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.

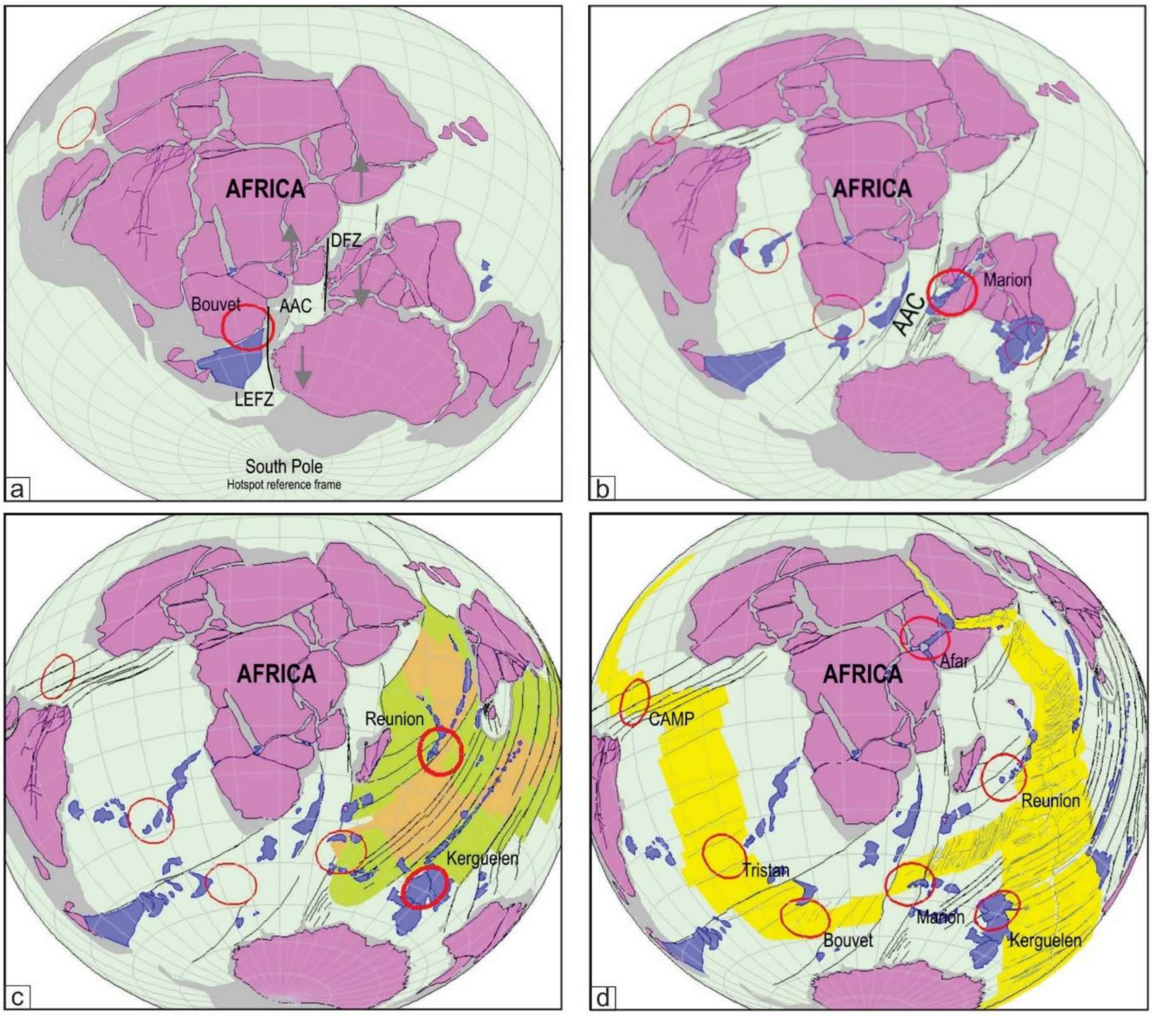

Figure 1.1 Phases of Gondwana breakup (after Reeves, 2009). a. Breakup between eastern and western Gondwana controlled by the strike-slip movement between Davie and the Lebombo-Explora fracture zones at 145 Ma, creating Africa-Antarctica Corridor (AAC); India and Antarctica started splitting at 130 Ma. 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.

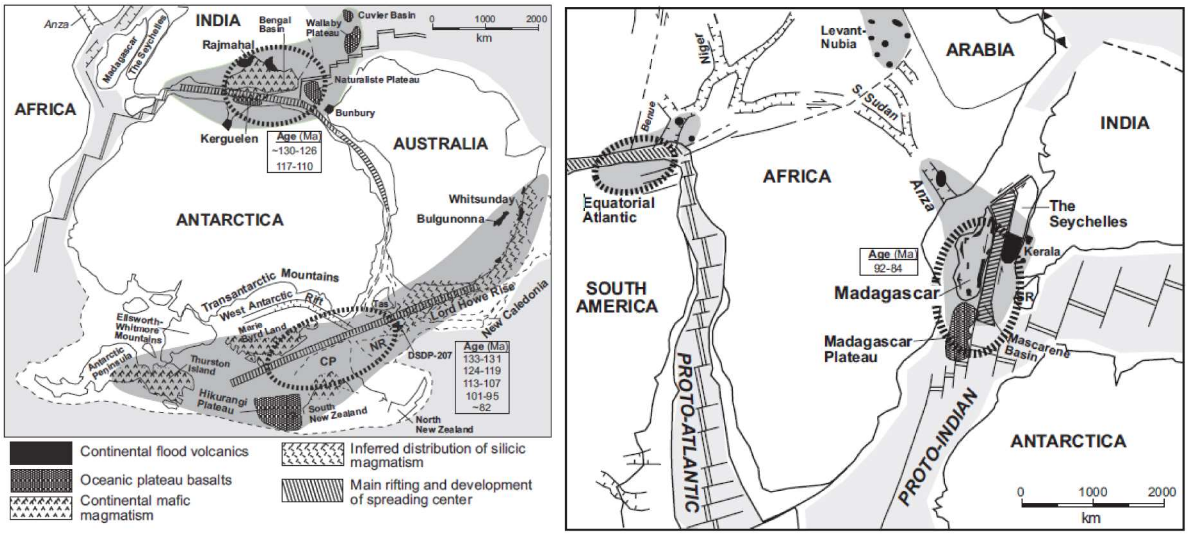

Figure 1.2 Reconstruction of Early Cretaceous Gondwana (eastern and central) after Segev (2002) showing a. showing plume province of the Rajmahal and Kerguelen, the breakup between India and Antarctica, and the passive rifting between Australia and Antarctica. b. Madagascar igneous and plume province,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

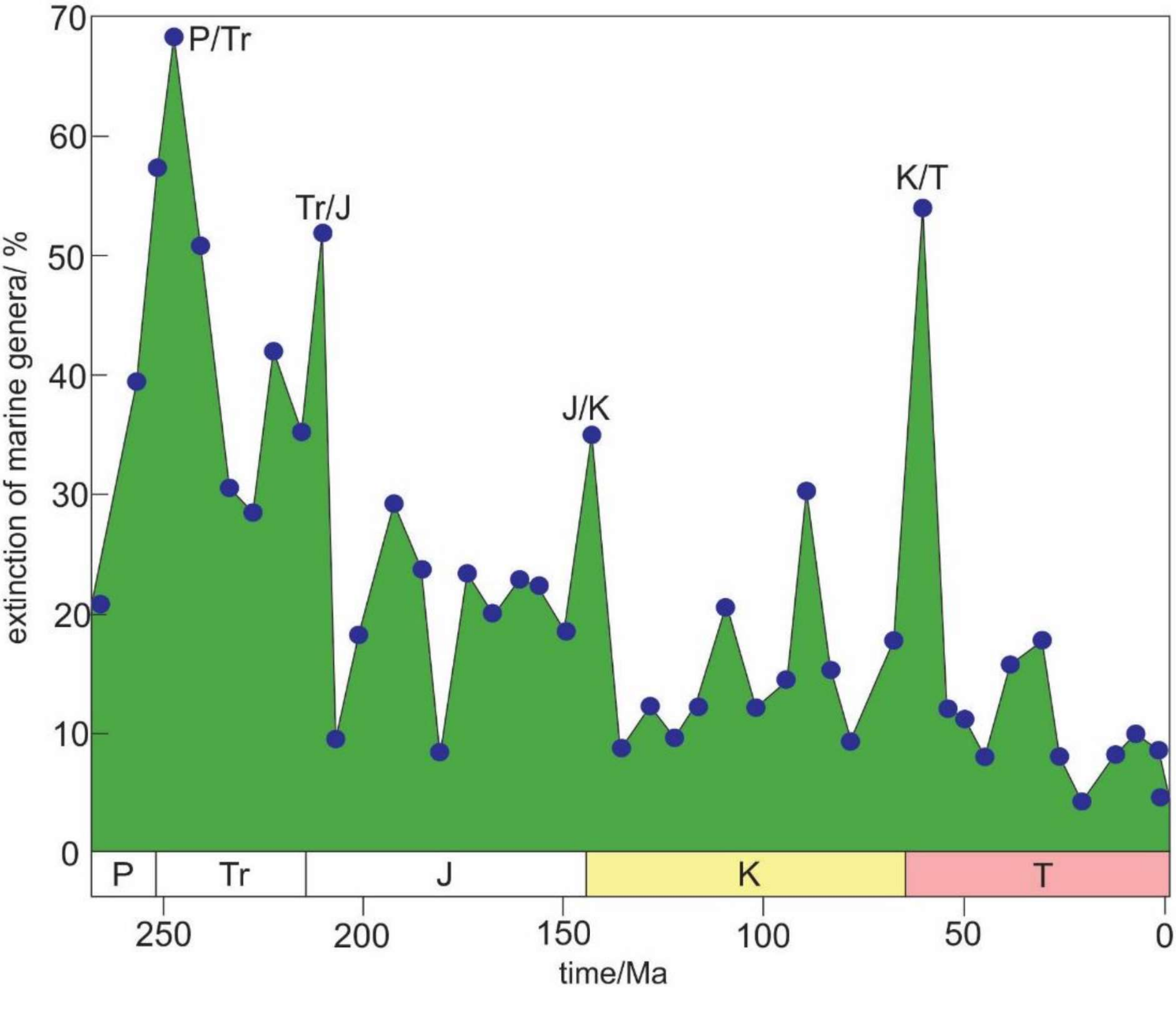

Figure 1.3 Extinction percentages of marine genera since last 270 Ma. The total number of genera is 10,383, of which 6350 are extinct (Sepkoski, 1990).

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.”

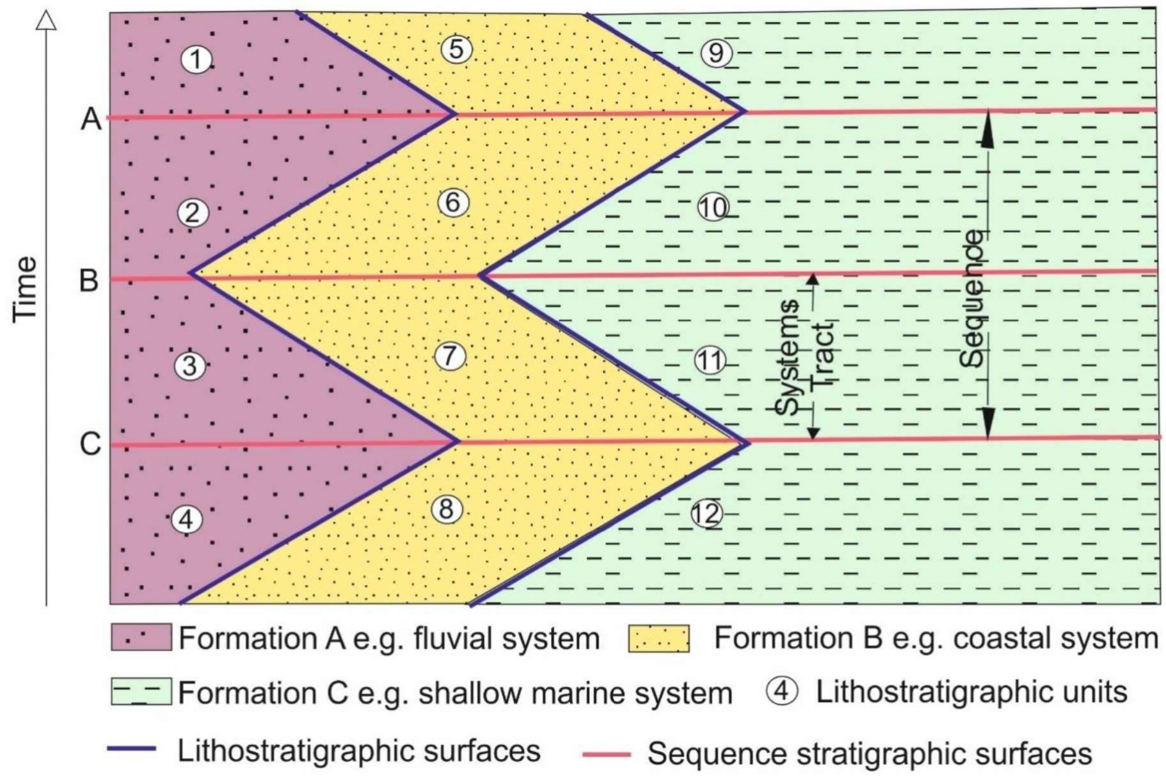

Figure 1.4 Conceptual contrast between lithostratigraphy and sequence stratigraphy (Emery and Myers, 1996 and Catuneanu, 2006).

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

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),

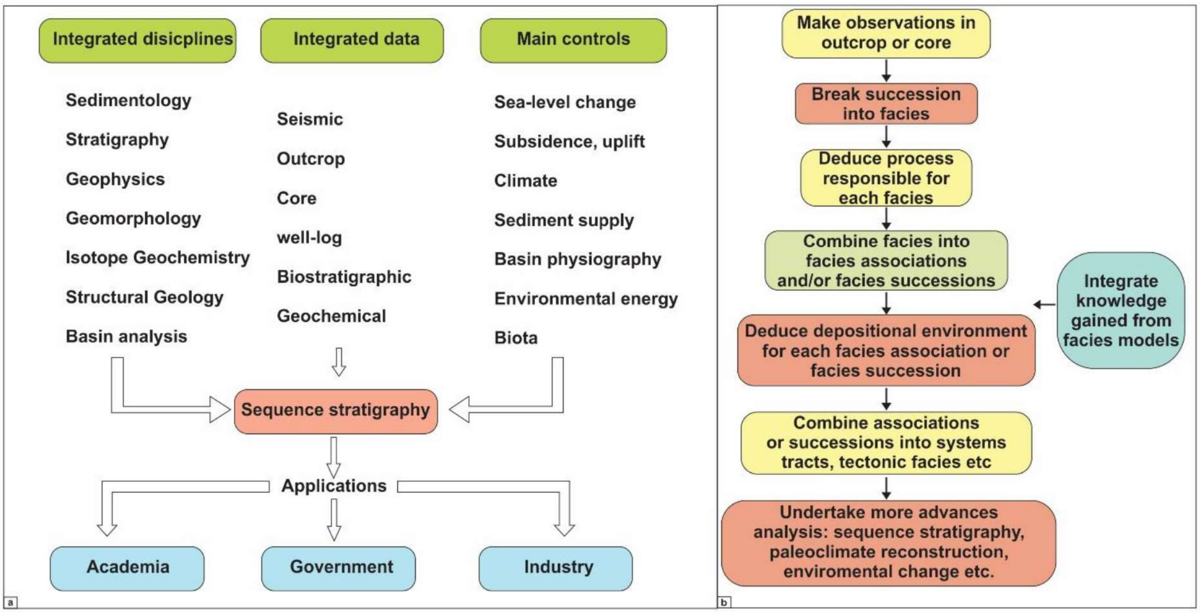

Figure 1.5 a. Flow chart explaining the progression of data assemblage for depositional environment interpretation and construction of sequence stratigraphic model followed in the present study (Dalrymple, 2010). b. Applications, controls, integrated disciplines, and data of sequence stratigraphy (Catuneanu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

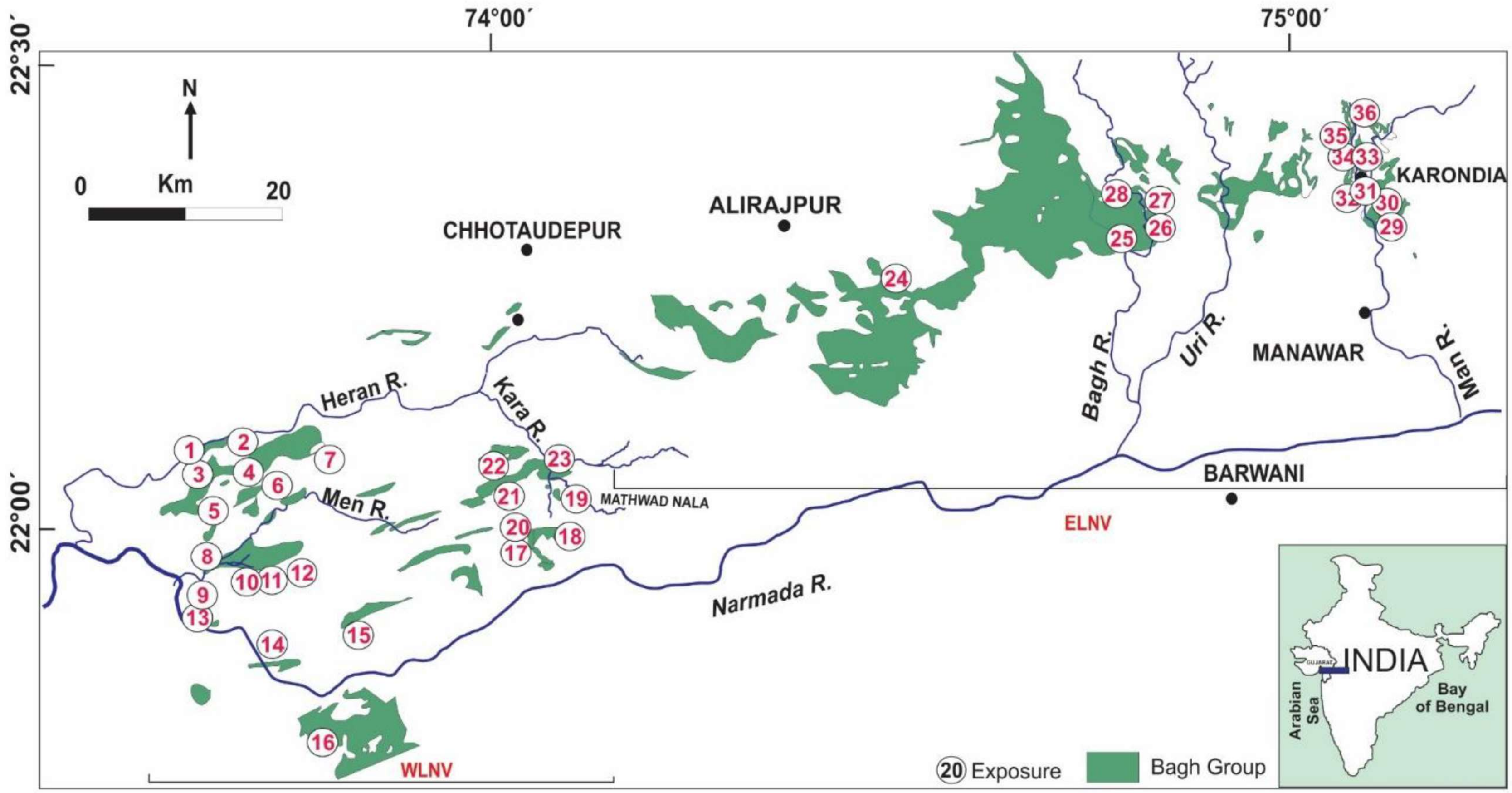

Figure 1.6 Map showing the studied sections of the Bagh Group of WLNV (location no. 1-23) and ELNV (location no. 24-36).

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.