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.

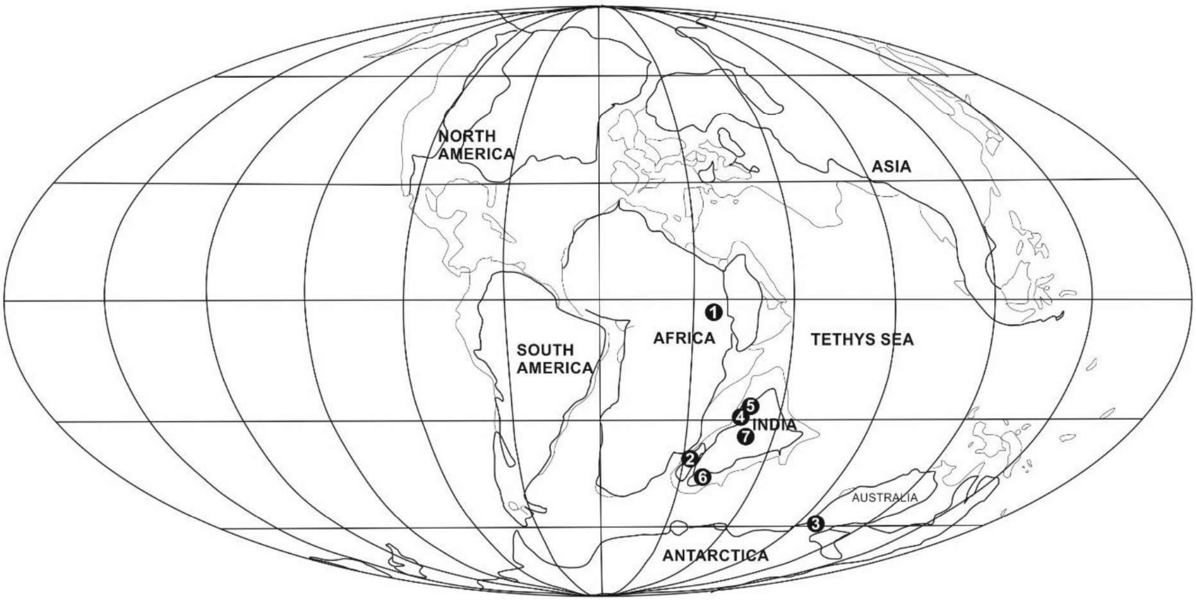


Figure 8.1 Paleogeographical map showing the distribution of the continents during Albian-Cenomanian (Bardhan et al., 2002) and position of the 1. Eastern Desert (Egypt), 2. Mahajanga Basin (Madagascar), 3. Carnarvon Basin (Australia), 4. Saurashtra-Kachchh basins (India), 5. Jaisalmer-Barmer basins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

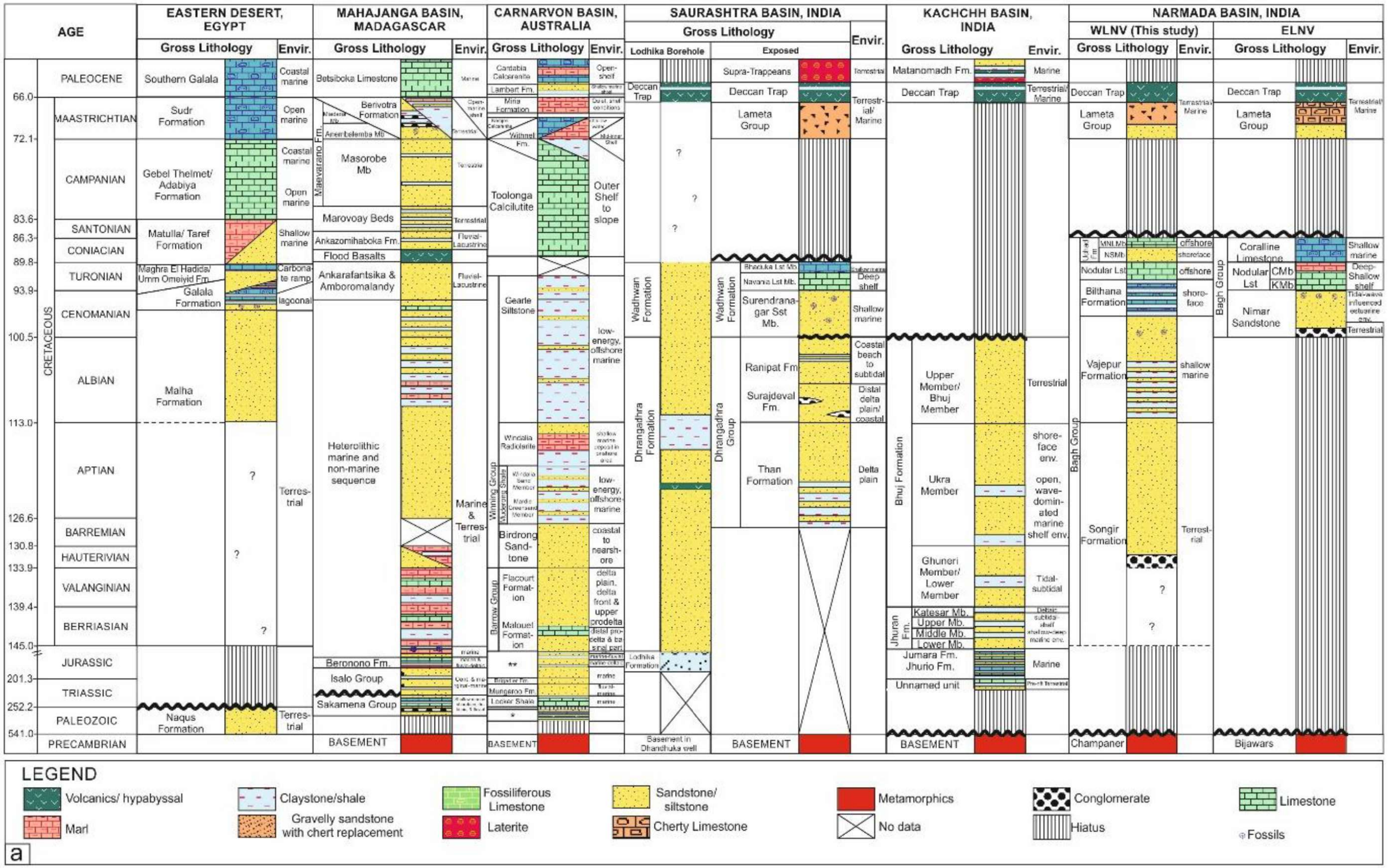
Uchad section in the WLNV, which is, in turn, overlain by the Men Nadi Limestone Member. The basins consist of Turonian transgressive facies deposited during the eustatic sea-level rise followed by regressive facies deposited during the end-Cretaceous tectonic activity. It is worth noting the interaction 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
Betsiboka Limestone
Berivotra Formation
Anembalemba Mb
Masorobe Mb
Maevarano Fm.
Marovoay Beds
Ankazomihaboka Fm.
Flood Basalts
Ankarafantsika & Amboromalandy
Heterolithic marine and non-marine sequence
Beronono Fm.
Isalo Group
Sakamena Group
BASEMENT
Toolonga Calcilutite
Gearle Siltstone
Windalia Radiolarite
Winning Group
Birdrong Sand-tone
Flacourt Format-ion
Malouet Format-ion
Barrow Group
Mungaroo Fm.
Locker Shale
Deccan Trap
Wadhwan Formation
Dhrangadhra Formation
Lodhika Formation
Basement in Dhandhuka well
Supra-Trappeans
Lameta Group
Surendrana-gar Sst Mb.
Ranipat Fm
Surajdeval Fm.
Than Formation
Dhrangadhra Group
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
Nodular Lst
Bilthana Formation
Vajepur Formation
Songir Formation
Bagh Group
Champaner
Coralline Limestone
Nodular Lst
CMb
KMb
Nimar Sandstone
Bijawars
Coastal marine
Open marine
Shallow marine
Carbonate ramp
lagoonal
Terres-trial
Fluvial-Lacustrine
Marine & Terres-trial
Outer Shelf to slope
low-energy, offshore marine
coastal to nearsh-ore
delta plain, delta front & upper prodelta
Terrestr-ial/ Marine
Deep shelf
Shallow marine
Coastal beach to subtidal
Distal delta plain/ coastal
Delta plain
Terrestrial
shore-face env.
open, wave-dominated marine shelf env.
Tidal-subtidal
Marine
offshore
shore-face
shallow marine
Terrest-rial
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

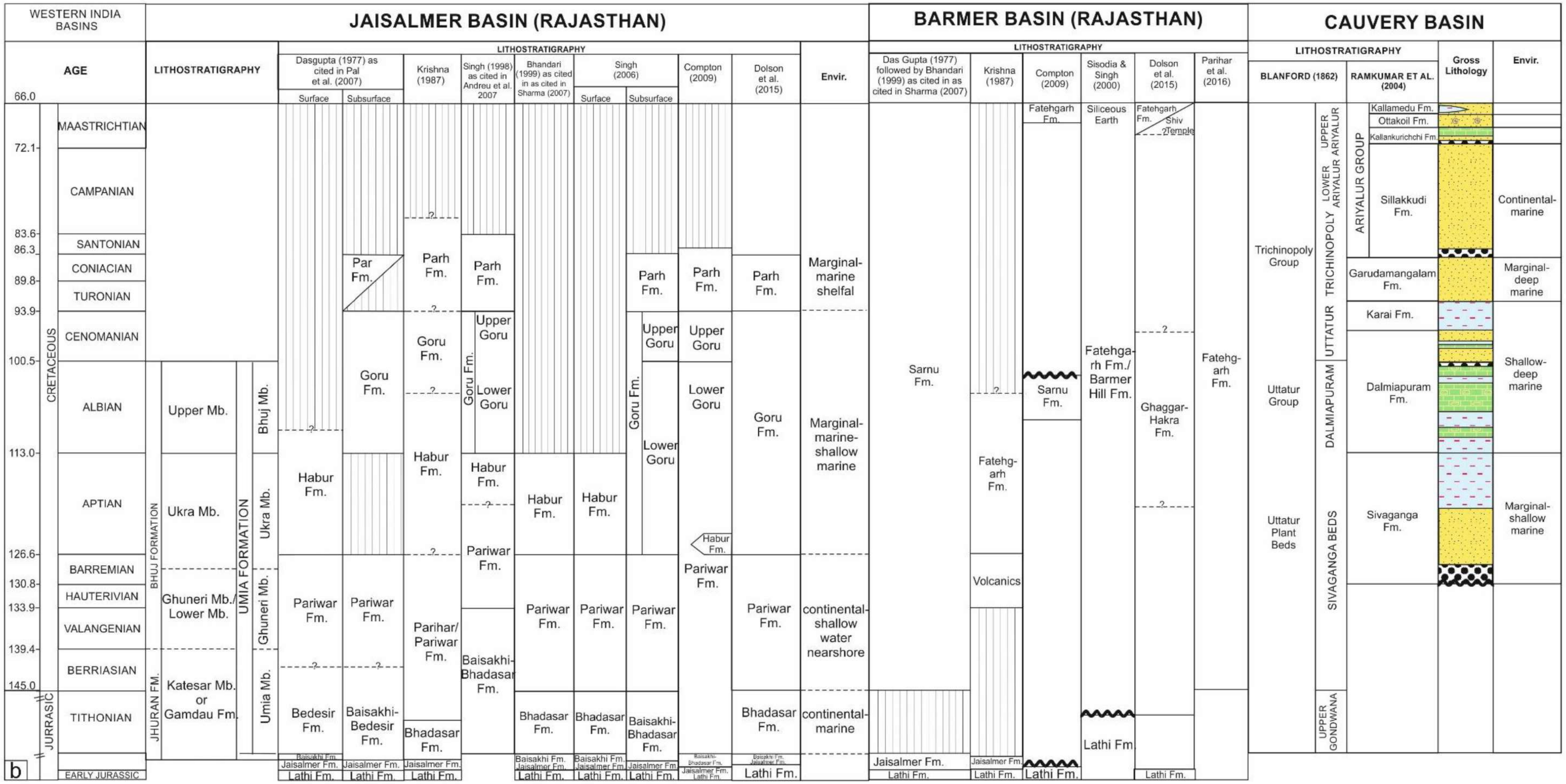


Figure 8.2 Generalized stratigraphic succession and the depositional environments of the Cretaceous Tethyan basins. a. Eastern Desert, Mahajanga, Carnarvon, Saurashtra, Kachchh and Narmada, and b. Jaisalmer, Barmer, and Cauvery (modified after Shitole et al., 2021).

(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.