PALYNOLOGY OF THE INTERTRAPPEANS OF SAURASHTRA PENINSULA, WESTERN INDIA: BIOSTRATIGRAPHIC AND PALEOENVIRONMENTAL IMPLICATIONS

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I. INTRODUCTION

The Saurashtra Peninsula is situated in the westernmost part of India and comprises volcanic rocks of the Large Igneous Province of India, known as Deccan Traps, formed during the Late Cretaceous – Early Paleogene. The flows have intermittently erupted and the time gap is represented by intertrappean sedimentary rocks, which are well-developed around the Chotila and Ninama areas of Saurashtra. These are rocks highly disrupted due to volcanic eruption, preserved as intra, intertrappean, and are exposed as patchy outcrops or covered by shrubs, soil, and scree materials of the younger volcanic flows. It has restricted their exposure and hence is mainly observed as stream sections, well sections, road cut sections, quarry sections, and low-lying plain surfaces due to erosion of the younger lava flows. In the present investigation, preserved sequences of the intra-, and intertrappean are observed and studied at fifteen localities (Fig. 1).

The Saurashtra Peninsula is a horst bounded by three intersecting rifts, the North Kathiawar Fault (western extension of Great Boundary Fault) towards the north, the western extension of Narmada Fault towards the South, the Western Margin Fault of Cambay Basin towards the east and the west Kathiawar Fault towards the west (Biswas, 1987). The Saurashtra - Kachchh sub-province (Kale, Bodas, et al., 2020; Mittal et al., 2021; Tandon & Gupta, 2020) is considered a part of DIVP covering the major part of the Saurashtra Peninsula (Fig. 1) and are characterized by several undulating plains, hills (Girnar, Barda, Alech, Osham, etc.), intrusives and dykes, and dyke swarms, composed of a varied range of rocks including basalt, granophyre, rhyolite, tholeiites, diorites and associated volcanics (Cucciniello et al., 2015; Sheikh et al., 2020; Sheth et al., 2012, 2022; Sheth & Pande, 2014). The associated sedimentary rocks are informally described using local geographic names (Borkar, 1973; Fedden, 1884; Samant et al., 2014). The systematic work on various geological aspects is carried out in the present investigations, lithostratigraphy, sedimentology, geochemistry, palynofossil, and biostratigraphy to infer the various paleoenvironmental parameters.

II. LOCATION

The Saurashtra-Kachchh sub-volcanic province is located in the western part of the Deccan Volcanic Province of India (Fig.1), study area is located on the central northern margin of the Saurashtra Peninsula (Fig. 1). It comprises the intra-, intertrappean sedimentary rocks exposed in patches, around Chotila town and Ninama village of the Surendanagar District. The present study is carried out in the following 15 localities (Fig.1) where their sequence is exposed as intra- or intertrappeans, 1- Ninama hill section, 2- Sukhbhadar river section, 3- Ninama well section, 4- Motamatra well section, 5- Motamatra road section 6- Shekhdod hill, 7- Lakhvad, 8- Chanpa hill section, 9- Bamanbor – Navagam section, 10- Bamanbor road section, 11- Rangpar GIDC section, 12- Redren Industry section, 13- Garida section, 14- Jalida section, 15- Jalsika section.

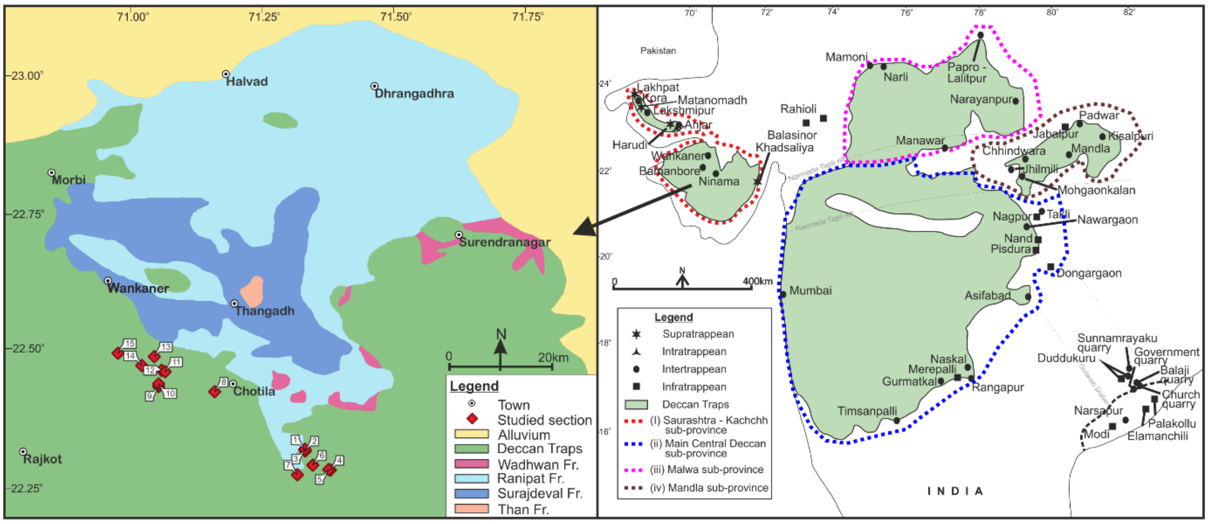

Fig. 1 Sub-provinces of the DVP of India with and infratrappean, intertrappean, intratrappean, and supratrappean localities, (modified after (Deshmukh & Sehagal, 1988; Kale, Dole, et al., 2020; Kapur et al., 2018; Kapur & Khosla, 2019; Mahoney, 1988; Mittal et al., 2021) and geological map of Saurashtra (modified after Khan & Ahmad, 1998) with studied sections of intra-, intertrappeans.

III. METHODOLOGY

An integrated approach of sedimentology and palynology data is utilised to understand the paleoenvironment, paleoclimate, and paleoecology of the area.

Field expeditions and laboratory techniques

i. Stratigraphic sections are measured at different localities and lithologs were prepared.
ii. High-resolution systematic sampling, laterally as well as vertically was done in different sections.
iii. Collected samples were analyzed for textural and mineral composition.
iv. Samples were disintegrated by following the standard techniques to separate the palynomorphs.
v. Separated palynomorphs were identified and documented.
vi. Qualitative and quantitative analysis of the palynomorph data was done, different biostratigraphic zones were established.
vii. Paleoenvironment was interpreted using palynological and sedimentological data.

IV. LABORATORY TECHNIQUES

The various steps to be followed for the maceration of the samples to extract palynofossil from the rocks.

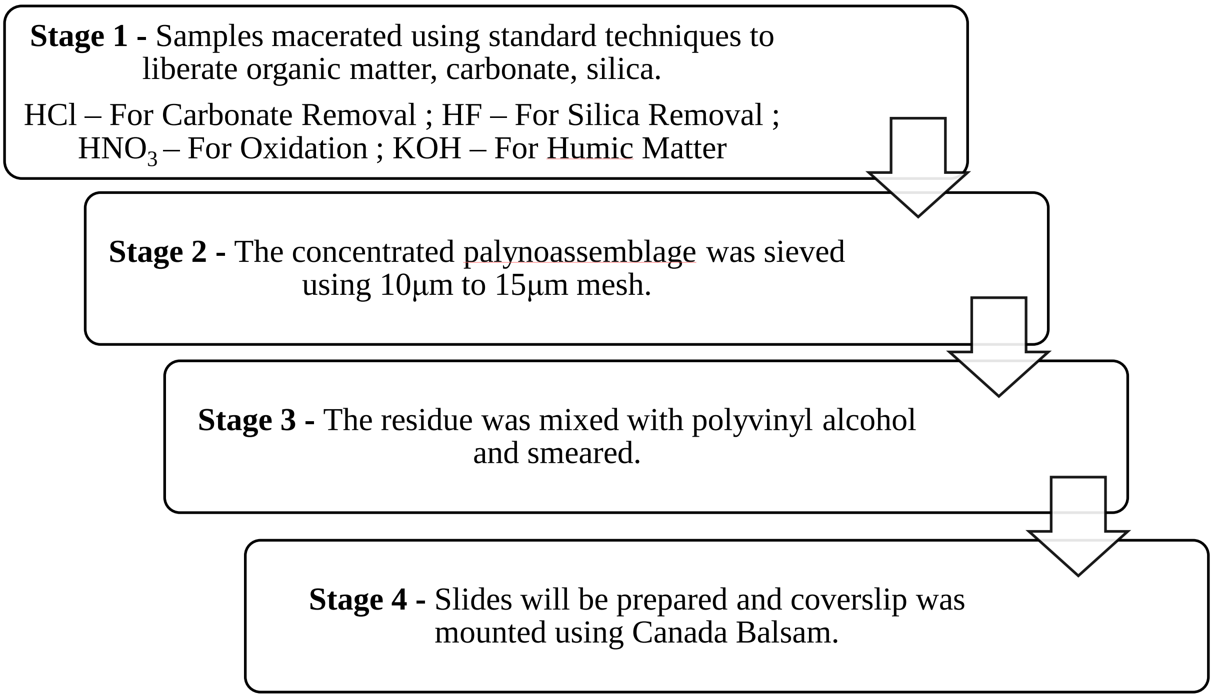

Fig. 1 Technique followed for palynomorph separation (Green, 2001; Traverse, 1974)

The samples were prepared following the standard palynological technique which includes treatment with 10% HCl, 40% HF to digest carbonates and silicates followed by mild oxidation with 10% HNO_3 to remove excess amorphous organic matter. To remove humic substances, a 5% KOH solution was also used and lastly, the washed samples were sieved with a 15 µm mesh sieve. The residue was examined under the light microscope (Leica DM EP; camera MC120HD) for organic content. Permanent slides were prepared by spreading evenly a drop of maceral with polyvinyl alcohol on glass cover slips. After drying, the coverslips were fixed on the glass slides using Canada balsam.

V. AIM AND OBJECTIVES

The present study aims to investigate the intertrappean sites of the Saurashtra peninsula for their sedimentology and palynology, to establish the biostratigraphy and interpret the paleoenvironmental conditions prevailing during their deposition.

The objectives of the Ph.D. work are:

1. Sedimentology and lithostratigraphy of the intra-, Intertrappean sequences.
2. Analysis of palynomorphs at high-resolution of different sections.
3. Identification and documentation will be attempted for palynomorphs and biostratigraphic framework will be established.
4. Integrated palynological and sedimentological data will be utilized to infer the paleoenvironment.

VI. OBJECTIVE I: SEDIMENTOLOGY AND LITHOSTRATIGRAPHY OF THE INTRA-, INTERTRAPPEAN SEQUENCES

A. LITHOSTRATIGRAPHY

The intra-, intertrappeans rocks of Saurashtra Peninsula are characterized by distinct sedimentary succession, observed in two different geographic areas, Ninama Basin and Chotila Basin. In both areas, the sedimentary sequences are thick, have partially variable lithology and have distinct contacts. The sequence of both these areas is classified lithostratigraphically (Table 1) according to the ISSC norms and assigned the stratotypes (Patel & Shah, accepted 2023).

	Chotila Basin		Ninama Basin	
Age	Formation	Lithology	Formation	Lithology
Deccan Traps				
Paleogene (Paleocene –Eocene)	**Bamanbor**	Red, buff, grey mudshale, fossiliferous sandstone - siltstone, chert and nodules of claystone with bivalves and gastropods	**Ninama Limestone**	Fossiliferous limestone, nodules of chert, argillaceous limestone, Marlite and calcareous shale
	Chotila Chert	Bedded and banded chert, mudshale		
	Rangpar	Mudshale, siltstone, claystone	**Sukhbhadar**	Mudshale, siltstone, mudstone, claystone, lithic arenite
Deccan Traps				

Table 1 Lithostratigraphy of the Intertrappean succession of the Ninama and Chotila Basins of the Saurashtra Peninsula, Gujarat (Patel & Shah, accepted 2023)

Stratigraphy of the Ninama Basin

This basin comprises of thick sedimentary sequence, sandwiched between the two lava flows characterized fine-grained (shale) dominating sequence along with lithic greywacke-arenite and capped by limestone, and is divided into two formations, Sukhbhadar Formation and Ninama Limestone.

Sukhbhadar Formation is the oldest stratigraphic unit of the Saurashtra Intertrappean resting nonconformably over the Deccan Traps. This unit is described based on surface and subsurface exposures where a 15 m thick section is observed in a dug well and an 18 m thick section is exposed on the left bank of the Sukhbhadar stream near Ninama village. A total 33 m thick unit consists of argillaceous and clastic rocks. The well section is 15 m deep from the surface which overlies the basalts and is considered the oldest part of the unit consisting of 1.5 m thick lithic arenite and lithic greywacke followed by a thick intercalated sequence of fine-grained clastics, claystone–mudshale–siltstone unit. The lower part of the stream section is characterised by 4 to 7-cm thick, thinly bedded siltstone with mudshale and is followed by thick intercalated claystone–mudshale–siltstone. The lower boundary of this formation has nonconformable contact with the Cretaceous-Paleogene volcanic rocks and the upper boundary is conformable with the overlying Ninama Limestone.

Ninama Limestone is well exposed on the left bank of the Sukhbadar tributary, characterized by dirty yellow-coloured bedded fossiliferous limestone, capped by thin 20-30 cm thick grey to black coloured limestone attaining a total thickness of ~3m. This unit is characterized by a unique lithology and homogeneous internal characters with variable fossil content. Laterally, lithological variations were observed, it comprises intercalated argillaceous limestone/marlite and shale sequence; which is dirty yellow, blocky in the lower part, becomes flaggy towards the top, with intercalated with buff-coloured calcareous shale. The top unit of grey-black limestone contains a high amount of organic content and palynofossils.

Based on palynofossils assemblages (present work) the age of the Ninama Basin is considered Paleocene to Eocene.

Stratigraphy of the Chotila Basin

This basin comprises a thick, fine-grained dominating sequence characterized mainly by mudshale, siltstone, chert and thin occasional bands of calcareous sandstone. This sequence is sandwiched between the two lava flows where the lower and upper contacts are nonconformable with basalt. It is characterised by extensively developed bedded chert which has helped in dividing it into three formations, namely, Rangpar Formation, Chotila Chert, and Bamanbor Formation.

Rangpar Formation is considered the oldest unit of the Chotila Basin and is exclusively consisting of fine clastics, a shale-dominated sedimentary unit that can be easily differentiated from the overlying thinly bedded, thick chert unit. This formation is well developed above the basalt and comprises a thick muddy shale-dominated sequence with interbedded thin siltstone layers and claystone nodules. The nature of the mudshale is highly fissile, gets easily crumpled into small fragments, and is devoid of macrofossils. This unit is locally disrupted by discordant lava forms.

Chotila Chert is mainly consisting of the chert layers, it is very consistent in the basin and distinct from the underlying muddy shale, the lower contact is gradational with shale at a very short vertical distance. This unit is characterized by unique, thinly bedded chert, homogeneous internal characters and may show lateral intercalations with silty-cherty mudstone and shale. The nature of the chert is highly variable in terms of porosity, compaction, density, and petrography. Petrographically the banded and bedded chert consists of microcrystalline and cryptocrystalline quartz (chalcedony), with alternate laminations of iron oxide and sometimes sparite with the development of calcite veins. Chert contains vertebrate fish fossil remains, *Indiaichthys bamanbornsis* (Borkar, 1975).

Bamanbor Formation the youngest unit of the Chotila Basin, overlies the Chotila Chert. It is mainly characterized by muddy shale, shaly sandstone, silty cherty mudstone with occasional thin chert layers. The 16.7m thick sequence is observed near the Bamanbor village, characterized by mudshale, yellowish siltstone, greyish-shale, yellow-buff shale, and lenses of calcareous sandstone and is capped by the younger lava flow of the Deccan Traps. The mudshale grades into shaly sandstone at the bottom and yellowish grey shale, followed by grey shale and sporadically contains a thin bed of chert which is again overlain by red shale and grey shale. The shaly sandstone is fossiliferous and contains mega shells of the mollusks including the bivalves and gastropods.

Based on fish remains, bivalves and palynofossils (present work), the age of the Chotila basin is considered Paleocene to Eocene.

B. LITHOFACIES

Ninama and Chotila Basin sequence is further analyzed based on field and laboratory studies, which have revealed seven lithofacies and five microfacies (Table-2) and six lithofacies, (Table-3), respectively.

Lithofacies Ninama Basin

Ninama Basin facies (Fig. 2) are divided into two categories, 1. Clastic Lithofacies, includes, a). Grey Shale facies (GSH), b). Silty mudstone facies (SM) and d). Calcareous Shale facies (CSH), c). Lithic Greywacke/Arenite facies (LGW) and 2. Carbonate Lithofacies includes a). Grey Black Limestone facies (GBL), b). Cherty Limestone facies (CL), c). Marlite facies (ML).

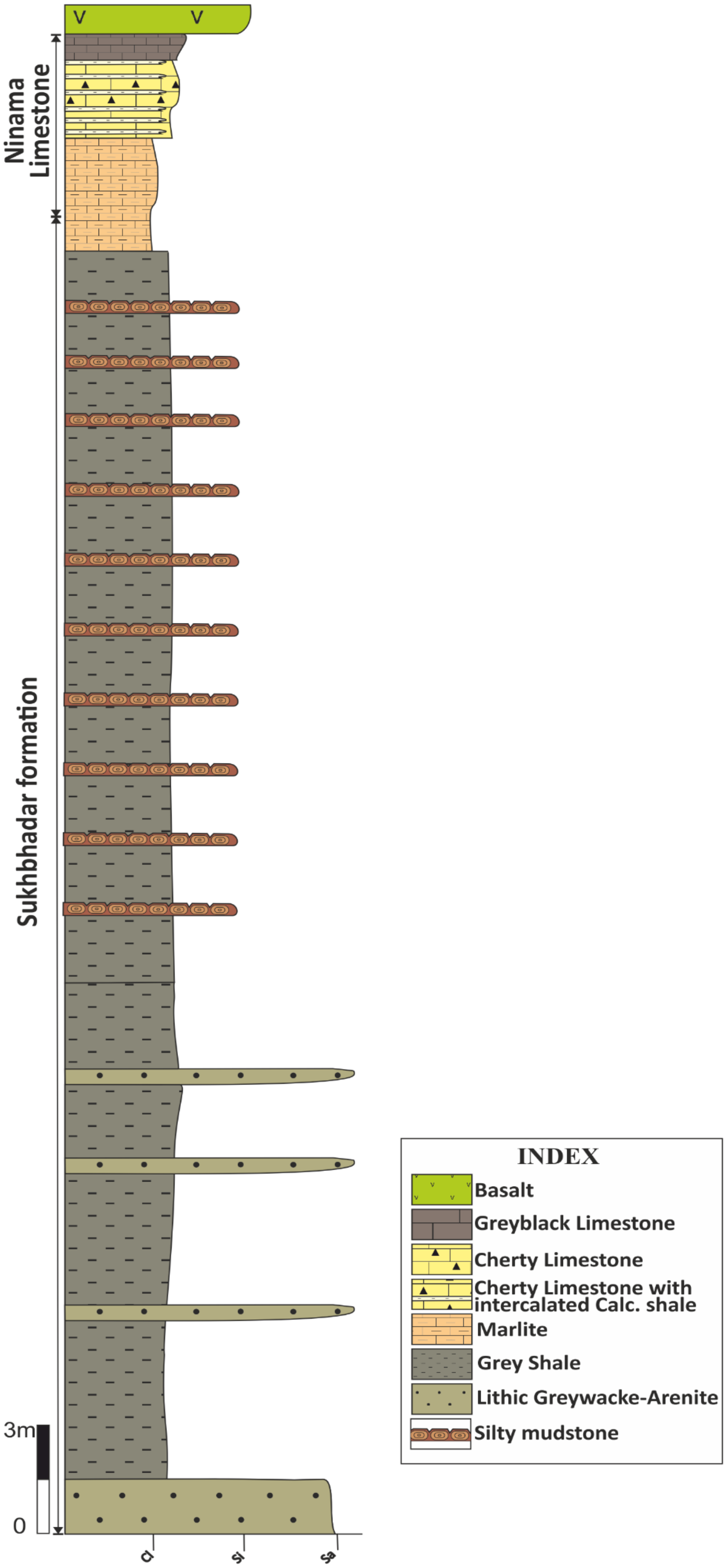

Fig. 2 Composite litholog of Ninama Basin sequence.

Sr. No.	Lithofacies	Characteristic Features
1.	Grey-Black Limestone GBL	Thick, massive, thinly to thickly bedded, hard and compact with rectangle joints, weathering on the surface gives light yellow to white colour, dark grey-black colour of the GBL is due to the presence of organic matter consist of mudstone microfacies.
2.	Cherty Limestone CL	Compact, hard and thinly bedded, yellow to buff coloured with the presence of light-coloured chert nodules, weathered surface appears grey to black in colour. Occurs at multiple levels. Microfacies includes, a. Peloidal wackestone-packstone b. Bioclastic bindstone, c. Cone-in-cone calcitic.
3.	Marlite ML	Dirty yellow to light orange in colour, blocky and massive in nature but laterally transforms into a thick-bedded form. Dirty yellow to light orange in colour. Argillaceous material occurs as a matrix, with few sand-size quartz grains. The iron oxide and high organic matter have also led to brown to grey-coloured shading Cladoceran bindstone microfacies
4.	Calcareous Shale CSH	Laminated to thinly bedded layers, highly friable and yellow to buff in colour, intercalated with limestone, fine clastics dominated over carbonates, lateral and vertical discontinuity of the layers.
5.	Grey Shale SH	Laminated, stratified and fissile, laterally and vertically appears in shades of beige, brown and grey, unevenly distributed clay and silt-controlled laminations and fissility laterally and vertically.
6.	Silty Mudstone SM	Reddish brown in colour, consists of high amounts of mud as compared to silt, characterized by shrinkage cracks, resulting in three-dimensional polygonal structures.
7.	Lithic Greywacke/ Arenite LGW	Dark grey to black in colored, fine to coarse grained, large lithic fragments of fine-grained volcanic rocks and shows transition from greywacke to arenite. Petrographically, facies comprise rock fragments of volcanic origin and quartz grains. Rock fragments are larger in size as compared to sand-size quartz grains and polygenetic in nature, mostly of fine grain basalts.

Table 2 Characteristics of the Ninama Basin Lithofacies.

Lithofacies of Chotila Basin

The Chotila Basin sequence consists of six lithofacies (Fig. 3) divided into two categories, 1. Clastic Lithofacies, a). Shaly Sandstone, b). Muddy Shale c). Silty-Cherty Mudstone; 2. Chemically Precipitated/Biochemical Lithofacies, a). Massive chert, b). Laminated chert, c). Black laminatd chert (Table 3).

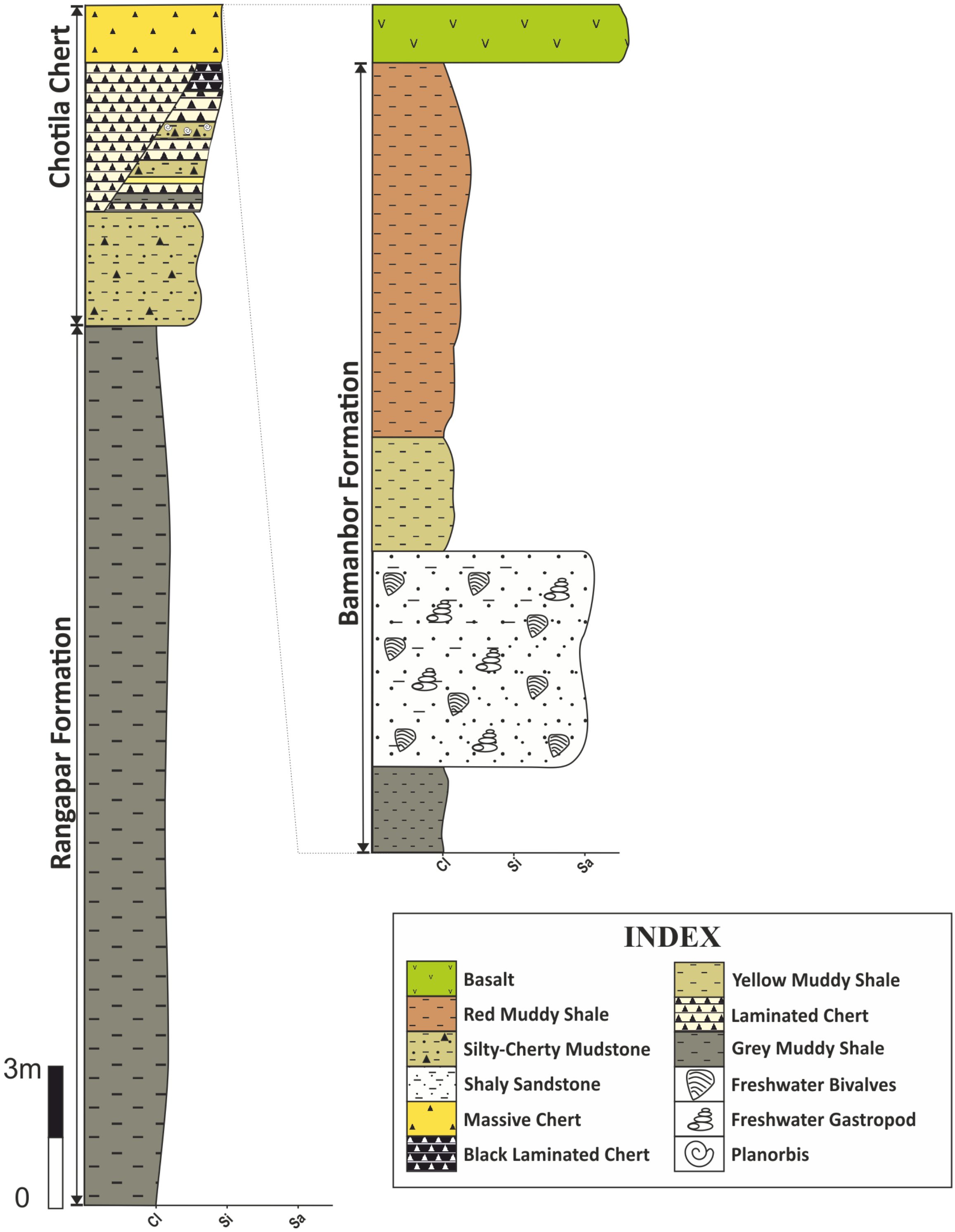

Fig. 3 Composite litholog of Chotila Basin sequence.

Sr. No.	Lithofacies	Characteristic Features
1.	Muddy Shale MSH	Fissile, soft and crumbly, dominated by argillaceous materials; varies in colour from dark grey to grey, red, and yellow.
2.	Silty-Cherty Mudstone SCM	Compact, thinly bedded, highly porous, silty-cherty mudstone, white to red in colour, with occasional planorbis gastropods.
3.	Shaly Sandstone SST	Fine-grained, grey to yellowish in colour and compact but highly indurated, contains mega shells of bivalve and gastropods and fish remains.
4.	Massive Chert MC	Occur as blocky layers, yellowish to white coloured.
5.	Black Laminated Chert BLC	Blackish grey to dark black in colour due to baking effect, compact and laminated.
6.	Laminated Chert LC	Laminated, compact, hard, white to grey chert with pseudo-ripples, folded and contain fish fossils. Chert facies revealed various structures includes continuous planar parallel folded chert, continuous planar parallel chert, continuous wavy parallel, continuous-discontinuous planar parallel, discontinuous planar parallel, discontinuous planar nonparallel chert and discontinuous wavy parallel.

Table 3 Characteristics of the Chotila Basin Lithofacies.

C. XRF FOR MAJOR OXIDE AND ELEMENTAL CONCENTRATIONS

The distribution and quantity of major oxides and various inorganic geochemical elements (major, minor, and trace) were measured by using a XEPOS HE XRF spectrometer. The analytical precision of major oxide was better than 5% and of elements was better than 10% (Das et al., 2017; Makwana et al., 2019). Lithofacies and inorganic geochemistry were integrated for understanding the depositional system. Various geochemical proxies using elemental ratios like Ca/(Ca+Fe) and Sr/Ba for salinity, V/(V+Ni) and V/Cr for paleoredox conditions, and Fe/(Ca+Mg) for water depth, were used to determine the variations in the depositional environment of the Ninama Basin (D. Khan, Liang, et al., 2023; D. Khan, Zijun, et al., 2023). The Chemical Index of Alteration (CIA-K), a weathering index, is used to assess the amount of chemical weathering due to associated climatic changes (Sheldon *et al.* 2002). This index does not include potassium (K) because diagenetic processes can yield elevated concentrations of K (Adams et al., 2011; Sheldon et al., 2002). The calculation is based on molar proportions using Nesbitt and Young (1982, 1989),

$$CIA\text{-}K = Al_2O_3 \times 100/(Al_2O_3 + CaO^* + Na_2O),$$

where CaO* is the CaO in silicate minerals only, so CaO correction was applied due to the presence of carbonates, and we assume that CaO* is equivalent to Na_2O if the CaO is higher than Na_2O (McLennan et al., 1993). To determine whether the severity of weathering is related to the quantity or quality of precipitation, quantitative Mean Annual Precipitation (MAP) was also calculated using CIA-K values.

MAP (millimetres/year) = $221exp^{0.0197CIA-K}$ (Sheldon et al., 2002; Sheldon & Tabor, 2009)

Ninama Basin

A total of 21 samples were analyzed, 3 of GBL, 6 of CL and ML, 8 of SH and 1 of SM, 3 of LGW. Here we summarize their variation in the ratios for Ninama Basin from bottom to top to interpret the paleoenvironmental variation during their deposition.

The ratios of Sr/Ba range from 0.06 to 7.10, and Ca/ (Ca+Fe) ranges from 0.09 to 0.96, which were taken as proxies to estimate the paleosalinity. V/ (V+Ni), ranges from 0.8 to 21.4, and V/Cr ranges from 0.21 to 9.48, taken as paleoredox indicators (Jones & Manning, 1994; D. Khan, Zijun, et al., 2023; Sajid et al., 2020). The ratios of Fe/(Ca+Mg) are used to analyze lacustrine water depth which ranges from 0.007 to 6.55 (Chen et al., 2016; D. Khan, Zijun, et al., 2023; Restituito, 1987). The CIA-K values in the samples vary from 29.6% to 90.74%. The MAP values range from 396 mm to 1321 mm.

Chotila Basin

A total of 68 samples were analyzed, 32 of MSH, 15 of SCM, 17 of MC and LC and 4 of SST. Here we summarize their variation in the ratios from bottom to top of Chotila Basin to interpret the paleoenvironmental variation during their deposition.

The ratios of Sr/Ba range from 0.17 to 7.97, and Ca/ (Ca+Fe) ranges from 0.002 to 0.56, which were taken as proxies to estimate the paleosalinity. V/ (V+Ni), ranges from 0.004

to 0.98, and V/Cr ranges from 0.01 to 23.10, taken as paleoredox indicators (Jones & Manning, 1994; D. Khan, Zijun, et al., 2023; Sajid et al., 2020). The ratios of Fe/(Ca+Mg) are used to analyze lacustrine water depth which ranges from 0.66 to 7.29 (Chen et al., 2016; D. Khan, Zijun, et al., 2023; Restituito, 1987). The CIA-K values in the samples vary from 55.53% to 99.59%. The MAP values range from 660 mm to 1558 mm.

VII. OBJECTIVE II: ANALYSIS OF PALYNOMORPHS AT HIGH RESOLUTION FOR DIFFERENT SECTIONS

A. Field sampling for palynology

For high resolution palynological analysis of intertrappean sediments, systematic and stratigraphic sampling was carried out.

B. Laboratory extraction and slide preparation of palynofossils

1. Cleaning, disaggregation, and weighing of samples.
2. The collected samples were crushed into pea-sized particles using a mortar and pestle, weighed to 20 grams, and added to labeled PPE beakers.
3. The collected samples in the beakers are then reacted with 10-40% HCl (Hydrochloric Acid) to remove carbonates depending upon the carbonate content of the sample.
4. The beakers were kept untouched for 8 to 10 hours until the reaction ceased (the time of reaction depends on the sample).
5. Once the reaction is complete, the beaker is filled will distilled water to its brim and the samples are washed until neutral.
6. The samples thereafter are treated with 40% HF to remove silicates.
7. Once the samples are completely deflocculated and as the reaction ceases, they are washed with distilled water until neutral.
8. Finally, the samples are reacted with the nitric acid (HNO_3) to readily remove the ferruginous content in the samples via oxidation, followed by washing until neutral.
9. The final residue is then treated with 5%- 10% KOH depending upon the amount of humic matter, to remove the unwanted amorphous organic matter. The treatment where an appropriate proportion of KOH is diluted in the respective beakers and kept to rest for 15 to 20 minutes until the unwanted sediments are dissolved in the water.
10. Once all the beakers with the samples are clean and clear they are then sieved using the 120 ASTM, followed by a 10μm sieve.

11. The fine-sieved samples are then collected into the beaker along with some distilled water, stirred, and poured quickly into their respective blue-capped veil (centrifuge bottles) and closed tightly. The remaining samples are filled into their respective labeled white-capped veil for further emergency cases.
12. The samples are then centrifuged at 900 to 1000 rpm for 10 mins.
13. The water from the centrifuge is decanted and the collected palynomorphs are mixed with polyvinyl alcohol, ready to be smeared on the slides.
14. The palynomorph-containing slides are now dried after which, mounted with Canada balsam.
15. To dry the slides and for permanency, the slides are cooked at 60-70°C until golden in color in an oven or over a hot plate.

VIII. OBJECTIVE III: IDENTIFICATION AND DOCUMENTATION WILL BE ATTEMPTED FOR PALYNOMORPHS AND HIGH-RESOLUTION BIOSTRATIGRAPHIC FRAMEWORK WILL BE ESTABLISHED.

A. Ninama Basin

The intertrappean sediments of Ninama Basin consist of an abundant and diverse group of palynofossils including sporomorphs (spores and pollen), phytoplanktons (dominated by algae and few dinoflagellates), plant-derived phytoclasts, thecamoebians, and abundant Amorphous Organic Matter (AOM). The sporomorphs likes *Arecipites bellus*, *Crotonipollis densus*, *Tricolporopollenites* spp., *Dermatobrevicolporites* spp., *Cupuliferoipollenites ovatus*, *Cupuliferoipollenites psillus*, *Palmaepollenites communis*, *Longapertites retipilatus*, *Longapertites triangulates*, *Matanomadhiasulcites* sp., *Matanomadhiasulcites maximus*, *Proxapertites cersus*, *Proxapertites crassimurus*, *Rhombipollis* spp., *Rhombipollis geniculatus*, *Cythidites australis*, *Hammenisporis susannae*, *Yeguapollis* sp., *Barringtoniapollenites retibaculata*, *Palmidites* sp., *Aquilapollenites ovatus*, *Monocolpopollenites* sp., *Mulleripollis bolporensis*, *Lakiapollis ovatus*, *Areliaceoipollenites reticulatus*, *Areliaceoipollenites psilatus*, *Cupanieidites flaccidiformis*, *Ephedripites* sp., *Acanthotricolpites bulbospinosus* pollens; fungal elements namely, *Plureicellaesporites bellus*, *Plureicellaesporites planus*, *Inapertisporites kedvessi*, *Inapertisporites maximus*, *Papulosporites multicellatus*, *Fusiformisporites* sp., *Monoporisporites circularis*, *Udaria saxenae*, *Palaeomycites* spp., *Palaeomycites acinus*, *Hypoxylonites subrotundus*, *Frasnacritetrus indicus*, *Perisporiacites* *varians*; testate amoebas namely, *Ceratohirudispora* sp., *Centropyxis aculata*, *Arcella arenaria* with few dinoflagellate cysts, abundant phytoclasts and AOM are characterising the 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. 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* spp. *Longapertites* spp. and *Dermatobrevicolporites* spp. 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 assemblage zones stratigraphically; 1. *Palaeomycites* spp. Abundance Zone, 2. *Inapertisporites* spp. Abundance Zone, 3. *Proxapertites* spp. – *Rhombipollis geniculatus* Assemblage Zone 4. *Longapertites* spp. – *Dermatobrevicolporites* spp. Assemblage zone. A Paleocene to Early-Middle Eocene age is suggested by *Longapertites retipilatus, Matanomadhiasulcites maximus, Rhombipollis geniculatus, Yeguapollis* sp*, Aquilapollenites ovatus, Lakiapollis ovatus*. Based on the relative dominance of the four categories, such as 1. palynomorphs (spores, pollen grains), 2. Amorphous Organic Matter (AOM), 3. phytoclast (opaque and translucent) and 4. biodegraded organic matter (BOM), the Ninama Basin sediments are dominated by 3 palynofacies; 1. BOM dominated palynofacies, 2. AOM-Phytoclasts dominated palynofacies and 3. Palynomorph-Phytoclast dominated palynofacies.

B. Chotila Basin

The intertrappean sediments of Chotila Basin are rich in Non-Pollen Palynomorphs (NPP's) like fungal spores and fungal elements, testate amoebas, phytoplanktons, phytoclasts, Chlorophyceae algae and various metazoans with few pollens. It includes well-preserved palynomorphs including sporomorphs (spores and pollen), phytoplanktons (dominated by algae and few dinoflagellates), plant-derived phytoclasts, thecamoebians, and abundant AOM. This basin is characterised by the presence of fungal spores and elements such as, *Hypoxylonites* sp., *Hypoxylonites minimus*, *Inapertisporites tetradus*, *Inapertisporites maximus*, *Inapertisporites novus*, *Inapertisporites kedvesii*, *Papulosporonites multicellatus*, *Polycellaesporonites psilatus*, *Pluricellaesporites* sp., *Pluricellaesporites planus*, *Pluricellaesporites saxenae*, *Protocolletotrichum deccansis*, *Dicellaesporites minutus*, *Polycellaesporonites globatus*, *Staphlosporonites setlyi*, *Meliolinites spinksii*, *Frasnacritetrus indicus*, *Helicomminites salvinites*, *Palaeomycites* spp., *Palaeomycites acinus*, *Perisporiacites varians*, *Frasnacritetrus tougourdeavi*, *Monocolpopollenites plicatus;* pollen like *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii*, *Rhoipites kutchensis*, *Dermatobrevicolporites dermatus*, *Tricolporopollenites* sp., *Proxapertites* spp., testate amoebas namely *Centropyxis aculata*, *Arcella arenaria*, Chlorophyceae algae, *Pediastrum* spp., metazoan elements like Lepidopterean scales. The Rangpar formation shows the dominance of fungal elements like *Palaaeomycites* spp. along with phytoplanktons and abundant AOM. The Chotila Chert shows the dominance of pollens like *Dermatobrevicolporites dermatus*, *Palaeomycites* spp. and *Arcella arenaria*; the uppermost Bamanbor Formation shows the dominance of *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii* with *Inapertisporites* spp. 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, range in the vertical column, and restricted occurrences of many palynotaxa. The temporal distribution pattern of fossil spores, pollen grains indicate three biozones stratigraphically, namely, 1. *Palaeomycites* spp. Abundance Zone, 2. *Proxapertites* spp. Assemblage zone, 3. *Florschuetzia rajpardiensis* Assemblage Zone. The presence of *Florschuetzia rajpardiensis*, *Meliapollis ramanujamii*, *Rhoipites kutchensis*, *Dermatobrevicolporites dermatus*, *Tricolporopollenites* suggests a Paleocene to Early -Middle Eocene age for the Chotila Basin. Based on the relative dominance of the four categories, such as 1. palynomorphs (spores, pollen grains), 2. amorphous organic matter (AOM), 3. phytoclast (opaque and translucent) and 4. biodegraded organic matter (BOM), the Chotila Basin sediments are dominated by two palynofacies; 1. AOM-BOM dominated palynofacies and 2. Palynomorph-Phytoclast dominated palynofacies.

IX. OBJECTIVE IV: INTEGRATED PALYNOLOGICAL AND SEDIMENTOLOGICAL DATA WILL BE UTILIZED TO INFER THE PALEOENVIRONMENT

The paleodepositional environment of the Ninama Basin and Chotila Basin intertrappean sequence is inferred based on sedimentology, geochemistry, and palynofossil.

The Ninama Basin, the ratio of Ca/(Ca+Fe) is 0.58 in LGW, 0.28 for SH and SM, 0.88 for CL and ML, and 0.85 for GBL. The values of Sr/Ba are 0.99 in LGW, 0.69 in SH and SM, 2.03 in CL and ML and 3.30 in GBL. The variable paleosalinity ratios and the lithofacies characteristics suggest the deposition of LGW in brackish to saline conditions, SH and SM in freshwater to brackish water conditions and CL and ML, and GBL in saline conditions. The value of V/(V+Ni) for LGW is 0.57 (dysoxic), for SH and SM 0.93 (euxinic), for CL and ML averages 0.88 (euxinic) and GBL averages 0.91 (euxinic). The lithofacies characteristics also corroborate with the paleoredox conditions of the Ninama Basin. The average values of Fe/(Ca+Mg) are 0.82 for LGW, 2.26 for SH and SM, 0.13 for CL and ML and 0.14 for GBL facies. The values and the lithofacies analysis for LGW facies indicate a moderate water depth during the deposition; subsequently, the average ratio increases for SH and SM facies suggesting deep water conditions. The average value of CL and ML; and for GBL facies is very low which suggests shallow water depths during the deposition probably as the basin experienced starving conditions for clastic inputs and high rates of evaporation. The CIA-K average value for LGW is 74.28%, SH and SM are 83.44%, CL and ML are 72.12%, and GBL is 62.66%. The CIA-K average values from the bottom to the top suggest a change in climatic conditions from humid-tropical to semi-arid. The MAP values average 961.59mm for LGW, 1153.80mm for SH and SM, 931.13mm for CL and ML, and 836.74mm for GBL. The value of MAP for LGW suggests moderate precipitation.

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.* Recovered fossil pollen grains of *Matanomadhasulcites maximus* (Annonaceae) *and Lakiapollis ovatus* (Bombacaceae) in the assemblage also represent megathermal families, distributed mostly in equatorial regions. The palynological studies of the Ninama Intertrappeans suggest a Paleocene to Early-Middle Eocene age as marked by *Longapertites retipilatus, Matanomadhiasulcites maximus, Rhombipollis geniculatus, Yeguapollis* sp*, Aquilapollenites ovatus* and *Lakiapollis ovatus* (Saxena & Trivedi, 2006; Venkatachala et al., 1988).

In the Chotila Basin, the ratio of Ca/(Ca+Fe) is 0.21 in MSH, 0.18 for SCM, 0.17 for MC and LC, and 0.12 for SST. The values of Sr/Ba are 2.67 in MSH, 0.62 for SCM, 1.53 for MC and LC, and 0.57 for SST. The paleosalinity ratios and the lithofacies characters suggest the deposition of MSH, SCM, MC and LC, and SST in freshwater-brackish conditions. The value of V/(V+Ni) for the MSH is 0.89 (euxinic), for SCM 0.81 (euxinic), for MC and LC averages 0.93 (euxinic) and SST averages 0.82 (euxinic). The average values of Fe/(Ca+Mg) are 3.00 in MSH, 2.17 for SCM, 2.87 for MC and LC, and 2.82 for SST (Chen et al., 2016). The relatively high values of lithofacies for Fe/(Ca+Mg) are likely due to the deep lacustrine conditions of the Chotila Paleolake. The CIA-K average value for MSH is 75.98%, SCM is 80.61%, MC and LC is 86.81%, and for SST is 80.20. The CIA-K average values suggest a humid-tropical climate. The MAP values average 992mm in MSH, 1095mm for SCM, 1248mm for MC and LC, and 1074mm for SST. The value of MAP suggests moderate to high precipitation.

The Chotila Basin is dominated by diverse fungal spores and few fruiting bodies belonging to Amorspores, Didynmospores, Phragmospores, Dictyospores, Helicospores, and also Staurospores. This high diversity in fungal spores, with representatives from all groups is commonly occurring 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 (Premaor et al., 2018). 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* suggests Paleocene to Early -Middle Eocene age for the Chotila Basin.

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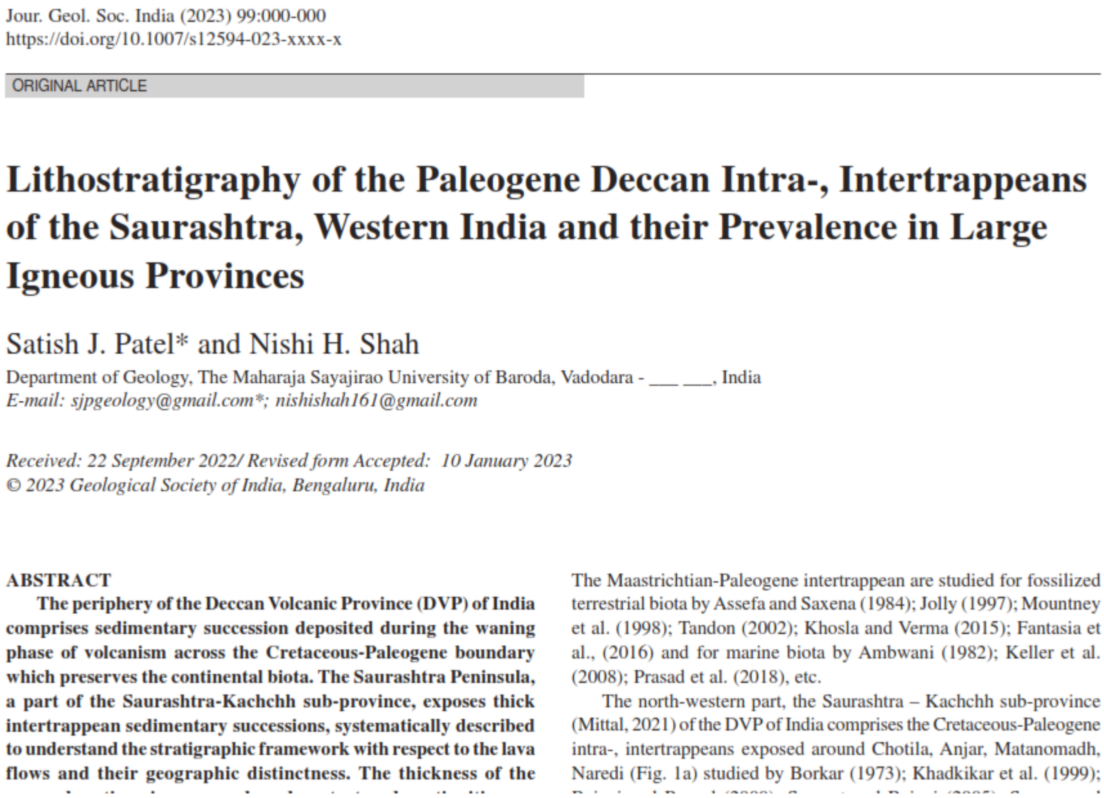
Research Scholar **Research Guide**

(Ms. Nishi H. Shah) **(Prof. Satish J. Patel)**

PAPERS, CONFERENCES, AND COURSE WORK

Research Papers

1. Patel, S. J. and Shah, N. H., (accepted 2023) Lithostratigraphy of the Paleogene Deccan Intra-, Intertrappeans of the Saurashtra, Western India and their Prevalence in Large Igneous Provinces; *Accepted*, Jour. Geol. Soc. India.



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ORIGINAL ARTICLE

Lithostratigraphy of the Paleogene Deccan Intra-, Intertrappeans of the Saurashtra, Western India and their Prevalence in Large Igneous Provinces

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ABSTRACT
The periphery of the Deccan Volcanic Province (DVP) of India comprises sedimentary succession deposited during the waning phase of volcanism across the Cretaceous-Paleogene boundary which preserves the continental biota. The Saurashtra Peninsula, a part of the Saurashtra-Kachchh sub-province, exposes thick intertrappean sedimentary successions, systematically described to understand the stratigraphic framework with respect to the lava flows and their geographic distinctness. The thickness of the

The Maastrichtian-Paleogene intertrappean are studied for fossilized terrestrial biota by Assefa and Saxena (1984); Jolly (1997); Mountney et al. (1998); Tandon (2002); Khosla and Verma (2015); Fantasia et al., (2016) and for marine biota by Ambwani (1982); Keller et al. (2008); Prasad et al. (2018), etc.

The north-western part, the Saurashtra – Kachchh sub-province (Mittal, 2021) of the DVP of India comprises the Cretaceous-Paleogene intra-, intertrappeans exposed around Chotila, Anjar, Matanomadh, Naredi (Fig. 1a) studied by Borkar (1973); Khadkikar et al. (1999);

2. Shah, N. H. and Patel, S. J., Lithofacies and Geochemical Analysis of Intertrappeans of the Ninama Basin, Saurashtra, Western India - An Integrated Approach for Paleolake Depositional System, *Communicated.*
3. Shah, N. H. and Patel, S. J., Freshwater Lacustrine Unionid Superfamily Deccanoidea nov., from the Bamanbor Formation of Chotila Basin, Saurashtra Intertrappean, India: An example of Disjunct Distribution, *Communicated.*

Conferences

1. Nishi H. Shah and Satish J. Patel, Facies and diagenetic evaluation of intertrappean rocks of the Ninama area, Saurashtra Peninsula, western India. National Conference on Resource Potential of the Sedimentary Basins and 37th Convention of Indian Association of Sedimentologists (IAS- 2022), 26-27 April 2022.

2. Nishi H. Shah and Satish J. Patel, Facies analysis and depositional environment of the Saurashtra Intertrappeans, western India. 38th Convention of Indian Association of Sedimentologists (IAS-2022) & National Conference on Current Understanding from the Indian Sedimentary Basins and Road Ahead, 9-11 December 2022.

Coursework

1. Six credit Departmental Course work on i. Advanced Stratigraphy, Paleogeography and Paleoecology and ii. Quaternary Geology.
2. Four credit Faculty Course work on Research Methodology in Science.
3. Two credit University Course work on Research and Publication Ethics (RPE).