village.

Orientation: Subvertical

Branching: Unbranched

Shape: Plug-shaped

Fill: Passive

Burrow wall: Unlined

Ichnogenus: *Lockeia* JAMES, 1879

Diagnosis: Bilaterally symmetrical traces; lower end with sharp median ridge; outline of hypichnion almond- or heart-shaped, tall vertical spreite may be present (Schlirf, 2000).

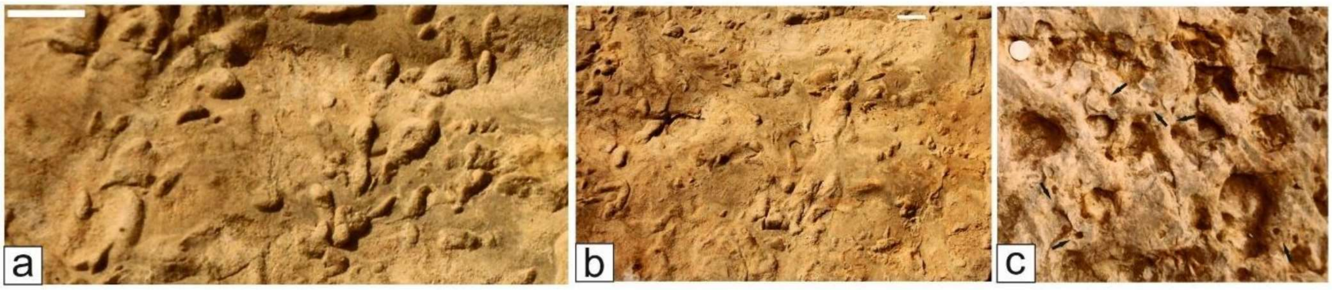


Plate 6.7 Subvertical unbranched burrows (coin diameter = 2.7 cm and Scale bar = 2 cm). a. *Lockeia cuncator* and b. *Lockeia siliquaria*, hypichnion, stout, almond-shaped structures in calcareous sandstone facies, Vajepur Formation, Uchad village. c. *Arenicolites* isp. paired openings of the burrow (marked with black arrows), mudstone facies, Nodular Limestone, Uchad village.

Ichnospecies: *Lockeia cunctator* SCHLIRF AND UCHMAN 2001

(Plate 6.7 a)

Diagnosis: Horizontal to oblique club-shaped or dumb-bell to almond-shaped probes more or less arranged in a row. Clubs diverge laterally, bilaterally, or semi-radially from the main axis of the row, all inclined in the same direction with respect to the row.

Description: Epichnial, horizontal to oblique dumb-bell shaped and almond-shaped probes, arranged in a row. The length and width of probes are irregular; length varies from 1.02 to 2.27 cm, and width ranges from 0.35 to 0.89 cm. Clubs diverge laterally from the central axis.

Interpretation: The lack of medial line and distorted shape of appendages separates it from the ichnogenus *Protovirgularia*. It is observed on the same slab on which *L. siliquaria* occurs, suggesting the ethological variability of the trace maker. According to Schlirf et al. (2001), *L. cunctator* indicates both locomotion and probing; the producer paused to probe the sediments and then moved forward. The almond-shaped forms are assigned to *Lockeia,* produced by the wedge-foot of resting bivalves, and the chevron-shaped forms to *Protovirgularia*, produced by the cleft-foot during locomotion (Uchman et al., 2011). Cabrere et al. (2019) marked that transitional irregular bilobate-shaped structures are difficult to be allocated to any anatomical part or behavioral activity of the bivalves. The enlargement of dumbells observed in the present specimen is interpreted to be due to the expansion of the foot during anchoring (Schlirf et al., 2001). It is also reported from the Jurassic rocks of the Jaisalmer Basin by Paranjape et al. (2013).

Occurrence: It occurs as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Ichnospecies: *Lockeia siliquaria* JAMES 1879

(Plate 6.7 b)

Diagnosis: Thin elongated to stout, bilaterally symmetrical, generally high relief almond-shaped to seed-like shaped, smooth hypichnial ridges, with strongly arcuate to almost obtuse terminations; occasionally showing vertical spreite(Schlirf et al., 2001).

Description: Small, stout, elongate mounds with smooth surface, tapered tip at both the ends, the outline of some mounds is not very distinct, semi-rounded nature at one of its ends; mounds are crowded, at few places they are slightly overlapping. The length varies from 0.81 to 2.67 cm; width ranges from 0.5 to 1.27 cm, and height is 0.38 cm.

Interpretation: *Lockeia* is the resting traces of the small burrowing pelecypods, possibly semi sessile forms (Osgood, 1970; Häntzschel, 1975). Stout shapes of mounds earlier regarded as *Lockeia amygdaloides* (Seilacher, 1953) are also observed on slabs on which narrower forms occur (Plate

6.7b). However, *L. amygdaloides* was considered a junior synonym of *L. siliquaria* (Seilacher and Selacher, 1994; Schlirf et al., 2001) based on the occurrence of all morphological shapes on the same slab. The almond to elongate shape structure of *Lockeia* differentiates it from the chevroned *Protovirgularia.* Isolated *Lockeia* structures are interpreted to be cubichnion produced by wedge-foot bivalves (Seilacher and Seilacher, 1994). The expansion of the bivalve foot in the protraction phase is observed to produce almond to oval-shaped structures peculiar to the ichnogenus *Lockiea* (Seilacher and Seilacher, 1994; Cabrera et al., 2019). According to Ekdale and Bromley (2001), *L. siliquaria* indicates the size and shape of the organism‘s shell, whereas *Protovirgularia* indicates the size and shape of the animal‘s foot. *Lockeia* is reported from fluvial to deep marine deposits (Kim, 1994). The ichnospecies *L. siliquaria* is also reported from the Jurassic rocks of the Kachchh and Jaisalmer basins (Joseph et al., 2012; Paranjape et al., 2013).

Occurrence: It occurs as epichnia in the calcareous sandstone facies of Vajepur Formation, Uchad village.

Orientation: Subvertical

Branching: Unbranched

Shape: U- and bow-shaped

Fill: Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Arenicolites* SALTER, 1857

Diagnosis: Vertical U-shaped tubes without spreite (Fürsich, 1974) and two apertures above (Rindsberg and Kopaska-Merkel, 2003).

Ichnospecies:*?Arnecolites* isp.

(Plate 6.7 c)

Description: Endichnial, vertical to slightly inclined paired burrows of U-shaped with circular cross-section and paired opening, perpendicular to bedding, burrow fill is identical to the host sediment. Burrow diameter is about 1.21 cm, and burrow arms are approximately 0.96 cm apart.

Interpretation: Based on paired circular opening on the surface, it has been provisionally assigned to the ichnogenus *Arenicolites*; however, paired vertical U-shaped tubes could not be located to establish the diagnostic U-shaped form of the burrow. It differs from *Diplocraterion* in absence of spreiten (Fürsich, 1974). It is interpreted as dwelling structures of suspension-feeding organisms like polychaete worms, amphipod crustaceans, and insects (Häntzschel, 1975; Chamberlain, 1977; Fillion and Pickerill, 1990; Rindsberg and Kopaska-Merkel, 2005). *Arenicolites* is considered to be an opportunistic suspension feeder (Bromley, 1990) typical of a shallow marine environment (Crimes, 1977). *Arenicolites* is considered to be a facies-crossing form reported from marine and fresh-water environments and occur as suspension-feeding or surface deposit-feeding form active during increased and reduced sedimentation rate, respectively (Crimes, 1977; Bromley and Asgaard, 1979; Uchman, 1995).

Occurrence: This ichnospecies occurs as negative epichnia in the mudstone facies of Nodular Limestone, Uchad village.

Orientation: Complex

Branching: Branched

Shape: Boxwork

Fill: Passive

Burrow wall: Lined/Unlined

Ichnogenus: *Thalassinoides* EHRENBERG, 1994

Diagnosis: Three-dimensional burrow systems consist predominantly of smooth-walled, essentially cylindrical components of variable diameter; branches Y- to T-shaped enlarged at bifurcation points (Howard and Frey, 1984).

Ichnospecies: *Thalassinoides horizontalis* MYROW, 1995

(Plate 6.8 a-b)

Diagnosis: Branching framework of smooth-walled, unlined burrows. It has an entirely bedding-parallel orientation, absence of vertically oriented offshoots from polygonal frameworks, and the diameter of both inner and outer burrow walls is consistent within specimens, including a notable lack of constrictions or swellings at both junctions and inter-junction segments (Myrow, 1995; Blisett and Pickerill, 2004).

Description: Smooth walled, unlined, three-dimensional, Y-shaped junctions with sharp branching, parallel to the bedding, more or less uniform burrow diameter. Burrow consists of thin cylindrical straight arms that bifurcate at an angle of 80^0-130^0, with no swelling at bifurcation points. The structure length is 10-12 cm, and the diameter varies from 0.6-1.0 cm.

Interpretation: The burrows of *Thalassinoides horizontalis* are made by small crustaceans or soft-bodied organisms in firmground sediments, and the burrow diameter is less than 1.0 cm. Burrow oriented parallel to the bedding, consistent diameter and lack of swelling at Y-T junction, vertical or inclined offshoots, and scratches differentiate it from the other ichnospecies (Myrow, 1995).

Occurrence: It occurs as endichnia in the sandy allochemic limestone facies of Bilthana Formation, Gulvani village, and the calcareous sandstone facies of Vajepur Formation, Uchad and Vajepur villages.

Ichnospecies: *Thalassinoides paradoxicus* KENNEDY 1967

(Plate 6.8 c-d)

Diagnosis: Irregularly branched, subcylindrical to cylindrical burrows oriented variably with respect to bedding; T-shaped intersections more common than Y-shaped, and diameter of offshoots may differ from the parent trunk (Howard and Frey, 1984).

Description: Three dimensional branched complex boxwork burrow, irregularly branched, oriented at various angles with respect to the bedding plane. Bifurcation is common within short distances, forming complex boxwork patterns. Dimension of the burrow is highly variable in different burrow populations; it ranges from 2.5 to 3 cm at the point of bifurcation, and diameters of offshoots range from 1.0 cm to 2.7 cm. The small blunt proterburence indicates an abandoned tunnel (Plate 6.8 c).

Interpretation: The specimen differs from the other ichnospecies by its short blind tunnels. The highly variable and irregularly branched system of *T. paradoxicus* distinguishes it from *T. suevicus* (Fürsich, 1974), a horizontal form consisting of enlarged Y-shaped bifurcations, and from *T. ornatus,* which is a large form with tunnels. *T. paradoxicus* is characterized by more T-shaped bifurcations than Y-shaped and less swelling at the junctions than *T. suevicus* (Rodríguez-Tovar et al., 2017). *T. horizontalis* is a strictly horizontally oriented burrow with a uniform diameter. The maze work indicates vigorous exploitation of deposit feeders (Giannetti et al., 2007). The narrowing in the

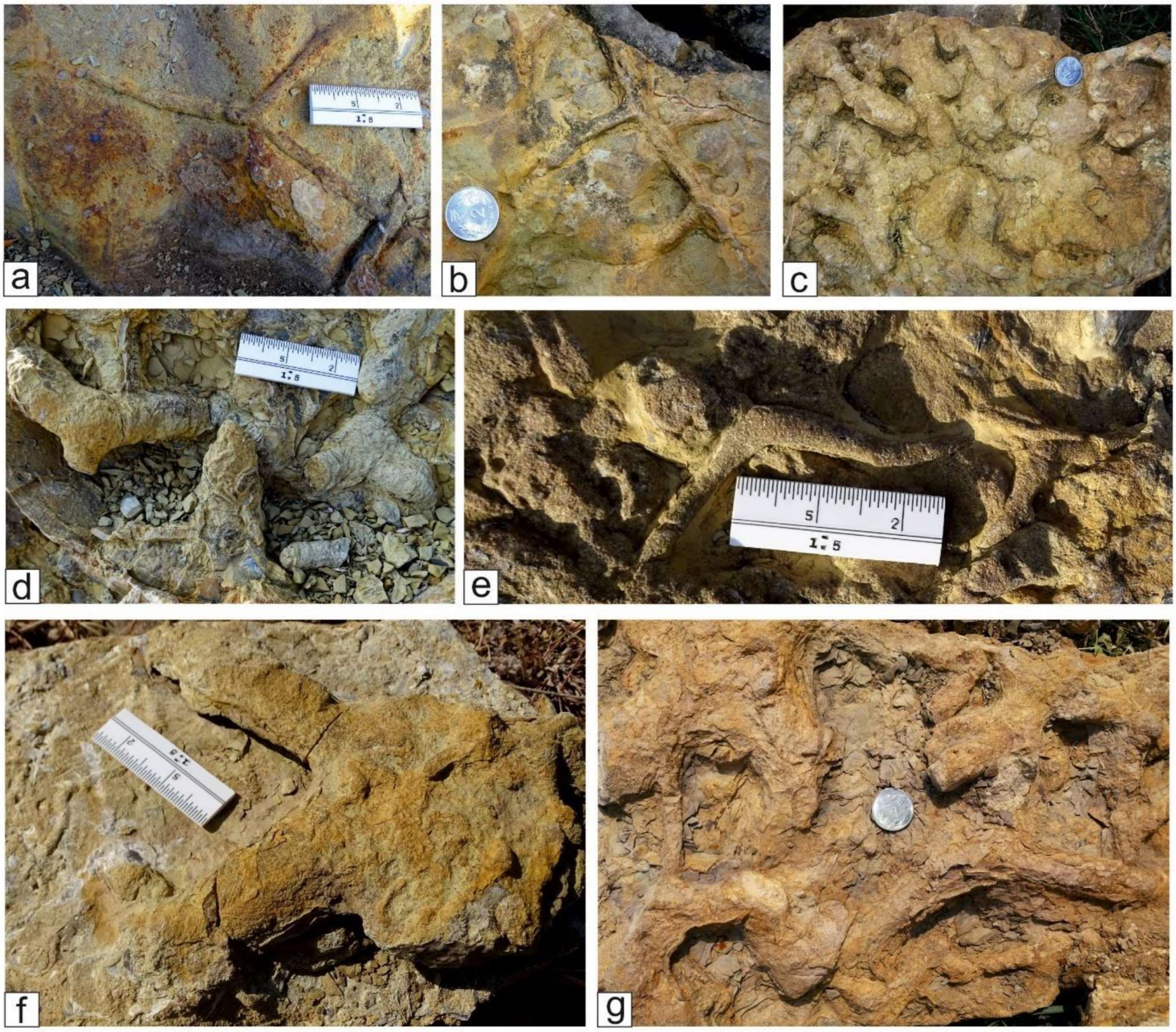


Plate 6.8 Maze and boxwork burrows of *Thalassinoides*. a. *T. horozontalis*, horizontal, straight, Y-shaped burrow, calcareous sandstone facies, Vajepur Formation, Uchad village. b. T-shaped sharp branching, calcareous sandstone facies, Vajepur Formation, Uchad village. c. *T. paradoxicus* displaying complex boxwork, irregular burrows, sandy allochemic limestone facies, Bilthana Formation, Uchad village. d. A close-up of *T. paradoxicus* displaying medium-sized tunnels and branches terminates at a short distance. e. *T. suevicus* displaying horizontal, curved tunnels and irregular branching in sandy allochemic limestone facies, Bilthana Formation, Uchad village. f. *T. suevicus* displaying swelling at bifurcation points in sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya. g. *Thalassinoides* isp. displaying three-dimensional, curved tunnels, sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya. Length of scale = 5 cm and Coin diameter = 2.7 cm.

cross-section of the burrows restricts the efficient water flow. Consequently, the organism depends strongly on the seafloor sediments for nutrition purposes (Giannetti et al., 2007), as observed in *T. paradoxicus* (Plate 6.8d). The presence of vertical and irregular branching in *T. paradoxicus* indicates the burrow required a firm, semi-consolidated substrate to avoid collapse of the burrow (Myrrow, 1995). It is interpreted to be a passively filled, fodinichnion burrow produced by crustaceans (Frey et al., 1984) or other types of arthropods (Ekdale, 1992). It is reported from Nimar sandstone Formation from the Bagh Group of ELNV by Sanganwar and Kundal (1997) and Kundal and Sanganwar (1998).

Occurrence: It occurs as endichnia in fossiliferous limestone facies of Bilthana Formation, Uchad, and Karvi villages and in the Nodular Limestone, Uchad village.

Ichnospecies: *Thalassinoides suevicus* REITH, 1932

(Plate 6.8 e-f)

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: Full relief, horizontal cylindrical burrow system parallel to the bedding, burrow system consists of curved and straight tunnels. Y-shaped branching is more common than T-shaped bifurcations. The photographs of two specimens show varying dimensions; one structure is characterized by a circular knob (Plate 6.8f) whereby burrow arms radiate from approximately six directions, and the diameter is 3.0 cm. The other specimen (Plate 6.8e) is characterized by a gently curved arm with a variable diameter (1.0 to 1.6 cm). Burrow fill is passive, different from the host sediments.

Interpretation: *Thalassinoides suevicus* and *Thalassinoides horizontalis* are regularly branched, horizontal forms. However, the large burrow diameter and enlarged Y-shaped bifurcation separate *T. suevicus* from the *T. horizontalis, T. paradoxicus, T. saxonicus,* and *T. ornatus*. The *Thalassinoides* occur at the middle position in the tier; however, the ichnospecies *Thalassinoides suevicus,* when occurs in sand deposits, indicates a shallow tier (Bromley, 1996) and is abundant in the silicified Chalk deposits of Cretaceous (Bromley and Ekdale, 1984). The absence of vertical components in *Thalassinoides suevicus* suggests the trace maker was a surface deposit feeder which depended mainly on the organism on the seafloor (Giannetti et al., 2007). *Thalassinoide*s is produced by crustaceans, mainly decapods (Frey et al., 1984). The enlargement of burrow walls at junctions and other places is interpreted to be due to the turning around of the shrimps or crustaceans unable to move bi-directionally (Frey et al., 1984; Ehrenberg, 1994).

Occurrence: It occurs in the sandy allochemic limestone facies of Bilthana Formation, Bhekhadiya and, Uchad villages.

Ichnospecies: *Thalassinoides* isp.

(Plate 6.8 g)

Description: Endichnial, full relief, horizontal to slightly oblique Y-shaped burrow system, diameter about 2.0 cm. It consists of short, regularly branched, curved arms. Preservation does not warrant classification at the ichnospecies level.

Interpretation: Due to its curved nature of branching and absence of visible vertical components, this specimen is kept open as *Thalassinoides* isp. According to Frey et al. (1984), *Thalassinoides* is a facies crossing form produced by crustaceans and indicates the shallow marine environment mainly reported from the Paleozoic and Mesozoic; however, occurrence in deep water in Tertiary are also reported (El-Sabbagh et al., 2017 and references therein).

Occurrence: *Thalassinoides* isp. occurs as endichnia in the sandy allochemic limestone facies, Bilthana Formation, Bhekhadiya village, and in fossiliferous limestone of Bilthana Formation, Uchad village.

6.2.2 TRAILS

Orientation: Horizontal

Lateral Elements: Unary

Shape: Straight or Curved

Fill: ---

Burrow wall: ----

Ichnogenus: *Archaeonassa* FENTON AND FENTON, 1937a

Diagnosis: Trails consist of regularly convex furrows bounded by low, narrow, subangular ridges. The furrows are smooth only in those trails, modified by water action. Others are crossed by rounded to subangular wrinkles, which are convex in the anterior direction. Burrows are round, oval, or irregularly elongate, deeper at one end than at the other; they generally terminate indistinct trails. They are distinct from round, abrupt pits and low mounds, which seem to be the work of annelids (Fenton and Fenton, 1937a).

Ichnospecies: *Archaeonassa* cf. *fossulsata* FENTON AND FENTON, 1937a

(Plate 6.9 a)

Diagnosis: Same as for ichnogenus

Description: Medium, horizontal, curved, epichnial trails lacking orientation. It has low relief, flattened, and broad central area but poorly preserved transverse ornamentation. The margins of the burrows are slightly elevated. The length of the trail is around 44.0 cm and is 2.0 - 2.5 cm wide.

Interpretation: The present specimen resembles *Archaeonassa fossulsata* but has poorly preserved faint transverse ridges in the central area and lacks transverse or oblique ornamentation on the ridges. It differs from bilobate *Gyrochorte* in lack of obliquely aligned plaited lobes, and the lack of back-filled nature differentiates it from *Scolicia* group trace fossils viz. *Psammichnites, Palaeobullia*. It shows variation in width and has a broad central region and hence resembles *Archaeonassa* type A species of Schatz et al. (2013) produced by gastropods. The trace maker of *Archaeonassa* is highly debated. Initially, it was interpreted as a grazing trail made by gastropods, echinoderms, or trilobites (Fenton and Fenton, 1937a; Buckman, 1994; Stanley and Feldmann, 1998; Häntzschel, 1975. Yochelson and Fedonkin (1997) proposed arthropods to be trace makers. Later Jensen (2003) suggested a molluscan origin for the trace.

Occurrence: It occurs as negative epichnia in the muddy micrite of Bilthana Formation, Uchad village.

Ichnospecies: *Archaeonassa* isp.

(Plate 6.9 b-d)

Description: It is crowded, long, horizontal, narrow, straight to gently curved epichnial grooves, V-shaped in cross-section, crossovers are common and abrupt termination in many trails. Prominent leeves characterize it on either side of the trail all along the length. It spread on top of the ripple calcareous sandstone where attained maximum length is 300 cm (Plate 6.9b) and width of 0.6-1.54 cm.

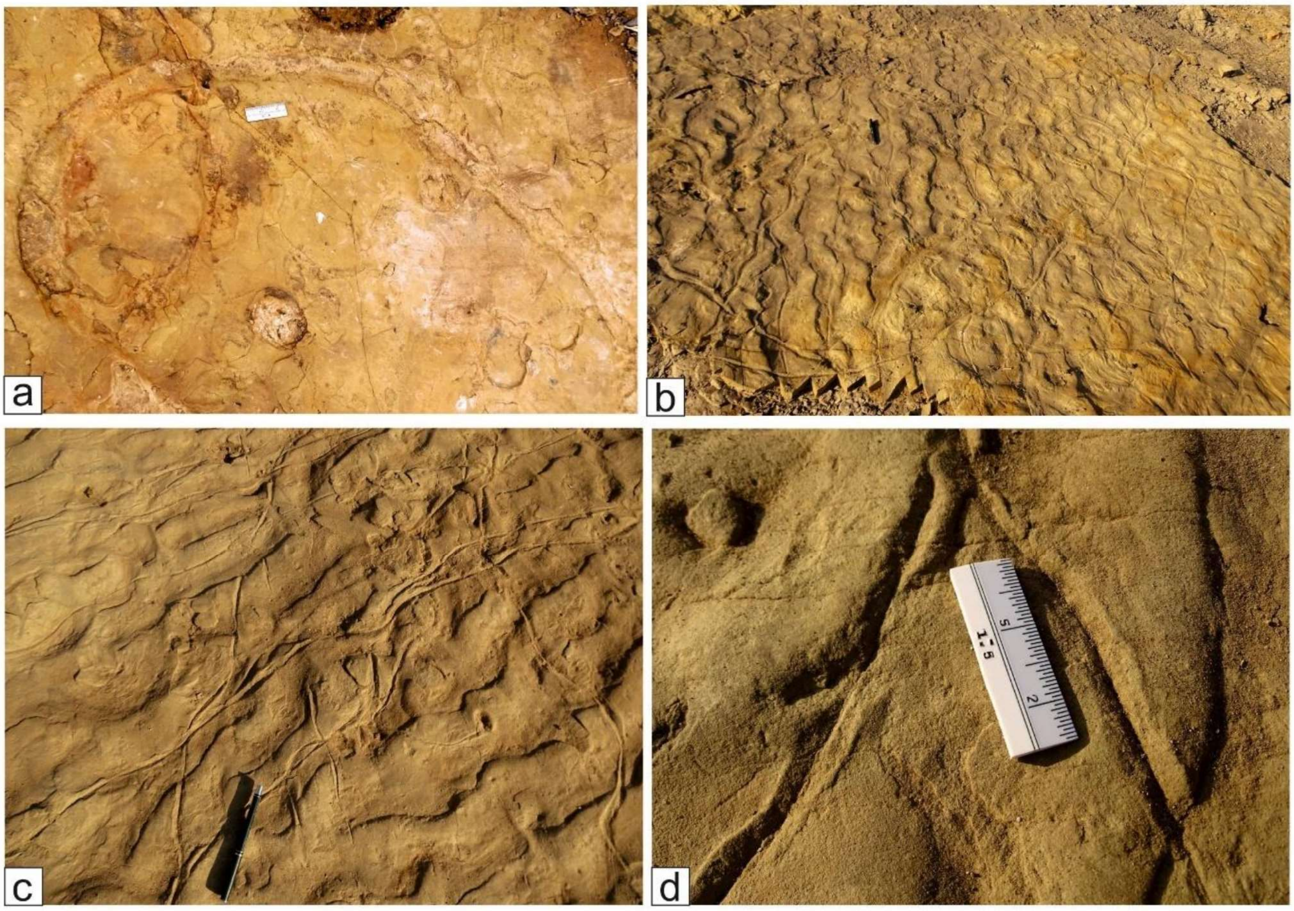


Plate 6.9. Photographs of *Archaeonassa* trails. a. *A. fossulata* with curved faint transverse ridges, muddy micrite, Bilthana Formation, Uchad village. b. *A.*isp., long narrow meandering trails on sinuous crested, rippled calcareous sandstone facies, Vajepur Formation, Devaliya village (length of pen = 15 cm). c. Trails showing cross-covers (length of pen = 15 cm) and d. Close-up of *Archaeonassa* isp.

Interpretation: Morphological characteristics described herein allow the ascribing the trail to *Archaeonassa fossulata,* but due to the lack of convex parallel ridges on both sides, it is placed under open ichnospecies level. It is synonymous with the *Archaeonassa* type C specimen of Schatz et al. (2013) and differs from type A and type B specimens due to deep narrow central depression. It differs from other horizontal trails like *Gordia,* which consists of characteristic loop nature, ribbon-like and lacks meandering; *Circulichnus,* which is knotted, cylindrical, winding ring; *Cochlichnus,* which is a thin epichnial meandering groove or hypichnial meandering ridges; *Helminthoidichnites* which is slightly winding, irregular ribbon-like and consist of occasional loops; *Helminthopsis* which is loosely meandering lacking loops but is hypichnial. *Archaeonassa* has been reported on the modern seafloor of Maktak, Coronation, and North Pangnirtung Fjords (Schatz et al., 2013) and interpreted to be produced by gastropods living in intertidal environments (Häntzschel, 1975; Buckman, 1994).

Occurrence: It is preserved as negative epichnia on the rippled calcareous sandstone facies of Vajepur Formation, Devaliya village.

Orientation: Horizontal
Lateral Elements: Unary
Shape: Straight or Curved
Fill: ---
Burrow wall: ----
Ichnogenus: *Helminthoidichnites* FITCH, 1850.

Diagnosis: Horizontal, small, thin, unbranched, simple, straight or curved, irregularly meandering or winding trails or burrows with occasional loops that commonly overlap among specimens but lack self overcrossing (Schlirf et al., 2001).

Ichnospecies: *Helminthoidichnites tenuis* FITCH, 1850
(Plate 6.10 a-b)

Diagnosis: Same as for the ichnogenus

Description: Horizontal, slender, unbranched, straight to slightly curved trail. Fill resembling the host rock. Diameter ranges from 0.3- 0.56 cm; maximum observed length is 40 cm. Diameters are constant within the individual trail. Trail cross-over each other (Plate 6.10 a-b).

Interpretation: It differs from similar-looking *Helminthopsis* and *Gordia* in lacking meanders and loops, respectively and possessing straight to slightly curved paths (Hofmann, 1990; Hofmann and Patel, 1989). It can be differentiated from *Helminthoidichnites multilaqueatus,* which is curved to multithreaded densely packed trails or burrows. The present specimen lacks the zigzag burrow shape and projections/offshoots of *Treptichnus bifurcus*. The burrows are a grazing trail produced by arthropods, nematomorphs, or insect larvae (Buatois et al., 1997; Schlirf et al., 2001; Uchman et al., 2009). However, an arthropod as a trace maker can be excluded if the specimen lacks two sets of densely packed oblique striations (Martín and Netto, 2018). Based on the transitions observed from *Gordia*to *Helminthoidichnites*, Gaigalas and Uchman (2004) suggested the same tracemaker.

Occurrence: It occurs as epichnia on the planar cross-stratified sandstone facies of Vajepur Formation, Kara River, Vajepur village.

Orientation: Horizontal

Lateral Elements: Unary

Shape: Winding with loops

Fill: ---

Burrow wall: ----

Ichnogenus: *Gordia* EMMONS, 1844.

Diagnosis: Smooth, cylindrical or subcylindrical, non-branching, winding, and irregularly curving burrows, commonly self-overcrossing.

Ichnospecies: *Gordia marina* EMMONS, 1844

(Plate 6.10 a)

Diagnosis: *Gordia,* in which level crossing is fully developed and meanders are unguided (Miller, 1989; Fillion and Pickerill, 1990; Uchman, 1998).

Description: Irregularly winding, horizontal, thin, unbranched burrows of uniform meander with cross-overs resulting in loops. Fill resembles the host rock. Preserved length of the burrow is about 25 cm, and the diameter ranges from 0.3 to 0.4 cm.

Interpretation: The presence of cross-overs differentiates it from *Helminthopsis* and *Helminthoidichnites*. The lack of median and transverse internal structures differentiates it from the meandering *Psammichnites*. The present specimen differs from *Gordia meandria,* which has a broader diameter and subtriangular shape in cross-section, and from *Gordia molassica,* which occurs as a discontinuous string. The ichnogenus is interpreted variably and assigned to be pascichnion, repichnion, or fodinichnion produced by worms, insect larvae, or gastropods (Gaigalas and Uchman, 2004; Wang et al., 2009 and references therein). *Gordia* is a facies crossing form reported from non-marine and marine settings (Pickerill et al., 1984; McIlroy, 1998; Gaigalas and Uchman, 2004).

Occurrence: It occurs as epichnia on the planar cross-stratified sandstone facies of Vajepur Formation, Vajepur village.

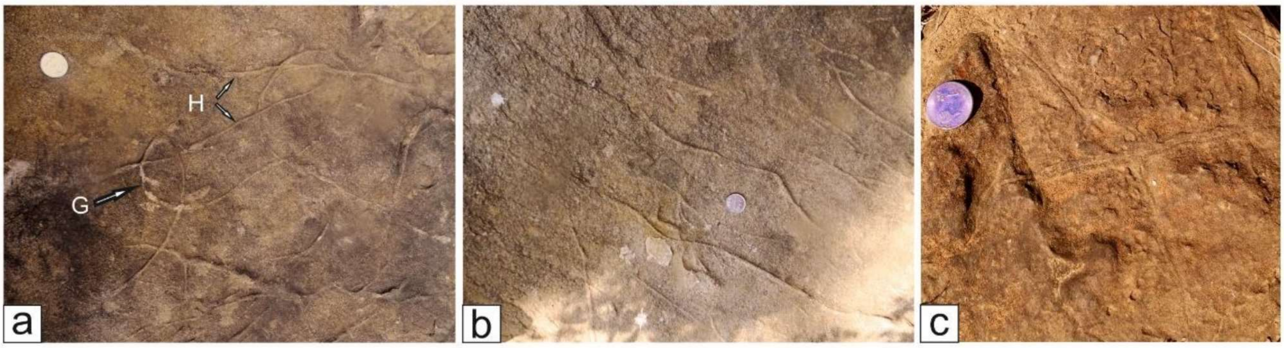


Plate 6.10 Photographs of winding and straight trails (coin Diameter = 2.193 cm). a. *Gordia* (G) and *Helminthoidichnites* (H) occurring as epichnia on the quartz arenite, Songir Formation, Vajepur section. b. *Helminthoidichnites* on the same bed. C. *Didymaulichnus* cf. *lyelli* longitudinally bisected trails in calcareous sandstone facies, Vajepur Formation, Mathsar village.

Orientation: Horizontal

Lateral Elements: Binary

Shape: Straight or Curved

Fill: ---

Burrow wall: ----

Ichnogenus: *Didymaulichnus* YOUNG, 1972

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

Ichnospecies:*Didymaulichnus* cf. *lyelli* ROUAULT, 1850

(Plate 6.10 c)

Diagnosis: Same as for ichnogenus.

Description: Horizontal, simple, smooth, straight to slightly curved, bilobate trails, 0.83- 0.27 mm wide, parallel to bedding, lobes are flat separated by a distinct furrow. Trails are narrow and overlap; the maximum observed length is 17-18 cm.

Interpretation: *Didymaulichnus* differs from bilobed *Gyrochorte* in lack of transverse meniscii on the lobes. The lack of rounded ridges (sharply defined lateral margins, Yochelson and Fedonkin, 1997) and width of central furrow more than the ridges differentiate it from *Archaeonassa,* and the absence of scratches distinguishes it from *Cruziana.* The trace producer of the *Didymaulichnus* is variably interpreted as mollusks (Glaessner, 1969; Häntzschel, 1975; Vossler et al., 1989) arthropods, specifically trilobites (Crimes and Herdman, 1970; Bradshaw, 1981) or worms (Zonneveld et al., 2012). Based on the morphological characteristics, gastropods as probable trace makers are suggested. *D. lyelli* differs from *D. alternatus* and *D. tirasensis* characterized by alternating deepening and shallowing segments, and *D. miettensis* and *D. rouaulti* in lack of lateral bevels or grooves. The absence of pits distinguishes it from *D. nankervisi.* The ichnogenus is reported from the offshore and marginal marine (tidal flat, deltaic and lagoonal) environments (see Ding et al., 2020 and references therein). It has also been reported from the Middle-Late Jurassic deposits of the Kachchh Basin, Western India (Darngawn et al., 2018; Joseph et al., 2020).

Occurrence: Occurs as epichnia on the calcareous sandstone facies, Vajepur Formation, Mathsar village.

6.2.3 TRACKWAYS

Orientation: Horizontal

Lateral Elements: Biserial - One Track

Shape: Bract-like

Fill: ---

Burrow wall: ----

Ichnogenus: *Oniscoidichnus* BRADY, 1949

Diagnosis: Track with low, sinuous median ridge and forward-pointing bract-like footprints on each side at 1mm interval; width of track about 1cm.

Ichnospecies: *Oniscoidichnus communis* CHIPLONKAR AND BADVE, 1970

(Plate 6.11 a-c)

Diagnosis: Trails have a depressed central axis with a small central ridge, fine longitudinal striations along the entire length of the trail, the variable shape of footmarks such as lobes, arcuate to sickle-shaped, seen on both the sides.

Plate 6.11 Trackways in sandstone-siltstone-shale facies (Scale bar = 1.0 cm and coin diameter = 2.7 cm). *Oniscoidichnus communis* track with tear-shaped appendages and median ridge occurs as a. Gently curved, Vajepur Formation, Mogra village. b. Appears strongly curved with prominent median ridge, Vajepur Formation, Bhekhadiya village. c. Zig-zag trail with poorly preserved median ridge, Vajepur Formation, Bhekhadiya village.

Description: Track with low sinuous to strongly curved median ridges and forward pointing footprints on each side. Length is variable in different specimens, it is about 12 cm, and the width is 1.2 cm (Plate 6.11a) whereas, in other specimens, the length ranges 12- 24 cm and width from 1.0-2.6 cm (Plate 6.11c); medial line present. Lateral elements of drop like or elongated that converge on the trace axis. According to Chiplonkar and Badve (1970), *O. communis* differs from *O. filiciformis* (Brady, 1949) based on close footmarks. The present specimen differs from the similar-looking *Cruziana, Nereites,* and *Psammichnites,* lacking scratch markings in the chevrons, wide median furrow, and median dorsal structure, respectively.

Interpretation: Brady (1949) interpreted *Oniscoidichnus* as an isopod trackway because of its resemblance to modern isopod *oniscus*. *Oniscoidichnus* can indicate the habituation of invertebrates in opportune terrestrial environments (Buatois et al., 1998). *Oniscoidichnus* indicates locomotion and shallow feeding. The small footprints and sharp turns are suggestive of a small-bodied organism.

Occurrence: All the traces are preserved as epichnia on the sandstone-siltstone-shale facies of Vajepur Formation, Mogra, and Bhekhadiya villages.

6.2.4 BIOEROSIONAL

Orientation: Complex

Branching: Unbranched

Shape: Clavate

Fill: ---

Burrow wall: Unlined

Ichnogenus: *Apectoichnus* DONOVAN 2018

Diagnosis: Elongate borings, commonly circular in section, smooth-sided, straight or sinuous to contorted and intertwined, with or without a calcareous lining. The boring may change direction and cause a constriction of the tube, but tubes are common of more or less constant diameter. May be solitary or gregarious (Donovan, 2018).

Ichnospecies: *Apectoichnus longissimus* KELLY AND BROMLEY 1984

(Plate 6.12 a-b)

Diagnosis: Same as for ichnogenus

Description: Full relief, preserved as clusters, tightly-spaced, strongly elongated straight to curved borings, some short borings of irregular shape also seen. Ellipsoidal, flattened and/or distorted cross-section. The length and width of boring are highly variable and range from 6 to 14 cm and 1.0 to 2.0 cm, respectively. Borings are parallel to subparallel to the bed surface and have fill identical to the host rock. Few borings have sharp boundaries with oxidized rims and tapering at one or both ends or with rounded termination.

Interpretation: *Teredolites* initially included two ichnospecies, *T. clavatus,* and *T. longissimus.* Donovan (2018) suggested the two ichnospecies do not share any common form but are included in the same ichnogenus considering their similar substrate (wood). Donovan (2018) also suggested that if the importance of substrate is to be denied, the two ichnospecies can be separated at the ichnogeneric level, and *T. longissimus* is considered to be the type ichnospecies of *Apectoichnus*.

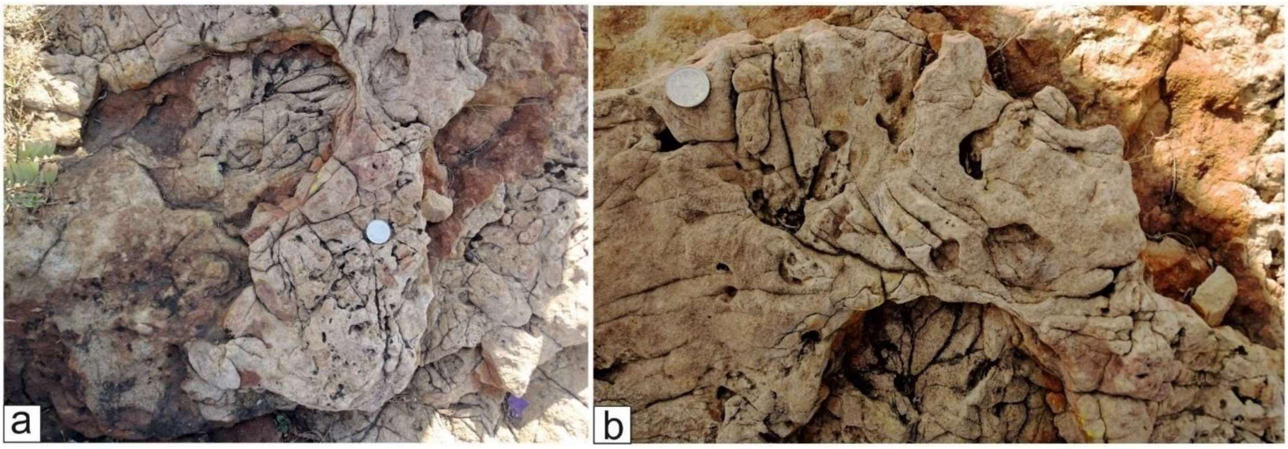


Plate 6.12 Bioerosional structure, *Apectoichnus longissimus*.a. shows variable shapes of borings in quartz arenite facies, Songir Formation, Songir section. b. Close-up of *A. longissimus* showing cylindrical to ellipsoidal boring.

Later Donovan and Evin (2018) transferred *T. clavatus* to *Gastrochaenolites* Leymerie (1842). *A. longissimus* can be differentiated from *Gastrochaenolites clavatus* (formerly *Teredolites clavatus*) based on the slender nature of borings (L:W ratio >5) as described by Kelly and Bromley (1984). Recently, Mayoral et al. (2020) identified the occurrence of *T. clavatus* in amber and contested one more host substrate. The lack of scratch marks differentiates some tongue-shaped Bagh specimens from *Glossifungites*. The ichnospecies *A. longissimus* is associated with *Teredinidae* bivalves (Savrda and King, 1993; Gingras et al., 2004; Kříž and Mikuláš, 2006) which are efficient filter feeders but are obligate wood-eaters (Shipway et al., 2019). However, its occurrence in the lithic substrate suggests its capability to ingest sandy substrate into which it bores. A similar exception to the occurrence of *Teredinidae* bivalves in the xylic substrate with shipworms efficiently boring the carbonate lithic substrate is demonstrated by Shipway et al. (2019). *Apectoichnus* and *Teredolites* are reported from marine and brackish settings (see Mayoral et al., 2020 and references therein). Shipway et al. (2019) reported *Teredinidae* bivalves in freshwater fluvial environments. Based on the variable axes of *Gastrochaenolites* or *Apectoichnus* Shipway et al. (2019) concluded phobotactic behavior of the trace maker and competition for limited space; are equally applicable to the Bagh specimens.

Occurrence: It occurs in the quartz arenite facies of Songir Formation, Chametha-Chosalpura villages.

6.3 UNDETERMINED BRANCHED MEANDERING BURROWS

Description: Horizontal to subhorizontal, branched meandering burrows. The irregularly spaced loops show sharp turns at places. Closely-spaced second-order loops branch from the first-order. It has a main shaft that curves outward and laterally branches (Plate 6.13) in the distal part with lined walls (Plate 6.13b, g), branches recurved, overall shows a dendritic pattern (Plate 6.13b), burrow walls lined, annulated at places (Plate 6.13g), burrows are filled with host sediments. The length of the burrows is highly variable, 10-15 cm long and width of 0.5 to 1.5 cm. Definite terminations not recognized.

Interpretation: The uneven spacing and branched nature of the structures in the present specimen differentiates it from *Helminthoida,* which is a tightly spaced, non-branching structure. The present specimen differs from other meandering ichnogenera like *Olenichnus* in having burrow-fill similar to the enclosing host rock and from the ichnospecies of the *Scolicia* group (*Taphrhelminthopsis, Taphrhelminthoida, Scolicia*) in lack of bilobate ridge and a medial groove. The structure displays a second-order branching loop with sharp turns from the center or the first-order loop (Plate 6.13 f-e). It thus differs from grapholgyptid ichnotaxa (*Cosmorhaphe, Helminthorhaphe, Lorenzia, Paleodictyon, Spirohaphe, Arabesca, Urohelminthoida*). The specimen resembles *Protopaleodictyon* but lacks net structure and appendix branching from the apex. It is separated from *Vagorichnus* due to the lack of ridge-like knob in the structure, while the lack of central furrow distinguishes it from *Nereites*. It can be easily distinguished from winding *Helminthopsis, Helminthoida,* and *Cochlichnus* burrow by its branched nature, from *Megagrapton* and *Multina* due to lack of net/polygon like structure, and *Paleomeandron* due to lack of rectilinear secondary meanders. The meniscate structure seen at a few places (Plate 6.13g) resembles the burrows of *T. serpentinum.* Similar traces were reported by Badve and Ghare (1980) from the Bagh Group rocks exposed south of the Narmada River. Badve and Ghare (1980) erected new ichnogenus and species *Annetuba chapdiensis* for the curving burrows with slightly raised margins. Half of the burrow is preserved as negative epichnia and half as endichnia; the burrows lack vertical shaft and tunnel filling with cross annulations, differentiating it from *Keckia* and *Micatuba*. Badve and Ghare (1980) erected new ichnospecies *Imponoglyphus kevadiensis* for the curved beaded chains observed on the same horizon but adjacent

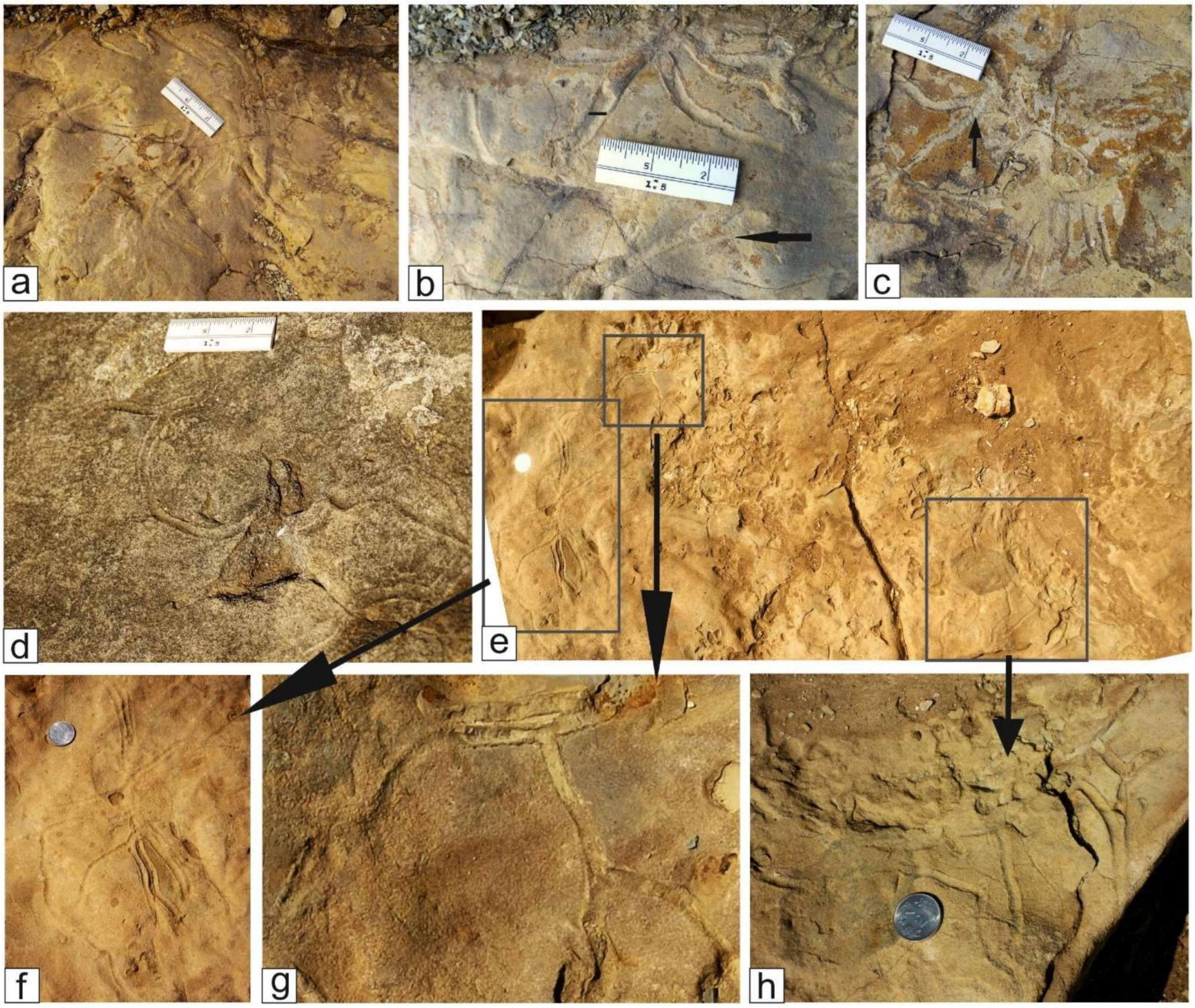


Plate 6.13 Undetermined branched meandering burrows on calcareous sandstone facies, Vajpeur Formation, Men River valley. a. The curved burrows, and b. Enlarged view of a. showing distal branching, lined tubes, half of which are eroded, and meniscate fill in subhorizontal burrow (marked by arrow). c. Sinuous branched burrows showing beaded chains seen in the eroded part of the lined burrow. d. Winding burrows forming irregular networks, false branching is seen here due to overcrossing at the same depths. e. Bioturbated surface characterized by various types of structures. f. Multiple and overlapped burrows, gently curved or forming loops with sharp u-shaped turns. g. Branching and meniscate fill of the lined burrow preserved as negative epichnia. h. Irregularly branched burrows preserved as positive epichnia.

section. However, the ichnospecies (*A. chapdiensis* and *I. kevadiensis*) are observed as parts of the same trace (Plate 6.13c) from the same stratigraphic horizon exposed in the Men River Valley. Based on the presence of a curved central shaft branching outward laterally in the distal part (Plate 6.13a-b) of burrows, lining, and meniscate structure, they can be tentatively assigned to *Hartsellea* *sursumramosa*. However, Knaust (2015) considered the ichnogenus *Annetuba* and *Hartsellea* to be junior subjective synonyms of *Arenituba verso*. The lack of radial nature in the *Annetuba* specimens of Badve and Ghare (1980) and in the present study differentiates it from *Arenituba*.

Occurrence: It occurs as epichnia on the calcareous sandstone facies of Vajepur Formation, Uchad village.

6.4. PSEUDO FOSSILS

In the lack of significant palaeoenvironmental fossils, it is common to explore it more intensely; thus, it is crucial to eliminate the possibilities of chemical and physical origin before assigning the structure a biogenic origin (Goldring et al., 2005). The sedimentary markings, particularly with a regular pattern, are often confused with trace fossils (Knaust and Hauschke, 2004). The illusion of biogenic origin becomes more common if the physical/chemical structure coexists with an actual biogenic structure. The weathered surface of rippled micritic sandstone belonging to the Vajepur Formation in the Devaliya village shows a structure resembling the spreiten of *Zoophycos villae;* moreover, it is cross-cut by grazing gastropod trails of *Archaeonassa* (Plate 6.14b). The superficial lobate shape of the spreiten-like structure winded by *Archaeonassa* trails is seen at most places, imitating the lobes of *Zoophycos*. The filaments appear to originate from a common point in a lobe-shape pattern and diverge up to the marginal tube-like appearing *Archaeonassa* trials (Plate 6.14c). However, *Archaeonassa* trails when cross-cutting the structure showing uneven margins, which further rule out the existence of the marginal tube (Plate 6.14b). The occurrence of *Zoophycos* on the rippled calcareous sandstone contradicts its origin in slope and deep basins during the early and late Cretaceous (Olivero, 2003; Buatois and Mángano, 2011). The mound structure from which trails of *Archaeonassa* originate coincides with the apex of the physical structure, superficially resembling the mound-shaped central shaft of *Zoophycos villae*; besides, the structure shows primary lamination of sandstone on its weathered surface, resembling the J-shaped curved furrowed radiating laminae of *Zoophycos villae*. The J-shaped curved laminae of the physical structure are described as rib and furrow pattern by Collinson and Thompson (1989), observed in ancient medium-fine grained sandstones, a horizontal expression of trough cross-bedding. The lack of branching, apex, and marginal tube and the presence of uneven margins of the filaments differentiate it from the biogenic origin of the structure.

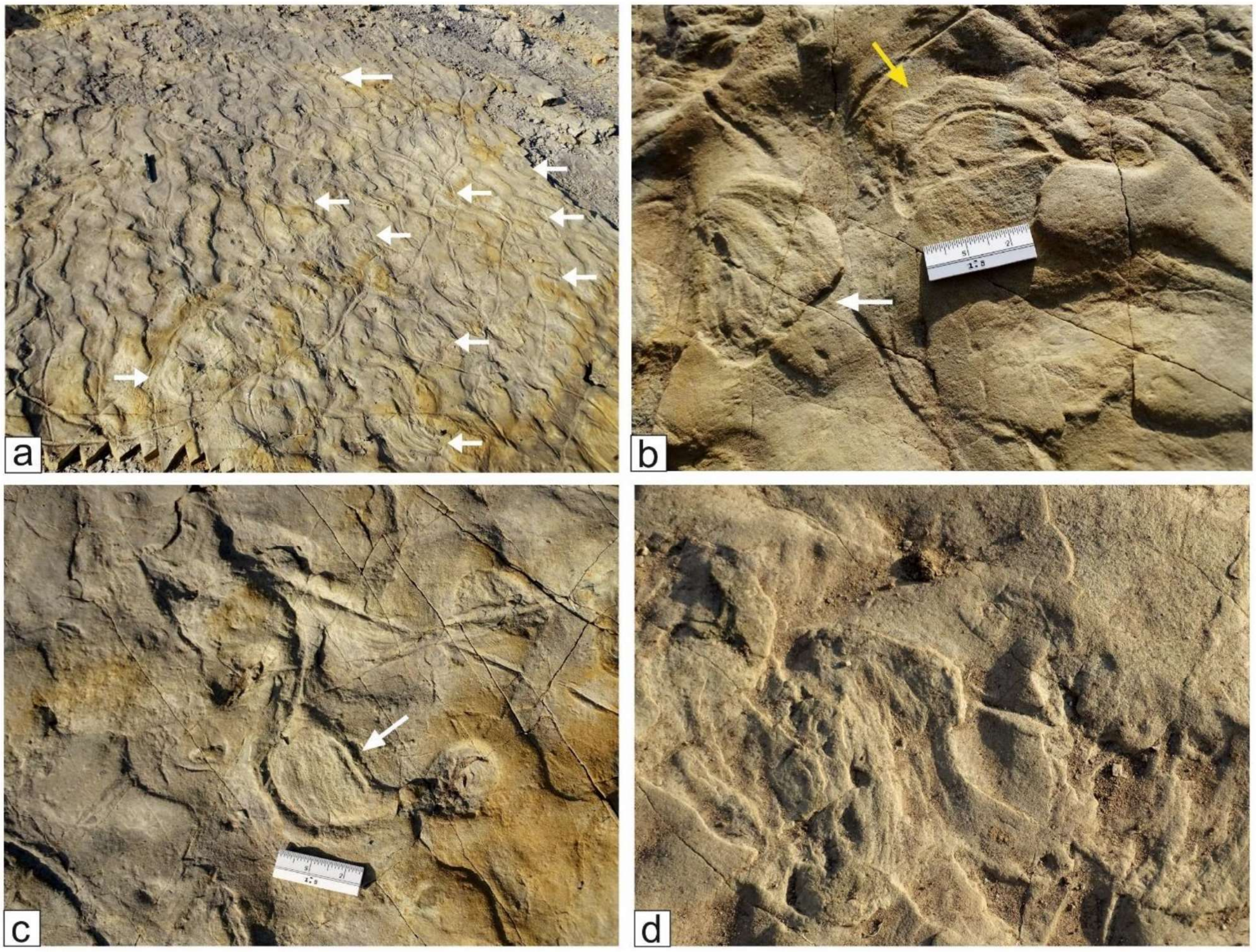


Plate 6.14 Examples of pseudofossil from the Vajepur Formation, Devaliya sectiona. Pseudofossils (marked with arrows) occurring along with long meandering trails of *Archaeonassa* on the sinuous rippled calcareous sandstone facies (length of pen = 15cm). b. The superficial lobate structure of the spreiten-like structure is cross-cut by *Archaeonassa* trails (marked by white arrow). c. *Archaeonassa* trails wind the superficial lobate outline of the spreiten-like structure. d. False biogenic laminae.

6.5 PALEOECOLOGICAL ANALYSIS

The study reports seventeen trace fossils from the Cretaceous sequence of the Bagh Group of the WLNV. To interpret the paleoecological parameters, the author made an attempt to analyze the trace fossils in terms of the ethology, ichnoassemblage, and ichnofacies discussed below.

6.5.1 ETHOLOGY

Trace fossils are the behavioral activities of the soft-bodied organisms produced due to the interaction with substrate and are preserved as tracks, trails, burrows, borings, etc. They are mainly reported from moderately bioturbated Vajepur Formation, Songir Formation, intensely bioturbated

Bilthana Formation, Nodular Limestone, and Narmada sandstone Member of Uchad Formation and preserved as epichnia, endichnia, and hypichnia.

Total seventeen ichnogenera are reported from the Cretaceous sequence of the WLNV, including, *Apectoichnus, Archaeonassa*, *?Arenicolites*, *Bergaueria, Conichnus, Conostichus, Didymaulichnus, Gordia, Helminthoidichnites, Lockeia, Oniscoidichnus, Paleophycus, Planolites, Ptychoplasma, Skolithos, Taenidium* and *Thalassinoides*. The overall density and diversity of the trace fossils are moderate; the maximum ichnogenera are reported from the Vajepur Formation. These trace fossils are further analyzed in terms of behavioral categories (Seilacher, 1953), representing five ethological categories viz. cubichnia (resting), repichnia (crawling/locomotion), pascichnia (grazing), fodinichnia (feeding), and domichnia (dwelling). The ethological categories include resting/dwelling traces like *Conichnus, Conostichus, Bergaueria,* and *Lockeia;* locomotion traces like *Didymaulichnus, Oniscoidichnus, Archaeonassa, Ptychoplasma*; grazing traces like *Gordia*, *Helminthoidichnites*, and *Planolites;* feeding traces such as *Taenidium*; dwelling traces like *Apectoichnus, ?Arenicolites*, *Paleophycus* and *Skolithos;* and dwelling-feeding combined activity, *Thalassinoides*. These ethological categories reflect the high density and diversity observed in the resting, crawling, and dwelling structures, moderate grazing, and least in the feeding structures.

Trace fossils are attributed to presumed polychaetes (*?Arenicolites*, *Gordia, Helminthoidichnites, Paleophycus, Planolites, Skolithos*) are common, as are burrows of mollusks (*Apectoichnus*, *Archaeonassa, Didymaulichnus*, *Lockeia, Ptychoplasma*) and arthropods (*Oniscoidichnus, Taenidium, Thalassinoides*) and sea anemones (*Bergaueria*, *Conichnus*, *Conostichus*).

Ichnotaxa	Frequency				Stratinomy			Ethology					Lithofacies								Trophic			Probable Trace maker	Stratigraphic range
	Very rare (1 specimen)	Rare (2-5 specimens)	Common (6-20 specimens)	Abundant (>20 specimens)	Epirelief	Fullrelief	Hyporelief	Cubichnion	Repichnion	Domichnion	Fodichnion	Pascichnion	Fine-grained sandstone-Siltstone	Calcareous sandstone	Planar cross-stratified sandstone	Sandy allochemic limestone	Bedded Quartz arenite	Mudstone	Micritic Sandstone	Fossiliferous limestone	Suspension feeding	Deposit feeding	Predation		
Apectoichnus				x		x				x							x					x		Bivalves	Early Cretaceous-Miocene
Archaeonassa			x		x				x			x	x	x								x		Mainly Gastropods and possibly arthropods and echinoderms in marine env. Annelids or mollusks in non-marine env.	Cambrian-Recent
?Arenicolites				x		x				x								x			x	x		Polychaetes or crustaceans	Cambrian-Recent
Bergaueria				x			x	x		x						x					x			Actinarian or ceriantharian coelenterates	Precambrian-Miocene
Conichnus		x					x	x		x			x			x					x			Actinarian (sea anemones)	Cambrian-Tertiary
Conostichus		x					x	x		x			x			x					x			Actinarian (sea anemones)	Ordovician-Cretcaeous
Didymaulichnus	x				x				x				x								x	x		Gastropods, bivalves or arthropods	Precambrian-Cretaceous
Gordia	x				x				x		x	x			x							x		Worms, insect larvae or gastropods	Precambrian-Recent
Helminthoidichnites	x				x							x			x							x		Arthropods, nematomorphs or insect larvae	Precambrian to Pleistocene
Lockeia			x		x			x						x								x		Bivalves	Ediacaran-Eocene and Late Cambrian-Pleistocene
Oniscoidichnus		x			x				x					x									x	Isopod	Paleozoic-Recent
Paleophycus			x		x					x			x	x		x					x	x	x	Polychaetes	Ediacaran-Recent
Planolites		x			x							x	x	x		x						x		Worms or arthropods in terrestrial env.	Precambrian-Recent
Ptychoplasma	x						x		x				x											Wedge-foot bivalves	Ordovician-Recent
Skolithos				x		x				x									x	x	x		x	Annelids or phoronids in marine env. or by insects and spiders in terrestrial env.	Precambrian-Recent
Taenidium		x				x					x	x		x								x		Arthropods (terrestrial myriapods), insects, annelids (earthworms) or variety of organisms	Cambrian-Recent
Thalassinoides				x		x					x			x		x		x		x	x	x		Infaunal crustaceans or other kind of arthropods	Cambrian-Recent

Table 6.3 Trace fossils abundance, preservation, behavior, trophic type, trace makers are shown in the various facies of the Bagh Group and their stratigraphic range.

6.5.2 ICHNOASSEMBLAGE

Trace fossils are grouped based on occurrence on particular lithofacies, which are exposed at different localities. The name of the ichnoassemblage is assigned based on the dominance of the trace fossils; nine ichnoassemblages have been identified, viz. *Apectoichnus*, *Archaeonassa, Bergaueria, Conichnus-Conostichus, Helminthoidichnites-Gordia, Lockeia-Planolites, Skolithos, Taenidium,* and *Thalassinoides* (Fig. 6.5).

1.	*Archaeonassa*	10.	*Palaeophycus*
2.	*Bergaueria*	11.	*Thalassinoides horizontalis*
3.	*Taenidium*	12.	*Lockeia*
4.	*Planolites*	13.	*Didymaulichnus*
5.	*?Arenicolites*	14.	*Ptychoplasma*
6.	*Conostichus*	15.	Indeterminate trace fossils
7.	*Conichnus*	16.	*Oniscoidichnus*
8.	*Skolithos*	17.	*Helminthoidichnites*
9.	*Thalassinoides paradoxicus* and *T. suevicus, T. isp*	18.	*Gordia*

Legend representing the trace fossils marked in ichnoassemblages diagram.

6.5.2.1 *Apectoichnus* assemblage

The ichnoassemblage consists of monospecific suites of *Apectoichnus longissimus* observed in the coarse-grained siliceous sandstones of the Songir Formation. Monodominant structure preserved as full relief in the quartz arenite facies suggests its capability to ingest sandy substrate into which it bores. This structure is probably produced by Teredinidae bivalves (Savrda and King, 1993; Gingras et al., 2004; Kříž and Mikuláš, 2006, Shipway et al., 2019) which is reported from a wide range of environments. *Apectoichnus* structure is considered as phobotactic behavior of the trace maker and is reported from the marine, brackish and fluvial environments (Shipway et al., 2019).

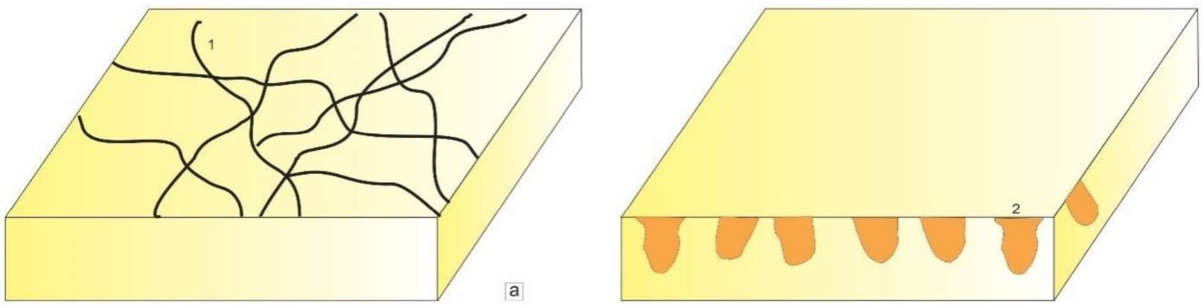


Figure 6.1 Diagrammatic representation of a). *Archaeonassa* and b). *Bergaueria* assemblages.

6.5.2.2 *Archaeonassa* assemblage

The assemblage is characterized by deposit-feeding organisms' high density, monospecific, simple crawling/grazing trails (Fig. 6.1a). It occurs as epirelief in the calcareous sandstone facies of Vajepur Formation at Devaliya and on the sandstone-siltstone-shale facies of Bilthana Formation at the Uchad section. It is preserved on the bedding plane of rippled sandstones. The ichnogenus *Archaeonassa* is a grazing structure produced by gastropods (Häntzschel, 1975) and has a wide geological range and is reported from Cambrian to the present (Fenton and Fenton, 1937; Buckman, 1994). According to Hofmann et al. (2012), the monospecific ichnoassemblage of *Archaeonassa fossulata* is representative of a break in sedimentation and low energy conditions in a stressed environment. *Archaeonassa* trails in rocks containing laminae and ripple marks are considered to be produced by gastropods in tidal environments and are typical of intertidal zones (Fenton and Fenton, 1937; Buckman, 1994). They are also considered to be superficial grazing structures produced by detritus feeders (Hofmann et al., 2012). According to Buckman (1994), *Archaeonassa* occurring on thinly-bedded, wave-rippled, muddy sandstones interbedded with shales is deposited in intertidal flat environment with fluctuating salinity. The lack of flat central region and presence of leeve on either side as observed in *Archaeonassa* isp. suggests epifaunal plowing and organism movement through the sediments directly beneath the sediment-water interface pushing sediment on either side (Jensen, 2003; Hofmann et al., 2012). The flat zone between the levees suggests mollusk-like animals be the producer (Jensen, 2003), also observed in the present specimens of *Archaeonassa fossulata*. The massive colonization of deposit feeders in this assemblage indicates reduced sediment supply in a probably tidal flat environment with fluctuating salinity.

6.5.2.3 *Bergaueria* assemblage

The assemblage consists of monospecific suites of *Bergaueria hemispherica* (Fig. 6.1b). The ichnoassemblage is a sea anemone-dominated suite consisting of high ichnodensity burrows preserved at the base of oyster-limestone beds (sandy allochemic limestone facies). *Bergaueria* reflects the filter feeders' (sea anemones) combined resting and/or dwelling behavior. The high density of burrows and its occurrence in the limestone-shale intercalated sequence suggests a stressed environment with varying energy levels (Shitole et al., 2019). The occurrence of *Bergaueria* indicates a slightly agitative and clean environment which supported the sea anemone to be stranded on the fine-grained partially dewatered sediments.

6.5.2.4 *Conichnus- Conostichus* assemblage

Thisichnoassemblage comprises an ethologically diverse group of trace fossils, including the *Conichnus, Conostichus, Oniscoidichnus, Paleophycus, Planolites, Thalassinoides,* and indeterminate trace fossils (Fig. 6.2a). It is dominated by vertical dwelling/resting burrows with a moderate occurrence of locomotory and feeding traces. It is developed in the sandy allochemic limestone facies intercalated with shale and the sandstone-siltstone-shale facies of Bilthana and Vajepur formations, respectively. The trace makers are mainly sea anemones, gastropods, crustaceans, polyphyletic vermiform, and arthropods.

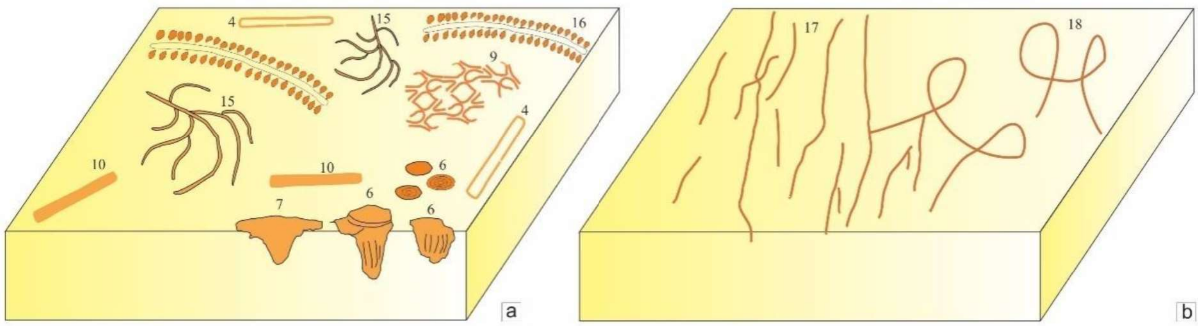


Figure 6.2 Diagrammatic representation of a).*Conichnus- Conostichus* and b). *Helminthoidichnites-Gordia* assemblage.

6.5.2.5 Helminthoidichnites-Gordia assemblage

The assemblage is characterized by simple grazing trails *Helminthoidichnites tenius,* and *Gordia marina* (Fig. 6.2b) represents variations within individual community i.e., a common producer. *Gordia* occurs in the same bed bearing *Helminthoidichnites,* on the top of thickly-bedded, medium-grained planar cross-stratified sandstones. This assemblage shows low ichnodensity, and ichnodiversity and co-occurrences of *Gordia* and *Helminthoidichnites* are reported by Gaigalas and Uchman (2004) and Uchman et al. (2009). It suggests locomotion in search of nutrients in the substrate and represents a short-term colonization window in low energy deposits between high energy conditions characterized by cross-stratified sandstones in a probably tidal flat environment. *Helminthoidichnites* and *Gordia* are mat grazers, grazing the organic matter on mats preserved below a thin veneer of sediments (Seilacher, 1990; Buatois and Mángano, 2012). According to Buatois et al. (2020), the trace fossil *Helminthoidichnites* is a facies-crossing form reported from various depositional environments but is more common in fluvial settings.

6.5.2.6 *Lockeia-Planolites* assemblage

The ichnoassemblage comprises a behaviorally diverse group of trace fossils, viz. *Didymaulichnus*, *Lockeia*, *Oniscoidichnus*, *Palaeophycus, Planolites, Ptychoplasma, Thalassinoides,* and undetermined trace fossils (Fig. 6.3a). It is mainly characterized by locomotion traces of bivalves preserved in the calcareous sandstone facies or sandstone-siltstone-shale facies occurring in the upper part of the Vajepur Formation. The presence of abundant *Lockeia* specimens in the Vajepur Formation suggests the substrate was rich in nutrients. Their close occurrence on the same bed suggests a behavioral variation of the bivalves, and the preservational variant aspect arising out of the different depositional environment and sediment consistency can be ruled out. The grazing trails of *Planolites beverlyensis* are commonly associated with *Lockeia* and occur in calcareous sandstone facies of Vajepur Formation, suggesting communalism. Moreover, the crawling trail *Didymaulichnus lyelli* and dwelling structure *Paleophycus tubularis* of suspension feeder (Hofmann et al., 2012) in calcareous sandstone bed suggest soft unconsolidated substrate of foreshore/shoreface environment.

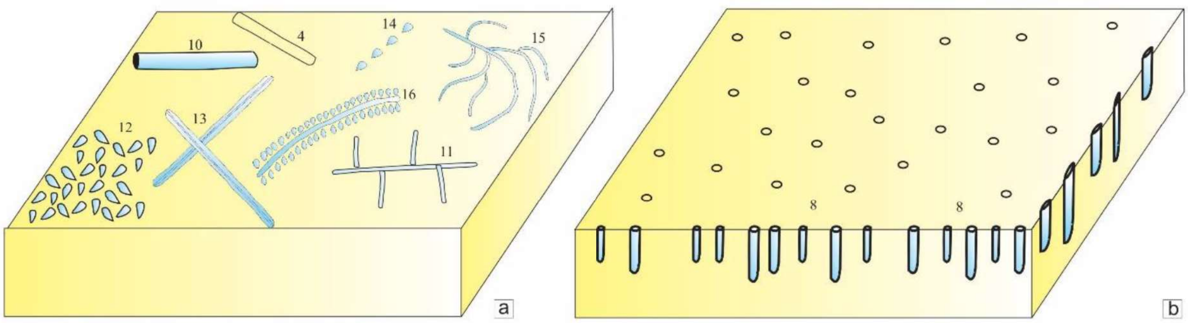


Figure 6.3 Diagrammatic representation of a). *Lockeia-Planolites* and b). *Skolithos* assemblage.

6.5.2.7 *Skolithos* assemblage

The ichnoassemblage is characterized by the monodominant occurrence of *Skolithos* (Fig. 6.3b) in the calcareous sandstone facies of the Narmada Sandstone Member of the

Uchad Formation. It is also associated with *Thalassinoides* in the fossiliferous limestone facies of the Bilthana Formation. It consists of vertical dwelling burrows of suspension feeders and indicates unconsolidated, shifting substrate and high wave and current energy conditions (Pemberton et al., 2001). The suspension-feeding as a dominant trophic type suggests moderate turbidity and thus the availability of food and oxygen in the water column.

6.5.2.8 *Taenidium* assemblage

*Taenidium*is an active back-filled meniscate structure and occurs with *Planolites* (Fig. 6.4a) in the middle part of the Vajepur Formation, which consists of cross-bedded, coarse-grained, calcareous sandstone facies. It is dominated by the deposit-feeding activity of various organisms (Díez-Canseco et al., 2016). Its co-occurrence with *Planolites* indicates the presence of nutrient-rich substrate, exploited for feeding purposes. The present study's horizontal forms of *Taenidium* suggest a stiffer, compacted substrate that offered resistance to burrowing in contrast to the vertical forms generated in less-compacted sediments (Díez-Canseco et al., 2016).

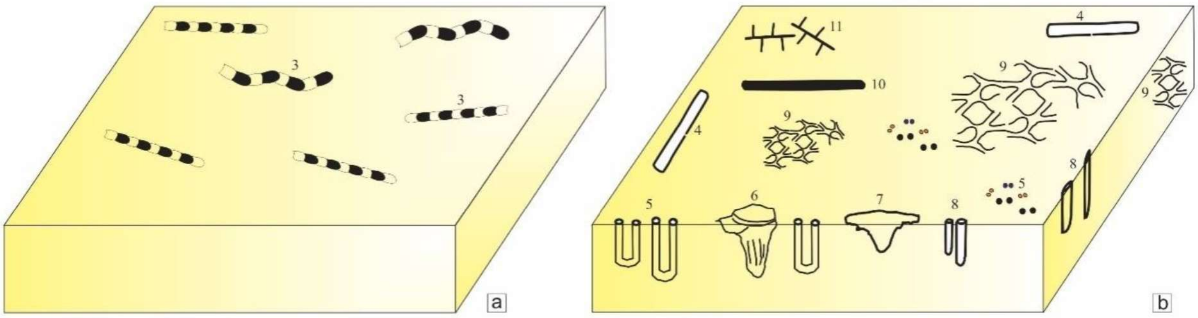


Figure 6.4 Diagrammatic representation of a). *Taenidium* and b). *Thalassinoides* assemblages.

6.5.2.9 *Thalassinoides* Ichnoassemblage

This ichnoassemblage occurs at three different level and occur either monodominant or associated with some less abundant forms. It predominantly occurs in the fossiliferous limestone facies of the Bilthana Formation and consists of various *Thalassinoides* species, including *T. paradoxides, T. suevicus,* and *Thalassinoides* isp. while it occurs with *Planolites* and *Palaeophycus* (Fig. 6.4b) in the calcareous sandstone of Vajepur Formation and with ?*Arenicolites* in mudstone facies of Nodular Limestone. This ichnoassemblage is extensively developed in the intercalated sequence of oyster limestone (fossiliferous limestone facies)-shale facies. The burrows were made in a cohesive muddy substrate and were passively filled with the overlying sediments. The recurring pattern of occurrence of *Thalassinoides* burrows in the oyster beds (fossiliferous limestone facies) is in accordance with their deposition in contrasting energy conditions, suggesting the trace maker's opportunistic behavior. The monodominant occurrence of *Thalassinoides* burrows as hyporelief in the oyster beds intercalated with the shale facies was caused due to the rapid passive fill of the burrow with the overlying sediments either due to the burial of the whole burrow causing death and decay of the organism in it (Tsujita, 2003), or due to the vacation of burrow because of exhumation of the cohesive sediments by the high energy event.

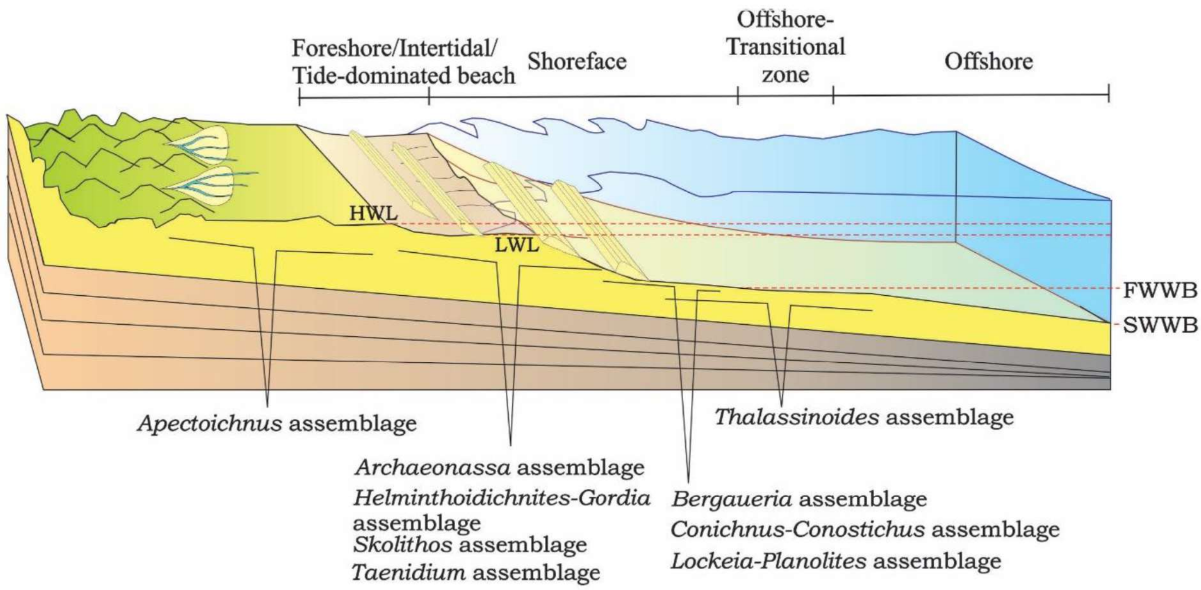


Figure 6.5 Schematic 3-dimensional diagram representing ichnoassemblages in the shallow marine depositional environment of the Western Lower Narmada Valley.

6.5.3 ICHNOFACIES

Ichnofacies constitute biogenic structures made by organisms in response to changes in energy conditions, deposition rates, food resource types, substrate consistency, water salinity, oxygenation, subaerial exposure, substrate moisture, and temperature (MacEachern et al. 2007). This ichnofacies concept, when linked with ichnological and sedimentological data, can help in deciphering depositional environment and paleoecological conditions. In the study area, trace fossils are most common in the Bilthana and Vajepur formations and are rare in the Songir, Nodular Limestone, and Uchad formations. The ichnoassemblages analyzed further represents *Skolithos, Cruziana,* and *Glossifungites* ichnofacies.

6.5.3.1 *Skolithos* Ichnofacies

This ichnofacies is composed of monospecific, crowded *Skolithos* burrows with thickly lined tubes observed in the calcareous sandstone facies of Narmada Sandstone Member (Plate 6.3b). The typical occurrence of *Skolithos* can be attributed to a short-term colonization window reflecting a change in energy conditions and water depth affected by bedform topography and sedimentation rate (Buatois and Mángano, 2011; Santos et al., 2017). The occurrence of vertical burrows (*Skolithos*) of suspension-feeders observed in the Narmada Sandstone Member suggests high-energy conditions at the time of colonization. The *Skolithos* Ichnofacies in the study area represent a sudden change in the environmental conditions from low energy offshore deposits of the Nodular Limestone to the high energy middle shoreface deposits of the cross-bedded Narmada Sandstone Member. Mángano and Buatois (2004) have also observed the *Skolithos* Ichnofacies that consist of opportunistic organisms, represented by their monodominant occurrence in shallow subtidal to intertidal deposits, as well as Knaust and Bromley (2012), have noticed that the middle shoreface environment is dominated by abundant suspension-feeding traces belonging to the *Skolithos* Ichnofacies. The presence of *Skolithos* Ichnofacies in the calcareous sandstone of the Narmada Sandstone Member suggests that opportunistic organism like tube-dwelling suspension-feeding polychaetes colonized in the marine habitats after a major environmental change like bottom substrate consistency followed by well-oxygenated bottom water conditions and abundant food supply (McCall and Tevesz, 1983; Vossler and Pemberton, 1988; Dam, 1990).

6.5.3.2 *Cruziana* Ichnofacies

This ichnofacies is associated with poorly sorted, unconsolidated marine substrates, indicating deposition in the subtidal environment between the fair-weather base and storm wave base in wave-dominated lower shoreface to distal fringes of the lower offshore region (MacEachern and Pemberton, 1992; MacEachern et al., 1992; MacEachern et al., 1999a; Pemberton et al., 2001). *Cruziana* Ichnofacies is observed in the sandstone-siltstone-shale, planar cross-stratified sandstone, and calcareous sandstone facies, with characteristics genera like *Archaeonassa*, *Didymaulichnus, Gordia, Helminthoidichnites, Lockeia, Oniscoidichnus, Palaeophycus, Planolites, Ptychoplasma, Taenidium,* and *Thalassinoides.* The ichnofacies include a wide range of behavioral traces, including feeding, dwelling, resting, dwelling, grazing, and locomotion. The *Cruziana* Ichnofacies consists of both suspension and deposit feeders and has a mixed association of horizontal, vertical, and inclined burrows (Miller III, 2011) due to the suspended and deposited components of food supplies in moderate energy settings. However, the dominance of horizontal feeding burrows of deposit feeders observed in the Bagh Group sediments suggests low to moderate-energy conditions. Moreover, the ichnofacies is characterized by diversified ethologies, indicating an overall stable environment with low to moderate sedimentation rates (Buatois and Mángano, 2011). The traces of deposit-feeding in different beds of the upper part of the Vajepur Formation consisting of the fair-weather suite are dominated by *Lockeia*, *Oniscoidichnus*, *Planolites*, *Paleophycus*, *Thalassinoides,* and horizontal undetermined traces. The high density and diversity of deposit-feeding traces suggest abundant nutrients and oxygenation in the sediments (Han and Pickerill, 1995). The presence of *Lockeia*and *Ptychoplasma* in the sandstone-siltstone-shale facies of Vajepur Formation suggests a compact, unconsolidated substrate which favored emplacement and preservation of burrows (Paranjape et al., 2013).

6.5.3.3 Glossifungites Ichnofacies

This is a substrate-controlled ichnofacies and typically developed at the omission surface and characterized by typical burrows. The burrows in firmground substrate need no reinforcement to stabilize the wall (Ghibaudo et al., 1996; MacEachern and Burton, 2000) and hence should be discussed in the context of *Glossifungites* Ichnofacies (Ekdale et al., 1984). *Thalassinoides* is one of the most common elements of the *Glossifungites* Ichnofacies, which are abundant in the post-Paleozoic rocks (Myrow, 1995; Pemberton et al., 2004). In the Bagh Group sequence, characteristic elements of the *Glossifungites* Ichnofacies, *Thalassinoides* burrows in the Bilthana Formation and the Nodular Limestone and plug-shaped *Conichnus*, *Conostichus,* and *Bergaueria* in the Bilthana and Vajepur formations are observed. These burrows are found in high density in the fossiliferous limestone facies of oyster beds, indicating opportunistic colonization.

Thalassinoides is considered a semi-permanent dwelling system that may have remained open for a long period during which the organisms circulated water through it, and

at omission surfaces, the burrows are filled passively with the contrasting post-omission sediments to a greater depth (Bromley, 1975). Their occurrence beneath the omission surface is interpreted as the existence of an open system at that depth beneath the seafloor (Bromley and Ekdale, 1984). The presence of burrows in the shale facies of the Bilthana Formation and the mudstone facies of Nodular Limestone indicate water circulation in the tunnels.
The dominance of vertical plug-shaped burrows like *Conichnus*, *Conostichus,* and *Bergaueria* of suspension-feeding sea anemones were observed in shale facies of the upper part of Vajepur and Bilthana formations (Patel et al., 2018; Shitole et al., 2019). The organisms made burrowed in the compact cohesive mud and left the burrow in intact form, evidenced by sediments filled with the overlying bed and were preserved at the bed-junction of the oyster bed and shale. The dominance of vertical plug-shaped burrows of suspension feeders observed in the present study suggests fluctuating energy conditions and an ample supply of nutrients carried by the bottom currents on the seafloor.

The ichnofacies is characterized by low diversity and high density branched, unbranched, sharp-walled, unlined, and passively filled, dwelling burrows of suspension feeders. The ichnofacies indicate a stable and cohesive substrate, mainly dewatered muds reflected by the unlined, sharp-walled, passively filled burrows (MacEachern et al., 1992). The passive fill of the burrows indicates the substrate stability as the burrows remained open and were filled by the transgressive sediments of the fossiliferous limestone and calcareous sandstone facies of the Vajepur and Bilthana formations.

6.6 DISCUSSION

The Bagh Group succession of the WLNV provides a glimpse of the Cretaceous ichnofauna of the invertebrate organisms in response to the fluctuating sea level, oxygen conditions, and changing sedimentation rates. This study highlights the animal-substrate interactions and other palaeoecological parameters that governed during the deposition. The trace fossils are observed throughout the sequence, and most of the trace fossils are reported from the sandy allochemic limestone facies, fossiliferous limestone facies, sandstone-siltstone-shale facies, and calcareous sandstone facies, whereas the quartz arenite facies, planar cross-stratified sandstone facies, and mudstone facies are bioturbated to a lesser degree. Most of them occur at the bed-junction of sandstone-shale or limestone-shale due to high preservation potential. These trace fossils show ethological diversity and are represented as cubichnia (*Bergaueria, Conichnus, Conostichus, Lockeia*), pascichnia (*Archaeonassa, Gordia, Helminthoidichnites*), domichnia (*Apectoichnus, ?Arenicolites, Paleophycus, Skolithos*), repichnia (*Didymaulichnus, Oniscoidichnus, Ptychoplasma*) and fodinichnia (*Planolites, Taenidium, Thalassinoides*). These ichnofossils can be grouped into nine ichnoassemblages that recur in time and space and represent *Skolithos, Cruziana,* and *Glossifungites* ichnofacies.

Monospecific occurrences of *Archaeonassa*, *Apectoichnus*, and *Bergaueria* are observed at different stratigraphic levels. The *Conichnus-Conostichus* and *Lockeia-Planolites* ichnoassemblage host a moderately diverse trace fossil association consisting of three to four ichnogenera. Generally, high intensity of bioturbation is reported from the shallow and marginal marine environments; however, the rocks in the study area are moderately bioturbated except for the Bilthana Formation, which consists of abundant *Thalassinoides* burrows of endobenthic decapod crustaceans.

The trace fossils like *Thalassinoides, Bergaueria, Conichnus, Conostichus,* and *?Arenicolites* preserved at the sandstone-shale or limestone-shale bed junction suggest a change in the hydrodynamic and substrate conditions. The *Skolithos* Ichnofacies occurs in the Narmada Sandstone Member and consists of monodominant occurrence of the *Skolithos* genus. Sedimentary structures such as planar, trough, and herringbone cross-stratification amalgamated with the *Skolithos* Ichnofacies observed in the sandstone unit of the Narmada Sandstone Member above the Nodular Limestone suggest deposition took place above the FWWB. The *Cruziana* and *Glossifungites* ichnofacies observed in the fossiliferous limestone, sandy allochemic limestone facies, and mudstone facies of Vajepur and Bilthana formations suggest deposition in lower shoreface to the offshore environment. Also, the large diameter of *Thalassinoides* burrows observed in the Nodular Limestone is consistent with low-moderate energy conditions, well-oxygenated, nutrient-rich waters of the shallow marine environment. The Nodular Limestone, Bilthana Formation, and Vajepur Formation were deposited in low to moderate energy conditions with intermittent high energy events in the intertidal to the subtidal environment.

The presence of cross-stratification in the middle-lower part of the Vajepur Formation and low degree of bioturbation suggest high energy conditions and rapid sedimentation rate with a short colonization window. Bioturbation is observed to increase towards the top of

Vajepur Formation and Bilthana Formation, suggesting a low sedimentation rate and a longer colonization window. The firmgrounds also support the low sedimentation rate. The presence of oyster shells in the oyster beds of the Bilthana Formation limited the burrowing activity; however, at the contact with the underlying shale bed, it increased the preservation potential by infilling the burrows. The transition from storm accumulations of oyster shells in Bilthana Formation to mudstones of Nodular Limestone suggests decreasing intensity of high energy storm events, reduction in wave/current strength, and increased bathymetry. The shells and early cementation at shallow depths that formed the firmgrounds did not favor the burrowing of organisms in the oyster-beds.

Bergaueria and *Thalassinoides* are abundant (>20 ichnotaxa) on discrete horizons suggesting opportunistic colonization and occurring related to the omission surfaces. This Bilthana Formation allowed the opportunistic suspension-feeding organisms to flourish during long periods of quiescence (Shitole et al., 2019). The sudden increase in ichnodiversity and ichnodenisty is observed towards the top of the Vajepur Formation suggests a low-energy, detritus nutrient-rich, shoreface environment. The ichnological analysis has provided valuable information on the distribution of the trace fossils and their paleoecological controls in the shallow marine environment during the Cretaceous sedimentation in the Narmada Basin.

CHAPTER 7
SEQUENCE STRATIGRAPHY

7.1 CONCEPTS OF SEQUENCE STRATIGRAPHY

The concept is defined as a succession of strata deposited during a complete cycle of change in accommodation and sedimentation; it encompasses all types of sequence and has the option of application of any model of choice (Catuneanu et al., 2009). It was introduced three decades ago (Payton, 1977) and is still undergoing refinement. The method could not be standardized as code in the International Subcommission on Stratigraphic Classification (ISSC) due to a lack of consensus amongst different schools of thought on its methodology and models (Catuneanu et al., 2009).

7.1.1 SEQUENCE

It is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). However, the latest study of Catuneanu et al. (2011) removes the criterion of unconformities at its boundaries and identifies sequence as "*A stratigraphic cycle defined by the recurrence of the same type of sequence stratigraphic surface in the rock record.*" Later studies defined various sequences viz. depositional, genetic stratigraphic, and transgressive-regressive, which are also referred to as models.

7.1.2 PARASEQUENCE

A parasequence like sequence is a relatively conformable succession of genetically related beds, but they are bounded by flooding surfaces and are progradational; they may be stacked to produce progradational, retrogradational, and aggradational parasequence sets which resemble the systems tract of a sequence (Van Wagoner et al., 1987, 1988, 1990; Catuneanu et al., 2009). Several authors have considered the concept of parasequence and sequence equivalent and objects of the same rank that differ in the internal architecture and are bounded by surfaces of deepening and shallowing, respectively (Zecchin, 2010). The usage of this term is dropped considering inconsistencies in its definition and limited applicability (coastal and shallow water settings) compared to a sequence that encompasses all depositional systems across the sedimentary basin. Its applications are limited to shallow marine cycles without intervening relative sea-level falls. Others extended the term in succession, recording the full cycle of relative sea level change or alluvial settings and even deep water (Walker, 1992; Catuneanu, 2006; Zechhin, 2007, 2010). Since the concept is limited to a specific architecture and depositional setting and cannot effectively describe cyclic succession, the author has also observed limited usage in sequence stratigraphic analysis in the present study.

7.1.3 SEQUENCE STRATIGRAPHY

The Sequence stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition or their correlative conformities (Posamentier et al., 1988; Van Wagoner, 1995) as they develop in response to variations in sediment supply and space available for sediment to accumulate (Posamentier and Allen, 1999). The relatively conformable sequence always includes the genetically related strata, but genetically related strata do not always consist of a conformable sequence because the presence of the subaerial unconformity (which lies as internal unconformity) within the genetically related sequence would break the continuity in paleogeographic evolution, leaving the succession not relatively unconformable and can no longer be considered negligible. Therefore recently, the concept of relatively conformable succession was removed from the definition of a sequence by Catuneanu (2019). It focuses on analyzing the variation in facies and the geometric of strata and recognizing the major surfaces to understand the chronology of basin fill and erosional events.

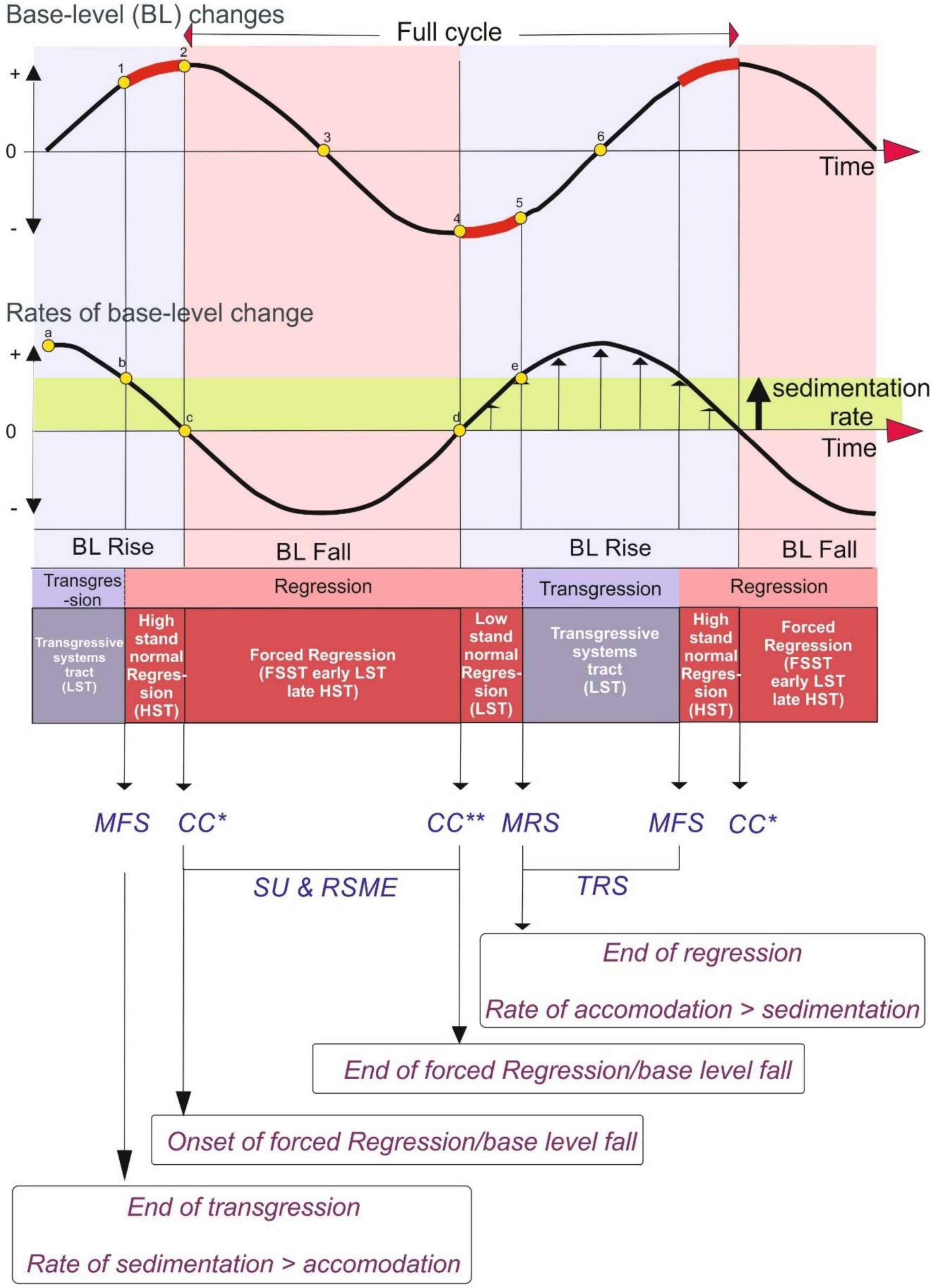
The concept of base-level changes and the rate of base-level changes is explained in Figure 7.1. No. 0-3 marks the positive base level; however, the base-level within it varies from rising (0-2) and falling (2-3). Similarly, no. 3-6 marks the negative base-level, but its base-level varies from falling (3-4) to rising (4-6). The trends of falling base-level during positive and negative base-level changes when combined give the base-level fall/ negative rate of base-level change (c-d), while the trends of rising base-level during positive and negative base-level changes when combined give a rise in base-level/ positive rate of base-level change (a-c; d-g). When combined with sedimentation, the rate of the base-level change gives rise to transgression or regression. The transgression occurs when the rate of base-level change curve is positive and above the sedimentation line. Normal regression occurs when the rate of base-level change curve is positive (either at the start of base-level fall or rise) but is less than the rate of sedimentation line (Fig. 7.1). Forced regression occurs when the rate of base-level change curve is negative and below the rate of sedimentation line.

7.1.3.1 Systems tract/Genetic units

It is defined as the linkage of contemporaneous depositional systems that forms the sequence's subdivision (Brown and Fisher, 1977), which is interpreted based on stratal stacking patterns at bounding surfaces and positions within the sequence (Van Wagoner et al., 1987, 1990; Van Wagoner, 1995). It includes all strata accumulated across the basin during a particular stage of shoreline shifts. The nomenclature for systems tract differs based on models viz. the systems tract nomenclature used for transgression is transgressive systems tract; early lowstand, late highstand, forced regressive wedge, and falling stage are used for forced regression; late lowstand, and lowstand are used for lowstand normal regressive deposits whereas highstand or early highstand are used for highstand normal regressive deposits.

7.1.3.2 Base level

Base-level is generally referred as the sea level, and lies below it (due to waves and currents and because rivers meeting sea erode below the sea level, which is the base level) and is considered as a dynamic surface moving with respect to changes in eustatic sea-level changes to which continental denudation and marine aggradation take place (Jervey, 1988; Schumm, 1993; Posamentier and Allen, 1999; Catuneanu, 2002). Its projection into the continent defines the level up to which continental denudation can take place (Plummer and McGeary, 1996). It is variably defined as the surface of balance between erosion and deposition (Cross, 1991), above which particles cannot come to rest and below which deposition and burial are possible (Sloss, 1962), placed at the lowest level of continental erosion or lowest point on a fluvial profile and is the highest level up to which a sedimentary succession can be built (Twenhofel, 1939). Sequence stratigraphy uses the base level



Base-level (BL) changes
Full cycle
+
0
-
1
2
3
4
5
6
Time
Rates of base-level change
a
b
c
d
e
sedimentation rate
Time
BL Rise
BL Fall
BL Rise
BL Fall
Transgres-sion
Regression
Transgression
Regression
Transgressive systems tract (LST)
High stand normal Regres-sion (HST)
Forced Regression (FSST early LST late HST)
Low stand normal Regres-sion (LST)
Transgressive systems tract (LST)
High stand normal Regres-sion (HST)
Forced Regression (FSST early LST late HST)
MFS
CC*
CC**
MRS
MFS
CC*
SU & RSME
TRS
End of regression
Rate of accomodation > sedimentation
End of forced Regression/base level fall
Onset of forced Regression/base level fall
End of transgression
Rate of sedimentation > accomodation

Figure 7.1 Transgression, regression, and forced regression defined by the interplay of base-level changes and sedimentation at the shoreline (Catuneanu, 2002, 2006; Catuneanu et al., (2009). LST marked by thick red lines represent the initial stage of base-level rise when the rates of base-level rise increase from zero and HST represent the late stages of base-level rise when the rates of base-level rise decrease to zero. CC* and CC** stand for correlative conformity in the sense of Posamentier and Allen (1999) and Hunt and Tucker (1992), respectively. Abbreviations: MFS – maximum flooding surface, CC – correlative conformity, MRS – maximum regressive surface, SU – subaerial unconformity, RSME – regressive surface of marine erosion, TRS- transgressive ravinement surface.

concept as a curve of base-level fluctuations, which describes changes in accommodation at the shoreline when consumed by sedimentation, giving rise to transgressive or regressive shifts in the shoreline (Catuneanu, 2002). In other words, the ratio between the rate of base-level changes and sedimentation gives rise to transgression and the two types of regression (Plint, 1988; Posamentier et al., 1992). The base-level fluctuations are affected by eustatic, tectonic, climatic, diagenetic, wave, and current energy changes and are independent of sedimentation (Catuneanu, 2002). The concept of base level is used for marine and lacustrine settings, whereas the concept of graded fluvial profile for alluvial settings.

7.1.3.3 Accommodation

The available space to be filled up to the base level for sediments is defined as accommodation (Jervey, 1988); this space can be either created or destroyed by the rise and fall of the base-level, respectively. The accommodation space is measured by the vertical distance between the seafloor and base level, and its consumption at higher and lower sedimentation rates results in shallowing and deepening of water, respectively (Catuneanu, 2002). Forced regression represents the negative accommodation, whereas progradation and retrogradation are represented by positive accommodation i.e., water deepening or shallowing can occur at the time of base-level rise depending on the balance between the rate of accommodation and sedimentation.

7.1.3.4 Transgression

The landward shift of shoreline results in the landward shift of facies and deepening of marine water close to shoreline due to a rise in base-level at a rate higher than sedimentation. Transgression in a fluvial sequence is indicated by tidal evidence, oyster beds, and brackish to marine trace fossils (Shanley et al., 1992; Miall, 1997; Catuneanu, 2002).

7.1.3.5 Regression

The seaward shifts of shoreline and facies result in the shallowing of the marine water close to shoreline driven by either high rates of sediment supply during base-level rise (normal regression) or base-level fall (forced regression). Marine facies overlain by nonmarine facies indicate regression in a marine sequence. Normal regression occurs in the early and late stages of base-level rise, whereas forced regression is due to base-level fall irrespective of the sedimentation rate (Catuneanu, 2002).

7.1.3.6 Stacking patterns (depositional trend)

The stratal stacking patterns changes in response to the base-level and rate of sedimentation changes. Each defines a genetic deposit/systems tract (transgressive, lowstand, and highstand normal regressive and forced regressive). The stratal stacking patterns reflect a combination of depositional trends (progradation, aggradation, retrogradation, and downcutting). Transgression gives rise to a retrogradational stacking pattern where the accommodation space/rate of base-level rise outpaces the sedimentation rate. Forced regression produces the progradation with downstepping pattern irrespective of the sediment supply, whereas Normal regression (HST and LST) also produces the diagnostic progradational stacking pattern accompanied by aggradation (in delta plain systems), wherein the rate of sedimentation outpaces the accommodation space/rate of base-level rise (Catuneanu, 2002). The progradational and downstepping pattern is formed in forced regression due to the successive drops in sea level forming a subaerial unconformity.

7.2 SEQUENCE STRATIGRAPHIC MODELS, SURFACES, AND BOUNDARIES

According to Catuneanu et al. (2009), an interplay between accommodation and sedimentation generates transgressive and regressive shifts in the shoreline, giving rise to genetic units/systems tracts (transgressive, forced regressive, highstand, and lowstand normal regressive). Each of these genetic units is defined by a stratal stacking pattern (retrogradational, progradational, and aggradational), bounding surfaces consisting of systems tracts/genetic units (LST, TST, HST, FSST). The depositional models have systems tracts, and their order of occurrence is the stratal stacking pattern. In the different sequence stratigraphic models, the sequence stratigraphic surface can be considered the sequence boundary, a systems tract boundary, or a within systems tract contact (Fig. 7.2). There is no general agreement on which surface should be treated as a sequence boundary. The maximum flooding surface, correlative conformity, and the maximum regressive surface form the sequence boundary for the genetic sequence stratigraphic surface, depositional sequences, and the transgressive-regressive sequence, respectively (Fig. 7.2). The fining-upward and coarsening-upward texture in siliciclastic shallow water settings is used to demarcate the MFS and MRS, respectively, whereas in carbonate platforms, dirtier and cleaner limestone are used to demarcate transgression and regression, respectively. However, the timings of these surfaces depend completely on the sediment supply, which varies along the coastline resulting in highly diachronous surfaces. Still, the boundaries like correlative conformities whose formation is based on base-level shift are independent of sediment supply, synchronous over a large area, and the criterion for recognizing them is based on changes in the stratal stacking pattern irrespective of the sediment supply. Therefore, the criterion of stratal stacking pattern rather than grain size variation is used to recognize the correlative conformities since the correlative conformities form based on changes in the direction of base-level shift. Accordingly, the correlative conformity *sensu* Posamentier and Allen (1999), which occurs at the onset of relative sea-level fall, forms the sequence boundary in the Depositional Sequence I and II. It marks the change in stratal stacking pattern from highstand normal regression to forced regression. It is placed at the base of the basin-floor submarine fan complex in deepwater settings. It occurs at the onset of forced regression due to a decrease in the accommodation space; it is marked by an increase in the average grain size, also known as the basal surface of forced regression.

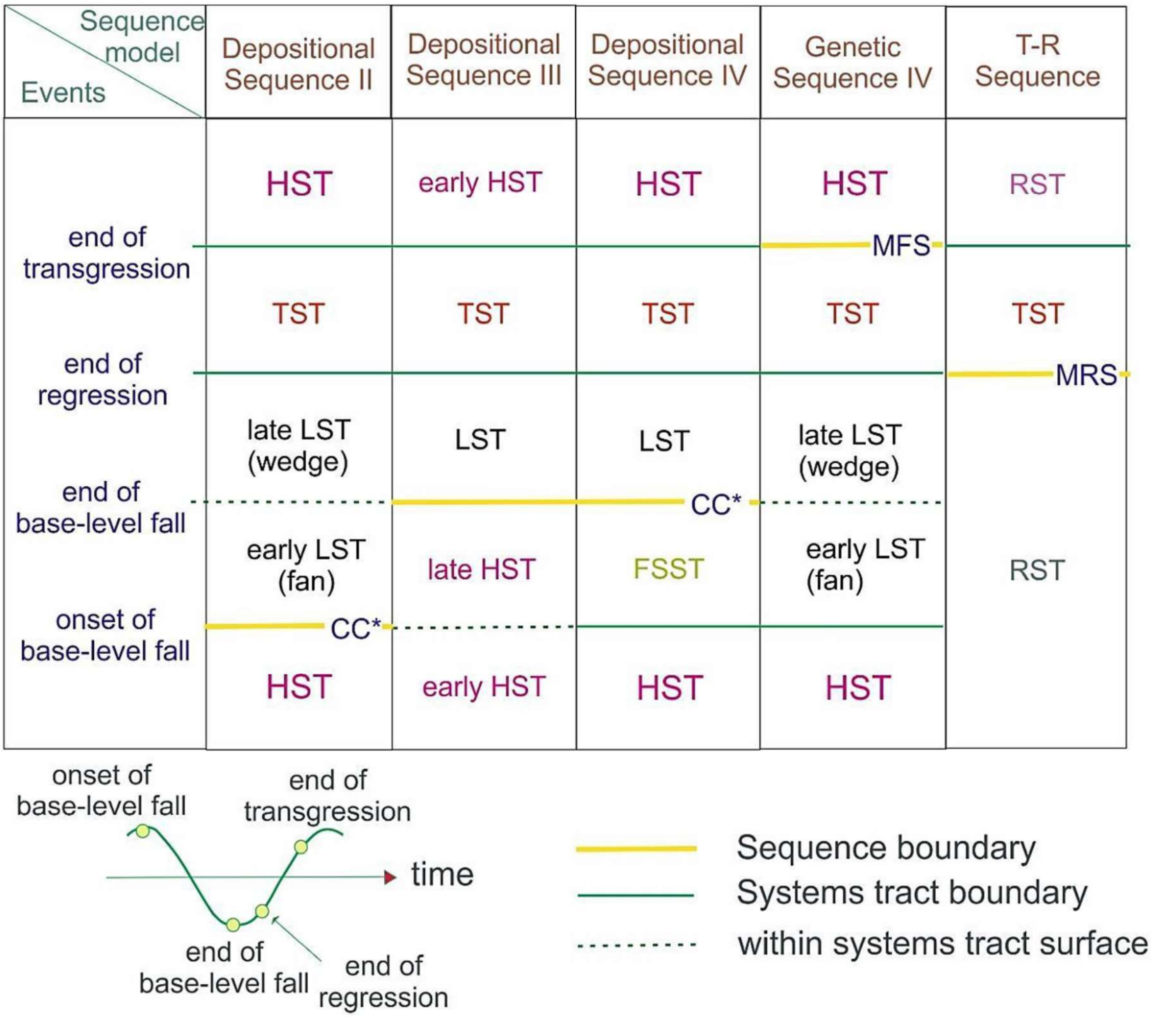


Figure 7.2 Position of sequence boundaries and the subdivision into systems tracts (Catuneanu et al. 2009). Abbreviations LST- Lowstand Systems Tract; HST- Highstand Systems Tract; TST- Transgressive Systems Tract; FSST- Falling-Stage Systems Tract; RST- Regressive Systems Tract; T-R- Transgressive-Regressive; CC*- Correlative Conformity; MFS-Maximum Flooding Surface; MRS- Maximum Regressive Surface.

Correlative conformity *sensu* Hunt and Tucker (1992) which occurs at the end of relative sea-level fall, forms the sequence boundary in Depositional Sequence III and IV (Fig. 7.2). It marks the stratal stacking pattern change from forced to lowstand normal regression. It is placed at the top of the coarsest sediments within the submarine fan complex in deepwater settings. An increase in the fluvial accommodation at the end of forced regression is represented by a decrease in the average grain size. The grain size variation observed at the top and bottom can be used to delineate the correlative conformities. The period between these two correlative conformities has no fluvial accommodation, and in the non-marine environment, it is marked by a subaerial unconformity, whereas in the marine environment, it is characterized by falling stage systems tract. Due to lack of fluvial accommodation, the sediment supplied to the coastline has coarser sediments than the normal regression; therefore, the base and top of the FSST are marked by the increase and decrease in the grain size, respectively. The correlative conformity *sensu* Posamentier and Allen (1999) and the correlative conformity *sensu* Hunt and Tucker (1992) can be distinguished based on the presence and absence of fluvial incision, respectively.

7.3 METHODOLOGY

The methodology of sequence stratigraphy constitutes model-independent workflow and model-dependent choices. The succession is divided into genetic units (systems tracts) separated by the sequence stratigraphic surfaces in the model-independent workflow. Then a model-dependent choice is made by selecting and thus elevating a particular surface to sequence boundary based on the model chosen. Names of constituent systems tracts and surfaces are model-dependent; however, specific terms based on shoreline trajectories viz. transgressive, normal regressive (lowstand and highstand), and forced regression are used as standard terms independent of the model adopted. Thus, the terminology used for the systems tracts and sequence stratigraphic surfaces for genetic units and the surface selected as sequence boundary in the model-dependent aspects does not affect the end result achieved in the analysis. Based on the difficulty encountered in identifying certain stratigraphic surfaces, it is now established that no single model can be generalized for all the case studies, and the interpreter is free to choose any of the models which would serve best to select surfaces and boundaries present in succession for correlating the relatively conformable sequence of genetically related strata. The maximum flooding surface in the genetic stratigraphic model is considered the sequence boundary (Fig. 7.1-7.2.) owing to their easier delineation in succession. The subaerial unconformities or the marine correlative conformities bound the depositional sequences; however, it poses certain problems in their usage as sequence boundaries, viz. their possible erosion during the subsequent transgressive event, identification based on recognition of base-level fall, making their identification difficult in base-level rise. The genetic stratigraphic surfaces are defined based on the base-level fall. They are independent of subaerial unconformities but, wherever available, are included within the sequence. This makes the model easier to apply to all types of cycles and those developed during constant base-level rise (Catuneanu et al., 2009).

The seven surfaces defined in Table 1 are the proper sequence stratigraphic surfaces, which can be used in part as sequence boundaries; apart from them, two other surfaces represent within trend facies contacts, namely, within trend normal regressive surface (normal regression) and within trend flooding surface (during transgression other than MRS, MFS or RS) which are highly diachronous (i.e., varies in age from place to place) with the rate of normal regression and shoreline transgression respectively. They mark lithological variation and have application more commonly in lithostratigraphy and allostratigraphy (Catuneanu, 2002). Within Trend Normal Regressive Surface has a conformable nature which does not rework the below lying deposits or systems tract boundaries and develops within LST or HST. Within Trend Flooding Surface, mark contact between shoreface sands and overlying shelf shales and develop within TST.

7.4 HIERARCHY

The different orders of cyclicity in the sequence are explained in terms of hierarchical order. The hierarchical level can also be explained as the scale of observation. The eustatic fluctuations of the global sea level are controlled by tectonics and climate. The lower orders can be recognized within a sequence with higher resolution data acquisition.

According to Catuneanu (2019), the concept of sedimentological and stratigraphical cycles are related because, at each hierarchical level or scale of observation, depositional systems (units of sedimentology) form the building blocks of systems tracts, which in turn are building blocks of sequence (both are units of sequence stratigraphy). A sequence stratigraphic unit is not controlled by age or scale; the smallest and largest scale of the systems tract and component depositional system is defined by beds and sequences, respectively. Thus, the depositional systems, although sedimentological, are related to the sequence stratigraphy (indirectly form the small element of sequence) and are a three-dimensional assemblage of lithofacies linked by genetically related processes and environments. The scale of depositional systems is not defined (varying from 10^0 to10^3 m). It depends on the purpose of the study and/or availability of data. Still, it requires minimum 10^2 years to form architectural elements (Miall, 2015). At each scale of observation/hierarchical level, they have paleogeographic significance and can be attributed to environments of deposition (Catuneanu, 2019). Thus, the systems tract can also be defined at different scales based on the purpose of the study and data availability; its lowest rank is defined by the stacking pattern of sedimentological units (beds, bedsets).

Hierarchical order	Duration (MY)	Cause
1st order	200-400	Formation and breakup of supercontinents
2nd order	10-100	Volume changes in mid-oceanic spreading centres
3rd order	1-10	Regional plate kinematics
4th and 5th order	0.01-1	Orbital forcing

Table 7.1 Hierarchical orders based on duration.

A sequence should not be regarded as 1st or 2nd order simply based on the duration (Table- 7.1), but each stage is considered as a 1st order sequence defined by a specific tectonic setting (accommodation controlled by subsidence); sequences of equal hierarchical rank in different basins may differ in terms of timing and scales. The sequence stratigraphic frameworks are basin specific, and the 1st order sequence is the fill of sedimentary basins deposited within a tectonic setting. Therefore, the limits of tectonic settings are defined by the 1st order sequence boundary. According to Catuneanu (2019), the depositional systems consisting of only sedimentological cycles are generally incorporated in the lowest rank and consist of only processes related to facies deposited in a specific environment; referred to as depositional systems *sensu stricto*. However, the higher rank depositional systems consist of lower rank stratigraphic cycles that incorporate the changes in systems tract, and the depositional systems are referred to as depositional systems *sensu lato*. The systems tract based on the stratal stacking pattern can exist at each scale except the lowest rank, consisting of only sedimentological cycles. There is no physical standard for the scale of any sequence stratigraphic unit.

7.5 SEQUENCE STRATIGRAPHIC ANALYSIS OF THE BAGH GROUP ROCKS

The composite lithologs of the Bagh Group of the WLNV revealed more or less complete development of the Cretaceous succession. It is Berriasian? (Neococmian) to Coniacian in age, whereby four different composite lithologs of (1) Navagam, (2) Men River Valley, (3) Mohanfort-Vajepur, and (4) Songir are used for sequence stratigraphic analysis. Four different models are suggested for sequence characterization (Catuneanu et al., 2009).

The choice of model in sequence stratigraphy is independent; however, the genetic type of deposits and the surfaces remain the same. For the sequence stratigraphic analysis of the WLNV basin, the interplay of base-level changes and sedimentation can be explained in the second-order Genetic Sequence model proposed by Fraizer (1974) and Galloway (1989) is used to define the sequential fillings. The integration of data on facies, conformable or unconformable stratigraphic contacts, pattern of stacking (depositional trends such as progradation, retrogradation, aggradation, and downcutting), variation of facies along the strike, stratal terminations, and geometries are used to identify the sequence stratigraphic surfaces and systems tracts. The stacking pattern helps to delineate sequence stratigraphic surfaces. Together with-it, systems tracts can be identified. Finally, the surfaces and systems tract help define the stratigraphic sequences. According to the genetic sequence model, the sedimentary succession of the Bagh Group deposits of the WLNV represents two different stratal stacking patterns, downstream controlled and upstream controlled (Catuneanu et al., 2019). Downstream controlled comprises conventional systems tracts, Transgressive Systems Tract (TST) and Highstand Systems Tract (HST) based on shoreline trajectory separated by the Maximum Flooding Surface (MFS). Upstream controlled stacking pattern characterized by channel dominated sequence comprises High Amalgamation System Tract (HAST).

The Bagh Group of the WLNV represents an intracratonic rift system characterized by continuous deposition of sediments from Berriasian? to Coniacian, which comprises the fluvio-marine genetic sequence of the 1st order. The 1st order sequence is further divided into five 2nd orders of depositional events, including HAST, LST, TST-I, HST-I, and TST-II. Based on the evidence of sedimentological and ichnological data in the Cretaceous Bagh Group, a 2nd order sequence separated by three sequence stratigraphic surfaces and one sequence boundary, Maximum Flooding Surface. These depositional events are further subdivided into fourteen 3rd order events based on stacking patterns.

7.5.1 1ST ORDER GENETIC SEQUENCE

As discussed earlier, the hierarchy of sequence is defined based on tectonic settings, and the limits of tectonic settings are defined by 1st order sequence boundary. The 1st order sequence is related to the formation and breakup of continents affecting the evolution of basins and global eustatic changes (Catuneanu, 2006). Accordingly, the 1st order sequences are applied to the entire sedimentary basin irrespective of their origin and the time span

(Catuneanu, 2019). The sequence stratigraphic analysis of the Cretaceous Bagh Group deposits ranging in age from Berriasian? (Neocomian) to Coniacian reveals a complete cycle of base-level changes (transgressive and regressive), which can be explained based on the Genetic sequence model. The genetic sequence is composed of one large-scale 1st order sequence (~56 MY). The genetic sequence model of the Bagh rocks exposed in the WLNV comprises the early syn-rift continental deposits followed by marine deposits, which marked the deepening and shallowing trend representing retrogradation, progradation, and aggradation stacking patterns.

7.5.2 2ND ORDER GENETIC SEQUENCE

The 2nd order sequences are related to the volumetric changes in the mid-oceanic ridge, relative sea-level, and accommodation caused by tectonism of scale affecting the basin and sedimentation, which would affect the basin; 3rd order with the regional plate kinematics affecting the base-level changes (Vail et al., 1991; Gale et al., 2002; Haq 2014). Accordingly, the 2nd order basin-fill within these packages corresponds to the shifts in the balance between accommodation and sedimentation (Catuneanu, 2006). The 2nd order sequence comprises HAST, LST, TST-I, TST-II, and HST-I (Fig. 7.3-7.4), and seventeen 3rd order events have been identified. These systems tract, sequences, and events are bounded by maximum flooding surface and systems tracts surfaces, including the transgressive surface of ravinement and flooding surfaces. To delineate the systems tract and sequence stratigraphic surfaces, sedimentologic characteristics in conjunction with ichnofacies such as *Glossifungites*, *Skolithos* and *Cruziana* are used, which are discussed below.

7.5.2.1 High Amalgamated Systems Tract (HAST)

The High Amalgamated Systems Tract is not related to the base-level changes; accommodation space created by tectonics and sediment supply are the main controls on the sedimentation. The stacking pattern in HAST is dominated by channel facies, low rates of floodplain aggradation, channel avulsion, and unconfined fluvial channels (Catuneanu, 2017). The high amalgamation systems tract is identified based on the progradation-aggradation stacking pattern observed in the WLNV above the Precambrian rocks. The HAST accumulated the initial continental coarse deposits in the fluvial channels, and the fan environment depicts two third-order events characterized by the deposition of conglomerates and sandstones. It is dominated by coarse-grained gravelly sandstones and conglomerates exposed around Agar, Naswadi, Chosalpura, Mohanfort, and Songir villages. This systems tract comprises a 130 m thick succession of the Berriasian? to Aptian deposited in the early rift phase. The gravelly and sandy sediments are characteristic of the alluvial fans and braided channels in fluvial systems, which gave rise to different facies like conglomerate (Plate 5.1-5.3), planar and trough-stratified sandstone (Plate 5.4), horizontal thinly-bedded sandstone, and massive sandstone (Plate 5.5-5.6). The conglomerates at the base of the Songir Formation overlie the Precambrian rocks, represents the hiatus which indicates prolonged erosion, non-deposition, and subaerial exposure. Thereafter, the deposition of thick siliciclastics suggests progradation and increasing accommodation with the advancement of rift opening. The initial coarse-grained gravelly sedimentation took place in the active channel and due to progradation and aggradation of the sediments, which occurs in the proximal portion of an alluvial fan. The advancement of fan is reflected in sedimentary characteristics giving rise to different facies like clast supported conglomerate with sandstone and planar stratified gravels. The further advancement of the fan aggrades relatively fine sediments shows amalgamation with clast-dominated conglomerates, matrix-dominated conglomerates, and planar stratified sandstone of the channel that are well developed in the Songir-Chosalpura and Mohanfort area. The horizontal stratified sandstone indicates the sheet flood over the alluvial fan. The stratified sandstone is poorly bioturbated and shows the presence of *Apectoichnus* trace fossil. The trace is interpreted to be produced by *Teredinidae* bivalves reported from freshwater fluvial settings (Shipway et al., 2019). The presence of dwelling traces produced by freshwater bivalves suggests high energy conditions and sedimentation rate. The Songir Formation is mainly characterized by high-density debris flow deposits with planar stratified sandstone of the channel, and the absence of flood plain deposits suggests a high amalgamation systems tract.

7.5.2.2 Lowstand Systems Tract (LST)

The opening of the Narmada rift in the early Cretaceous gave rise to coastal deposits above the alluvial fan sediments of the Songir Formation. The LST forms during the initial stage of the base-level rise and is characterized by aggradational and progradational deposits of the coastal beach-bar complexes and tidal flat deposits. Lowstand Systems Tract is developed during the Aptian, lower part of the Vajepur Formation, and represents three 3rd

order events. It is dominated by the deposition of intercalated sandstone-carbonaceous shale, intercalated sandstone shale, and thickly-bedded sandstone.

The basal part of the LST comprises thick 60 m quartz arenite facies deposited over the Songir Formation. The large-scale planar cross-stratification of sandstones indicates the high-energy foreshore environment. The lower part of the quartz arenite is non-bioturbated, but few identifiable trace fossils like *Helminthoidichnites* and *Gordia* are observed in the upper part. The absence of bioturbation in the lower part can be attributed to the high sedimentation rate. The clastic deposits suggest increased accommodation due to the prograding shoreline. The analysis of facies association and the trace fossils suggests that the initial phase of sea-level rise was outpaced by sedimentation, which gave rise to lowstand systems tract and, thus, a progradational and aggradation depositional trend during rising sea-level.

The overlying Quartz arenite of LST comprises two contemporaneous deposits; intercalated sandstone-carbonaceous shale and intercalated sandstone-purple shale (Plate 5.9 c-d). The sandstone-carbonaceous shale sequence is developed in the Navagam area, and the base comprises thick carbonaceous shale that grades above in intercalated sandstone-shale. This deposit was developed in slowly rising sea-level, which encroached the land and expanded the tidal flat area. The succession in the basal part characterized by thick carbonaceous shale suggests tidally influenced sediments filled restricted circulation and accommodation space in slowly prograding coastline, whereas the overlying intercalated sandstone with shale suggests accommodation space was filled in the foreshore environment by prograding coastline with repetition of carbonaceous shale suggest a renewal of tidal flat environmental condition.

The intercalated thick sandstone-purple shale succession is well developed in the Kara River (Vajepur) and Men River (Devaliya) sections at the base are attributed to autocyclic pauses in the deposition. The sandstones in the lower part show the presence of cross-beds formed by superimposed barrier-bar complex, and intercalated purple shale suggests a tidally-influenced shoreline. The amalgamated beach-bar complex is characterized by cross-bedded sandstones that dip in the same direction, suggesting increased accommodation space filled by prograding coastline. The large-scale cross-stratification and mud balls observed in the

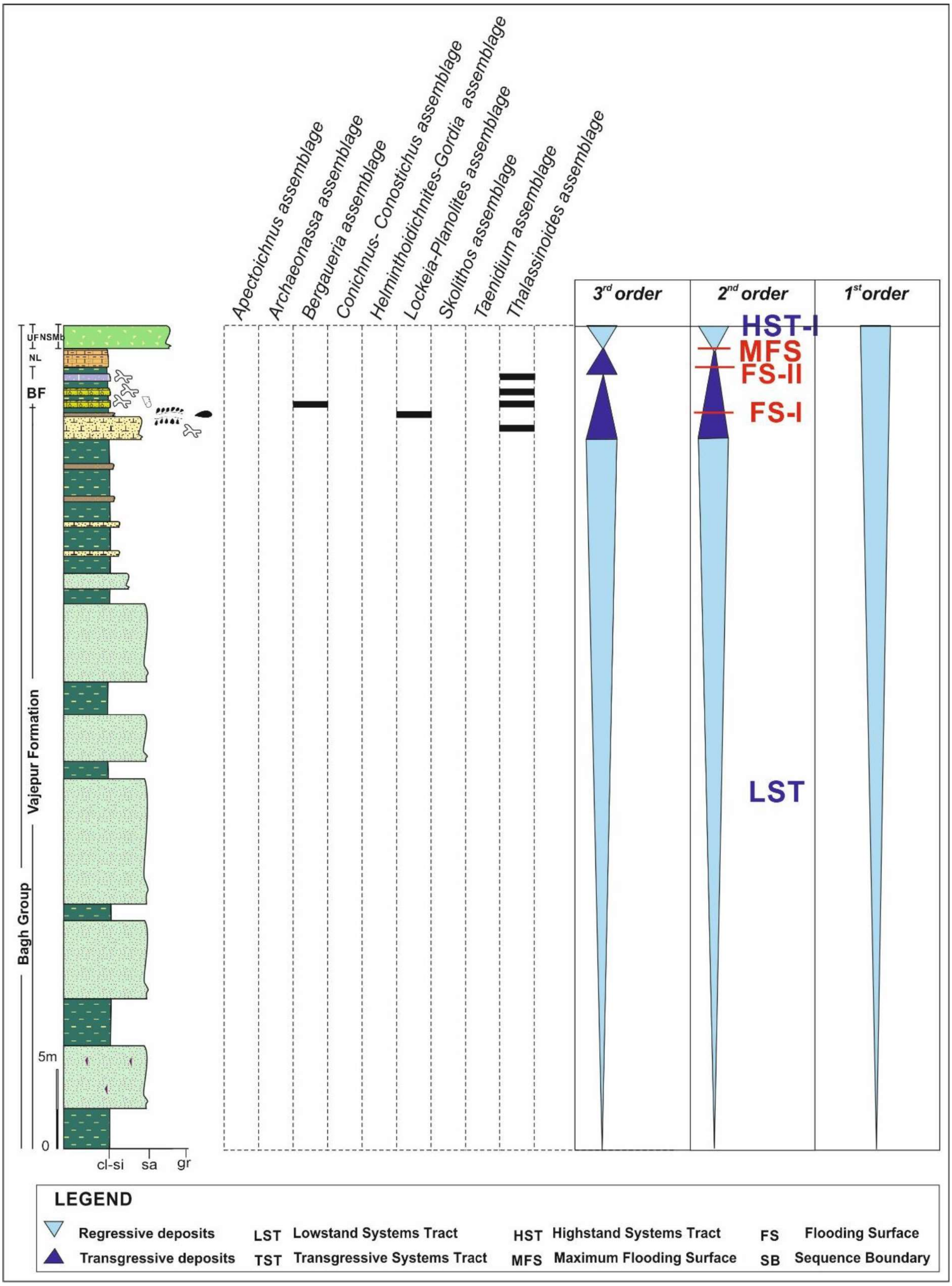


Figure 7.3 Bagh Group succession of the Mohanfort-Vajepur section showing distribution of the ichnoassemblages and genetic sequence of 1st, 2nd and 3rd order.

bedded quartz arenite and the calcareous sandstone facies are regarded to be migration of bars by tidal currents. These sandstones are characterized by sedimentary structures like combined -flow ripples, undulatory to linguoid and sharp-crested wave ripple, and trace fossils like *Planolites* and *Taenidium* (Plate 6.2b-c) suggest tidally-influenced sandy shoreline. The presence of shale indicates tidal current lost the energy in the higher reaches of the intertidal zone and allowed the deposition of the fine-grain sediments, which compensate with accommodation space.

The thick sandstones above the intercalated sandstone-carbonaceous in the Vajepur, Navagam, and Men River Valley are fine to coarse-grained, laminated, or cross-bedded. The laminated nature and lack of bioturbation indicate the sandstones were deposited in the swash zone. Overlying cross-bedded sandstones suggest the beach bar complex developed in the foreshore environment. The amalgamation of the laminated sandstone with cross-bedded sandstone suggests accommodation space was filled due to aggradation and progradation of the coastline.

7.5.2.3 Transgressive Systems Tract (TST) – I

This systems tract is dominated by carbonates, mixed siliciclastics-carbonates, and siliciclastics rocks of the marine environments. It consists of five 3rd order events that characterize rippled calcareous sandstone, micritic sandstones, sandstone-siltstone, intercalated oyster limestone (fossiliferous limestone and sandy/silty allochemic limestone)-shale and limestone (mudstone) deposits. TST sequence consists of abundant body fossils (oysters and ammonites) and trace fossils (*Archaeonassa, ?Arenicolites, Bergaueria, Conichnus, Conostichus, Lockeia, Oniscoidichnus, Planolites, Palaeophycus, Ptychoplasma, Skolithos, and Thalassinoides*).

The calcareous sandstone facies at the base of TST are flaggy and characterized by ripples on each bed and consist of invertebrate fossils (oyster and echinoderms), trace fossils towards the top. The absence of bioturbation in the lower part can be attributed to the high sedimentation rate. *Archaeonassa* isp. in the rippled calcareous sandstone facies is suggests the presence of invertebrate grazers like gastropods. The presence of body fossils and trace fossils in the calcareous sandstone above the cross-bedded sandstone of LST marks the

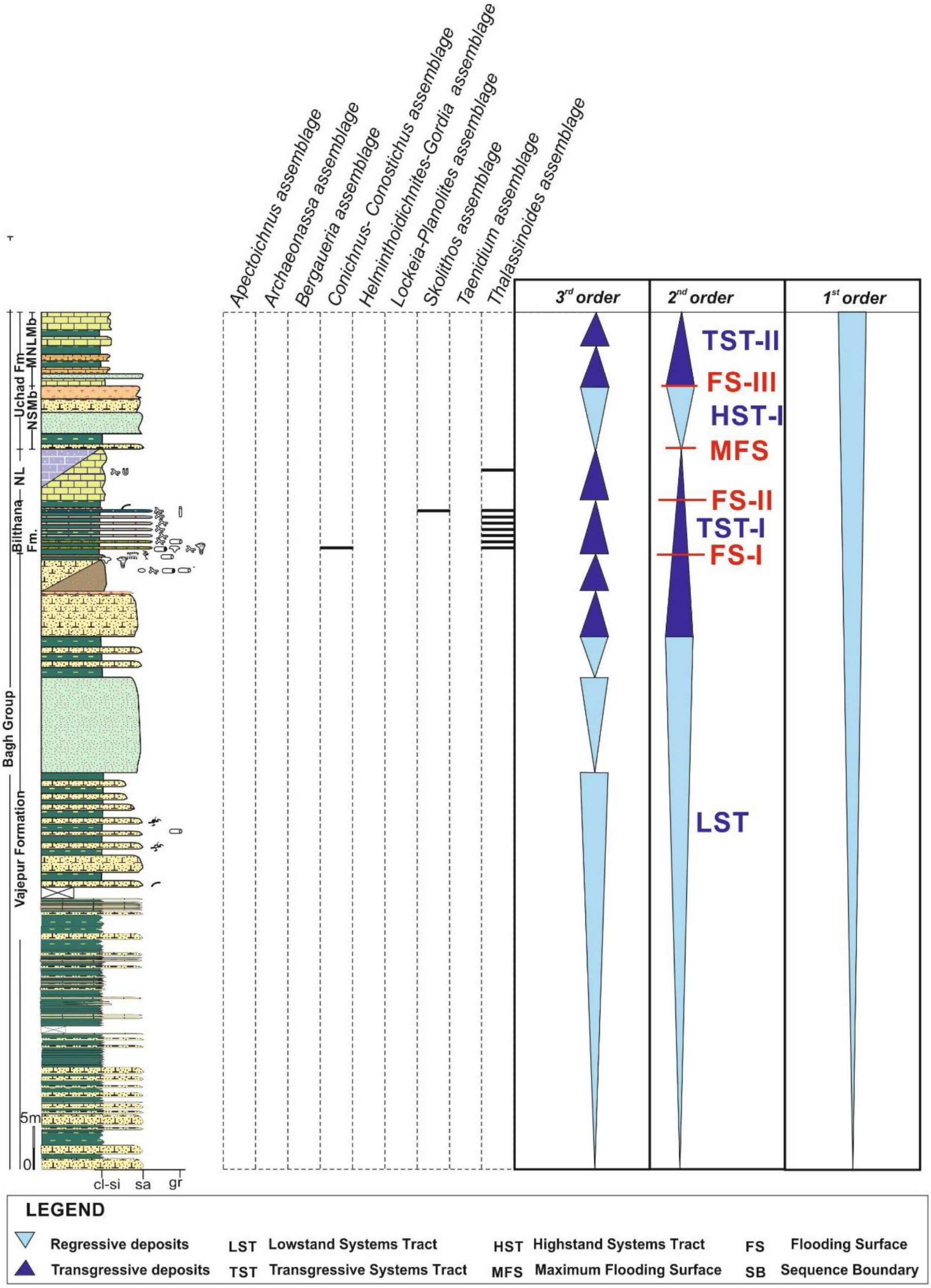


Figure 7.4 Bagh Group succession of the Men River Valley showing the distribution of ichnoassemblages and genetic sequence of 1st, 2nd, and 3rd order.

deepening of the sea. Overlying thinly bedded fine-grained micritic sandstone suggests deposition took place in the moderately agitated shoreface environment. The thinly bedded sandstone-siltstone unit is characterized by sinuous crested ripples consisting of abundant plug-shaped burrows such as *Conichnus, Conostichus* with *Oniscoidichnus, Planolites, Palaeophycus, Thalassinoides,* and *Ptychoplasma.* The calcareous sandstone-siltstone of Vajepur Formation marks the Flooding Surface-I (FS-I) overlying shales of Bilthana Formation, and Flooding Surface-II (FS-II) is marked between the oyster-shale and mudstone facies of the Nodular Limestone (Fig. 7.3-7.4). These stratigraphic surfaces marked the abrupt increase in water depth (Catuneanu, 2002) and allowed the deposition of the fine-grain clastic and carbonate sediments.

The intercalated oyster limestone-shale facies is characterized by abundant oysters and plug-shaped burrows, *Bergaueria, Conichnus, Conostichus* with *Planolites, Palaeophycus, Skolithos,* and *Thalassinoides*. The development of *Cruziana* ichnofacies in the sandstone-siltstone facies and substrate-controlled *Glossifungites* ichnofacies in cohesive mud represents FS-I. The time gap characterized by *Glossifungites* ichnofacies is indicated by the firmground substrate colonized by the sea anemones and crustaceans, which was initially dewatered due to burial, and the firmer the substrate greater is the temporal break generally of allocyclic nature (Gingras et al., 2001). The *Cruziana* and *Glossifungites* ichnofacies observed in the TST-I suggest deposition in the lower shoreface to the offshore environment below FWWB and above SWWB. Flooding surface- II (FS-II) marked at the top of shales of Bilthana Formation too represents an abrupt increase in the water depth characterized by deposition of ammonite-bearing mudstones of Nodular Limestone. The deposits of the fine clastics are replaced by the carbonates owing to the increase in water depth and accommodation space.

This is further overlain by poorly fossiliferous mudstones facies of Nodular Limestone containing the *Placenticeras*ammonite of the Turonian age. A thick and basin-wide occurrence of the Nodular Limestone suggests the deposition of thick carbonates in deeper water below the SWWB due to base level rise and increasing accommodation space. Mudstone facies of Nodular Limestone has marked the maximum transgression in the WLNV coinciding with worldwide Cenomanian-Turonian eustatic sea-level rise. The Vajepur Formation, Bilthana Formation, and Nodular Limestone represent a transgressive systems tract evident from the retrogradational stacking pattern of landward shifting facies and a fining-upward succession characterized by an increase in the carbonate content towards the top.

7.5.2.4 Highstand Systems Tract (HST) – I

The Highstand Systems Tract developed during the late stage of base-level rise characterized by sandy micrite facies deposited over the mudstone facies of the Nodular Limestone exposed around Uchad village (Fig. 7.4). It consists of five 3rd order cycles comprising sandy micrite, micritic sandstone, quartz arenite, calcareous sandstone, and gravelly sandstone. HST-I is dominated by mixed siliciclastic-carbonates and siliciclastic rocks well-developed at Navagam and Men River Valleys sections. The sudden increase in fine sand influx above the mudstone with their variable proportions at different places has given rise to the different types of mixed siliciclastic-carbonate rocks. The accommodation space filled with mixed clastic- nonclastic sediments resulted in the progradation of the coastline. The sandy micrite is devoid of body, and trace fossils marked the early stage of HST-I, lateral increase in clastic proportion is represented by micritic sandstone. The intensely bioturbated micritic sandstone consists of abundant *Skolithos* burrows belonging to *Skolithos* ichnofacies observed at Navagam village. This sequence further grades upward with the interbedded calcareous sandstone and quartz arenite facies of the Narmada Sandstone Member characterized by herringbone cross-stratification (Plate 5.8a) and ripple marks. Lithological and ichnological evidence suggests high wave and current energy, shifting substrate of the shoreface environment. The HST-I is represented by gravelly sandstone at the top, suggesting a high wave energy coastline. This gravelly sandstone comprises a number of gravel lag deposits of the high-energy beach environment indicating the maximum base-level drop in the WLNV. The sedimentary structures, ichnological and lithological evidence suggest shifting substrate and a high-energy shoreface environment where the rates of sedimentation exceeded the rate of base-level rise, giving rise to normal regression with an aggradational and progradational stacking pattern. It is bounded by the maximum flooding surface (MFS) at the base. A coarsening upward sequence of the HST-I shows the gradation in the facies where the lower part corresponds to the progradation of the shoreface facies over the offshore facies and the upper part corresponds to high energy upper shoreface-foreshore facies.

The development of HST-I over TST is observed throughout the Western Lower Narmada Valley basin, which suggests a low rate of base-level rise due to an increase in the rate of sedimentation. Sedimentary structures such as planar, trough and herringbone cross-stratification, and the *Skolithos* ichnofacies observed in the HST-I suggest deposition mainly above the FWWB in the regressive coastline. The Coniacian sequence aggraded and prograded over the Turonian transgressive deposits and correlates with global eustatic sea-level drop.

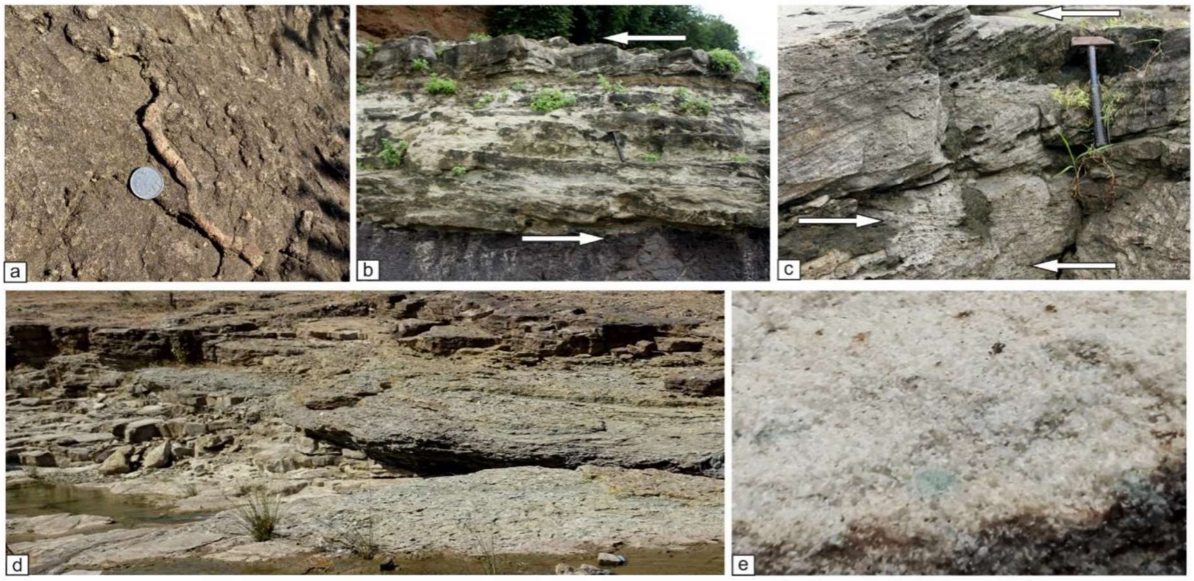


Plate 7.1 Field photographs showing primary and biogenic sedimentary structures and compositional variation. a. *Thalassinoides* with collapsed branches represented as circular scars on the burrow, Narmada Sandstone Member, Navagam section. b-c. Bidirectional cross-stratified sandstones, Vajepur Formation, Men River valley. d. Coarse-grained sandstone of the Vajepur Formation demarcating the Transgressive Ravinement Surface, Men River Valley. e. Glauconitic grains in the calcareous sandstones of Vajepur Formation, Men River valley.

7.5.2.5 Transgressive Systems Tract (TST) – II

The Transgressive Systems Tract–II was developed during the Coniacian age and observed in the succession of the Men Nadi Limestone Member of the Uchad Formation. It comprises four 3rd order events and mainly consists of carbonates (mudstone) with quartz arenite, muddy micrite, and shale. The micritic sandstone of the underlying HST-I grades to mudstone and marks the base-level increase immediately followed by progradation and gave rise to quartz arenite facies in TST-II. This event marked the temporary withdrawal of carbonate sedimentation that further renewed upward, giving rise to mixed siliciclastics-carbonates (muddy micrite) with fine-grained clastics, suggesting increasing base-level and accommodation place in the shoreface environment. Further increase in the base-level resulted in the deposition of carbonates and fine-grained clastics. The gradual change from siliciclastics to mudstones suggests deposition took place in a calm environment below the SWWB. Overall, TST-II shows the increasing proportion of carbonate sediments with delicate bivalve shell fragments upward, marking the second flooding episode in the WLNV.

The Flooding Surface-III (FS-III) is identified at the contact of sandstone of the Narmada Sandstone Member and carbonate of the Men Nadi Limestone Member (Fig. 7.4), which suggests minor submarine erosion or non-deposition across which there is an abrupt increase in water depth developed during transgression (Catuneanu, 2006). This facies contact is not a part of a systems tract boundary or of a sequence boundary but serves to demarcate the internal facies detail as Within Trend Flooding Surface (Catuneanu, 2002). The development of Flooding Surface-III (a minor unconformity) suggests a rapidly rising sea level. TST-II indicates the rate of sea-level rise exceeded the sedimentation rate giving rise to a retrogradational stacking pattern.

7.5.3 MAXIMUM FLOODING SURFACE (MFS) / SEQUENCE BOUNDARY

The Sequence Boundary integrated with the transgressive surfaces at the top of mudstone facies of Nodular Limestone represents a Maximum Flooding Surface (MFS). It separates the retrograding strata (TST-I) of Nodular Limestone from the prograding deposits (HST-I) of Narmada Sandstone Member of Uchad Formation. The Maximum Flooding Surface is characterized by either sharp or gradational contact in the WLNV Basin. The contact between TST-I and the overlying HST-I is gradational at Navagam, marked by an increasing proportion of fine clastics in carbonate, characterized by sandy micrite/micritic sandstone to bioturbated, *Skolithos* and *Thalassinoides* (Plate 7.1a) bearing fine gravelly calcareous sandstone.

The TST-I is characterized by thick nonclastic (carbonate) deposits that suggest a diminishing in terrigenous supply to the basin, marking the Maximum Transgressive Surface. It has sharp contact with overlying Narmada Sandstone Member, clastic facies of shoreface deposits (HST-I), and thus high preservation potential (Catuneanu et al., 2006). The Sequence Boundary MFS in the WLNV marks the beginning of normal regression represented as gradational or sharp contact and suggests minor erosion in HST-I.

7.5.4 SYSTEMS TRACT BOUNDARIES

The genetic sequence Bagh Group succession of the WLNV is represented by the HAST, LST, TST-I, HST-I, and TST-II. Apart from the Sequence Boundary, Maximum Flooding Surface (MFS), Sequence Stratigraphic Surface (Transgressive Ravinement Surface), and Systems Tract Boundary are identified (Catuneanu, 2019). The Transgressive Ravinement Surface separates the TST-I from the LST, while the Systems Tract Boundary separates the HAST and LST.

The surface between the alluvial fan facies of the HAST and the overlying tidal flat facies of the LST is observed between Songir Formation and Vajepur Formation at Vajepur, marked by an abrupt change in bed geometry and lithology. The gravelly sandstones of the HAST are overlain by the intercalated sandstone-shale succession of the foreshore-tidal flat environment. During the base-level rise, the higher sediment supply developed the aggradation and progradational stacking pattern of a beach-bar complex in the Vajepur Formation. Systems Tract Boundary consists of bi-directional cross stratified (Plate 7.1b-c) calcareous sandstone and intercalated with purple shales; glauconitic grains (Plate 7.1e) indicate the onset of base-level rise.

Transgressive Ravinement Surface marks the contact between LST and the overlying TST-I. The ravinement surface concept was first introduced by Stamp (1921) to demarcate the first stage in the landward movement of a transgressing sea characterized by a wave-deposited coarse conglomerate of coastal origin. The coarse-grained sandstone with oyster-lag deposits (Plate 7.1d) of the Vajepur Formation marks the ravinement surface and separates the LST from the above fine-grained shoreface deposits of the TST-I. This change shown by the stacking pattern from progradation to retrogradational suggests the increased rate of base-level rise. The preservation of thick normal regressive coastal deposits of the Vajepur Formation suggests prolonged stages of lowstand normal regression and high rates of sediment aggradation (Catuneanu, 2006).

7.6. DISCUSSION

The eustatic sea-level changes are brought by either change in the volumes of ocean water (glacio-eustatic changes) or change in the volume of spreading of oceanic ridges (Plint et al., 1992). A global greenhouse was reported in several studies during the Cretaceous, which raised the average temperatures, and major plate-reorganization events changed the volumes of oceanic ridge basalts. All such factors probably induced the Cretaceous global transgression; the transgressive Tethys Sea encroached in the LNV and deposited thick calcareous sandstone with mixed siliciclastics – carbonate sediments and limestone during Cenomanian-Coniacian. These transgressive deposits are represented as Vajepur Formation, Bilthana Formation, Nodular Limestone, and Uchad Formation in the WLNV (Shitole et al., 2021) and coincide with the high global sea level. The eustatic sea-level rise during the Cenomanian-Turonian can be caused by the fast rate of spreading, which generated large volumes of oceanic lithosphere, thereby increasing the ridge volume and raising the sea level (Ramkumar, 2015). The high rates of seafloor spreading are attributed to the major plate reorganization event, which generated intra-plate stresses and reactivated the Narmada rift along the pre-existing crustal weakness.

The sequence stratigraphic analysis of the Bagh Group rocks based on sedimentology and ichnology revealed slowly transgressing Tethys Sea over the fluvial rift sediments. Unconventional High Amalgamation Systems Tract characterizes the Pre-Albian succession; this early developed rift precludes correlation of the pre-Albian succession with the eustatic curve (Fig. 7.5). The post-Aptian succession is characterized by the transgressive deposits representing the encroachment of the Tethys Sea, whereby the trend of the eustatic and WLNV curves indicates the eustatic changes mainly influenced the sedimentation. The global Cretaceous sea-level changes of Haq (2014), averaging the highstands and the lowstands by Ruban (2014), is correlatable with the Albian-Coniacian transgressive deposits of the Western Lower Narmada Valley, with a minor Early-Coniacian regression (Fig. 7.5) which is observed worldwide (Haq, 2014) and attributed to the uplifts or tectonic events.

An integrated data of sedimentology and ichnology of the Cretaceous Bagh Group sequence of the Western Lower Narmada valley revealed the Genetic Sequence up to 3rd order (Galloway, 1989). The intracratonic WLNV rift basin comprises a well-developed fluvio-marine genetic sequence resulting from the interaction of tectonics and sea-level changes. The Genetic Sequence model (Fig. 7.6) shows the development of the Systems Tracts including, HAST, LST, TST-I, HST-I, and TST-II, Sequence Boundary (MFS), Sequence Stratigraphic Surface, and Systems Tract Boundary.

The initial phase of the rifting received continental sediments of the braided channel and alluvial fan during the Early Cretaceous, represented by the HAST before the Albian.

The sequence of HAST unconformably overlies the Precambrian and marks a long hiatus indicating prolonged subaerial exposure and erosion. The conglomerate and sandstone facies of the Songir Formation consist of sediments derived from the Precambrian basement. The Thick fluvial

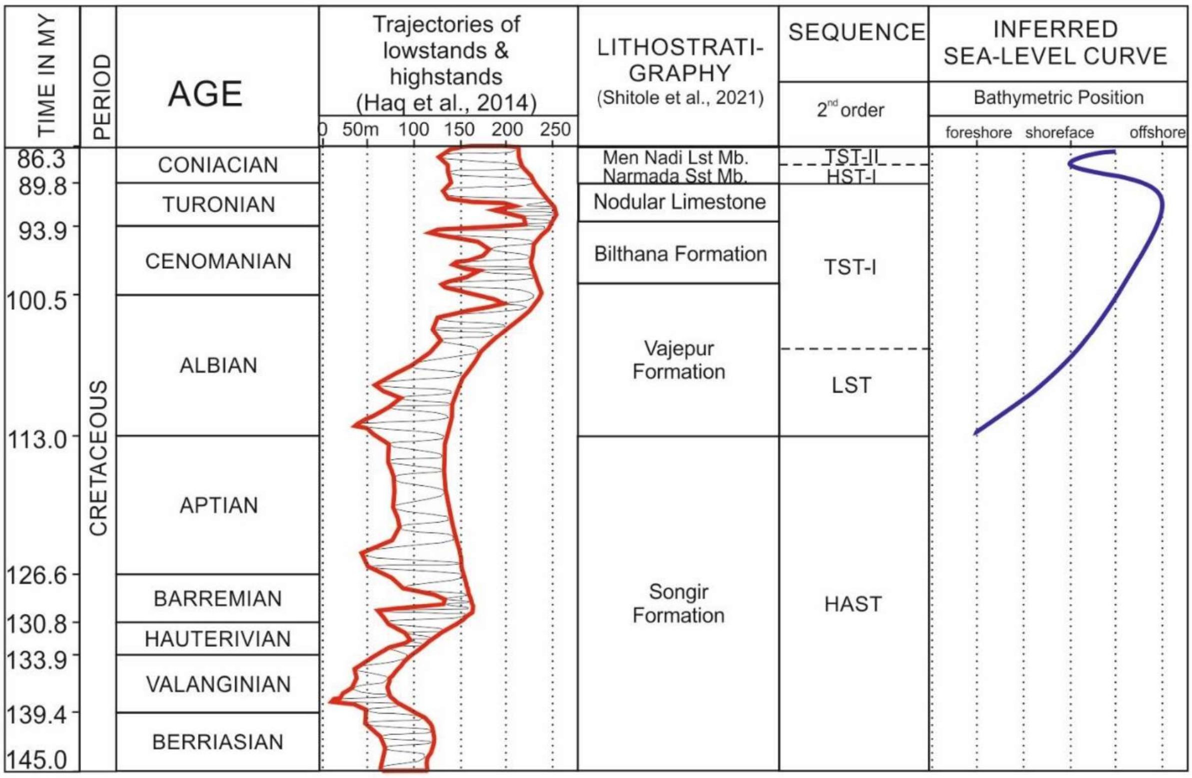


Figure 7.5 Comparison of Cretaceous shoreline trajectory of the WLNV with the eustatic curve (Haq, 2014) based on systems tracts, sequence boundary, sequence stratigraphy surfaces, and systems tract boundary (Ruban, 2014). The Pre-Albian succession is characterized by unconventional High Amalgamation Systems Tract, while conventional systems tracts characterize Post-Aptian succession.

sedimentary sequence of the Songir Formation suggests advancement of the alluvial fan with increased accommodation space giving rise to prograding and aggrading of HAST. Further advancement of the rift and increased base-level during the Albian gave rise to deposition of the LST over the HAST. The Vajepur Formation depicts the change in lithology and bed geometry compared to the lower Songir Formation, which marked the shifting of unconventional HAST to conventional LST (Fig. 7.6). The LST conformably overlies the HAST and is characterized by intercalated sandstone-shale succession deposited in a tidally-influenced beach/foreshore environment. It is interpreted as prograding and aggrading deposits consuming the accommodation space created during the rising base-level.

The upper part of the Vajepur Formation is characterized by Cenomanian transgressive deposits of TST-I, which conformably overlies the sandstone–shale sequence of the LST. Initially, TST-I is characterized by fine-grained rippled calcareous sandstone facies and, in an upward direction, shows the development of carbonate-rich sediments, including the fossiliferous limestone, sandy allochemic limestone, and shale facies of the Bilthana Formation; sandy micrite and mudstone facies of the Nodular Limestone of Turonian. The oyster bearing limestone consists of *Thalassinoides* and plug-shaped structures, indicating omission surfaces developed in the shoreface environment. Further rise in base level gave rise to mudstone of Nodular Limestone, which formed in the offshore environments.

The abrupt change in facies during the Coniacian over the Turonian TST-I marked a change in base level due to aggradation of the sediments or local tectonics. Sediments of the Narmada Sandstone Member characterize HST-I deposited during the high stands of sea level, which consumed the accommodation space and resulted in progradation and aggradation. The fine-grained pebbles were observed in the calcareous sandstone at the base of the HST-I, suggesting they were less transported and moved rapidly with the regressing sea.

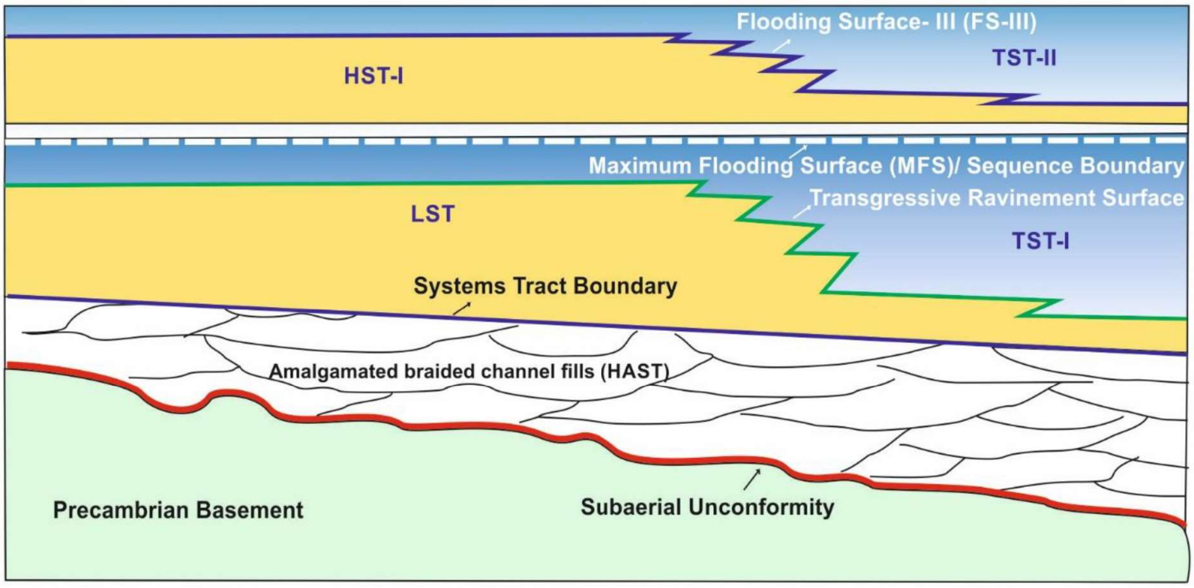


Figure 7.6 Conceptual sequence stratigraphic model of the Cretaceous Bagh Group rocks, WLNV showing stratal stacking pattern.

The second transgressive event occurred in the Coniacian, which gave rise to the conformable succession of TST-II over the HST-I (Fig.7.6). The TST-II is observed in the Men Nadi Limestone Member, characterized by muddy micrite, shale, and mudstone facies with delicate shell fragments suggesting low energy distal shoreface environments.

A sudden change or passing the threshold in an environmental parameter leads to the formation of discontinuity in the sedimentation process marked by a sharp change in facies or a surface in a stratigraphic section and is independent of scale (Hillgartner, 1998). Moreover, lithology and trace fossils help demarcate sequence stratigraphic surfaces, which correspond to changes in sea level in the WLNV Basin. One major unconformity and three major types of discontinuities are identified in the Bagh Group sequence (Fig. 7.4): 1. erosional discontinuities observed in the Vajepur Formation characteristic of Transgressive Ravinement Surface (TRS) and Maximum Flooding Surface (MFS) observed at the top of mudstone facies of TST-I. 2. depositional discontinuity i.e., Marine Flooding Surface, which represents abrupt deepening observed between calcareous sandstone-siltstone facies of Vajepur Formation and shale facies of Bilthana Formation (FS-I), between the fossiliferous limestone-shale facies of Bilthana Formation and mudstone facies of the Nodular Limestone (FS-II) and at the top of Narmada Sandstone Member (FS-III). 3. non-depositional hiatus in the Bilthana Formation indicated by the presence of firmgrounds.

Moreover, the minor discontinuities are also identified in the study area based on the presence of trace fossils that largely coincide with the minor flooding surfaces (Fig.7.4). It is observed at the top of the bioturbated rippled calcareous sandstone characterized by the trace fossils of *Cruzian*a Ichnofacies of the Vajepur Formation in contact with shales of the Bilthana Formation within the TST-I. The abundant occurrence of *Thalassinoides* in the shale towards the top of Bilthana Formation and *Bergaueria*, *Conichnus,* and *Conostichus* at its bottom represent submarine erosion by short-term high-energy events, where the semi-consolidated micrite offered resistance to erosion. This shale bed was a stable substrate colonized by firmground trace makers, indicated by the presence of sharp-walled and unlined burrows of suspension feeders, which were later passively filled. *Glossifungites* Ichnofacies at the sharp-based contact between the shale and oyster beds of Bilthana Formation and in the middle-level of the Nodular Limestone marks a hiatus (short-lived discontinuity) in the deposition.

Based on sedimentological and ichnological data, the sequence stratigraphic analysis of the Cretaceous succession of the WLNV Basin revealed that it was evolved due to intra-cratonic rifting, initially filled by fluvial deposits and later by eustatic sea-level rise.

CHAPTER 8
COMPARATIVE STUDY OF PERVASIVE TETHYAN BASINS

8.1 INTRODUCTION

The breakup of Pangea began with continental rifting during the Late Triassic. Pangea separated into the continents of Laurasia and Gondwana, which were further fragmented during the Middle Jurassic, widening the Tethys Sea between the Gondwana and Laurasia at the equator.

When rifting further developed, oceanic spreading centers formed between the landmasses. The east-west oriented Tethys Sea existed from 250- ~50 million years ago and separated the Gondwana and Laurasia (Rafferty, 2010). Gondwana in the south during much of the Mesozoic Era (252 to 66 million years ago) before these landmasses fragmented into the modern continents, which consist of South America, Africa, Peninsular India, Australia, and Antarctica. During the Jurassic Period (around 180 million years) the Gondwana separated into eastern (Madagascar, India, Australia, and Antarctica) and western (Africa and South America) part. During the Middle Jurassic, North America initiated separation from Eurasia and Gondwana and Africa from South America during the Late Jurassic (Reeves, 2009). During the end-Cretaceous, the Central Indian Ocean was opened between Australia-Antarctica and India and Madagascar also, Madagascar detached from Africa, and South America drifted in north-west direction. The Late Cretaceous witnessed the separation of India from Madagascar and Australia from Antarctica. The Gondwanian Tethyan margin extended from Arabia in the west to Australia in the east, with Madagascar, east Africa, and India in between (Krishna, 2017).

The Neo-Tethyan Basin consists of several intra-, peri-cratonic rift basins in India, Africa, Australia, and Antarctica. The fragmentation and drifting of continents deposited thick marine successions in troughs along their margin. The Jurassic marine deposits occur on the margins of Eurasia and Gondwana, i.e., along the northern and southern boundaries of the

Tethys Sea. Many of the Earth's tropical continental shelves at this time were found around the margins of the Tethys Ocean; each one of them preserved a thick sedimentary succession of continental and marine deposits of the Mesozoic Era. A large percentage of Mesozoic sedimentary succession occurs in various parts of Gondwana. Mesozoic witnessed several transgressions and regressions; the last Cretaceous transgression flooded large parts of the continents.

A comparative study on stratigraphy, sedimentology and trace fossils was carried out between the LNV and various Tethyan Basins. To evaluate the impact of Cretaceous Gondwana segmentation and the eustatic sea-level rise on the other Tethyan basins, the sedimentary sequence of the Bagh Group (Narmada Basin) was compared with the Eastern Desert (Egypt), Mahajanga Basin (Madagascar), Carnarvon Basin (Australia), Saurashtra-Kachchh, Jaisalmer-Barmer, and Cauvery basins (India). The comparison was explained in the light of eustatic changes and tectonic events during the disintegration of Gondwana. Lithostratigraphic correlation of the Tethyan basins during the Cretaceous helps understand the Cenomanian-Turonian eustatic history and the effect of Late Cretaceous tectonic changes. The synthesis of the earlier ichnological work on Cretaceous rocks of western India and their comparison compiled with the lithostratigraphy of the area allows evaluating the rift events, fauna, depositional control in trace fossil distribution, and the impact of global Cretaceous eustatic changes of the Tethys Sea on the shallow marine fauna in various pervasive basins in India.

8.2 SEDIMENTOLOGY, STRATIGRAPHY, AND ICHNOLOGY OF THE CRETACEOUS SEQUENCES OF THE PERVASIVE TETHYAN BASINS

The Cretaceous Period witnessed several global events like the splitting and drifting of continents, eustatic sea-level changes, mass extinctions, oceanic anoxic events, and volcanism. Imprints of these events are preserved in the Cretaceous sedimentary succession of the Tethyan basins. The Lower Narmada Valley preserves a nearly complete Cretaceous sedimentary record of the fluvio-marine environments (Shitole et al., 2021). The Cretaceous lithostratigraphy along with an ichnological record of the Bagh Group rocks of the WLNV, is compared (Fig. 8.1) with the available record with the eastern part of the LNV, global Tethyan basins (Eastern Desert, Egypt; Mahajanga Basin, Madagascar; Carnarvon Basin, Australia) and the Indian subcontinent (Kachchh-Saurashtra basins lying adjacent to the study area, Jaisalmer-Barmer basins of Rajasthan occurring to northwest of the study area and with the Cauvery Basin, southern India). This study would facilitate an understanding of the development of the sedimentary succession and animal response to the environment during the Cretaceous period in the southern Tethyan Basins of the Gondwanaland and provide a comparative evaluation of the depositional processes.

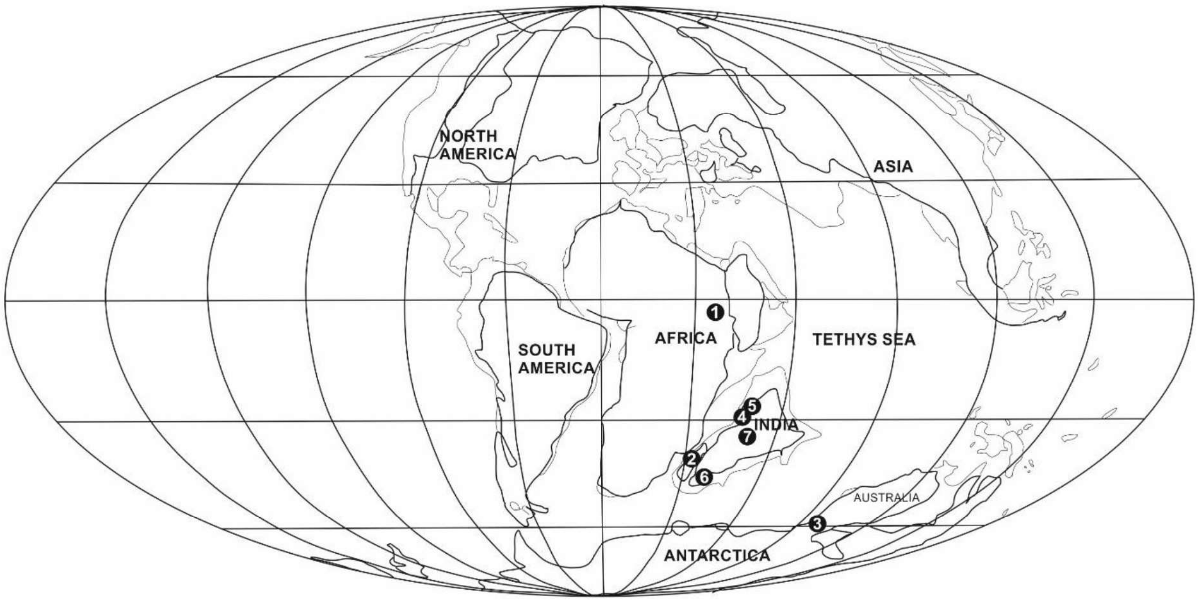


Figure 8.1 Paleogeographical map showing the distribution of the continents during Albian-Cenomanian (Bardhan et al., 2002) and position of the 1. Eastern Desert (Egypt), 2. Mahajanga Basin (Madagascar), 3. Carnarvon Basin (Australia), 4. Saurashtra-Kachchh basins (India), 5. Jaisalmer-Barmer basins (India), 6. Cauvery Basin (India) and 7. Narmada Basin (India) (modified after Shitole et al., 2021).

8.2.1 EASTERN DESERT (EGYPT)

During the Late Cretaceous, Egypt was located at a higher palaeo-latitude (0°-20° N) in the northern hemisphere (Boucot et al., 2013) and was a part of the African/Arabian Plate, compared with the Indian subcontinent (~30°- 60° S) (Fig. 8.1). The Bagh Group rocks in WLNV comprise Berriasian? to Coniacian, and the Eastern Desert in Egypt contains Early Cretaceous to Santonian Tethyan deposits (Fig. 8.2). Lithologically, the Lower Cretaceous – Middle Cenomanian rocks of the Malha Formation in the Eastern Desert (Wilmsen and Nagm, 2013) and the Songir Formation of the Bagh Group in the Narmada Basin are characterized by continental siliciclastic deposition at the base. The overlying Galala Formation and Maghra El Hadida Formation range in age from Upper Cenomanian-Lower Turonian in the Eastern desert Wadi Qena and Wadi Araba region (Wilmsen and Nagm, 2013) and unconformably overlie the Malha Formation (Hewaidy et al., 2012). The formation consists of cross-bedded and glauconitic sandstones, shales, silty marls, marls, oyster shell beds, nodular fossiliferous limestones with calcareous algae, and rudist bivalves deposited in a shallow-marine, open lagoonal environment (Ismail et al., 2009; Nagm, 2009; Nagm et al., 2014; Wilmsen and Nagm, 2012, 2013). The Vajepur Formation (Albain-Cenomanian) consists of cross-bedded calcareous, siliceous, and glauconitic sandstones and shales; Bilthana Formation (Cenomanian-Turonian) consists of Oyster limestones and shales and mudstones, and silty marls characterize the Nodular Limestone (Turonian). The lithological composition of the Vajepur, Bilthana, Nodular Limestone, and the Galala Formation suggests a similar deposition during the major Tethyan Cenomanian-Turonian transgression in both basins. The underlying Lower Cretaceous- Middle Cenomanian Malha Formation is concomitant with the Cenomanian eustatic sea-level rise (Wilmsen and Nagm, 2012). The Galala Formation and the Nodular Limestone of the Bagh Group succession comprise abundant *Thalassinoides* burrows and ammonites of Cenomanian-Early Turonian (Chiplonkar et al., 1977a; Kumar et al., 2018; Nagm and Wilmsen, 2012). The shallow marine cross-bedded sandstones intercalated with shales or siltstones, oysters, and carbonates at the base mark the onset of Cenomanian transgression, with siliciclastics derived from the pre-existing rocks in the Eastern Desert (Ismail et al., 2009) and in the Narmada Basin. The upper Cenomanian to upper Turonian Maghra El Hadida Formation in Wadi Araba and its equivalent Middle to Upper Turonian Umm Omeiyid Formation in the Wadi Qena region overlies the Galala Formation in the Eastern Desert (Wilmsen and Nagm, 2013). Maghra El Hadida and the Umm Omeiyid formations consist of shaly siltstone and calcareous sandstone at the base, followed by marls occasionally intercalated with sandstones and fossiliferous limestone and marls at the top (Nagm, 2009; Nagm and Wilmsen, 2012; Wilmsen and Nagm, 2013). The carbonate content is observed to increase towards the top in the Nodular Limestone of the Bagh Group and the Maghra El Hadida and Umm Omeiyid formations of the Eastern Desert. They represent the maximum flooding in the basins and have yielded abundant age-diagnostic ammonites. The top of the succession in the Taref Formation and Matulla Formation of uppermost Turonian?/Coniacian to Santonian (Wilmsen and Nagm, 2013) in the Eastern Desert and the Narmada Sandstone Member of Coniacian age in the WLNV is characterized by siliciclastic-dominated unit along a sharp contact, except for the

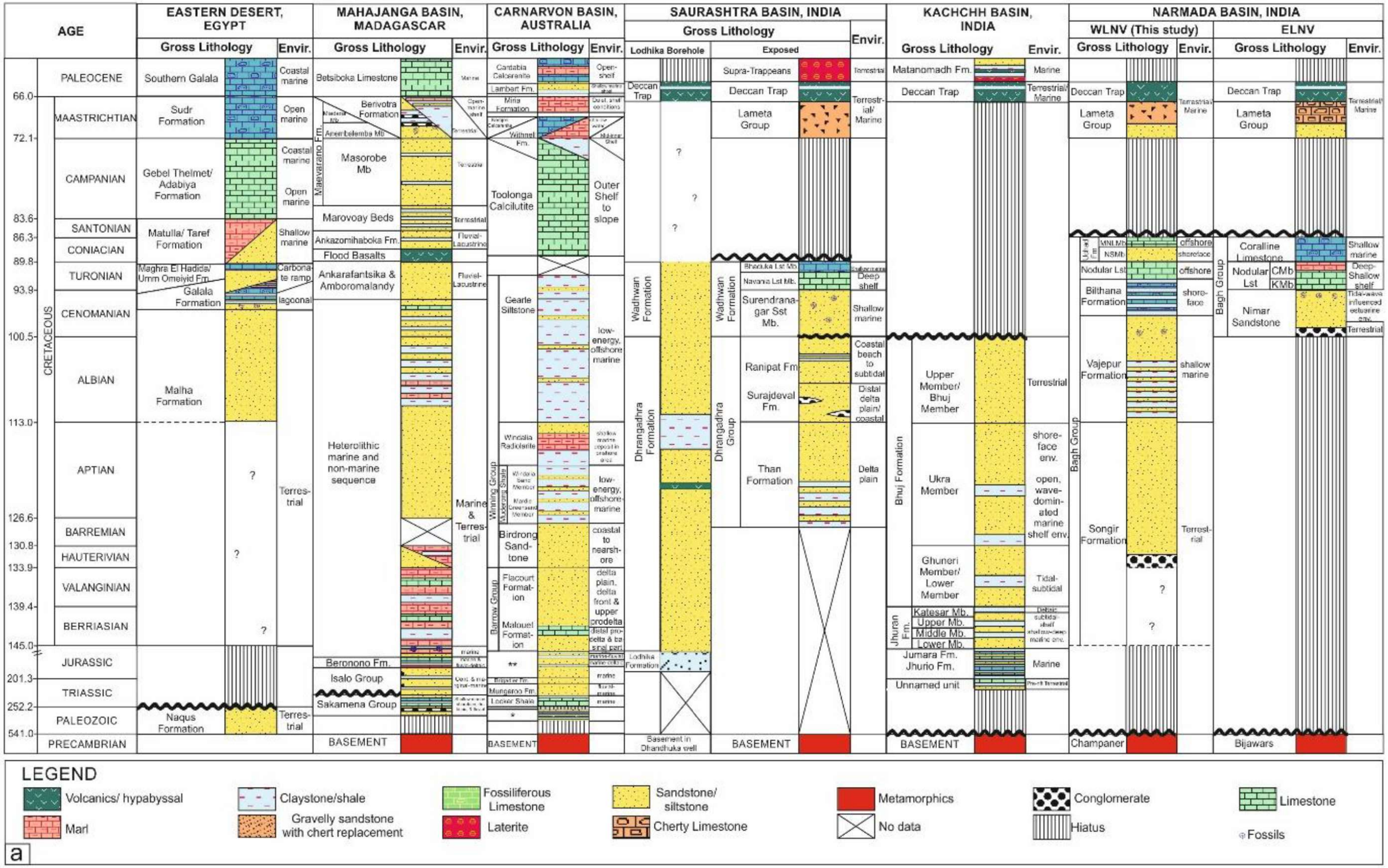
Uchad section in the WLNV, which is, in turn, overlain by the Men Nadi Limestone Member. The basins consist of Turonian transgressive facies deposited during the eustatic sea-level rise followed by regressive facies deposited during the end-Cretaceous tectonic activity. It is worth noting the interaction of weathering and erosion roles for deriving siliciclastics from the older rocks; eustatic sea-level influenced the carbonate sedimentation and tectonics in creating similar depositional conditions (Shitole et al., 2021).

8.2.2 MAHAJANGA BASIN (MADAGASCAR)

Oceanic rifting during Permo-Triassic in the Somali and Comoros basins initiated the separation of the India-Madagascar Block from Africa, resulting in the evolution of the Morondava, Mahajanga, and Amilobe basins on the western margin of Madagascar (Rogers et al., 2000). The Permo-Triassic continental deposit of the Sakamena Group is overlain by the Middle Triassic-Middle Jurassic marginal-marine deposits of the Isalo Group in the Mahajanga Basin (Besairie, 1972; Rogers et al., 2000), which is further overlain by the Late Jurassic-Cretaceous heterolithic sequence of marine and continental deposits (Fig. 8.2). During the Aptian-Albian to Turonian, the marine succession in the basin graded to terrestrial deposits with a few marine tongues (Obrist-Farner et al., 2017). In the WLNV, fluviatile sedimentation commenced in the Early Cretaceous with the reactivation of the Son-Narmada Lineament (Tripathi and Lahiri, 2000). The Cenomanian-Turonian? Ankarafantsika and Amboromalandy formations of the Mahajanga Basin comprises siliciclastics of fluvial to lacustrine environments (Rogers et al., 2000), whereas the Cenomanian-Turonian succession in WLNV is characterized by fine-grained siliciclastics and carbonates of marine origin (see Shitole et al., 2021 and references therein). The Cenomanian and Turonian marked the highest sea-level during the Cretaceous (Haq and Huber, 2017); however, Turonian succession in the Mahajanga Basin consist of interbedded marine and continental succession. This can be attributed to a fall in sea level caused by a high rate of sediment supply to the basin and local tectonics; in contrast, the succession in LNV of the Turonian age is characterized by deposition of basin-wide Nodular Limestone, which marks the maximum eustatic sea level rise. Falling sea level during the Coniacian age deposited the Coralline Limestone (ELNV) and sandstone-limestone of the Uchad Formation (WLNV). Coniacian in the Mahajanga Basin is characterized by flood basalts, which marked the separation of Madagascar from the India-Seychelles Block (Storey et al., 1995). According to Bardhan et al. (2002), the presence of the Turonian-Coniacian ammonite species *Placenticeras kaffarium* and the Coniacian *Barroisiceras onilahyense* in both the basins is indicative of a narrow oceanic gap between the plates. It is further supported by the occurrence of echinoid species in the Nodular Limestone of the Bagh Group, showing affinity with Madagascar's Late Turonian Antantiloky region (Smith, 2010). Like Turonian, the Coniacian deposits too are different in both the basins. The LNV consists of high-energy shoreface deposits of cross-bedded bryozoan limestone of Coralline Limestone in the ELNV and cross-bedded sandstone of the Narmada Sandstone Member (WLNV), whereas the Ankazomihakona Formation of the Mahajanga Basin consists of fluvio-lacustrine siliciclastics deposits (Shitole et al., 2021).

8.2.3 CARNARVON BASIN (AUSTRALIA)

The intracratonic Carnarvon Basin formed due to multiple rifting phases in the NW shelf of Australia during the Palaeozoic and Mesozoic breakup of Gondwanaland (Barrett et al., 2021). The early-rift phase has Silurian to Early Jurassic pre-rift active margin fluvio-marine deposits (Fig. 8.2). Middle-Late Jurassic seafloor spreading in the Gascoyne and Cuvier abyssal plains reactivated the rifts and played a crucial role in the breakup of Australia from Greater India and later with Antarctica (Geoscience Australia, 2013). The main syn-rift phase in the Carnarvon Basin started during the Middle Jurassic and deposited the transgressive Calypso Formation (Geoscience Australia, 2013). During Late Jurassic, marine sediments of Dingo Claystone were deposited, followed by deltaic sediments of the Barrow Group (Berriasian-Valanginian). The fluvio-deltaic Barrow Group represents the late syn-rift phase in the Carnarvon Basin, and its deposition ceased during the Valanginian forming an unconformity (Hocking, 1990). U-Pb studies of zircon from the northwest shelf of Australia suggest Early Cretaceous volcanism related to rift initiation between India and Australia (Hu et al., 2010; Lewis and Sircombe, 2013). Early Berriasian-Valanginian marks the complete breakup of Australia and the Indian subcontinent characterized by a hiatus in the depositional record recognized as Cretaceous Valanginian (KV) unconformity (Geoscience Australia, 2013; Gibbons et al., 2012; Longley et al., 2002; Müller et al., 1998; Paumard et al., 2018; Veevers, 1988). The Barrow Group is overlain by the transgressive deposits of the Winning Group of Hauterivian to Lower Turonian age (Hocking et al., 1987). After the breakup with the Indian subcontinent during Valanginian-Berriasian (Veevers et al., 1991; Williamson et al., 2012), rifting accompanied by crustal subsidence and sea-level rise resulted in transgression in the Carnarvon Basin in the post-rift phase (Chongzhi et al., 2013; Geoscience Australia, 2013; Paumard et al., 2018). While in the WLNV, the early-rift phase during the



AGE
EASTERN DESERT, EGYPT
MAHAJANGA BASIN, MADAGASCAR
CARNARVON BASIN, AUSTRALIA
SAURASHTRA BASIN, INDIA
KACHCHH BASIN, INDIA
NARMADA BASIN, INDIA
WLNV (This study)
ELNV
Gross Lithology
Envir.
Lodhika Borehole
Exposed
PALEOCENE
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
JURASSIC
TRIASSIC
PALEOZOIC
PRECAMBRIAN
CRETACEOUS
66.0
72.1
83.6
86.3
89.8
93.9
100.5
113.0
126.6
130.8
133.9
139.4
145.0
201.3
252.2
541.0
Southern Galala
Sudr Formation
Gebel Thelmet/ Adabiya Formation
Matulla/ Taref Formation
Maghra El Hadida/ Umm Omeiyid Fm
Galala Formation
Malha Formation
Naqus Formation
Coastal marine
Open marine
Shallow marine
Carbonate ramp
lagoonal
Terres-trial
Betsiboka Limestone
Berivotra Formation
Anembalemba Mb
Maevarano Fm.
Masorobe Mb
Marovoay Beds
Ankazomihaboka Fm.
Flood Basalts
Ankarafantsika & Amboromalandy
Heterolithic marine and non-marine sequence
Marine & Terres-trial
Beronono Fm.
Isalo Group
Sakamena Group
BASEMENT
Fluvial-Lacustrine
Cardabia Calcarenite
Lambert Fm.
Miria Formation
Withnell Fm.
Toolonga Calcilutite
Gearle Siltstone
Windalia Radiolarite
Winning Group
Birdrong Sand-tone
Flacourt Format-ion
Malouet Format-ion
Barrow Group
Mungaroo Fm.
Locker Shale
Open-shelf
Outer Shelf to slope
low-energy, offshore marine
coastal to nearsh-ore
delta plain, delta front & upper prodelta
Deccan Trap
Wadhwan Formation
Dhrangadhra Formation
Lodhika Formation
Basement in Dhandhuka well
Supra-Trappeans
Lameta Group
Bhadula Lst Mb.
Navania Lst Mb.
Surendranagar Sst Mb.
Ranipat Fm
Surajdeval Fm.
Than Formation
Dhrangadhra Group
Terrestrial
Terrestr-ial/ Marine
Deep shelf
Shallow marine
Coastal beach to subtidal
Distal delta plain/ coastal
Delta plain
Matanomadh Fm.
Upper Member/ Bhuj Member
Ukra Member
Ghuneri Member/ Lower Member
Bhuj Formation
Katesar Mb.
Upper Mb.
Middle Mb.
Lower Mb.
Jhuran Fm.
Jumara Fm.
Jhurio Fm.
Unnamed unit
Marine
Terrestrial/ Marine
shore-face env.
open, wave-dominated marine shelf env.
Tidal-subtidal
Nodular Lst
Bilthana Formation
Vajepur Formation
Songir Formation
Bagh Group
Champaner
offshore
shore-face
shallow marine
Terrest-rial
Coralline Limestone
Nodular Lst
CMb
KMb
Nimar Sandstone
Bijawars
Deep-Shallow shelf
LEGEND
Volcanics/ hypabyssal
Marl
Claystone/shale
Gravelly sandstone with chert replacement
Fossiliferous Limestone
Laterite
Sandstone/ siltstone
Cherty Limestone
Metamorphics
No data
Conglomerate
Hiatus
Limestone
Fossils
a

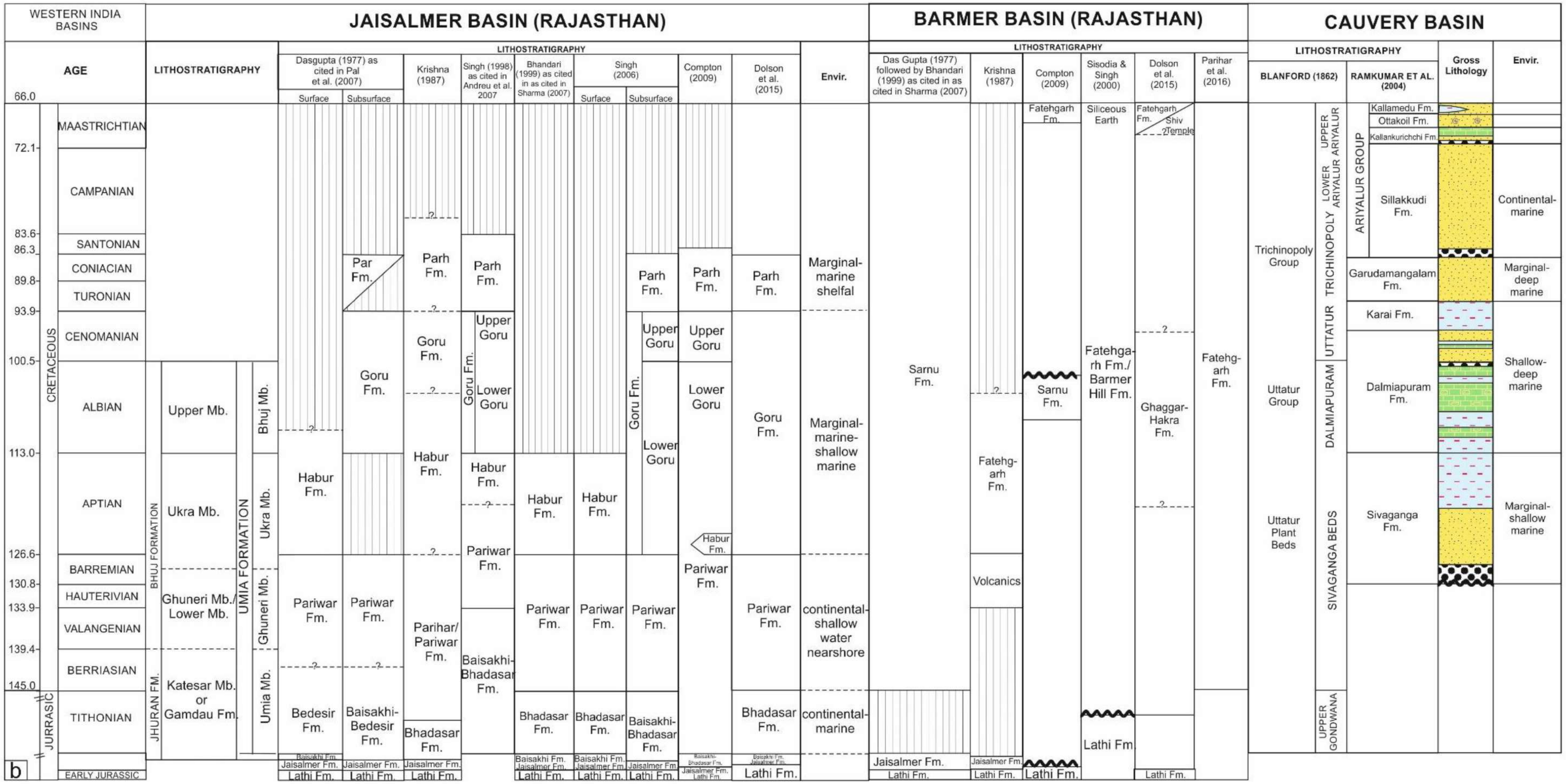


Figure 8.2 Generalized stratigraphic succession and the depositional environments of the Cretaceous Tethyan basins. a. Eastern Desert, Mahajanga, Carnarvon, Saurashtra, Kachchh and Narmada, and b. Jaisalmer, Barmer, and Cauvery (modified after Shitole et al., 2021).

(Neocomian) Berriasian? (Murty et al., 1963) fluvial sediments of the Songir Formation were deposited (Shitole et al., 2021). Transgressive deposits of the Late Hauterivian to Barremian Birdrong Sandstone and Muderong Shale accumulated in the Carnarvon Basin (McLoughlin et al., 1995), overlain by the lowstand deposits of the Late Aptian Windalia Radiolarite (Williamson et al., 2012). The Birdrong Sandstone is the basal transgressive unit of the Carnarvon Basin, while the Vajepur Formation (Nimar Sandstone in ELNV) of the WLNV. Major marine Cretaceous transgression in the Carnarvon Basin is represented by the upper Winning Group (Munderong Shale, Windalia Radiolarite, and Gearle Siltstone) and the Nodular Limestone across Narmada Basin. Both the basins experienced post-Coniacian uplift and erosion.

8.2.4 SAURASHTRA-KACHCHH BASINS (INDIA)

Saurashtra Basin is located adjacent to the Narmada Basin on the western margin of the Indian Peninsular and has a basin-fill resembling the Bagh Group of LNV. Deccan Traps largely cover the Saurashtra Basin, but it does contain surface exposures of Dhrangadhra Group and Wadhwan Formation ranging in age from Barremian to Turonian (Racey et al., 2016). The basal Dhrangadhra Group is divided into Than, Surajdeval, and Ranipat formations in ascending order (Fig. 8.2). The Cretaceous sedimentary deposits of the Saurashtra Basin (Neocomian-Coniacian) are correlatable with the Bagh Group rocks (Shitole et al., 2021). Based on the similarity observed in the rock types, Rode and Chiplonkar (1935) considered the deposits westward extension of the Bagh Group rocks. Based on plant fossils of Neocomian-Aptian age, Rajanikanth and Chinnappa (2016) correlated the Than Formation of Dhrangadhra Group with Gardeshwar Formation of Borkar and Phadke (1974), and was subsequently amended as Vajepur Formation in WLNV by Shitole et al. (2021). Rifting in the Narmada Basin initiated with the deposition of the Songir Formation, which consists of cross-bedded sandstone, gravelly sandstones, and conglomerates of debris-flow deposits of alluvial fan environment, while the Surajdeval Formation of Dhrangadhra Group is characterized by deltaic distributaries and coastal nearshore tidal settings (Casshyap and Aslam, 1992). The overlying Wadhwan Formation is subdivided into Surendranagar Sandstone, Navania Limestone, and Bhaduka Limestone members (Fig. 8.2). The Albian-Cenomanian Surendranagar Sandstone Member is characterized by pebbly to fine-grained fossiliferous sandstones of the shallow marine environment (Racey et al., 2016). Similarly, the Vajepur Formation in WLNV consists of fine- to medium-grained calcareous sandstones. The Aptian-Albian Ranipat Formation and Surendranagar Sandstone Member (Racey et al. 2016) of Saurashtra Basin are lithologically correlatable with the lower and upper part of the Vajepur Formation (Shitole et al., 2021), respectively.

The trace fossils in the Saurashtra Basin are recorded from the Ranipat and Wadhwan formation; therefore, only the post-Aptian succession of the Saurashtra Basin can be correlated with the Narmada Basin. Aslam (1991) reported *Ophiomorpha*?, *Planolites, Skolithos,* and *Thalassinoides* from the Ranipat Formation belonging to *Skolithos-Cruziana* ichnofacies and suggested nearshore to a littoral marginal-marine environment of deposition. The Vajepur Formation of the Narmada Basin also consists of calcareous sandstone, siltstone, and shale facies and have yielded *Archaeonassa, Conichnus, Conostichus*, *Oniscoidichnus*, *Paleophycus*, *Planolites, Taenidium,* and *Thalassinoides*, suggesting *Cruziana* ichnofacies. The Turonian Navanaia Limestone and the Bhaduka Limestone members of the Saurashtra Basin correlate with the Bilthana Formation and Nodular Limestone of WLNV and Bryozoan/Coralline Limestone of ELNV, respectively (Shitole et al., 2021). Two lithostratigraphic units, the Bhaduka Limestone of Saurashtra and the Coralline Limestone of ELNV, are correlated based on similar fauna (Smith, 2010; Racey et al., 2016). Abundant marine fossils like bryozoans, gastropods, echinoderms, bivalves, and brachiopods in the Bhaduka Limestone (Borkar and Kulkarni, 1992; Chiplonkar and Borkar, 1973) and trace fossils (*Feddenichnus* and *Planolites*) suggests the Turonian succession to be deposited in a shallow marine environment.

Based on the basin-fill architecture of the LNV and Saurashtra Basin, it can be inferred that they were tectonically stable passive margin basins that gradually developed into a typical rift sequence in the interior of the continent. The Jurassic palynoflora recovered from the lower part of the Dhrangadhra Group, poorly developed terrestrial deposits at the base in the Lodhika borehole (Fig. 8.2) (Singh et al., 1997) suggests the Saurashtra rift opened before the Narmada.

Amongst all the sedimentary basins of western India, the Kachchh Mesozoic basin comprises thick fluvio-marine sedimentary successions that are highly fossiliferous and bioturbated. It consists of pre-rift (Late Triassic), syn-rift (Jurassic), and post-rift (Early Cretaceous) deposits of more than 2500 m thickness (Biswas, 2016). Jurassic ichnofauna of Kachchh Basin suggests the existence of marine conditions in the mainland Kachchh (Patel and Patel, 2015; Bhatt and Patel, 2017), Patcham Island (Joseph et al., 2012; Patel et al., 2014), Island belt (Darngawn et al., 2018) and deltaic conditions in Wagad Highland (Joseph and Patel, 2018).

The analysis of Cretaceous ichnofauna from the Kachchh Basin suggests the development of deltaic sequence in the post-rift phase of regressive sea reported by several authors (Table 8.1a). A thick wave-dominated deltaic sequence of the Bhuj Formation was deposited with regression of the Tethys Sea during the Late Jurassic-Early Cretaceous (Bhatt and Patel, 2017). The compositional maturity of the Bhuj Formation suggests stabilization of the Kachchh Basin from a syn-rift to post-rift phase (Chaudhuri et al., 2020), and sedimentation ceased in the Kachchh Basin during the Aptian (Fig. 8.2). Rifting commenced in the Narmada Basin in the Berriasian? with deposition of thick clastics of the terrestrial environment of the Songir Formation and the post-Aptian Vajepur Formation of the nearshore environment in syn-rift phase. The Kachchh Basin consists of early Cretaceous deposits characterized by diverse trace fossils. The early Cretaceous deposits have been variably interpreted based on trace fossils from marginal marine (deltaic) to the shallow marine environment; interpreted as regressive deposits of the initial shallow marine environment and later of marginal-marine deltaic environment. Desai and Saklani (2015) have reported *Conichnus* from the Lower Cretaceous Ghuneri Member (Bhuj Formation) and suggested tidal conditions in a marine setting. The presence of sea-anemone burrows in the Early Cretaceous Bhuj Formation of Kachchh Basin and the Vajepur Formation and Bilthana Formation of Narmada Basin suggests flourishment of sea anemones in the Tethys Sea. The Early Cretaceous ichnotaxa of Kachchh Basin suggests marine conditions in contrast with the Narmada Basin, whose sedimentary record is dominated by terrestrial environment. This suggests high energy regressive environment in the Kachchh Basin during the Early Cretaceous, whereas post-Albian ichnological record suggests marine influence in the Narmada Basin. Marine sedimentation continued in the Narmada Basin till the Coniacian and deposited the Vajepur Formation, Bilthana Formation, Nodular Limestone, and the Uchad Formation. The Early Cretaceous period gave rise to post-rift deposits in Kachchh Basin and early-, syn-rift deposits in the Saurashtra and Narmada basins up to the Coniacian (Shitole et al., 2021). The time-slice of the Cretaceous sedimentation record of the Narmada Basin is almost similar to Saurashtra Basin. However, the Kachchh Basin comprises the marginal-marine deposits of the Early Cretaceous compared to terrestrial deposits of the Narmada Basin. There is no record of Post-Albian rift sedimentation in the Kachchh Basin (Biswas, 2016) while the Narmada Basin comprises the marine sedimentary succession of the Cenomanian-Turonian transgression.

8.2.5 JAISALMER-BARMER BASINS (INDIA)

The western margin shelf of Rajasthan carved out into four basins, Jaisalmer, Barmer, Bikaner-Nagaur, and Sanchor. The Jaisalmer Basin is pericratonic, while Barmer is the intracratonic basin and consists of Cretaceous sedimentary deposits (Andreu et al., 2007). Sedimentation in the Jaisalmer Basin was initiated in the Permo-Carboniferous Period (Pal et al., 2007) and continued up to the Cretaceous. The Mesozoic lithostratigraphy of the Jaisalmer Basin possesses variable names of the units (Fig. 8.2b). Recently, Dolson et al. (2015) proposed a lithostratigraphy wherein the Mesozoic succession is grouped into the Jurassic (Lathi, Jaisalmer, Baisakhi, and Bhadasar formations) and Cretaceous (Pariwar, Goru, and Parh) periods. The Berriasian-Barremain Pariwar Formation comprises sandstone-shale intercalated deposits. Based on the trace fossils, it is interpreted to be deposited in shallow water near shore environment (Mude et al., 2012). The Lower Aptian Habur Formation (Bhandari,1999, Singh, 2006), equivalent to the Lower part of the Goru Formation (Dolson et al., 2015) consists of limestones, mixed siliciclastic-carbonates, marls, and calcareous sandstones with abundant ammonites and brachiopods (Dasgupta, 1977; Pal et al., 2007). The Aptian-Cenomanian Goru Formation is recorded from the borehole and comprises marginal-marine to shallow marine sediments (Dolson et al., 2015). The Turonian-Coniacian Parh Formation is recorded from the boreholes overlying the Goru Formation, consisting of planktonic foraminifers (Singh, 2006). It consists of marginal-marine shelfal argillaceous limestone with interbeds of calcareous clay, marl, and siltstone (Pal et al. 2007; Dolson et al., 2015). The recorded trace fossils from the Pariwar and Habur formations suggest a shallow marine depositional environment (Borkar and Kulkarni, 2001; Mude et al., 2012). The Cretaceous succession of the Jaisalmer and the WLNV are comparable, where both basins comprise shallow marine transgressive-regressive deposits. Pariwar Formation comprises shallow marine deposits, whereas equivalent to WLNV, Songir Formation consists of fluvial sediments. During the lower Aptian, a part of the Goru Formation (Habur Formation, Singh, 2006) comprising limestones and ammonites suggests an offshore environment (Pal et al., 2007). The transgression is started much later in the WLNV; during the Albian, siliciclastics rocks of the Vajepur Formation were deposited in the marginal marine environment. The peak of the transgression of the WLNV represents the limestone of the Bilthana Formation and Nodular limestone of Cenomanian and Turonian, where Jaisalmer Basin comprises the shelfal deposits of the Parh Formation of Turonian-Coniacian age.

The Pre-rift Jurassic Lathi Formation in the Barmer Basin overlies the Proterozoic basement of the Malani Igneous suite (Dolson et al., 2015) and comprises reservoir-quality sandstones deposited in the terrestrial environment (Sharma, 2007). The Jurassic succession in the Barmer Basin is separated from the overlying Cretaceous sedimentary rocks with an unconformity (Sisodia and Singh, 2000; Compton, 2009; Dolson et al., 2015; Parihar et al., 2016). The age is variably assigned to the Ghaggar-Hakra Formation, Lower Cretaceous (Beaumont et al., 2019), and Aptian-Cenomanian (Dolson et al., 2015). This formation comprises sandstones deposited in fluvio-lacustrine environment and consists of Karentia volcanics (Aptian) often related to the separation of the Indian Plate with Madagascar (Dolson et al., 2015). Beaumont et al. (2019) has correlated the Ghaggar-Hakra Formation with Early Cretaceous fluvial Himmatnagar Sandstones of Cambay Basin, fluvio-marine Nimar Formation of the Narmada Basin, the fluvio-deltaic Bhuj Formation of the Kachchh Basin, and the fluvial Dhrangadhra Group of the Saurashtra Basin. The fluvial sequence of the Ghaggar-Hakra Formation is also comparable with the part of the Songir Formation (Berriasian?-Aptian) of the WLNV (Shitole et al., 2021).

The age of the overlying Fatehgarh Formation is variably assigned (Fig. 8.2b) as Cretaceous (Krishna, 1987; Sisodia and Singh, 2000; Parihar et al., 2016), Paleocene (Dolson et al., 2015), Maastrichtian to Palaeocene (Compton, 2009) and Aptian? Age (Borkar and Kulkarni, 2002). Compton (2009) encountered a fluvial sequence of Fatehgarh Formation in the well sections below the Upper Cretaceous Raageshwari volcanics in the Barmer Basin and considered equivalent to the Deccan Traps. Owing to a lack of unanimity on the age (Borkar and Kulkarni, 2002) of the Fatehgarh Formation of the Barmer Basin and the absence of an equivalent rock unit, it is difficult to correlate it with the Bagh Group of the WLNV.

8.2.6 CAUVERY BASIN (INDIA)

The Cauvery Basin of the southern Indian Peninsula comprises of well-developed Cretaceous sequence, which rests unconformably over the granitic-gneiss of the Archean. The Cretaceous succession was earlier divided into the Gondwana, Uttatur, and Ariyalur groups (Tewari et al., 1996); later, Ramkumar et al. (2004) revised the stratigraphy and abandoned the Gondwana and Uttatur groups and retained Ariyalur Group (Sillakudi, Kallankurichchi, Ottakoil, and Kallamedu formations) for the Cretaceous succession of the Cauvery Basin.

The oldest Sivaganga Formation of the Barremian-Aptian age comprises conglomerates, sandstones, and claystones deposited in high-energy coastal environments, subaqueous fan-deltaic environments, and shallow marine environments, respectively (Ramkumar et al., 2004). The equivalent Songir Formation in the WLNV consists of conglomerates and sandstones deposited in braided-fluvial and alluvial-fan environments (Shitole et al., 2021). During the Early Cretaceous, deposits of the Narmada Basin witnessed a terrestrial environment, whereas the age-equivalent Cauvery Basin experienced marine inundation. According to Paranjape et al. (2016), the unconformity that demarcates the breakup of India and Australia (118 MY) and separates the syn-rift succession from the overlying passive margin phase is observed between the Sivaganga Formation and the overlying Dalmiapuram Formation. Paranjape et al. (2011, 2015-2016) reported trace fossils from the upper part of the Sivaganga Formation and suggested it was deposited in a fluvial to paralic tidal estuarine environment.

The overlying Aptian-Cenomanian Dalmiapuram Formation consists of fossiliferous limestones, shales, siliciclastics, and conglomerates deposited in an energetic coast to calm deeper ramp environment (Ramkumar et al., 2004). The equivalent Albian-Cenomanian of Vajepur Formation of the Narmada Basin also consists of transgressive deposits of a shallow marine environment. The Cenomanian-Turonian Karai Formation consists of sandy and gypseous clays with belemnites and ammonites deposited in a progressive deepening and later shallowing Cauvery Basin (Ramkumar et al., 2004). The Cenomanian-Turonian, Bilthana, and Nodular Limestone formations in the WLNV represent a progressive deepening upward sequence.

The overlying Turonian-Coniacian Garudamangalam Formation of the Cauvery Basin and the Coniacian of the Narmada Sandstone Member (WLNV) are dominated by sandstones deposits. Abundant body fossils (oysters and ammonites) and trace fossils are recorded from the Garudamangalam Formation (Ramkumar et al., 2004). Nagendra et al. (2010) reported trace fossils from this formation belonging to *Skolithos* and *Cruziana* ichnofacies. The sedimentological, paleontological, and ichnological evidence of the Garudamangalam Formation suggest deposition in a shallow marine environment. Abundant body fossils oysters and trace fossils *Bergaueria, Conichnus,* and *Conostichu*s (Patel et al., 2018, Shitole et al., 2019) are recorded from the Cenomanian-Turonian of the WLNV. The development of nodular limestone, fossiliferous limestones, and shales in the WLNV suggest a shallow marine environment. Compared with the Cauvery Basin, WLNV experienced one more transgressive phase during the Coniacian. The Coniacian unconformity is present in the Cauvery and the Narmada basins, where Sillakkudi Formation (Santonian-Campanian) unconformably overlies the Garudamangalam Formation while prolonged hiatus in Narmada Basin, which continued up to the Maastrichtian.

8.3 SUMMARY

The separation of the Indian Plate from the Gondwana during the Mesozoic resulted in the sequential evolution of the intra- and peri-cratonic rift basins and their inundation by the Tethys Sea. The Narmada Basin of Central India comprises an almost complete sequence of the Cretaceous Period. A comparison is made with adjoining, Mahajanga, Eastern Desert, Carnarvon, and Indian subcontinent basins to understand the sedimentology, stratigraphy, and tectonics. The Indian subcontinent was situated in the central part of the Gondwana during the Cretaceous comprises pre-, syn-, and post-rift basins filled with fluvio-marine sediments.

A marine deposition is observed in the Kachchh Basin of India and the Mahajanga and Morondova basins of Madagascar during Toarcian (Early Jurassic). The Berriasian–Valanginian (Lower Cretaceous) marks the separation of India from Australia with the deposition of the deltaic Barrow Group in the Carnarvon Basin and the Berriasian–Aptian deltaic succession in the Kachchh Basin. According to Paranjape et al. (2016), the unconformity that demarcates the breakup of India and Australia (118 MY) and separates the syn-rift succession from the overlying passive margin phase is observed between the Sivaganga Formation and the overlying Dalmiapuram Formation. Rifting was initiated during the Early Cretaceous in the Narmada, Mahajanga, Cauvery, and Saurashtra basins which deposited the Songir Formation, Malha Formation, Sivaganga Formation, and the Than Formation, respectively (Shitole et al., 2021). The early Cretaceous Songir and Vajepur (lower part) formations of the Bagh Group rocks are similar to the Than Formation of the Saurashtra Basin. The Songir Formation of the Bagh Group and the Than Formation of the Saurashtra Basin is poorly bioturbated as compared to the Vajepur Formation of the WLNV. The similarity in the Early and Late Cretaceous depositional environment is observed in the Eastern Desert, Saurashtra, and the Narmada basins, where the former is characterized by terrestrial and later consist of marine deposits, suggesting a similar role played by tectonics and sediment supply (Figure 8.2). The Late Cretaceous transgressive deposits in these basins were possibly due to the late development of the rift.

High sea level was observed during the Early Cretaceous deposited carbonates in the Carnarvon, Cauvery, and parts of the Madagascar basins while the Narmada Basin was filled with fluvial sediments. Transgression in the Carnarvon Basin was early compared to the other Tethyan basins due to the flexure on the western continental margin post-separation from India in the Valanginian (McLoughlin et al., 1995).

The Turonian transgression (Haq and Huber, 2017) is observed as the presence of marine deposits and fossils (ammonites and echinoderms) recorded from other parts of Madagascan basins (Smith, 2010; Walaszczyk et al., 2004), except the Mahajanga Basin. The terrestrial conditions witnessed by the Mahajanga Basin during the Cenomanian–Turonian were possibly due to the tectonic events and outpouring of flood basalts related to the separation of Madagascar from India (Late Turonian–Early Coniacian). The age of the youngest unit observed in the Bagh Group coincides with India's rift event from Madagascar (Shitole et al., 2021).

The Jurassic oscillating Tethys Sea withdrew from the Jaisalmer Basin during the Early Cretaceous, but the nearshore deposits of the Pariwar Formation (Mude et al., 2012) marked the marine incursion. The overlying the Goru and Parh formations represent transgression in the basin during the Aptian-Coniacian coeval with the global Cenomanian-Turonian transgression. It is also interesting to note that the Jaisalmer and Narmada basins consist of Aptian-Coniacian transgressive deposits. Overall, both the basins are characterized by the transgressive and regressive deposits of the Early and Late Cretaceous and later experienced post-Coniacian uplift. The Jurassic-Cretaceous of the Barmer Basin characterized the pre-rift succession while the Late Cretaceous? (Upper part of Fatehgarh Formation)-Tertiary, the syn-rift succession (Compton, 2009). More data is required to correlate the Upper Cretaceous succession of the Barmer Basin and the WLNV. The Narmada Basin got filled with sedimentary deposits and volcanics by the Late Cretaceous, whereas rifting began in the Barmer Basin, continuing with the Cambay trend (Dolson et al., 2015).

Overall, the Tethys Sea basins of the Cretaceous, Mahajanga, Eastern Desert, Carnarvon, and Narmada basins are comparable durational deposits, but the eustatic sea-level changes and local factors like rifting have influenced the deposition of sediments, fluvial or marine that got the basin filled. The Cretaceous Indian subcontinent basins like Narmada, Saurashtra-Kachchh, Cauvery, and Jaisalmer-Barmer are also controlled by rifting phenomena and eustatic sea-level changes. They are characterized by marine-influenced sediments in the Cauvery, Kachchh, Jaisalmer-Barmer basins, initial fluvial, and later marine deposits in the Narmada and Saurashtra basins.

CONCLUSIONS

The Cretaceous Bagh Group sequence of the Western Lower Narmada Valley attains a thickness of more than 300 meters and is exposed as detached outcrops. A detailed investigation was done on sedimentological and ichnological aspects by the author to analyze the sequence stratigraphy, which leads to the following conclusions:

- The lithostratigraphy of Cretaceous succession of WLNV is amended and assigned the Bagh Group according to ISSC ranging in age from Berriasian? (Neocomian) to Coniacian.

- Bagh Group is divided into five formations, namely Songir, Vajepur, Bilthana, Nodular Limestone, and Uchad formations in ascending order. The old names such as Songir Bilthana and Nodular Limestone are retained; Vajepur and Uchad formations are the new units introduced. The Uchad Formation is further subdivided into the Narmada Sandstone and Men Nadi Limestone members.

- The stratigraphic succession of the Bagh Group comprises siliciclastics, mixed siliciclastic-carbonates, shales, and carbonates rocks which are further classified into fourteen facies, conglomerate, planar and trough cross-stratified sandstone, horizontal-thinly bedded sandstone, massive sandstone, bedded quartz arenite, shale, calcareous sandstone, micritic sandstone, sandstone- siltstone-shale, sandy/silty allochemic limestone, fossiliferous limestone, sandy/silty micrite, mudstone, and muddy micrite.

- The Songir Formation at the base of the Bagh Group succession is composed of non-marine sediments and deposited in a fluvial-braided and alluvial-fan environment. It lies unconformably above the Precambrian basement and corresponds to the initial rift phase.

- The overlying Vajepur Formation marks the onset of base-level rise during the Albian. It is represented by the cross-stratified sandstone-shale in the lower part and the laminated and rippled calcareous sandstones (marine fossils) in the upper part.

- The Bilthana Formation constitutes oyster beds intercalated with the shale and shows the presence of well-preserved body and trace fossils. The succeeding Nodular Limestone is widely traceable in the LNV containing abundant ammonites of the Turonian age. The sedimentological and ichnological evidence suggests deposition of Bilthana Formation in lower shoreface/offshore transition and Nodular Limestone in the offshore environment.

- Uchad Formation differs from the underlying Nodular Limestone in having a distinct lithological assemblage and bed geometry. The Narmada Sandstone Member represents the high-energy shoreface environment, whereas the overlying Men Nadi Limestone Member consists of distal shoreface deposits.

- Sandy allochemic limestone, micritic sandstone, sandstone-siltstone-shale, fossiliferous limestone, mudstone, bedded quartz arenite, planar cross stratified sandstone, and calcareous sandstone facies are low-to moderately bioturbated and show the presence of twenty-six ichnospecies belonging to seventeen ichnogenera, including *Apectoichnus, Archaeonassa*, *?Arenicolites*, *Bergaueria, Conichnus, Conostichus, Didymaulichnus, Gordia, Helminthoidichnites, Lockeia, Oniscoidichnus, Paleophycus, Planolites, Ptychoplasma, Skolithos, Taenidium,* and *Thalassinoides.*

- Overall density of the trace fossils is low and represents five ethological categories, including cubichnia, pascichnia, domichnia, repichnia and fodinichnia.

- Nine trace fossil assemblages, namely *Apectoichnus, Archaeonassa, Bergaueria*, *Conichnus-Conostichus, Helminthoidichnites-Gordia, Lockeia-Planolites, Skolithos, Taenidium,* and *Thalassinoides* represent three ichnofacies namely*, Skolithos, Cruziana,* and *Glossifungites* which reflect the environmental conditions (bathymetry, salinity, oxygenation, energy conditions, sedimentation rate, substrate characteristics)

- Occurrence of abundant plug-shaped burrows- *Bergaueria hemispherica*, *Conichnus conicus, Conostichus stouti,* and *Conostichus broadheadi* recorded from the Cenomanian-Turonian Bilthana Formation is limited to the fine-grained, soft, unconsolidated, non-fluidized clastic sediments, which appears to be favorable for sea anemone colonization.

- Uniform fill, prominent relief, and lack of slump structures suggest that all the sea anemones simultaneously vacated the burrow, which was subsequently filled by the overlying sandy allochemic limestone indicating an increase in energy conditions in the shoreface environment.

- The presence of densely packed, unaltered, least abraded, disarticulated, unoriented oyster shells with faint growth lines and the presence of *Thalassinoides* and plug-shaped burrows at the sole of the oyster limestone bed suggests surface exhumation followed by storm events in the offshore-transition environment.

- The increase in ichnodiversity observed in the upper part of the Vajepur Formation suggests a low-energy, nutrient-rich, shoreface environment. In contrast, the ichnofauna of the Bilthana Formation is dominated by comparatively deeper feeding burrows of *Thalassinoides* followed by plug-shaped burrows.

- The high ichnodiversity and ichnodensity of deposit-feeding burrows in the sandy allochemic limestone and fossiliferous limestone facies of the Bilthana Formation suggest concentration of nutrients in a well-oxygenated substrate, while the occurrence of plug-shaped burrows of suspension feeders suggests ample supply of nutrients from the water column.

- An abrupt decline of body fossils and trace fossils in the Nodular Limestone and the presence of pyrite suggest reduced oxygen or dysoxic conditions.

- Overall, the Cretaceous Bagh Group is characterized by low-moderate ichnodiversity, dominated by large *Thalassinoides* burrows suggesting flourishment of decapod crustaceans followed by sea anemones, gastropods, polyphyletic vermiform, and arthropods.

- The *Cruziana* ichnofacies is characterized by moderate diversity of horizontal structures made by mobile organisms, suggesting low to moderate-energy conditions, and abundant nutrients and oxygenation in the sediments in the shoreface environment.

- The *Glossifungites* ichnofacies are characteristics of the Bilthana Formation suggesting unlithified, stable, cohesive substrate such as dewatered muds produced due to burial and later made available to the organisms due to erosion.

- The *Skolithos* ichnofacies observed in the Narmada Sandstone Member suggest changes in the substrate consistency, well-oxygenated bottom water conditions, and abundant suspension food supply in the shoreface environment.

- Sedimentological and ichnological data of the Bagh Group revealed first-order genetic sequence characterized by various System Tracts, Sequence Stratigraphic Surface, Systems Tract Boundary, and Sequence Boundary.

- HAST is characterized by the alluvial fan and braided channel deposits in Songir Formation represented by conglomerates facies, planar and trough cross-stratified sandstone facies, horizontal-thinly bedded sandstone facies, and massive sandstone facies.

- LST is characterized by prograding and aggrading deposits, which filled the accommodation space created by the rising base-level. LST is poorly bioturbated and consists of *Helminthoidichnites*-*Gordia* and *Taenidium* assemblage. The low ichnotaxonomic diversity and density of trace fossils suggest deposition in a stressed foreshore environment.

- The TST-I comprises rippled quartz arenite/calcareous sandstone and micritic sandstone facies of the Cenomanian Vajepur Formation; fossiliferous limestone-shale, shale, sandy allochemic limestone facies belonging to Bilthana Formation of Cenomanian-Turonian age, and the mudstone and sandy micrite facies of the Turonian Nodular Limestone. The lower part of the TST-I comprises abundant plug-shaped burrows of sea anemones with *Archaeonassa, Oniscoidichnus*, *Lockeia, Ptychoplasma,* and *Thalassinoides,* while the upper part comprises abundant marine body fossils and trace fossils of shoreface to the offshore environment.

- TST-I is characterized by the Maximum Flooding Surface (Sequence Boundary), two minor Flooding Surfaces (FS-I and FS-II), and Transgressive Ravinement Surface (TRS); it shows a retrogradational stacking pattern and a fining-upward succession characterized by an increase in the carbonate content towards the top suggesting the rate of base-level rise outpaced the sedimentation during the Turonian.

- The transgressive phase shows an abrupt change in lithofacies and ichnofacies (*Skolithos*) in Narmada Sandstone Member represented by the Highstand Systems Tract-I (HST-I) where progradation and aggradation took place during the highstand of base-level and high rate of sedimentation has outpaced the accommodation space resulting in normal regressive deposits.

- TST-II marks the second transgressive event during the Coniacian characterized by muddy micrite, shale, and mudstone facies of the Men Nadi Limestone Member. The facies variation across the minor within trend surface (Flooding Surface-III) shows a retrogradational stacking pattern due to base-level rise.

- The sedimentological and ichnological data of the WLNV reveal the stratigraphic succession is correlatable with pervasive Cretaceous Tethyan basins like ELNV, Eastern Desert, and Saurashtra while differs from the Carnarvon, Mahajanga, Cauvery, and Kachchh.

- The (Berriasian?-Aptian) Songir Formation is correlatable with the Early Cretaceous fluvial Himmatnagar Sandstones of Cambay basin, fluvial Nimar Formation of the ELNV, the fluvio-deltaic Bhuj Formation of the Kachchh Basin, and the fluvial Dhrangadhra Group of the Saurashtra Basin.

- Albian-Cenomanian calcareous sandstone of Vajepur Formation (WLNV) is correlatableSurendranagar Sandstone Member (of the Saurashtra Basin); the Turonian Nodular Limestone of WLNV and ELNV are correlatable with the Navanaia Limestone of the Saurashtra Basin, and Coniacian Uchad Formation is correlatable with Bryozoan/Coralline Limestone of the ELNV and the Bhaduka Limestone Member of the Saurashtra Basin.

- The age of the youngest unit of the Bagh Group, Coralline Limestone of the ELNV and Men Nadi Limestone Member of the WLNV, coincide with the rift event of India from Madagascar and outpour of flood basalts in the Mahajanga Basin.

The WLNV basin preserves a complete Cretaceous geological record and witnessed regional and global events. Sedimentological and ichnological evidence document the intracratonic rift events with the major marine transgression of the Cretaceous, which have facilitated correlation with the pervasive Tethyan Basins.

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Amended lithostratigraphy of the Cretaceous Bagh Group, Western Lower Narmada Valley, India: A comparison with pervasive Tethyan basins

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The evolution of the Narmada, Saurashtra, and Kachchh basins in the western margin of the Indian Craton is associated with the Middle Jurassic segmentation of Gondwana. The Narmada Basin was evolved during the Early Cretaceous and preserved a thick clastic and non-clastic sequence of the Bagh Group. The succession lies unconformably on the Precambrian rocks, and a complete sequence is exposed in the Western Lower Narmada Valley (WLNV). Until now, it has been described using various informal lithostratigraphic units emphasizing local lithic characters, which have no relevance with the stratotypes and do not fit into the concept of the International Subcommission on Stratigraphic Classification (ISSC). In the present study, the Bagh Group succession is mapped across the Lower Narmada Valley (LNV) and correlated between sections. The units in WLNV were revised and redefined assigning the stratotypes as per the ISSC. The amended lithostratigraphy of the Bagh Group comprises five formations, viz. Songir, Vajepur, Bilthana, Nodular Limestone, and Uchad. The Uchad Formation is a newly recognized youngest unit and is subdivided into the Narmada sandstone and the Men Nadi Limestone members. The lithological and palaeontological evidences indicate that the Bagh Group succession of the WLNV developed in a fluvio-marine environment during the Berriasian? (Neocomian) to Coniacian age. The Cretaceous succession of the WLNV is also compared with the pervasive Tethyan basins, including the Eastern Desert (Egypt), Saurashtra–Kachchh (India), Mahajanga (Madagascar), and Carnarvon (Australia). The Albian–Coniacian lithostratigraphy of the Narmada Basin is comparable to the Eastern Desert, although located at different palaeolatitudes, which suggest similar eustatic and tectonic conditions. It also shows a similar sedimentation pattern compared with the adjoining Saurashtra Basin during the Cenomanian–Coniacian. However, it differs from the Kachchh, Mahajanga, and Carnarvon basins, which can be attributed to different palaeolatitudes, as well as the development of rift-related events. The deposition of the Bagh Group in WLNV terminated with the separation of the Indian Plate from Madagascar and the outpouring of flood basalts during the Coniacian.

KEYWORDS
Gondwana, Gujarat, lithostratigraphic revision, Lower Narmada Valley, Tethys Sea

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Ethological and environmental significance of *Bergaueria hemispherica* from the Late Cretaceous of the Bagh Group, Western India

Signification éthologique et environnementale de Bergaueria hemispherica *du Crétacé supérieur du groupe de Bagh, Inde occidentale*

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ABSTRACT

The probable trace maker of *B. hemispherica* is the fact that one encounters different age groups of sea anemone burrows extended at variable depths in soft, unconsolidated, non-fluidized mud to get stability. It occurs as densely packed, vertical to subvertical, usually unornamented, occasionally showing faint, thin, ring-like structures, allochemic sandstone-filled cylinders with hemispherical base extending to variable depths in the shale. The diameter-to-height ratio calculated for 44 burrow specimens shows that the diameters of most of the specimen are smaller than their height. The probable trace maker of *B. hemispherica* is the fact that one encounters different age groups of sea anemones, which extended their column at variable depth in soft, unconsolidated, non-fluidized mud to get stability. The inclined nature of paired burrows towards each other suggests social aggression while unpaired inclined burrows suggest swaying in search of food. The mono-odominant occurrence of *B. hemispherica* as pre-storm colonization of r-selected organisms (sea anemones) suggest sstressed environment and simultaneous vacation of the burrower reflects rapid sedimentation due to high-energy storm events. Further, storm and inter-storm events deposited sandy allochemic limestone and shale series, respectively, but did not form an identical condition for the colonization of the sea anemone. The species *B. hemispherica* of the Bagh Group revealed physicochemical parameters (energy conditions, turbidity, sedimentation rate, bathymetry, suspended organic matter, substrate consistency, oxygen, and salinity) of the Late Cretaceous transgressive sea.

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Turonien

RÉSUMÉ

La trace fossile de *Bergaueria hemispherica* appartenant à un groupe de terriers en forme de bouchons est préservée sous l'aspect d'hypichnia dans le calcaire sableux allochimique du Crétacé supérieur du groupe de Bagh affleurant près du village de Karvi, district de Chlota Udepur, Inde occidentale. Elle apparaît très tassée, verticale à subverticale, en général non ornementée ; elle présente occasionnellement des structures en forme d'anneaux, minces et décolorés, des cylindres remplis de grès allochimique à base hémisphérique s'étendant

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Plug Shaped Burrows *Conichnus - Conostichus* from the Late Cretaceous of Bagh Group, Gujarat, Western India

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ABSTRACT

Plug-shaped ichnofossils *Conichnus conicus*, *Conostichus broadheadi* and *C. stouti* are found in the intercalated micritic sandstone and sandy allochemic limestone shale sequence of Bagh Group, Narmada district, Gujarat. These ichnospecies occur at two stratigraphic levels and shows distinct morphological features interpreted as resting/dwelling structures of sea anemone. The occurrence of these ichnospecies along with oyster fossils genera like *Bosostrea* and *Indostrea* indicate shallow marine environment.

INTRODUCTION

The Late Cretaceous Bagh Group is well developed on the northern side of the Narmada river in the western Madhya Pradesh and Gujarat. Many workers have explored Bagh Group on different aspects such as sedimentology, paleontology and tectonics. Few of them focused on ichnological aspects of Bagh Group exposed in Madhya Pradesh (Chiplonkar and Badve, 1970, 1972; Chiplonkar and Ghare, 1977; Singh and Dayal, 1979; Badve, 1987; Nayak, 2000) and Gujarat (Ghare and Badve, 1980). Chiplonkar and Badve (1978) have reported bivalve species of *Bosostrea* (*B. bosei, B. lata, B. trigonoides, B. flexuosa and B. scidiformis*) and *Indostera* (*I. indica, I. falciformis, I. oclavat, I. reniformis and I. deflecta*) from the oyster limestone of Ambadungar region of Gujarat.

The present work describes the plug shaped burrows *Conichnus* and *Conostichus*, collected from sandy allochemic limestone and micritic sandstone beds intercalated with shales, exposed at Uchad (Lat. 21°56' 0" N, Long. 73°37'43" E) and Bhekhediya (Lat. 21°57' 55" N, Long. 73°40'28" E) villages of Tilakwada taluka of Narmada district (Fig.1).

MATERIAL AND METHOD

The present study was carried out in Men River basin at Uchad and Bhekhadiya villages. Lithologs were measured; systematic samples collected and positions of plug shaped burrows are marked on litholog. The ichnofossil specimens were photographed and identified as *Conichnus* and *Conostichus*; and preserved in museum of Department of Geology, The Maharaja Sayajirao University of Baroda. Total three ichnospecies of two ichnogenera were identified and classified according to ICZN. It is further described considering the morphology and preservational aspects in order to decipher paleoecology.

SEDIMENTOLOGY

Ray (1981) has classified Bagh Group of Gujarat into two formations viz. lower Songir and upper Uchad. The Songir Formation is subdivided into Mohanfort member and Raisingpur member while the Uchad Formation is subdivided into Bilthana member and Galesar member. The Songir Formation comprises of conglomerate, grit and

shale intercalation, mudstone, micritic sandstone, ferruginous sandstone, muddy micrite and sandy micrite.

Uchad and Bhekhadiya section attains a thickness of 37.2 m and 20.6 m respectively (Fig.2) and exposes the rocks of the Raisingpur member of Songir Formation, and Bilthana and Galesar members of Uchad Formation. Raisingpur member comprises of fine grained rippled micritic sandstone. Bilthana member comprises of fissile rippled micritic sandstone with shales and oyster-rich sandy allochemic limestone while Galesar member comprises of thinly bedded mudstone, sandy micrite, and micritic sandstone having nodular appearance, pink to grey shales, fine to medium grained x-bedded ferruginous sandstone and quartz arenite and muddy micrite.

PLUG SHAPED BURROWS

Plug shaped burrows occur abundantly in clastic and non-clastic sediments of shallow marine environments throughout the Phanerozoic Eon. A large group of single entrance plug shaped burrow exhibit narrow range of morphological variations. Pemberton et al. (1988) revised the ichnotaxonomy of the plug shaped burrows and related ichnogenera and differentiated the structures based on overall burrow geometry, wall ornamentation, distal termination and internal structure and observed that diameter/height ratios remain remarkably consistent for specimen displaying similar configuration and thus recognized four basic patterns. Other morphological features show substantially different degrees of importance resulting from behavioural patterns (Fürsich, 1973; Bromley and Frey, 1974). On the basis of the above criteria, Pemberton et al. (1988) described five distinct valid ichnogenera amongst the plug-shaped burrows namely *Astropolichnus, Bergaueria, Conichnus, Conostichus* and *Dolopichnus*. Two ichnogenus, namely *Conichnus* and *Conostichus* are identified from sandy allochemic limestone and micritic sandstone of Bagh Group is described in detailed below.

Ichnogenus: *Conichnus* Myannil, 1966

Diagnosis: Conical, amphora-like, or acuminated subcylindrical structures oriented perpendicular to bedding plane; base may be rounded or may exhibit a distinct, papilla-like protuberance. Fillings may reveal patterned internal structures such as chevron laminae but not radial medusoid symmetry.

Ichnospecies: *Conichnus conicus* Myannil, 1966
(Fig. 3a-c)

Diagnosis: Indistinctly to thinly lined conichnians tapering to a smooth, rounded, but distinctly basal apex.

Category: Conical-shaped.

Stratinomy: Hypichnia in micritic sandstone and sandy allochemic