

CHAPTER-9

DISCUSSION AND CONCLUSIONS

9.1 INTRODUCTION

The systematic field and laboratory study of the Saurashtra Intertrappeans resulted in various types of sedimentological, stratigraphical, geochemical, and palynological data. Investigator has also discussed their procedural phenomenon and mentioned how the data sets are obtained in detail in the foregoing chapters. To understand what happened during the deposition of the intertrappean sediments it is a prerequisite to analyse all the data sets conventionally and combination with each other to obtain the full picture of the basins. A rigorous attempt is made to understand the evolution of the basins, the obtained data sets are interpreted logically and conventionally. The data sets are used herein to understand the paleoecological parameters, paleoclimatic conditions, depositional environments of the Saurashtra Intertrappeans, and paleogeographic position of the Indian Plate.

9.2 PALEOVEGETATION

The Saurashtra Intertrappeans contain various types of palynofossils (Table 9.1) of the Paleogene time, and their affinity to the modern flora has helped in understanding the vegetation of the past. It has also been correlated with nearby equivalent deposits such as Bhavnagar, Kachchh, and Cambay lignite mines to understand the gradient in the paleovegetation. The detailed comprehensive list is provided in Table 9.1 which shows the diversity in the palynoflora, and paleovegetation, reflecting the local environmental gradients by its affinity, habitat, and distribution.

Taxa	Affinity	Habitat	Distribution
<i>Acanthotricolpites bulbospinosus</i>	Areceaceae	-	Tropical
<i>Aquilapollenites ovatus</i>	Uncertain	-	-
<i>Araliaceoipollenites psilatus and</i>	Araliaceae	-	Tropical- subtropical

<i>Araliaceoipollenites reticulatus</i>			
<i>Arecipites bellus</i>	Arecaceae	Coastal warm regions	Tropical rainforests
<i>Barringtoniapollenites retibaculata</i>	Lecythidaceae	-	-
<i>Crotonipollis densus</i>	Euphorbiaceae	-	Tropical rainforest
<i>Cupanieidites flaccidiformis</i>	-	-	-
<i>Cupuliferoipollenites pusillus</i> and <i>Cupuliferoipollenites ovatus</i>	Fagaceae	Low montane and possibly lowland trees	-
<i>Cytheidites australis</i>	Cyathea (Cyatheaceae)	Along swamps and river streams, Freshwater, water edge elements	Tropical to subtropical west montane forests
<i>Dermatobrevicolporites dermatus</i>	Bombacaceae	Swampy evergreen forests	Tropical region
<i>Ephedripites</i> sp.	Ephedraceae	Herbs/shrubs of dry and warm scrub	-
<i>Florschuetzia rajpardiensis</i>	Ancestral to Sonneratia (Lythraceae)	Fresh or brackish swamps	-
<i>Hammenisporis susannae</i>	Ceratopteridaceae	-	-
<i>Lakiapollis ovatus</i>	Durio (Bombacaceae)	Swamp and lowland areas, Megathermal	Tropical to subtropical evergreen forests
<i>Longaapertites triangulates</i> and <i>Longapertites retipilatus</i>	Arecaceae (Eugissona)	Low-lying shrubby forests and swamps	Tropics of Southeast Asia
<i>Malvacearumpollis</i> sp.	Dissiliaria, (Picodendraceae)	Seasonal evergreen rain forests, possibly dry areas and along braided rivers	-
<i>Matanomadhiasulcites maximus</i>	Annonaceae	Semi-humid regions adjacent to the coast	Tropical lowland evergreen forests
<i>Meliapollis ramanujamii</i>	-	Freshwater swamp and water edge elements	-
<i>Monocolpopollenites plicatus</i>	-	-	-

<i>Monocolpopollenites</i> sp.	Areaceae	-	-
<i>Mulleripollis bolporensis</i>	-	-	-
<i>Palmaepollenites communis</i>	Areaceae	Coastal swamps	Tropical to subtropical evergreen forests
<i>Palmidites</i> sp.	Areaceae	Low lands, steep hillocks	Tropical to subtropical forests of India and SE Asia
<i>Proxapertites cersus</i> and <i>Proxapertites crassimurus</i>	Araceae	Moist regions	Tropical-subtropical to Temperate
<i>Proxapertites</i> spp.	-	-	Pantropical palm group
<i>Rhoipites kutchensis</i>	Anacardiaceae	Coastal habits	Tropical to subtropical forests
<i>Rhombipollis geniculatus</i>	-	-	-
<i>Tricolporopollenites</i> spp.	Gunneraceae	Perennial herbs widely distributed in super-humid areas with heavy rainfall	Tropical-subtropical
<i>Yeguapollis</i> sp.	-	-	-

Table 9.1 Affinity, habitat, and environmental distribution of the pollen grains of the Ninama and Chotila basins.

		Cambay Basin	Bhavnagar Surkha Mine	Kachchh Lignite Mines
Pollen taxa	<i>Aquilapollenites ovatus</i>	+	-	-
	<i>Araliaceoipollenites psilatus</i>	+	-	-
	<i>Araliaceoipollenites reticulatus</i>	+	-	-
	<i>Arecipites bellus</i>	+	+	-
	<i>Barringtoniapollenites retibaculatus</i>	-	-	-
	<i>Cupanieidites flaccidiformis</i>	-	-	-
	<i>Cupuliferoipollenites ovatus</i>	-	-	-
	<i>Cupuliferoipollenites psillus</i>	-	-	-
	<i>Cythidites australis</i>	-	+	+

	<i>Dermatobrevicolporites dermatus</i>	-	+	+
	<i>Dermatobrevicolporites dermatus</i>	-	-	-
	<i>Ephedripites</i> sp.	-	-	-
	<i>Florschuetzia rajpardiensis</i>	+	-	-
	<i>Hammenisporis susanna</i>	-	-	+
	<i>Incrotonipollis neyvelii</i>	-	-	-
	<i>Lakiapollis ovatus</i>	+	+	+
	<i>Longapertites retipilatus</i>	+	+	-
	<i>Longapertites triangulates</i>	+	+	-
	<i>Malvacearumpollis</i> sp.	-	-	+
	<i>Matanomadhiasulcites maximus</i>	-	+	+
	<i>Meliapollis ramanujamii</i>	+	-	+
	<i>Monocolpopollenites plicatus</i>	-	-	-
	<i>Mulleripollis bolporensis</i>	+	-	-
	<i>Palmaepollenites communis</i>	+	+	+
	<i>Palmidites plicatus</i>	-	+	+
	<i>Proxapertites cersus</i>	+	+	+
	<i>Proxapertites crassimurus</i>	+	+	+
	<i>Proxapertites</i> spp.	+	-	-
	<i>Rhoipites kuctchensis</i>	+	+	-
	<i>Rhombipollis geniculatus</i>	+	-	-
	<i>Rhombipollis</i> spp.	+	-	-
	<i>Tricolporopollenites</i>	-	-	-
	<i>Yeguapollis</i> sp.	+	-	-
Fungal Remains	<i>Ceratohirudispora</i> sp.		-	
	<i>Diporisorites sirmaurensis</i>		-	
	<i>Frasnacritetrus indicus</i>		-	
	<i>Frasnacritetrus tougourdeavi</i>		-	
	<i>Fusiformisporites</i> sp.		-	+
	<i>Helicominites salvinites</i>		-	
	<i>Hypoxylonites minimus</i>		-	
	<i>Hypoxylonites</i> sp.		-	
	<i>Hypoxylonites subrotundus</i>		-	
	<i>Inapertisporites kedvessi</i>		+	
	<i>Inapertisporites maximus</i>		+	
	<i>Inapertisporites novus</i>		+	
	<i>Inapertisporites tetradus</i>		+	
	<i>Meliolinites spinksii</i>		+	
	<i>Monoporisorites circularis</i>		+	
<i>Palaeomycites acinus</i>		-		

	<i>Palaeomycites</i> spp.		-	
	<i>Papulosporites multicellatus</i>		-	
	<i>Perisporiacites varians</i>		-	
	<i>Pluricellaesporites globatus</i>		-	
	<i>Pluricellaesporites planus</i>		-	
	<i>Pluricellaesporites</i> sp.		-	
	<i>Polycellaesporites saxenae</i>		-	
	<i>Polycellaesporonites bellus</i>		-	
	<i>Protocolletotrichum deccansis</i>		-	
	<i>Staphlosporonites setlyi</i>		-	
	<i>Udaria saxenae</i>			
Testate Amoeba	<i>Centropyxis aculata</i>			
	<i>Arcella arenaria</i>			
Chlorophyceae	<i>Pediastrum</i> sp.	+		

Table 9.2 Palynotaxa of the Ninama and Chotila basins shows their affinity with the other parts of Gujarat i.e., Cambay Basin, Bhavnagar Surkha Mine, and Kachchh Lignite deposits in the equivalent time durations. Note: Fungal spores are incomparable due to the unavailability of their systematics in the Cambay and Kachchh basins.

9.3 PALEOECOLOGY

Paleogene intertrappean sediments of the Saurashtra Peninsula contain diverse assemblages of the palynofossils, including pollen, spores, and fungal elements with mega invertebrates. Fifty-eight taxa of fungal elements, pteridophyte spores, and pollen of gymnosperms and angiosperms, and five new species of the bivalve are described. However, there is limited usage of the palynofossils like spores and pollens because of their migratory nature whereas the sedimentation pattern of the lake is governed by local environments. For the different paleoecological parameters interpretation, the investigator has combined with other geological data to bring out to logical interpretation.

9.3.1 PALEOSALINITY

The Ninama Basin succession consists of a wide range of palynofossils (Table 9.2), their abundance and diversity are change suggesting fluctuations in salinity in the lake. The elemental ratio of Ca/(Ca+Fe) and Sr/Ba of the various lithofacies are also comparable. The initial phase of the depositional in the basin characterized by the LGM facies where the ratio of Ca/(Ca+Fe) is 0.58 suggests brackish water conditions. This facies is devoid of palynofossils

and textural parameters suggest deposition took place in a relatively high-energy environment. The CL, ML, and GBL facies consist of a highly diverse group of palynological fossils but are ubiquitously characterised by pollen grains like *Arecipites bellus*, *Longapertites retipilatus*, and *Matanomadhisulcites maximus* in the basin. The Ca/(Ca+Fe) ratio for CL and ML (0.88), and GBL (0.85) suggest deposition in saline conditions (Khan et al., 2023a). The presence of the abundant stenohaline palynoflora suggests fewer fluctuations in water salinity. GSH and SM facies dominate the sequence of the Sukhbhadar Formation and occur in cyclicity. The palynoflora is sparse in the lower part and their moderate occurrence is observed in the Sukhbhadar Formation. Two different elemental ratios, Ca/Ca+Fe is 0.28 and Sr/Ba 0.69 ratio suggests deposition in freshwater (He et al., 2017) and/or saline water (Wei and Algeo, 2020; Gu et al., 2022), respectively. This is highly plausible that there is a stratigraphic temporal evolution of elemental ratio which reflects the change in water paleosalinity from brackish water during the early short period to fresh-saline water, and dominantly saline water in the late stage of the lake which is consistent with paleoclimate change (He et al., 2017) may have restricted the distributions of the palynoflora.

During the deposition of the LGW, GSH, and SM facies of the Sukhbhadar Formation, the Ca/(Ca+Fe) ratio shows a lower value, while CL, ML, and GBL facies of the Ninama Limestone show a higher ratio. The varying elemental ratios of Ca/(Ca+Fe) and Sr/Ba indicate inconsistent salinity of the Ninama Lake marked by the varying rate of sedimentation and water influx. The lower elemental ratio of the clastic facies (LGW, GSH, and SM) suggests a relatively thick water column, and renewal of the water in the lake periodically during the deposition indicates low or fluctuating salinity (Anadon et al., 1991; Gallois et al., 2018). The higher elemental ratio of the limestone facies (CL, ML, and GBL) suggested a decrease in water level due to sedimentation and gradual depletion of lake level due to precipitation of carbonates and enhancement of the salinity in the Ninama Basin, the condition is highly probable in semi-arid climatic conditions (He et al., 2017).

The Chotila Basin, adjoining to the Ninama Basin, characterised by similar types of deposits in the initial phase and later shows varying sediment characteristics as well as palynofossils assemblages (Table 9.2). It is characterized by a fewer number of pollens as compared to fungal assemblages (Fig. 8.2). The elemental ratio of Ca/Ca+Fe of the Bamanbor Formation facies shows CS (0.20), SS (0.14), FSS (0.23); ratio of the Chotila Chert facies LC and MC (0.16), MS (0.20), and Rangpar Formation facies CS (0.21). These ratios suggest all

the lithofacies were deposited in freshwater conditions (He et al., 2017; Khan et al., 2022, 2023b).

The elemental ratios of Sr/Ba are highly variable e.g., in the Bamanbor Formation the CS facies on the top with (0.78), SS (0.59) and FSS (0.50), Chotila Chert facies MS (0.54) and Rangpar Formation facies LC and MC (1.5) and CS (2.6). The Sr/Ba ratio suggests the deposition of CS, SS facies of Bamanbor Formation, and MS facies of Chotila Chert in brackish water; the abundance of the colonial alga, and biodegraded sedimentary organic matter in most of the beds is significant. This green alga flourishes in lacustrine environments but also occurs in weakly saline brackish water (Knights et al., 1970; Grice et al., 1998; Clausing, 1999); while deposition of FSS in freshwater and the deposition of LC-MC in Saline water (Wei and Algeo, 2020; Gu et al., 2022).

The elemental ratios of Ca/Ca+Fe and Sr/Ba are not comparable for any of the facies of the Chotila Basin. Hence, stratigraphic temporal evolution of these elemental ratios a wider range of the paleosalinity is considered for the basin. The deposition of CS facies of Rangpar Formation in a freshwater-to-brackish water environment is followed by the deposition of MS and MC and LC facies in fresh to saline and fresh to brackish water, respectively. The deposition of FSS facies suggests a freshwater condition in the basin, followed by fresh to brackish water conditions during the deposition of SS and CS facies of the Bamanbor Formation. The salinity of the FSS facies follows the presence of freshwater palynomorphs like *Meliapollis ramanujamii*, *Lakiapollis ovatus*, and *Florschuetzia rajpardiensis* which are freshwater lake and water-edge elements (Sahay et al., 2016) and mega invertebrate of the Mollusca, including bivalves and gastropod.

9.3.2 PALEOREDOX

Two different ratios, V/(V+Ni) and V/Cr are considered for evaluating the paleoredox conditions of the Ninama Basin. The value of V/(V+Ni) of the Sukhbhadar Formation facies is being of 0.57 for LGW facies (dysoxic) and GSH and SM facie being of 0.93 (anoxic); and Ninama Limestone facies CL and ML show averages of 0.88 (anoxic) and facies GBL average of 0.91 (anoxic) (Fig. 5.3). The values of V/Cr of the Sukhbhadar Formation facies being of 1.56 (oxic) for LGW, 5.22 (anoxic) for GSH and SM, and Ninama Limestone facies CL and ML is 3.06 (dysoxic) and 1.86 (oxic to dysoxic) for GBL facies.

The elemental ratios for both the paleoredox indicators, V/V+Ni and V/Cr show dissimilar results. This variation might have been caused due to local depositional parameters

that have affected the distributions of the microorganisms. Hence, their wide ranges for each lithofacies are considered to couple the data of both the ratios. The LGW facies do not bear any type of palynomorph, though it shows the oxic-dysoxic conditions suggested in the initial phase, the growth of the organisms was hampered by some other parameters. It gradually changes to an anoxic condition during the GSH and SM, and ML and CL facies, the presence of fungal elements indicates anaerobic type organisms have appeared or it may develop a dysoxic condition alternatively may have not been recorded. Finally, deposition of the GBL took place in oxic to anoxic conditions during the close of the Ninama Basin and is well supported by the presence of an abundant and diverse group of palynomorphs (Fig. 8.1).

For the Chotila Basin, both the elemental ratios of paleoredox indicators, $V/V+Ni$ and V/Cr have nearly identical results. The value of $V/V+Ni$ for Bamanbor Formation facies CS is 0.88 (anoxic), SS is 0.82 (anoxic) and FSS is 0.79 (suboxic); the ratio of the Chotila Chert facies MS is 0.87 (anoxic) and LC and MC are 0.93 (anoxic) and the Rangpar Formation facies CS is 0.89 (anoxic). The value of V/Cr , for Bamanbor Formation facies CS, is 6.21 (anoxic), SS is 5.01 (anoxic), FSS is 1.45 (oxic); Chotila Chert facies MS is 5.52 (anoxic) and LC and MC are 4.59 (anoxic) and Rangpar formation facies CS is 5.4 (anoxic).

As compared to Ninama Basin the elemental ratios of both the paleoredox indicators, $V/V+Ni$ and V/Cr are identical in the Chotila Basin. Initially, the deposition of CS facies of the Rangpar Formation shows anoxic conditions as evidenced by a high percentage of Amorphous Organic Matter (Venkatachala, 1981; Tyson, 1989, 1995; Pacton et al., 2011) and it continues through the deposition of the MC and LC and MS facies of the Chotila Chert. The presence of fishes such as *Paleopristolepis chiplonkari*, *Horacupea intertrappean*, *Paleopristolepis feddeni*, *Perca cf. angusta*, *Indiaichthys bamanbornsis* and *Percromorpha indet* fishes (Borkar, 1973, 1975, 1984; Arratia et al., 2004) in the Chotila Chert suggest water body conditions have supported life. This condition gradually changes and becomes oxic during the deposition of FSS facies of the Bamanbor Formation is also comparable with the presence of bivalves and gastropod fossils, and, at last, Chotila Basin experiences the anoxic conditions during the deposition of SS and CS facies of Bamanbor Formation suggest may be due to the outpouring of the volcanic lava and possibility of mixing of the hydrothermal solution.

9.3.3 PALEODEPTH

The average values of paleodepth are calculated for the Ninama Basin to understand the sedimentation processes. The ratios of $Fe/(Ca+Mg)$ for Sukhbhadar Formation facies shows

0.82 for LGW, 2.26 for GSH and SM, and Ninama Limestone facies CL and ML show 0.13 and GBL is 0.14. The basin is characterized by coarse-grained sediments in the initial phase of deposition, the values of LGW facies indicate a moderate water depth during the deposition, where the topographic low provided the accommodation space for the accumulation of the coarse-grained weathered and unweathered sediments. The overlying sequence is characterised by thick fine-grained sediments of the Sukhbhadar Formation which is 2.26 of the GSH and SM facies. The sudden change in average ratio suggesting the lake is filled at its full capacity resulted in a thick water column. The accumulation of fine-grained clastic sediments in deep water conditions is due to gravity in calm conditions. The Ninama Limestone facies CL, ML, and GBL show nearly identical average values, but it is very low as compared to the lower Sukhbhadar Formation. This value suggests that Ninama Basin was shallow in depth of the water column and allowed to precipitation of the carbonate materials. The pervasive occurrence and uniform thickness of the limestone in the basin suggest uniform conditions prevailed in the Ninama Lake and can also be envisaged shallowing based on the presence of the abundant palynofossils. Overall, the average values of $Fe/(Ca+Mg)$ suggest that paleodepth has controlled the sedimentation pattern in the basin.

Analysis of the elemental ratio $Fe/(Ca+Mg)$ of the Chotila Basin shows a significant difference in average value as compared to the Ninama Basin. Bamanbor Formation facies CS is 2.52, SS is 3.08, and FSS is 1.60; the Chotila Chert facies MS has 2.35, and LC and MC being equal, 3.30 and Rangpar Formation facies CS being 3.00. The value of each lithofacies of the Chotila Basin suggests a deep lacustrine condition, but minor variation in the overall average values is reflected in short-term changes in water level may indicate the climatic variation may halt the drawing of water into the basin. The facies SS, LC, MC, and CS show almost identical depth, The uniform distribution of the MS facies suggests shallowing of the basin and has promoted the precipitation of the silica. The shallowing of the basin during the deposition of the FSS facies of the Bamanbor Formation suggests the shallowest condition of the basin that corroborated with the deposition of coarse-grained sediments. The value of SS and CS facies at the close of the basin suggest further an increase of the paleodepth and finally, it is filled by the Deccan lava and halted the sedimentation.

9.4 PALEOCLIMATE

9.4.1 PALEOWEATHERING AND PALEOCLIMATIC CONDITIONS

To infer the paleoweathering and paleoclimatic conditions the average value of Ti/Al and CIA-K for various lithofacies of the Ninama Basin are considered, respectively. Ti/Al values of the Sukhbhadar Formation facies LGW is being of 0.22, GSH and SM are 0.15, Ninama Limestone facies CL and ML are 0.13 and GBL is 0.11. Likewise, the CIA-K average value of the Sukhbhadar Formation facies LGW is 74.28%, GSH and SM are 83.44%, and Ninama Limestone facies CL and ML are 72.12%, and GBL is 62.66%.

The average values of the SH, SM, and LGW facies are closer to the Ti/Al values of Average Deccan Basalt Composition (ADBC) 0.19 (Fig.) (Crocket and Paul, 2004). These high Ti/Al values are indicative of the mafic composition of the host rocks and the relatively high rate of detrital input in the basin during the deposition of the Sukhbhadar Formation. It is also supported by the average values of CIA-K from suggest humid-tropical climatic conditions during the LGM facies. The value of the LGW facies also suggests a humid tropical climate that is prone to chemical weathering and the presence of lithic grains suggests the physical weathering of the host rocks, short transportation, and rapid deposition. The value of facies GSH and SM are close to ADBC but a little less than the average value marked by the change in climatic conditions from humid-tropical to semi-humid tropical where rain precipitation was a little inconsistent. The CIA-K values of GSH and SM suggested the Mean Annual Precipitation (MAP) calculated to be an average of 1185 mm indicating intensified weathering that is linked with quantity of precipitation.

The average Ti/Al values of the Ninama Limestone facies CL and ML (0.13) and GBL (0.11) bear a lower value as compared to average Ti/Al values ADBC. Further, the average value of the CL and ML decreases as compared to GSH and SM facies of the Sukhbhadar Formation suggesting a moderately semi-humid climate and GBL facies show a relatively low average value, which suggests a semi-arid climate. The facies of the Ninama Limestone suggest a decrease in clastic sediment input in the basin may reflect the change in intensity of the rain precipitation which has halted the chemical weathering. The presence of *Frasnacritetrus* sp. as grassland fungi in ML facies, suggests, a warm climate (Antoine et al., 2006). The average values are consistent with the current climate in western India, which is hot and semi-arid with seasonal rainfall (Venkatesh et al., 2021).

Similarly, the average values of Ti/Al and CIA-K of the Chotila Basin are also calculated for the interpretation of the paleoweathering and paleoclimatic conditions. This value shows much difference as compared to the upper part of the Ninama Limestone sequence. The Ti/Al ratio of the Rangpar Formation facies CS is 0.21, the ratio of Chotila Chert facies MS is 0.13, LC and MC are 0.27 and Bamanbor Formation facies CS is 0.17, SS is 0.17 and FSS is 0.20. Likewise, the CIA-K average value of Rangpar formation facies CS is 76.59, the value of Chotila Chert facies MS is 84.64, LC and MC are 86.58, and Bamanbor Formation CS is 85.95, SS is 81.23 and FSS is 79.0.

The facies CS of the Rangpar Formation and CS, SS, and FSS facies of the Bamanbor Formation are in and around the average value ADBC (0.19) as given by Crocket and Paul (2004). These average values of the Ti/Al are indicative of the mafic composition of the host rocks and the relatively high rate of detrital input in the basin. The CIA-K values suggest the Mean Annual Precipitation (MAP), the average precipitation is calculated as being 1209.39 mm, 1095.55 mm, and 1049.14 mm for CS, SS, and FSS facies respectively for the Bamanbor Formation. The nearly identical value, 1000mm is also obtained for CS facies of the Rangpar Formation. These values suggest intense chemical weathering of the country rocks and a high rate of rain precipitation in the humid tropical climate.

The Ti/Al ratios of the Chotila Chert facies show highly variable, where MS shows 0.13, while LC and MC being of 0.27. A total of 17 samples of the LC and MC facies are analyzed for paleoweathering the 11 samples show an average value is less than 0.14 while 6 samples show an average value is 0.52. The abnormal ratio of the Ti/Al for the samples of LC and MC facies may be due to either secondary enrichment of elements or most probably a chance. CIA-K values were also used to calculate the Mean Annual Precipitation (MAP) to understand the intensity of weathering linked to the quantity of precipitation. MAP values of Chotila Chert are 1176.31mm and 1245.77 mm for MS, MC, and LC lithofacies respectively. A high diversity of fungal remains belonging to the families like Amorsporae, Didymosporae, Phragmosporae, Dictyosporae, Helicosporae, and Staurosporae, in the Chotila basin, can also be interpreted as an indication of the prevalence of a humid climate in the area of deposition (Singh & Chauhan, 2008). The presence of *Meliolinites* is also indicative of high humidity coupled and high temperature (Dilcher, 1963; Singh & Chauhan, 2008). The presence of *Frasnacritetrus* as grassland fungi, in both, facies of the Rangpar Formation and Chotila Chert, suggests a warm climate (Elsik, 1969; Antoine et al., 2006). The *Dicellaesporites* and *Pluricellaesporites* belonging to saprophytes present in FSS facies of the Bamanbor Formation

suggest optimum moisture and temperature conditions (Kalgutkar and Braman, 2008) during the deposition. In a nutshell, the average value CIA-K for the various lithofacies of the Chotila Basin over 1000 mm, is suggestive of relatively high precipitation indicating the humid-tropical climate.

9.5 DEPOSITIONAL MODEL

The three-dimensional depositional environmental models of the Ninama Basin (Fig. 9.1) and Chotila Basin (Fig. 9.2) have been constructed based on lithofacies (Table 5.1), various geochemical proxies (Table 5.3-5.6) and palynomorphs (Fig. 8.1). The detailed investigation has allowed us to reconstruct a three-phase depositional facies model for Ninama Lake as well as Chotila Lake and interpret the evolution of basinal history.

9.5.1 NINAMA BASIN

9.5.1.1 Phase 1

This phase is characterized by an abundance of terrigenous input in the shallow to moderately deep open lacustrine environment. The terrigenous input in the basin is sourced from the nearby Deccan Trap carried by the seasonal streams (Fig. 9.1).

The source of the detrital influx is terrestrial as suggested based on the Ti/Al ratios, 0.22 which is closely related to ADBC, and the mafic igneous rocks, i.e., the Deccan Trap. The CIA-K (74.28%) value suggests a humid climate. The zone of LGW deposition is possibly oxic to dysoxic as suggested by the V/Cr and V/(V+Ni) ratio, and the water salinity probably varied from fresh to brackish evident from Sr/Ba and Ca/(Ca+Fe) ratios. The ratio of Fe/(Ca+Mg) suggests moderate water depth during this phase. The coarse-grained, poorly sorted clasts of quartz and volcanic rock fragments are the result of the weathering of the surrounding Deccan Trap, with their subsequent transportation by seasonal streams into the local topographic depression initiating the deposition of sediments. The absence of palynomorphs or any other fossils suggests initial conditions were unfavorable for the biological growth. It may be due to the transportation and deposition of the clasts in the basin suggesting the turbidity current has played an active role during Phase 1.

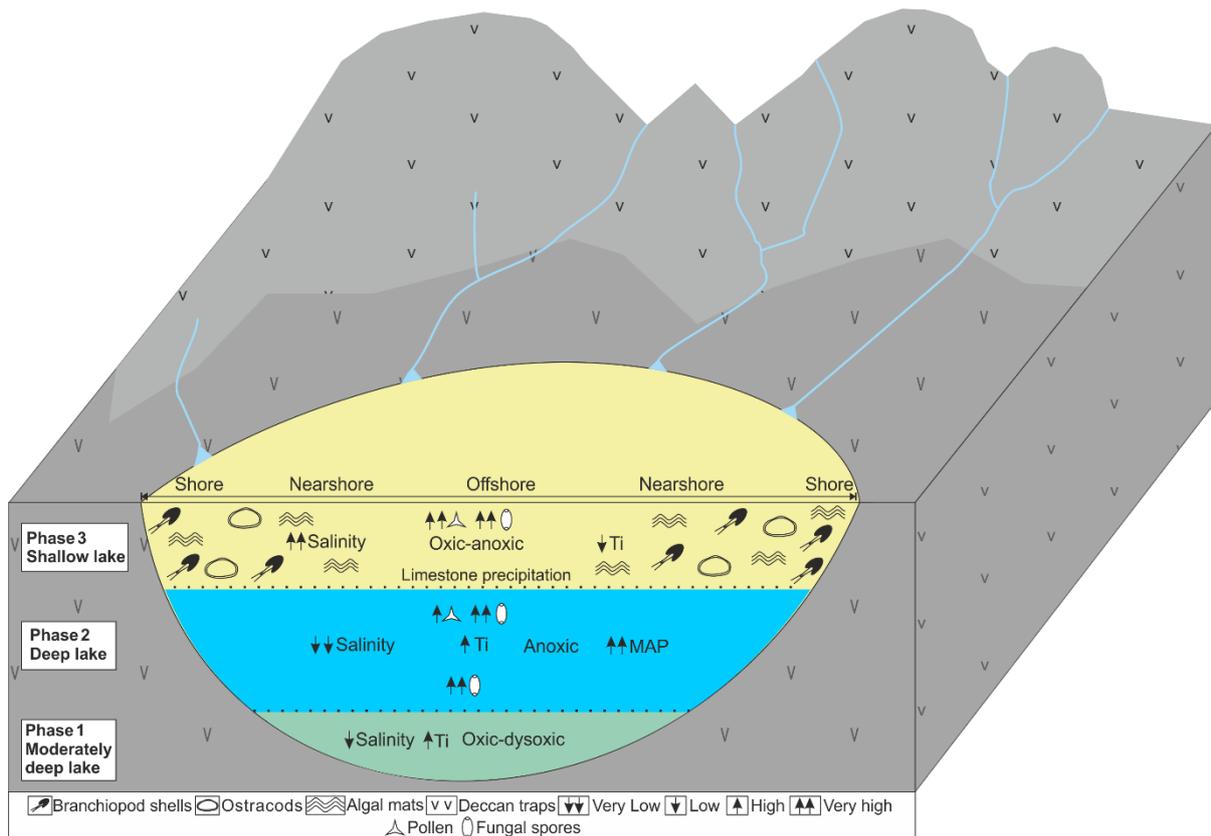


Fig. 9.1 Three-dimensional model of Ninama paleolake, depicting 3 phases of deposition. Phase 1- Deposition of LGW facies, reflects high clastic input, brackish to saline, oxic-dysoxic moderately deep lake and absence of palynofossils; Phase 2- Deposition of GSH and SM facies with moderate to high terrestrial input, freshwater to brackish water, anoxic deep lake with abundant fungal spores and moderate pollens; Phase 3- Deposition of ML, CL and GBL facies with low to moderate terrestrial input, saline, oxic-anoxic shallow lake with abundant of fungal spores and pollens.

9.5.1.2 Phase 2

This phase is characterized by the lacustrine sequence of fine-grained sediments; lithofacies SH, well laminated, occasionally interrupted by turbidity currents marked by the presence of LGW and well-preserved repetitive SM layers indicate calm conditions. The coarse terrigenous input is limited, while the fine clastics are deposited by settling in the offshore and nearshore parts of the lake (Fig. 9.1). High terrestrial input of fine clastics, derived from the nearby mafic sources, in reducing conditions of deep lake environment is evident from the lithofacies and elemental ratios (Na/K, V/V+Ni, V/Cr, and Fe/Ca+Mg), respectively. The humid climate with relatively high precipitation of over 1185 mm per annum and probably minimal evaporation, had also supported the proliferation of mycorrhizal fungi. It also indicates

a fresh to brackish water condition in the paleolake. The high reducing conditions are correlatable with the water depth of the lake. During this phase, the lake was periodically subjected to variable fluxes of coarse clastic inputs probably by seasonal streams debouching into the lake. The formation of Fe-Mn-rich mud layers of SM facies indicates the stagnant water conditions in the lacustrine environment and the presence of subaqueous desiccations which marks the dewatering and shrinkage of the layers. The reason for the development of the subaqueous shrinkage cracks in the basin can be due to the presence of clay-rich sediments which can promote shrinkage and crack due to salinity fluctuations, affirmed by the paleosalinity geochemical ratios or microbial processes which can also result in the same (McMahon et al., 2017). This phase depicts the gradual increase in water levels, allowing the deposition of fine clastics dominated GSH and SM facies, in calm and quiet waters of offshore and near-shore lake environments. The chemical data suggest conditions were favorable for the development of fresh and brackish water palynomorphs reflected in Phase 2, initially, it was poorly represented but their diversity and abundance were increased in an upward direction.

9.5.1.3 Phase 3

The final phase of the deposition took place during the shallowing of the paleolake. It is characterized by the deposition of the carbonate facies GBL, CL, and ML. The final phase of the carbonate deposition happened in two consecutive events. The CL and ML deposited in shallow waters of Ninama paleolake in an anoxic environment with low to moderate terrestrial input of fine clastics which indicates pronounced seasonality in the semi-arid conditions. The semi-arid conditions have probably led to the shallowing of the lake, and high evaporation rate as evidenced by the $Fe/(Ca+Mg)$ value of 0.13, CIA-K value of 72.12%. The recurring CSH layers in CL and ML facies are suggestive of a continuous influx of fine sediments in the lake waters. The presence of well-developed laminated algal mats suggests the flourishing of algae in the lake, and associated ostracod and cladoceran (Plate 5.3g) fragments within the laminae suggest their postmortem transport and taphonomic modification. Various intraclasts of these laminated wackestone-packstones are also noted, suggesting the reworking of the sediments in the agitated waters. The microfacies packstone, wackestone, and bindstone indicate shore to nearshore low to moderate energy environment of deposition (Flügel, 2010). The precipitation of GBL facies suggests further shallowing of the paleolake and extreme conditions leading to a high rate of evaporation, and high salinity with low terrestrial input. The carbonate mudstone microfacies and paleoenvironmental proxies suggest that lake waters were nonconductive for the development of the higher group of life forms.

9.5.2 CHOTILA BASIN

9.5.2.1 Phase 1

The initial phase of the deposition in the Chotila Basin is not observed due to the absence of surface exposure of lower contact of the sediments with the lower lava flow. The oldest CS facies, of the Rangpar Formation, in the Chotila Basin mark the earliest phase, which is dominated by the fine-grained terrigenous input in shallow to moderately deep open lacustrine environment. This terrigenous input in the basin is brought by ephemeral, seasonal streams, originating from the Deccan Trap country (Fig. 9.2). The source of the detrital influx is terrestrial as suggested based on the Ti/Al ratio, 0.21 which is closely related to ADBC, and the mafic igneous rocks, i.e., the Deccan Trap. The CIA-K (76.59%) value suggests a humid climate and 1000 mm of rain precipitation. The palynomorph data also corroborates with the average of CIA-K and MAP values and also, suggests a humid climate. The zone of CS facies shows V/V+Ni and V/Cr ratios of 0.89 and 5.4 suggesting deposition is possibly in anoxic condition, and the water salinity probably varied from fresh to brackish water evident from Sr/Ba and Ca/(Ca+Fe) ratios. The ratio of Fe/(Ca+Mg) suggests moderate to deep water depth during this phase. The fine-grained nature of the CS facies of the Rangpar Formation is the result of the weathering of the surrounding Deccan Trap, with their subsequent transportation by seasonal streams into the local topographic depression which initiated the deposition of sediments. This phase is poorly fossiliferous in the initial stage and later their abundance increases suggesting a conducive environment for the microorganisms. Phase 1 is more uniform in the form of sedimentation patterns throughout their development in the basin but shows inconsistency in the development of the microorganisms. Transportation and deposition of the fine grain sediments in the basin suggest the calm to low energy conditions, which has allowed the settlement of sediments in the lake due to gravity, also evident by the thin horizontal layers.

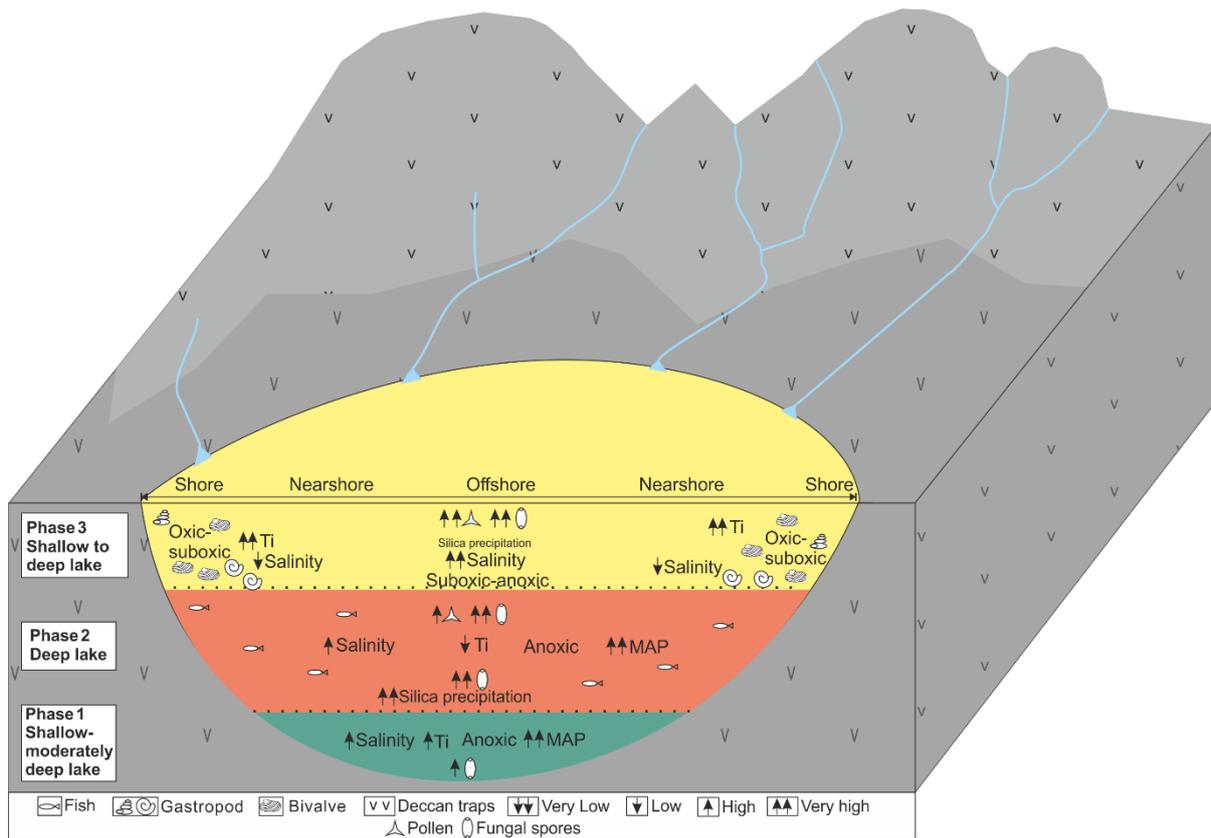


Fig. 9.2 Three-dimensional model of Chotila paleolake, depicting 3 phases of deposition. Phase 1- Deposition of CS facies of Rangpar formation, showing high rate of fine argillaceous clastic input, in brackish, anoxic, shallow to moderately deep lake with fungal spores; Phase 2- Deposition of LC, MC and MS facies, of Chotila Chert with variable terrestrial input, in brackish water, anoxic deep lake and abundant fungal spores and moderate pollens; Phase 3- Deposition of FSS and CS facies of Bamanbor Formation, in shallow to deep lake, high terrestrial input, variable salinity, and oxic-anoxic condition, with abundance of fungal spores and pollens.

9.5.2.2 Phase 2

Phase 2 shows marks a change in the environment and sediment characteristics as compared to Phase 1. It is characterized by the dominant precipitation of silicious materials, biochemically, marked by facies like LC, MC, and intercalated argillaceous, MS facies. The Ca/Ca+Fe ratio suggests fresh water while Sr/Ba ratio suggests deposition took place in brackish water. The ratios of Fe/(Ca+Mg) suggest that Chotila Basin experienced shallow to deeper depths of the water column as compared to the Rangpar Formation and allowed precipitation of the silica in the paleolake. The LC, MC, and MS facies deposited in shallow to deep waters of Chotila paleolake in an anoxic environment with low to moderate terrestrial

input of fine clastics which occurred as an intercalated sequence that indicates pronounced seasonality in the humid conditions. The humid conditions have probably led to the deepening of the lake, as evidenced by Fe/(Ca+Mg) value for MS (2.35) and LC and MC (3.30), CIA-K values of 84.64 and 86.58, respectively, which suggests deep and calm condition, also suitable for the silica precipitation. The thinly bedded nature and pervasive occurrence in the basin, the Chotila Chert suggest a continuous influx of fine sediments in the lake waters. The presence of well-developed various types of laminated structures suggests local variation in sedimentation pattern in the basin.. The Chotila Chert consists of fish namely, *Paleopristolepis chiplonkari*, *Horaclupea intertrappea*, *Paleopristolepis feddeni*, *Perca* cf. *angusta*, *Indiaichthys bamanbornsis*, and *Percromorpha indet* fishes (Borkar, 1973, 1975, 1984; Arratia et al., 2004) and turtle remains (Shringarpure, 1985) microfossils suggest that lake waters were conducive for the development of the higher group of life forms. The deposition of the MS, LC, and MC facies of the Chotila Chert suggests that precipitation of the silica took place in tolerable Ph of the brackish water in the lake.

9.5.2.3 Phase 3

Phase 3 is characterized mainly by fine-grained succession, developed in the Bamanbor Formation, and is capped by the Deccan Traps. The facies CS and SS are well laminated with thick fine-grained sandstones (FSS) facies deposited during Phase 3. The fine sand size grains suggest terrigenous input, while the fine clastics are deposited by settling in the offshore and nearshore parts of the lake. This phase also consists of thin, 30 to 40-cm cherty bands exposed in the Rangpar Industry section marking the change in sedimentation patterns. The value of elemental ratios of SS and CS facies suggest deeper water lake sedimentation and subsequent shallowing of the basin during the deposition of the FSS facies of the Bamanbor Formation. Again, at the close of the basin, the presence of the SS and CS facies suggest further an increase of the paleodepth and finally, it is filled by the Deccan Trap which halted the sedimentation. The elemental ratios, Na/K, V/V+Ni and V/Cr, and Fe/Ca+Mg of the SS and CS, FSS facies suggest high terrestrial input of fine clastics, derived from the nearby mafic sources, in fresh to brackish water, suboxic to anoxic conditions of deep lake environment, respectively. The CIA-K values suggest the Mean Annual Precipitation (MAP) of CS, SS, and FSS facies is being of 1209.39 mm, 1095.55 mm, and 1049.14 mm respectively, these values suggest a high rate of rain precipitation in the humid-tropical climate, minimal evaporation and intense chemical weathering of the country rocks. Phase 3 is nearly identical to Phase 1 in terms of sediment characteristics but much different from the environmental point of view (Fig. 8.2). FSS facies

consisting of freshwater bivalves and gastropods in oxic to suboxic conditions are correlatable with average values of Sr/Ba (0.23), V/V+Ni (0.79), and V/Cr (1.45). Phase 3 of the Chotila basin is characterized by highly diversified and abundant palynomorphs suggesting a conducive environment for the micro- as well as mega organisms (Fig. 9.2).

9.6 PALEOGEOGRAPHY

9.6.1 TIMING OF INSULAR INDIA

Pangea, the supercontinent, existed 300-200 million years ago, during the Late Paleozoic Era until the very Late Triassic, North America adjoining with Africa, South America, and Europe (Chatterjee and Scotese, 1999; Cocks and Torsvik, 2011). Terrestrial life, animals, and plants evolved and subsequently dispersed in all the parts of the Pangea. The Indian subcontinent was part of this supercontinent in the southern hemisphere (Briggs, 2003), and it was also an epicenter of the terrestrial deposits ranging in age from Lower Permian to Triassic. Different types of terrestrial organisms were residing there, and also crossing physical limits; with evolving endemic communities.

Pangaea broke into Laurasia and Gondwanaland about 200 million years ago, during the Early Jurassic, which followed the subsequent split of Gondwanaland about 180 million years during the Late Jurassic (Rogers and Santosh, 2004). The evolution and transmigration of the organisms were apparent from Pangea to Gondwanaland and subsequently in all the migrating continents. During the Middle-Late Jurassic period, the separation of the India-Madagascar Plate from the Somali coast of Africa, which experienced a vast island continent-biogeography in the southern Tethyan Ocean. The freshwater deposits have a continuous record in India, after the breakup of Gondwanaland in the Late Jurassic, through the Cretaceous and Cenozoic era. Following the breakup of Gondwana, during the late Cretaceous and Paleocene time, the Insular India (Indian subcontinent) remained an isolated landmass as the Indian Plate drifted across the Tethys Ocean. The Indian plate separated from Madagascar around 88 million years ago, but complete isolation occurred during the Maastrichtian. The extensive lava outpouring and its northward movement were rather quick and a connection was established with Asia around 55 million years ago.

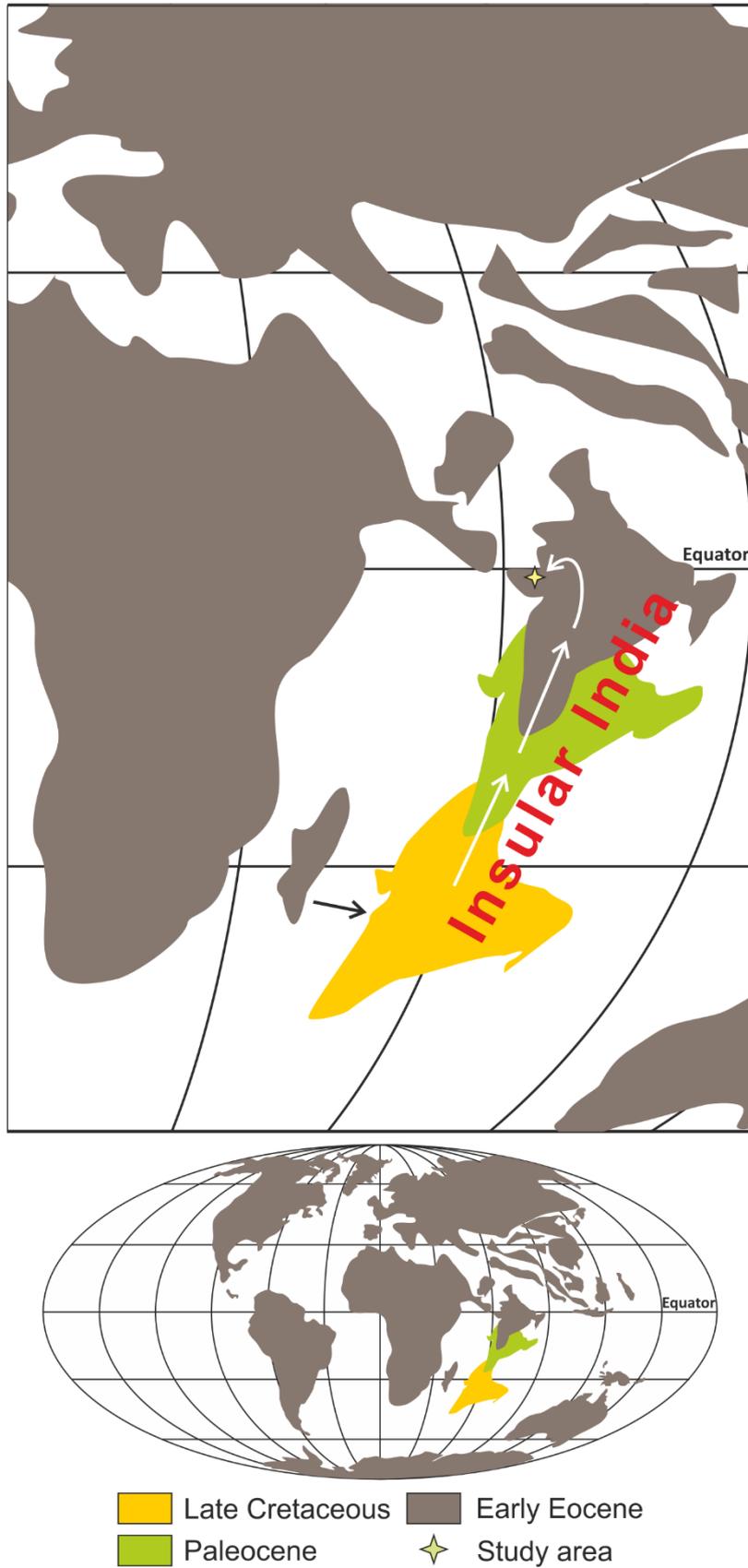


Fig. 9.3 Paleogeographic position of Insular India during its northward drift in the Tethys Ocean during Late Cretaceous, Paleocene and Early Eocene.

After the Gondwana break, nearly a continuous record of the biota-rich terrestrial deposits is observed on the Indian Plate. The Jurassic freshwater deposits recorded from the Kota Limestone (Govindan, 1975) and Early Cretaceous deposits of thick fluvial-lacustrine deposit, Songir Formation in the Lower Narmada Valley (Shitole et al., 2021), intertrappeans of Cretaceous and supra-, intra- intertrappeans of Paleogene, Siwalik's of Himalaya and fluvial Quaternary deposits.

9.6.2 EVOLUTION OF INTERTRAPPEAN BASINS

Insular India (now, the Indian subcontinent) detached completely from the Gondwanaland, had experienced the outpouring of several lava flows of the Reunion hot spot during the Late Cretaceous-Paleogene (Mahoney, 1988), called the Deccan Continental Flood Basalts (DCFB), which covered nearly 5,00,000 sq. km in western and central India. The undulating topography of DCFB led to the formation of perennial and ephemeral freshwater pools due to seasonal residual water drawn from streams, which became a host to various life forms. These volcanic activities changed the ecosystem, climate, and physiography of the terrestrial realms. The pools, usually formed across the Cretaceous-Paleogene, filled by the sediments were covered by the subsequent Deccan lava flows forming intertrappean sedimentary sequence which has patchy occurrence in the Indian continent (Blanford, 1872; Khosla and Sahni, 2003; Chenet et al., 2008). The Deccan Intertrappeans of India, comprise a unique stock of life as compared to Gondwana and Laurasia. The sediment thickness of these units is also highly variable and comprises, a wide range of terrestrial fossils of vertebrates, invertebrates, and micro- and plant fossils (Prasad et al., 1995; Prasad and Khajuria, 1996; Khosla and Sahni, 2003; Wilson et al., 2007; Samant and Mohabey, 2014; Khosla, 2015; Khosla and Verma, 2015; Kapur and Khosla, 2019). Extensive data is available on freshwater palynofossils from central, eastern, and southern intertrappean successions and are described systematically and interpreted for paleoenvironment.

In the Saurashtra Peninsula, the lake deposits which were hospitable for the different kinds of organisms in the paleotopographic low of Deccan Trap were covered by an eventual lava flow that occurred after a long cessation period. This intertrappean sequence dated based on palynomorphs suggests Paleogene age (Samant et al., 2014). Though the taxa recovered from the different intertrappean localities are meager nonetheless their presence is significant as they have never been reported from the study area earlier as well as their counterparts; hence,

they throw light on terrestrial ecosystems, changing ecological conditions during their deposition and waning phase eruption of Deccan Traps.

The investigator has identified two different lacustrine successions, Ninama Basin and Chotila Basin, based on lithology, which also contain different types of mega vertebrates and invertebrates. During the initial phase of deposition, both basins are characterized by identical sediments, but they are unfossiliferous. This is due to the intense activities of the lava outpouring, which resulted in hostile conditions for the organisms. The long cessation period in the lava outpouring, around 60 million years ago, was an improvement in the climatic conditions, when the Indian plates were over the equator (during the northward drift), small but significant microorganisms appeared. During this time, Insular India sailed through the Tethys Ocean as a vast island continent. This period is characterized by various groups of organic life, including abundant angiosperm and gymnosperm pollen grains, pteridophytic spores, and highly diversified fungal remains belonging to the families like Amorsporae, Didymosporae, Phragmosporae, Dictyosporae, Helicosporae, and Staurosporae; Testate Amoebas, Dinoflagellates and other phytoplanktons, algae and other organic remains. With the varieties of palynomorphs, different types of fishes are also found such as *Paleopristolepis chipionkari*, *Horaclupea intertrappean*, *Paleopristolepis feddeni*, *Perca* cf. *angusta*, *Indiaichthys bamanbornsis* and *Percromorpha indet* fishes (Borkar, 1973, 1975, 1984; Arratia et al., 2004). Before the close of the Chotila Lake, sedimentation was halted by lava flows, the lake was experiencing freshwater conditions inferred based on presence of the freshwater/mildly brackish palynomorph like *Meliapollis ramanujamii*, *Lakiapollis ovatus*, *Florschuetzia rajpardiensis* and are freshwater mega invertebrate of the Mollusca, mainly bivalves and gastropod.

The various geochemical analysis, the presence of various kinds of organisms, and the overall sediment characteristics of the Ninama and Chotila basins indicate that paleoecological parameters were highly fluctuating. These are reflected in a wide range of salinity, depth control on sedimentation, paleoredox conditions, weathering of the host rocks, and climatic conditions that have controlled the rain precipitations in tropical and sub-tropical environments, also overlapping with the Paleocene-Eocene Thermal Maximum (PETM) (Keller et al., 2018; Prasad et al., 2018).

During the deposition of the intertrappean sediments in the Saurashtra Peninsula, Insular India experienced the vast island continent biogeography, there was no intermigration of the flora and fauna, hence, evolution was mostly allopatric. This isolation led to the evolution

of numerous species that were restricted to the Indian landmass. The Indian Plate made a connection with Mainland Asia via Burma terrain which acted as a Gondwanan biotic ferry (Bolotov et al., 2022). They evolved independently, and played a major role in shaping the distribution of India's present-day biota (Rao, 1989), which likely originated from Gondwana through vicariance and dispersal, and spread across the Indo-China via Indo-Malaya; Iran-Afghanistan blocks and Kohistan-Dras Island arc (Bhatia et al., 1996; Verma et al., 2016), supporting the 'Out of Africa Model' (Hoeh et al., 2002; Graf and Cummings, 2009; Karanth, 2021). This assumption also needs to be tested with supportive evidence of the intercontinental paradigm.

9.7 CONCLUSIONS

The present study deals with the various types of geological analysis that led to the integration and interpretation of continental succession in a meaningful way. The intertrappean successions of the Saurashtra Peninsula are exceptional as compared to central India in biotic associations and, in time and space. At the same time, equivalent supratrappean successions of Mainland Gujarat, Saurashtra (Bhavnagar lignite mine), and Kachchh are lignite bearing which makes them further incomparable. Looking at the strengths and limitations of the generated data, the investigator has dealt with a multi-dimensional approach to investigate the intertrappean succession and integrated the data to understand the evolution of the paleolakes sequences associated with the Deccan Volcanic Province of India and drawn the following conclusions.

1. The detailed field investigation for sedimentology and horizontality, continuity, and correlations, of the intertrappean sequences of the Saurashtra Peninsula, has revealed two paleolake depositional systems, named Ninama Basin and Chotila Basin.
2. The rigorous attempt has proven that the sedimentary deposits have provided valuable data for identifying different basins and dividing them into formations.
3. India's intertrappean succession are first time in history, successfully divided into formal lithostratigraphic units.
4. Ninama Basin succession comprises the lower Sukhbhadar Formation and upper Ninama Limestone.

5. Chotila Basin succession comprises the lower Rangpur Formation, Chotila Chert, and upper Bamanbor Formation.
6. The present study has opened a new avenue for studying and classifying sedimentary deposits associated with DVP of India according to the standard stratigraphic norms. The standardization of stratigraphic units for each basin will be unique and may help in resolving important lithological and paleontological events that are associated with the LIP's of India.
7. Lithofacies of the Ninama Basin and Chotila Basin are distinct.
8. Ninama basin comprises a fine-grained dominating sequence with sandstone and is capped by limestone, further divided into seven lithofacies namely, Grey Shale (GSH), Calcareous Shale (CSH), Silty Mudstone (SM) Lithic Greywacke (LGW), Grey Black Limestone (GBL), Cherty Limestone (CL) and Marlite (ML).
9. Chotila Basin comprises a thick, fine-grained dominating sequence characterized mainly by shale, mudstone, siltstone, chert, and thin occasional bands of calcareous sandstone further divided into eight lithofacies, Fossiliferous Shaly Sandstone (FSS), Grey Shale (GS), Silty Shale (SS), Mudstone (MS), Fossiliferous Silty Mudstone (FSM), Massive Chert (MC), Laminated Chert (LC) and Black Chert.
10. XRF analysis revealed the qualitative and quantitative major oxide and, minor and trace elements concentration in various lithofacies.
11. Analysis of the inorganic (major oxides, minor and trace elements) geochemical proxy revealed various paleoenvironmental parameters such as paleosalinity, paleoredox, paleodepth, paleoclimate, paleoweathering, and mean annual precipitation.
12. Fine-grained sandstone of the Bamanbor Formation of the Chotila Basin contains new stocks of freshwater bivalves, belonging to order Unionida.
13. A new superfamily, two new families; two new subfamilies, three genera, and seven species are identified from the bivalve stocks belonging to order Unionida.
14. The higher-level category includes the superfamily Deccanoidea nov. consisting of one family, Deccanoidae nov, comprising two sub-families, Deccanoinae nov. and Chotiloinae nov.
15. Three genera *Deccanoida* nov., *Bamanboria* nov., and *Chotilia* nov. include seven species, *Deccanoida conrugis* gen. et sp. nov., *Deccanoida aleta* gen. et sp. nov.,

Deccanoida costaria gen. et sp. nov., *Bamanboria oblongis* gen. et sp. nov., *Chotilia. Trappeansis* gen. et sp. nov., *Chotilia. tuberculata* gen. et sp. nov. and *Chotilia. deccansis* gen. et sp. nov.

16. The taphonomic expressions of the collected new species as single valves and butterfly positions suggest their post-mortem transportation probably from shore to offshore lake environment.
17. The palynological analysis of the basins has resulted in the recovery of various palynofossils like pollens, pteridophytic spores, fungal spores and fruiting bodies, testate amoeba, freshwater algae, phytoclasts, opisthokonts, dinoflagellates and other phytoplanktons, structural terrestrial organic matter, and amorphous organic matter.
18. Ninama Basin consists of pollens like *Acanthotricolpites bulbospinosus*, *Aquilapollenites ovatus*, *Arecipites bellus*, *Araliaceoipollenites psilatus*, *Araliaceoipollenites reticulatus*, *Barringtoniapollenites retibaculata*, *Crotonipollis densus*, *Cupanieidites flaccidiformis*, *Cupuliferoipollenites ovatus*, *Cupuliferoipollenites psillus*, *Cythidites australis*, *Dermatobrevicolporites dermatus*, *Ephedripites* sp., *Hammenisporis susannae*, *Lakiapollis ovatus*, *Longapertites triangulates*, *Longapertites retipilatus*, *Matanomadhiasulcites maximus*, *Matanomadhiasulcites* sp., *Monocolpopollenites* sp., *Mulleripollis bolporensis*, *Palmaepollenites communis*, *Palmidites* sp., *Proxapertites cersus*, *Proxapertites crassimurus*, *Rhombipollis geniculatus*, *Rhombipollis* spp., *Tricolporopollenites* spp., and *Yeguapollis* sp.
19. Ninama Basin consists of Fungi and fungal elements namely, *Ceratohirudispora* sp., *Frasnacritetrus indicus*, *Fusiformisporites* sp., *Hypoxylonites subrotundus*, *Inapertisporites kedvessi*, *Inapertisporites maximus*, *Monoporisporites circularis*, *Palaeomycites acinus*, *Palaeomycites* spp., *Papulosporites multicellatus*, *Perisporiacites varians*, *Polycellaesporites bellus*, *Plureicellaesporites planus*, and *Udaria saxenae*; with testate amoebae such as *Centropyxis aculata* and *Arcella arenaria* with Dinoflagellates, Phytoplanktons, Chlorophyceae, Phytoclasts, Opisthokonta, and AOM which characterizes the basin.
20. Chotila Basin consists of pollen spores such as *Dermatobrevicolporites dermatus*, *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii*, *Monocolpopollenites plicatus*, *Proxapertites* spp., *Rhoipites kutchensis* and *Tricolporopollenites* spp.

21. Chotila Basin consists of fungal spores and elements such as, *Dicellaesporites minutus*, *Diporisoronites sirmaurensis*, *Frasnacritetrus indicus*, *Frasnacritetrus tougourdeavi*, *Helicomminites salvinites*, *Hypoxylonites minimus*, *Hypoxylonites* sp., *Inapertisporites kedvesii*, *Inapertisporites maximus*, *Inapertisporites novus*, *Inapertisporites tetradus*, *Meliolinites spinksii*, *Palaeomycites acinus*, *Palaeomycites* spp., *Papulosporonites multicellatus*, *Perisporiacites varians*, *Pluricellaesporites planus*, *Pluricellaesporites* sp., *Polycellaesporonites globatus*, *Polycellaesporonites psilatus*, *Polycellaesporites saxenae*, *Protocolletotrichum deccansis* and *Staphlosporonites setlyi*.
22. Other small groups are represented by testate amoeba namely, *Centropyxis aculata* and *Arcella arenaria*; dinoflagellates; phytoplanktons; chlorophyceae, *Pediastrum* spp.; Phytoclasts; Opisthokonta, metazoan elements like *Lepidopteran scales* and AOM.
23. In the Ninama Basin, the lower part of the Sukhbhadar Formation shows the dominance of fungal elements like *Palaeomycites* sp., *Udaria singhii*, etc.; the upper part shows the dominance of *Inapertisporites* spp.
24. The lower part of Ninama Limestone shows the dominance of *Proxapertites* sp., *Rhombipollis* sp., followed by *Longapertites* sp., *Paleomycites* sp., and the upper part shows the dominance of *Rhombipollis* sp. *Matanomadhiasulcites maximus*, *Longapertites* spp. and *Dermatobrevicolporites dermatus*.
25. In the Chotila Basin, the Rangpar formation shows the dominance of fungal elements like *Palaeomycites* spp. along with phytoplanktons and abundant AOM.
26. The Chotila Chert shows the dominance of pollens like *Dermatobrevicolporites dermatus*, *Palaeomycites* spp., *Proxapertites* sp., and *Arcella arenaria*; the uppermost Bamanbor Formation shows the dominance of *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii* with *Inapertisporites* spp.
27. The stratigraphic and ecologically significant palynotaxa were quantitatively assessed for delineation of the palynostratigraphic zonation. The different palynozones also demarcate the first and last appearance of the palynomorphs in the sections, their maximum abundance, vertical range, and restricted occurrences of many palynotaxa. The temporal distribution pattern of fossil spores, pollen grains, and recovered from individual samples indicates four biozones in the Ninama Basin; 1. *Palaeomycites* spp. Abundance Zone, 2. *Inapertisporites* spp. Abundance Zone, 3. *Rhombipollis geniculatus* - *Proxapertites* spp.

- Assemblage Zone 4. *Dermatobrevicolporites dermatus* - *Longapertites* spp. Assemblage zone.
28. The temporal distribution pattern of fossil spores and pollen grains indicates three biozones for the Chotila Basin namely, 1. *Palaeomycites* spp. Abundance Zone, 2. *Proxapertites* spp. Assemblage zone, 3. *Florschuetzia rajpardiensis* Assemblage Zone.
 29. The Ninama Basin is rich in terrestrial elements like *Longapertites* sp. and tropical to sub-tropical pollens like *Hammenisporis susannae*, *Monocolpopollenites kutchensis*, *Proxapertites* spp., *Tricolporopollenites* sp., and *Rhoipites kutchensis*.
 30. Recovered fossil pollen grains of *Matanomadhasulcites maximus* (Annonaceae) and *Lakiapollis ovatus* (Bombacaceae) in the assemblage also represent megathermal families, distributed mostly in equatorial regions.
 31. The palynological studies of the Ninama Intertrappeans suggest a Paleocene to Early-Middle? Eocene age as marked by *Longapertites retipilatus*, *Matanomadhasulcites maximus*, *Rhombipollis geniculatus*, *Yeguapollis* sp., *Aquilapollenites ovatus* and *Lakiapollis ovatus*.
 32. The Chotila Basin is dominated by diverse fungal spores and a few fruiting bodies belonging to Amorsporae, Didymosporae, Phragmosporae, Dictyosporae, Helicosporae, and Staurosporae. This high diversity in fungal spores, with representatives from all groups, commonly occurs in tropical and subtropical areas of the world. They are associated with vegetation that thrives in the warm humid climate of tropical and subtropical regions.
 33. The presence of fungal fruiting bodies of the family indicates that a warm humid climate with heavy precipitation prevailed during the deposition of the sediments of Chotila Basin. The presence of *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii*, *Rhoipites kutchensis*, *Dermatobrevicolporites dermatus*, and *Tricolporopollenites* sp. suggests Paleocene to Early-Middle? Eocene age for the Chotila Basin.
 34. Sedimentological and Palynological data of the Ninama Basin suggests a relatively deeper paleolake with subsequent shallowing during the precipitation of limestone; however, the salinity and redox values suggest an overall change from brackish water to saline water in oxic to anoxic environment towards the top. The moderate to high values of CIA and MAP are suggestive of a semi-humid climate; with local changes in

deposition due to shallowing of the basin; which is also verified by the GBL, ML, and CL facies and the presence of palynofossils of tropical and subtropical region.

35. Sedimentological and Palynological data of Chotila Basin also suggests a deep paleolake, with suboxic-anoxic conditions and fresh to brackish water as suggested by the presence of the palynomorphs and freshwater bivalves, gastropods, and fishes. The high values of CIA and MAP are suggestive of a semi-humid to humid climate, which is also verified by the presence of palynotaxa belonging to the tropical and subtropical regions.
36. The Ninama and Chotila Basins intertrappean succession suggests overall warm tropical, humid to semi-humid conditions during the Paleogene, also overlapping with the Paleocene-Eocene Thermal Maximum (PETM).
37. The distinct three-phase depositional event has been inferred for Ninama Lake and Chotila Lake to evaluate to evolution of the basin.
38. In the Ninama Basin - Phase 1 marks the deposition of LGW facies in high energy conditions, coarse terrigenous sediment input, moderate water depth, humid climate, oxic to dysoxic conditions, brackish waters, and low to moderate precipitation.
39. Phase 2, marks the deposition of GSH and SM facies where suspended clay and silt-sized particles are settled in fresh to brackish deep lake, with anoxic conditions, humid-warm tropical climate, and moderate precipitation over 1000mm.
40. Phase 3 suggested the shallowing of the lake, evidenced by the CL, ML, and GBL facies which suggest high evaporation in semi-arid conditions and saline anoxic waters with low to moderate terrestrial inputs.
41. In the Chotila Basin, Phase 1 is dominated by the fine-grained terrigenous input in shallow to moderately deep lake, fresh to brackish water, anoxic condition, humid climate, 1000 mm of rain precipitation, poorly fossiliferous in the initial stage, and later their abundance increases suggest conducive environment for the microorganisms.
42. Phase 2 is characterized by silicious deposits, brackish water, shallow to deep water, anoxic environment, low to moderate terrestrial input, and semi-humid conditions; the presence of vertebrates and palynomorphs suggests conducive conditions.
43. Phase 3 is characterized thick fine-grained sequence that suggests high terrigenous input, deposited in the offshore (SS and CS facies) and nearshore (FSS facies) parts of the lake, humid-tropical climate, minimal evaporation, and intense chemical weathering of the

country rocks. Fresh to brackish water, suboxic to anoxic conditions of deep lake environment, and high Mean Annual Precipitation (MAP). Highly diversified and abundant palynomorphs suggest a conducive environment for the micro as well as mega organisms and finally, it is filled by the Deccan Traps.

44. The Insular Indian Plate travelled across the equatorial region in the Tethyan Ocean during the Paleogene time; the unfossiliferous lower part suggests harsh conditions in the paleolake due to former and contemporaneous volcanic activity and later consist of an abundant and diverse group of palynofossils suggesting conducive conditions until the youngest flow of Deccan Traps, filled the lakes.

The intertrappean successions of the Ninama and Chotila basins are unique as far as their time (Paleogene) span is concerned, as they are exclusively developed in Insular India. It is sandwiched between the two lava flows of the Large Deccan Igneous Activity of India and their top flow marked the cessation of the Deccan activity in the Indian Sub-continent. The presence of palynomorphs has resolved the many unsolved questions of Insular India, particularly on paleoecology, paleoclimate, age, and paleogeography. The uniqueness of the biota of the Indian sub-continent is linked with the Gondwana, which later evolved allopatrically followed by their intermigration in Eurasia, resulting in high diversity.