CHAPTER-4

LITHOSTRATIGRAPHY OF THE SAURASHTRA INTERTRAPPEANS

4.1 INTRODUCTION

The succession of any sedimentary basin must be divided into logical stratigraphic units following the standard norms which facilitate the other investigator for documenting and inferring the geological events. Otherwise, if informal terminology were used for different exposures from different localities, multiplicity in terminology would occur which creates chaos in nomenclature when the successions are subjected to the different types of geological investigations. Therefore, lithological characters of the succession are to be observed, and measured and their distinctness should be marked in the field, which is easily graspable and mappable, and hence, it is also, easily codified. Consequently, the succession must be divided into rock stratigraphic units primarily which serve basic purposes for further investigation.

The intertrappean succession of the Saurashtra peninsula has been studied by many workers (Fedden, 1884; Borkar, 1986; Arratia et al., 2004; Borkar et al., 2014; Samant et al., 2014; Sheth et al., 2022; Patel and Shah, 2023) and have reported the mega vertebrates and palynofossils by using the informal terminology. This type of practice is observed across the India for all the intertrappean successions. Investigator felt that any geological work to be carried out for the intertrappean succession of the Saurashtra Peninsula, succession must be divided into formal lithostratigraphic units, which will serve as the basic purpose for the investigation. Hence, a rigorous attempt has been made to map the area, successions were measured at different localities and lithologs were prepared and correlated with other localities. Based on basic field investigation and laboratory data, composite lithologs were prepared. The composite logs serve the basic purpose and have enabled the investigator to recognize two different types of successions. Thus, these composite successions have helped in dividing into formal lithostratigraphic units. Two different types of successions deserve two different types of lithostratigraphic classification. Investigator has named them as Ninama Basin and Chotila Basin and suggests two separate schemes that contains distinct formal lithostratigraphic units.

The intertrappean successions that occurred with Large Igneous Provinces (LIPs) posed many problems like the continuity of the strata, thickness of the units, smashed with younger flow and later denudation of the outcrops. Investigator has observed that their four LIPs across the Cretaceous-Paleogene, including Madagascar, North Atlantic Igneous Province (NAIP), Parana – Etendeka Flood Basalt Province, and Deccan Trap Province (DIP) of India. An attempt has been made for the earlier three provinces to describe the units lithostratigraphically. The DIP of India consists of intertrappean succession at many places but a lone attempt is found (Sahni et al., 1984).

The DIP of India is divided into four sub-provinces including Saurashtra - Kachchh, Main Central Deccan, Malwa, and Mandla (Ray et al., 2003; Self et al., 2022). The Saurashtra-Kachchh sub-province lies in the westernmost part of the DIP and also contains sedimentary succession in the form of intra- and intertrappean across the Cretaceous-Paleogene. In particular, the intertrappean succession of the Saurashtra Peninsula has been studied by many workers (Fedden, 1884; Borkar, 1973; Shringarpure, 1985; Arratia et al., 2004; Thakre and Samant, 2014; Sheth et al., 2022) and reported the mega vertebrates and palynofossils by using the informal terminology. This type of practice is observed across India for all the intertrappean successions. Investigator has felt that for any geological work to be carried out for the intertrappean succession of the Saurashtra Peninsula, succession must be divided into formal lithostratigraphic units, which will serve as the basic purpose for the investigation. Hence, a rigorous attempt has been made to map the area, successions were measured at different localities and lithologs were prepared and correlated with other localities. Based on basic field investigation and laboratory data, composite lithologs were prepared. The composite logs serve the basic purpose and have enabled the investigator to recognize two different types of successions. Thus, these composite successions have helped in dividing into formal lithostratigraphic units. Two different types of successions deserve two different types of lithostratigraphic classification. Investigator has named them Ninama Basin and Chotila Basin and suggests two separate schemes that contain distinct formal lithostratigraphic units.

4.2 CONCEPTS OF INFRA-, INTRA, SUPRA AND INTERTRAPPEANS

The association of sedimentary succession with the LIP is observed throughout the Phanerozoic era (Ernst, 2014) which preserves the biota of the continental, marginal marine and marine realm. The mode of occurrence of these rocks is unusual, largely controlled by the availability of the space and the agency bringing the sediments from the source area. The younger lava flows may affect sedimentary succession, modifying their original position and resulting into discontinuous nature with varying thickness, but contains endemic fauna and flora. Deposits occurring with lava flows can be differentiated, into four types of sedimentary units, identified based on their position which includes, Infratrappean, Intertrappean, Intratrappean and Supratrappean (Fig. 4.1). These informal terminologies are used by paleontologists, stratigraphers, sedimentologists and volcanologists, locally (Prakash, 1960; Ambwani, 1982; Ashok Sahni et al., 1984; Mukhopadhyay and Shome, 1996; Tandon, 2002; Srivastava et al., 2017; Keller et al., 2018) as well as globally (Assefa and Saxena, 1984; Williamson and Bell, 1994; Jolly, 1997; Durant, 2006; Abbate et al., 2014). It is necessary to define them formally which will facilitate the description of such stratigraphic units.

The 'Infratrappean' deposit (Fig. 4.1a) lies below the lava flows and there is no time gap between the two different rock units, i.e., the older sequence is completely interrupted due to the lava flow and the same sequence may also be continuous in nature in the uncovered area or elsewhere (Fig. 4.1a). The dinosaurian fossil-bearing Lameta Formation of Jabalpur, Rhaioli, Bagh-Kukshi, Duddukuru and Nand - Dongargaon are infratrappean in position and represent an important record of the Late Cretaceous (Prasad, 1989; Prasad and Singh, 1991; Khajuria and Singh, 1992; Prasad and Khajuria, 1995; Tandon, 2002; Khosla and Sahni, 2003; Tripathi, 2006; Shome and Chandel, 2013; Mankar and Srivastava, 2015; Lourembam et al., 2017; Kapur and Khosla, 2019; Dhiman et al., 2022).

The 'Intertrappean' (Coulthard, 1829; Malcomson, 1837; Hislop, 1860; Blanford, 1867) sedimentary unit is sandwiched between the two different phases of lava flows with a significant time gap and a nonconformable (Fig. 4.1b) contact. The thickness is highly variable, controlled by the availability of the space and rate of sedimentation. This isolated nature of the basin reflects unique lithology and fossil assemblages suggesting a local depositional setting. The intertrappean sequence is reported from the peripheral parts of the DVP of India for example, Rajahmundry (Keller et al., 2008), Gurmatkal (Jalal et al., 2020), Asifabad (Prasad and Sahni, 1987), Nagpur (Ashok Sahni et al., 1984), Chhindwara (Nambudiri and Chitaley, 1991; Samant et al., 2008, 2013), Anjar (Ghevariya, 1988; Bajpai et al., 1993; Bhandari and Colin, 1999; Khadkikar et al., 1999; Bajpai and Prasad, 2000; Shukla et al., 2001; Dogra et al., 2004; Parthasarathy et al., 2008; Srivastava et al., 2017), Bamanbor and Ninama (Fedden, 1884; Borkar, 1973, 1975, 1984; Shringarpure, 1985; Adatte et al., 2014; Samant et al., 2014).

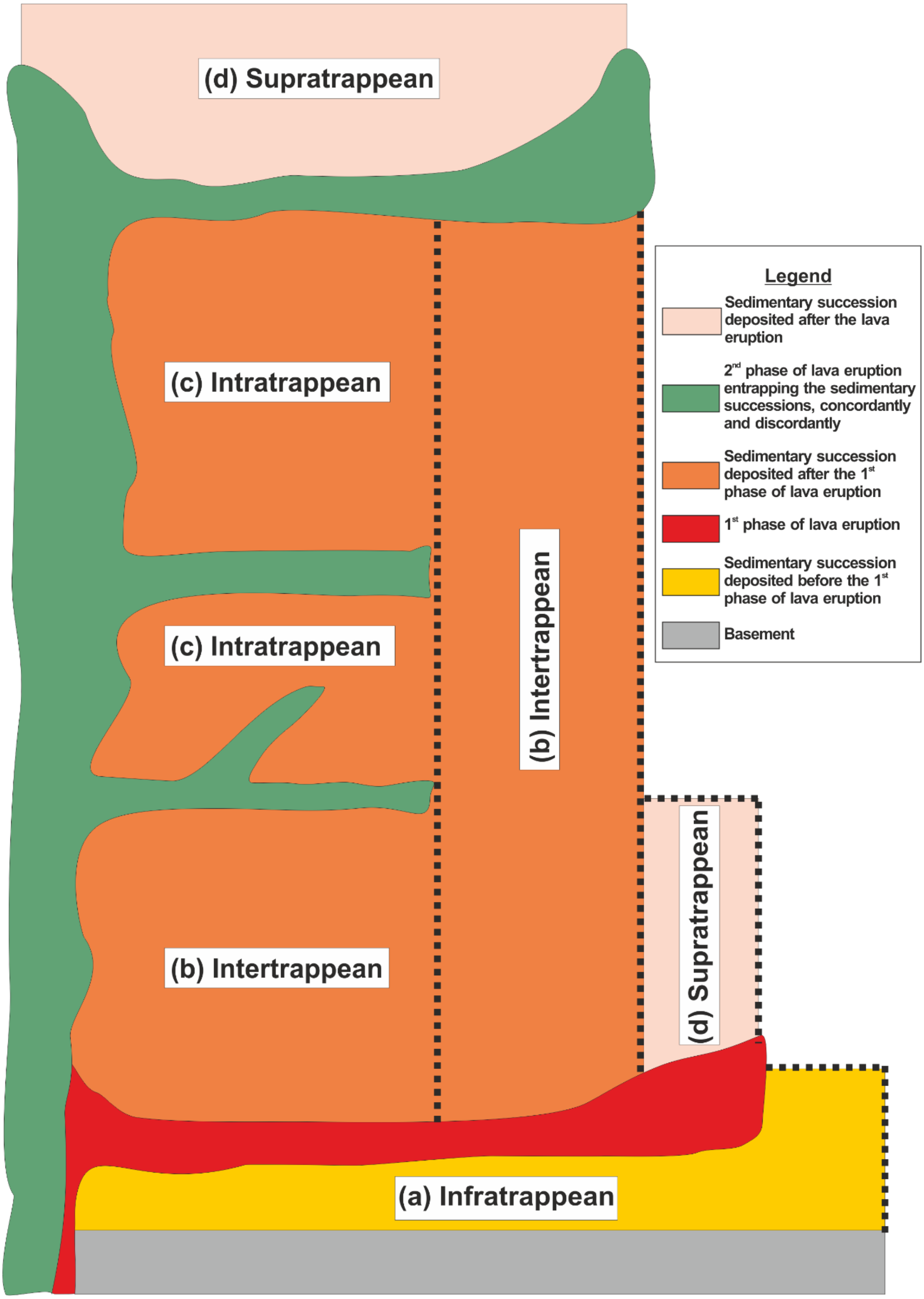

Fig. 4.1 Diagrammatically illustrated varying positions of the sedimentary successions in relation with the different phases of lava flow, (a) Infratrappean, (b) Intertrappean, (c) Intratrappean, and (d) Supratrappean.

The ‘Intratrappean’ sedimentary unit is associated with younger lava flow where it penetrates along the bedding plane at single or multiple levels within the same sequence in a concordant relationship, occurring as sills (Fig. 4.1c). An uncovered sequence may appear as Intertrappean due to inability of lava to cover a part of the sequence (Fig. 4.1c) and hence the intertrappean and intratrappean sequences are subjective (Fig. 4.1b, c). Variable inflation in the lava field produces variable flow thickness and leads to interfingering, overriding, and/or discordance of lava-sediment disposition (Fig. 4.1c) (Ernst et al., 1995). The intertrappean and intratrappean deposits are observed in Anjar (Srivastava et al., 2017), Rajahmundry (Keller et al., 2008) and BTVP (Williamson and Bell, 1994; Jolly, 1997).

The ‘Supratrappean’ sedimentary sequence lies nonconformably above the lava flow where the basin is formed due to erosion or topographic low (Fig. 4.1d). The intertrappean sequence can partly be covered with the subsequent flow and may remain uncovered elsewhere forming supratrappean units with respect to older flow (Fig. 4.1d). The supratrappean sequence is laying nonconformably over the last phase of the Deccan Volcanics (Prasad and Khajuria, 1995) and is reported from Bhavnagar (Thakur et al., 2010) and Kachchh (Mukhopadhyay and Shome, 1996).

Hence, the inter-, intra- and supratrappean terms are interchangeable depending on the relationship between and within the lava flows (Fig. 4.1b, c, d) and sedimentary units; while the infratrappean sequence always lies below the lava flow with conformable or unconformable lower contact (Fig. 4.1a).

4.3 INTERNATIONAL STATUS

The intermittent eruptive nature of the lava flows of the LIP’s represented by interlayered sedimentary which preserves the important biota of the continental realms which are useful for bio-chronostratigraphy and the evolution of the fauna and flora. Investigator has and able to identify four LIPs across the Cretaceous-Paleogene, including Madagascar, North Atlantic Igneous Province (NAIP), Parana – Etendeka Flood Basalt Province, and Deccan Trap Province of India, where attempts have been made to classify the intertrappean succession lithostratigraphically.

The Mahajanga basin of the Madagascar LIP preserves the basalt flow of the Turonian-Coniacian age interbedded within continental/transitional sediments (Papini and Benvenuti, 2001) named Ankarafantsika and Amboromalandy Formations of Cenomanian-Turonian?

consists of sandstones of fluvial to the lacustrine environment (Rogers et al., 2000) while Ankanzomhiab beds, siliciclastics deposits of fluvio-lacustrine environments overlies the basalt flow (Papini and Benvenuti, 2001).

The Etendeka (volcano-sedimentary) Group of Parana-Etendeka Flood Basalt Province preserves the aeolian deposits before and during the lava outpouring (Mountney et al., 1998; Jerram et al., 1999). The deposition of the Main Aeolian Unit (Mountney et al., 1998) of the Etjo Formation (Milner et al., 1994) was interrupted by the eruption of Etendeka flood basalts; the Upper Aeolian Unit (Mountney et al., 1998) of Awahab Formation (Milner et al., 1994) overlies the Main Aeolian unit and the flood basalts; and the Tafelkop Interdune Member Basalts of Awahab Formation are characterised by dune deposits within olivine and plagioclase phyric basalts (Jerram et al., 1999, 2000) forming infratrappean and intertrappean units, respectively.

The NAIP extends along the east and west coast of Greenland, Faroe Island, the Voring Plateau of Norway, Rockall bank, Baffin Island of Canada and the British Tertiary Volcanic Province (BTVP) in the British Isles (Ernst et al., 1995, 2005; Jolly, 1997; Ernst, 2014; Johansson et al., 2018). The BTVP preserves exceptional Intertrappean and Intratrappean sedimentary sequences in lava fields of Antrim, Mull, Skype, Rum, Canna, Sanday, Muck, Eigg, and Ardnamurchan (Jolly, 1997). The intratrappean sediments of the Skye lava field are referred to as erosion surfaces E1-E5 (Jolly, 1997); the E1, the oldest erosional surface consisting of tuffs, red boles, carbonaceous shales, coal; the E2, called Minginish Conglomerate is divided into three members composed of polymictic conglomerate, sandstone, siltstones and coal; E3 level grading into boles, shales and coal from Manginish Conglomerate; E4 Eynort Mudstone overlying Fiskavaig Lava Group were deposited in local ephemeral lake basins on the flow traps; E5 are the thickest sediments of Skye referred as Preshal Beg Conglomerate (Williamson and Bell, 1994).

4.4 NATIONAL STATUS

The Indian DVP Deccan Volcanic Province (DIP) of continental flood basalts, is one of the world's largest LIPs, divided is further subdivided into four sub-provinces, (Saurashtra - Kachchh, Main Central Deccan, Malwa, and Mandla.). Volcanism caused by the rifting and rapid migration of the Indian plate across the Reunion Island hotspot altered sediments and affected the lifeforms (Cox, 1989; Mahoney, 1988; Deshmukh and Sehagal, 1988; Tandon, 2002; Cripps et al., 2005; Prasad and Sahni, 2014a; Keller et al., 2018). The typical DVP sedimentary deposits have limited thickness, lateral extent, patchy nature, and variable lithology, which hinder correlation and limit their usefulness in stratigraphic subdivisions. (Prasad and Khajuria, 1990; Prasad and Singh, 1991; Khadkikar et al., 1999; Khosla and Sahni, 2003; Chenet et al., 2008; Keller et al., 2009, 2012, 2018; Malarkodi et al., 2010; Bajpai et al., 2013; Adatte et al., 2014; Prasad and Sahni, 2014b, 2014a; Smith et al., 2015; Font et al., 2016; Kapur et al., 2018; Mohabey and Samant, 2019; Kapur and Khosla, 2019; Samant et al., 2020). The first attempt was made by Sahni et al. (1984) to formalise the Nagpur Intertrappean, assigning Takli Formation, but its discontinuous nature succumbed to their its identity. Investigator has made rigorous attempts and formalised the lithostratigraphic unit of the intra-, intertrappean succession of the Paleogene of the Saurashtra Peninsula, a part of the DVP of India. This pioneering work will inculcate the futuristic shape of the sedimentary successions associated with DVP.

4.5 PREVIOUS WORK

The intertrappeans of the Saurashtra were first described by Fedden (1884) where he had identified the Porcelaneous shale in Chotila and Limestone in Ninama. He described the sedimentary deposits as interstratified with trap flows. The cherty porcelaneous shale outcrops on the west and south of Chotila, near Bamanbor, Nawagam, Kherdi and Kalasar respectively. He also reported small imperfect fish skeletons from west of Chotila. The presence of pseudoripples due to severe lateral compression was also noted by him. Fedden reported the intertrappean of Ninama, Lakhwad and Shekhdod hills, 30 km South of Chotila, which consisted of argillaceous and cherty limestones.

Borkar (1973, 1984, 1986), described the intertrappean beds from Bamanbor, Deothan, Mewasa, Wankaner, Chotila, Kheri, and Ninama, as freshwater-lacustrine, originating out of confined river systems due to their thickness, lateral extension and reported the occurrences of vertebrate fossils including those of the fishes, like *Horaclupae intertrappean*, *Palaeopristolepis feddeni*. Borkar (1975, 1984) described fragmentary specimens of *Palaeopristolepis chiplonkari*, Pristolepidae from Bamanbor, near Chotila. He suggested a Paleocene – Early Eocene age for the Intertrappean beds of Ninama and Bamanbor and also consequentially for the associated Deccan lava flows in the area.

Shringarpure in 1985, reported the existence of Tryonychid turtles from the highly crumpled grey, brownish yellowish earthy shales of Bamanbor. However, they were identified but not further classified due to their fragmentary nature and poor preservation. He also suggested a warm, temperate and tropical condition with fluviatile and lacustrine environments which prevailed between the lava flows.

Arratia et al 2004, described a new taxon, *Indiaichthys bamanborensis* and *Percomorpha* indet from the intertrappeans of Bamanbor and suggested a Late Cretaceous to Early Paleocene age.

Recently, Samant et al 2014, worked on the palynology and clay mineralogy of the intertrappeans of the Ninama area and described palynofossils belonging to the Paleocene, including, *Intrareticulites brevis*, *Neocouperipollis* spp., *Striacolporites striatus*, *Retitricolpites crassimarginatus* and *Rhombipollis* sp. The study also suggested an arid climate based on the correlation of palynology and clay mineral assemblage. Recently, Patel and Shah (2023) have classified the intertrappean succession of the Saurashtra Peninsula into formal lithostratigraphic units.

4.6 LITHOSTRATIGRAPHY

The Paleogene sedimentary succession of the Saurashtra Peninsula occurred as supra-, intra- and intertrappeans. The supratrappean succession occurred in subsurface and their exposures were only seen in the lignite mine area, and it is classified as Khadsaliya Formation (Thakur et al., 2010; Singh et al., 2017), which is not part of the present investigation. The investigator has mainly concentrated her work on the exposed intra-, and intertrappeans succession of the north-central part of the Saurashtra Peninsula that borders the Mesozoic sedimentary. The intra-, and intertrappeans succession were thoroughly worked by Patel and Shah (2023) and gave the comprehensive lithostratigraphic formal units (Table 4.1) first time in the history of the intertrappean succession investigation. They considered two different sedimentary basins, i, e., Ninama and Chotila and gave separate formal stratigraphic unit names which are summarized in Table 4.1 and units are described in detail according to the stratigraphic norms.

In the earlier attempt, the Saurashtra intertrappeans were studied for a paleontological viewpoint from different places including around Ninama, Bamanbor, Lakhvad, and Chotila villages (Fedden 1884; Borkar 1973; Arratia et al. 2004; Samant et al. 2014; and Sheth et al. 2022). They also noticed the occurrence of different types of rocks, fossiliferous limestone, bedded siltstone, mudshale, marlite, and chert. Recently, Patel and Shah (2023) covered the entire exposed succession of the Saurashtra Peninsula for their lithostratigraphy and also noticed their lithological character in detail.

<table>
<tr><td></td><td colspan="2">Chotila Basin</td><td colspan="2">Ninama Basin</td></tr>
<tr><td>Age</td><td>Formation</td><td>Lithology</td><td>Formation</td><td>Lithology</td></tr>
<tr><td colspan="5">Deccan Traps</td></tr>
<tr><td rowspan="4">Palaeocene – Early-Middle? Eocene</td><td>Bamanbor</td><td>Red, buff, grey mudshale, fossiliferous shaly sandstone, chert lenses, and nodules of claystone with bivalves and gastropods</td><td rowspan="2">Ninama Limestone</td><td rowspan="2">Fossiliferous limestone, Argillaceous limestone, Chert nodules, Marlite? and calcareous shale, chert</td></tr>
<tr><td rowspan="2">Chotila Chert</td><td rowspan="2">Bedded and banded chert, Silty-cherty mudstone, Black laminated chert</td></tr>
<tr><td rowspan="2">Sukhbhadar</td><td rowspan="2">Mudshale, siltstone, Lithic arenite-greywacke, thin bands of mudstone with concretionary nodules</td></tr>
<tr><td>Rangpar</td><td>Mudshale and siltstone</td></tr>
<tr><td colspan="5">Deccan Traps</td></tr>
</table>

Table 4.1 Formal lithostratigraphic units of the Saurashtra Peninsula (Patel and Shah, 2023). Note: Two different types of sequence are divided into two separate lithostratigraphic units owing to their distinctness in the nature of the sediments.

4.6.1 NINAMA BASIN

The Ninama Basin sedimentary succession occurred as intra- and intertrappeans which are well exposed in and around the Ninama, Lakhwad, Shekhdod, Motamatra villages etc. The complete well-exposed succession is observed in the Sukhbhadar River near Ninama village. It is also observed in freshly dug well sections near Ninama and Motamatra villages. The Ninama Basin succession mainly consists of a thick, fine-grained sequence with lithic greywackes at the base followed by the thick sequence of the fine-grained sediments that include the mudshale, mudstone, siltstone, and shale; capped by the chemically formed limestone, marlite and cherty limestone (Fig. 4.1). The succession is divided into the lower Sukhbhadar Formation and upper Ninama Limestone (Patel and Shah, 2023).

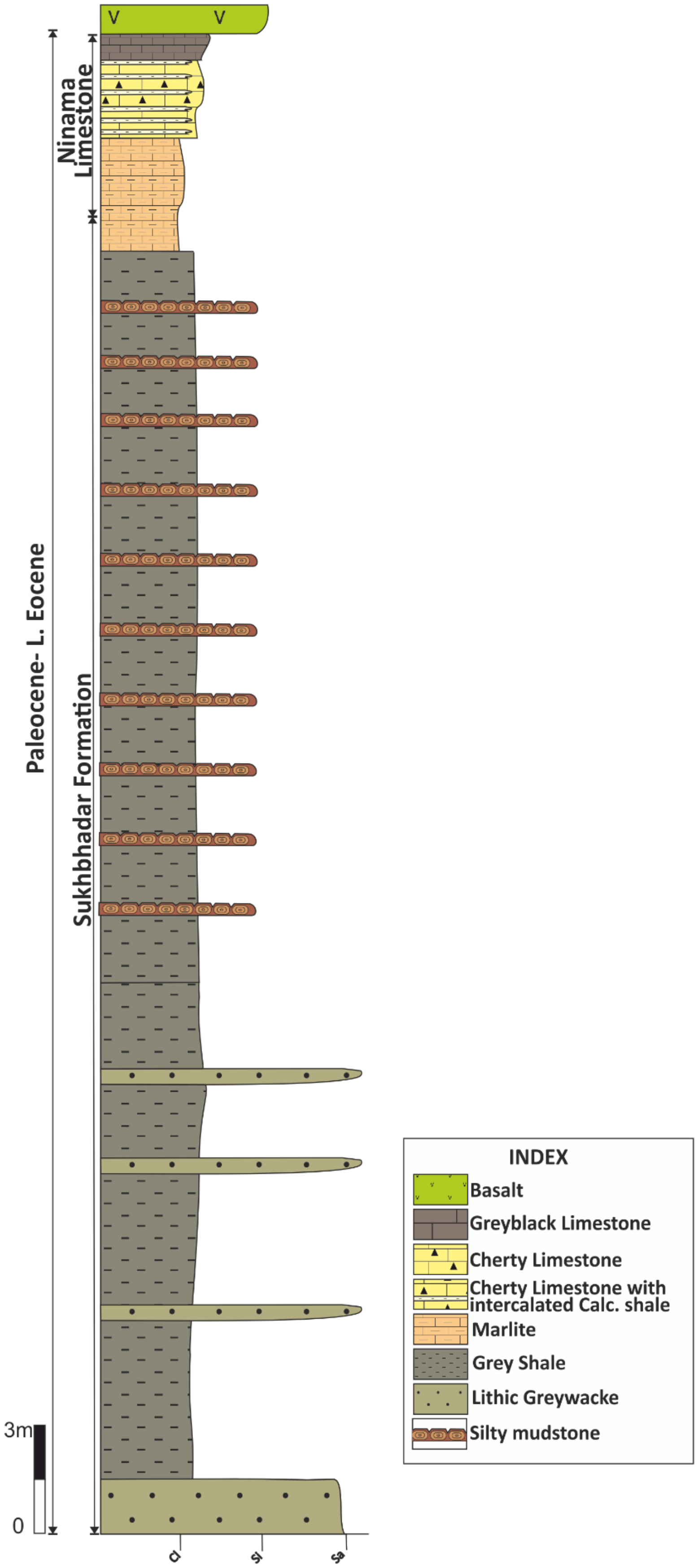

Fig. 4.2 Composite litholog representing lithofacies of Ninama Basin.

4.6.1.1 Sukhbhadar Formation

Historical Background: The formation's name is derived from the Sukhbhadar stream, a tributary of the Bhadar River.

Intent and Utility: It is the oldest stratigraphic unit of the Saurashtra Intertrappean, which rests nonconformably above the Deccan Traps. The overlying limestone-dominated layer is distinguished from this shale-dominated unit. It is found along the Sukhbhadar stream near Ninama village (Plate4.1a) as well as in freshly dug wells near Ninama (Plate 4.1c) and Motamatra villages.

Designation: Designated herein as a Formation that shows consistent lithology.

Stratotype: The stratotype for this formation is well exposed on the left bank of the Sukhbhadar stream near Ninama Village, (22°18’01” N, 71°20’04” E). It is also found at Motamatra (Plate 4.1d), Lakhvad villages and Shekhdod hill.

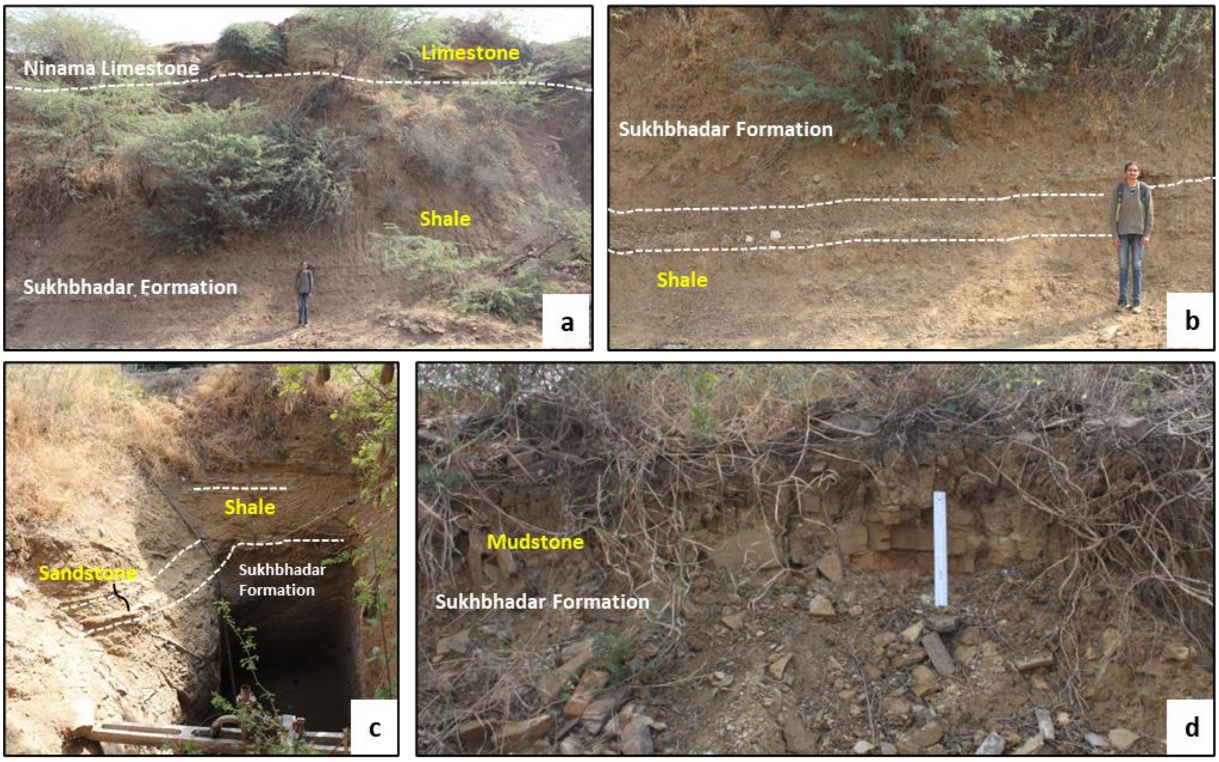

Plate 4.1 a. Sukhbhadar river section showing the shales of Sukhbhadar Formation and Limestone of the Ninama Limestone. b. Close-up of the Sukhbhadar Formation shows the thinly bedded mudstone. c. Ninama well section shows the thick shale with intercalated lithic sandstone/greywacke. d. Contact between the shale of the Sukhbhadar Formation and Ninama Limestone near Motamatra, limestone (mudstone) is thinly bedded to flaggy in nature.

Unit description: This unit is 33 m thick, with an 18 m thick exposed part on the left bank of the Sukhbhadar stream (Plate 4.1a) and a 15 m thick section in a dug well (Plate 4.1c), primarily consisting of argillaceous and coarse clastic rocks (Plate 4.1c). The good sections expose the oldest part of the unit as they overlie the basalts; the bottom part is distinguished by a 1.5 m thick lithic arenite followed by a thick intercalated sequence of fine-grained argillaceous clastics, claystone-mudstone-siltstone unit. Frequent thin bands of lithic arenite are followed in the unit. Lithic arenite is made up of coarse to very coarse, poorly sorted angular to subrounded volcanic clasts, as well as medium to coarse, monocrystalline and polycrystalline quartz and plagioclase. The Sukhbhadar stream segment (Plate 4.1a) reveals 4 to 7 cm of thinly bedded brown siltstone with mudshale (Plate 4.1a), followed by an 18m thick layer of intercalated claystone-mudshale-siltstone (Plate 4.1a and b). Mudshale dominates the intercalated sequence, with siltstone and claystone layers interfingering and merging laterally with mudshale at a very short distance (Plate 4.1b). Fine to very fine-grained, well-sorted quartz grains are cemented together in fine argillaceous, calcareous, and ferruginous cement in the siltstone strata.

Boundaries: 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 along the Sukhbhadar stream (Plate 4.1a and 2a).

4.6.1.2 Ninama Limestone

Historical Background: The formation is named after the Ninama village of Chotila Taluka, Surendranagar district. Ninama section was first time studied by Fedden, (1884), and considered an intertrappean, following which Borkar (1973, 1974) and Samant et al., (2014) described them.

Intent and Utility: It is characterized by distinct lithology and fossil content compared to the Sukhbhadar Formation and is overlain by the volcanic rocks observed in a freshly dug well at Motamatra village (Plate 4.2b). It mainly consists of limestone which at times intercalates with shale laterally observed at the top of the two small hills near Ninama village (Plate 4.3 c, e).

Designation: The unique lithological characteristics of this unit are designated as a Formation, and it shows consistency in the Ninama Basin.

Stratotype: It consists of 2-3 m thickly bedded limestone, exposed above the Sukhbhadar Formation near the Ninama village (Plate 4.2a) and the quarry section at the top of the two east-west running hills, lying 600 m northwest of the Ninama village (Plate 4.3a-e). This unit laterally shows lithological variation, appears as marlite or shaly limestone and is intercalated with shale (Plate 4.2c and e). It is also observed at Shekhdod hill, Lakhvad (Sheth et al., 2022), and Motamatra village (Plate 4.2d and 3e).

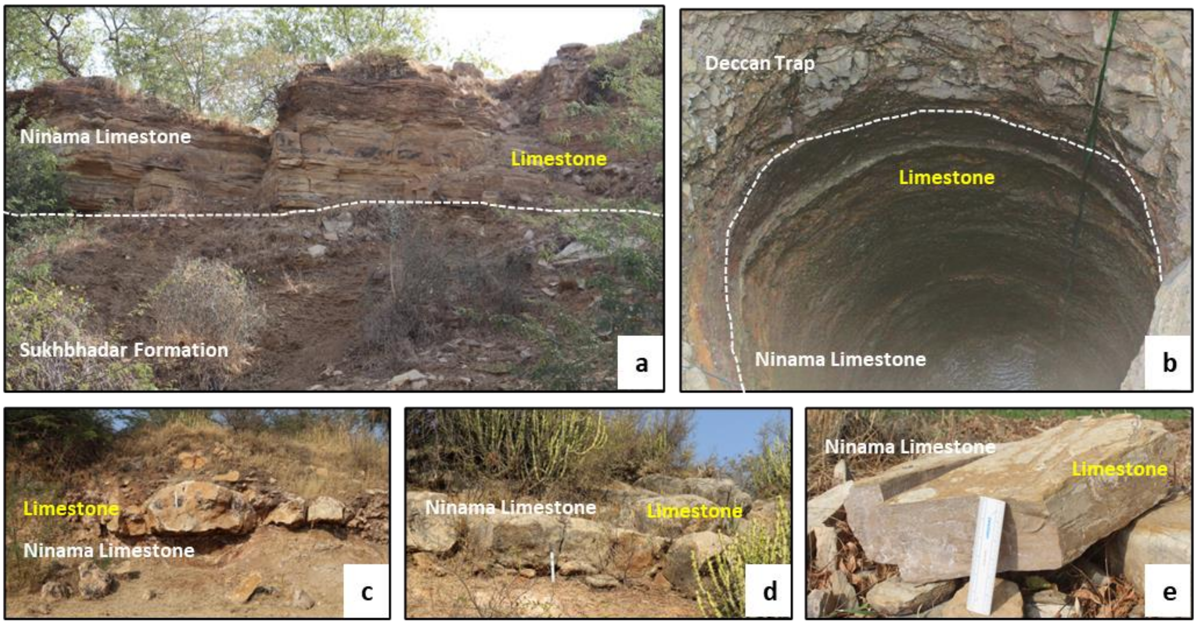

Plate 4.2 a. Thick limestone of the Linam Limestone overlain the shales of the Sukhbhadar Formation, Sukhbhadar river section near Ninama. b. The well section near Motamatra village shows Sukhbhadar Formation and Ninama Limestone nonconformably overlain the Deccan lava flow. c. Thick limestone bed grade to flaggy limestone in Shekhdod hill. d. Thick limestone bed in the Shekhdod hills. e. Flaggy limestone band exposed as superficial surface near Motamatra village.

Unit description: This formation is characterized by dirty yellow bedded fossiliferous limestone, capped by 20-30 cm thick grey to black limestone attaining a total thickness of ~3m (Plate 4.2a) but their thickness increases in the hill sections, 3-4 m with lithological variations comprising intercalated marlite and shale sequence (Plate 4.2c-e). This variation is also observed in surface and subsurface successions at the Motamatra (Plate 4. 1d and 2e), Lakhvad, and Shekhdod hill. The marlite is dirty yellow, blocky in the lower part, becomes flaggy towards the top, and is intercalated with buff calcareous shale. Limestone contains micrite, sparite, and abundant bioclasts (microfossils); spiritized material shows evidence of diagenesis including the recrystallization, replacement of calcite by chert, and development of secondary porosity. The top unit, grey to black limestone contains a high amount of organic content and palynofossils (Samant et al., 2014).

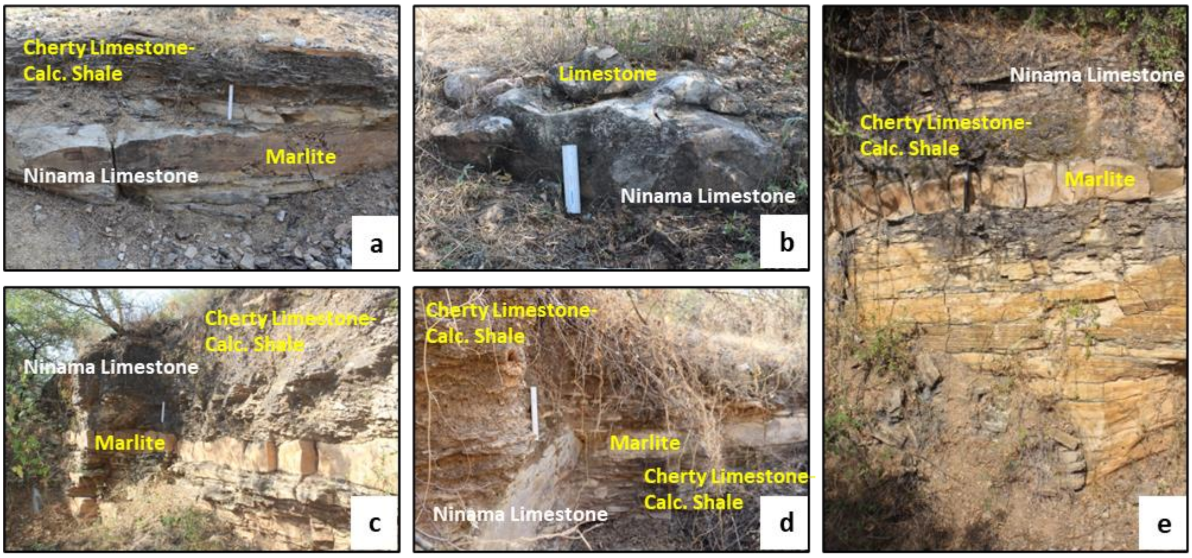

Plate 4.3 Exposures of the Ninama Limestone around Ninama village and Ninama hill sections. a. Gradational contact between the marlite and calcareous shale and cherty limestone. b. Black limestone. c. d. and e. The thick sequence of Ninama Limestone in the quarried section shows the bands of the marlite, calcareous shale and cherty limestone.

Boundaries: The lower boundary of the Ninama Limestone has gradational contact with the Sukhbhadar Formation (Plate 4.1a and 2a) and the upper contact is nonconformable with the overlying lava flows (Plate 4.2b) in well section near Motamatra village.

4.6.1.3 Age and Environment of Deposition

Borkar, (1973, 1986) has recorded fish remains such as *Horaclupea intertrappea* and assigned a Paleocene age. Recently, Samant et al. (2014) reported palynofosssil assemblage including *Intrareticulites brevis, Neocouperipollis* spp., *Striacolporites striatus, Retitricolporites crassimarginatus* and *Rhombipollis* sp. from the Ninama Limestone and suggested a Paleocene age. The Paleocene-Eocene age is suggested for the Sukhbhadar Formation and the Ninama Limestone based on fossil evidence.

The lower lithic arenite deposits suggest moderate energy conditions and the overlying thick mudstone unit suggests changes in energy conditions in brackish water lacustrine environment. Samant et al. (2014) suggested near marine taxa (*Neocouperipollis*, Palm) as well as freshwater taxa such as *Pediastrum* and Typha-like pollen which were deposited in a mixed (estuarine to near marine) environmental condition. They also suggested alkaline conditions possibly due to excessive evaporation and the prevalence of an arid climate based on lithology and clay mineralogy. The Ninama Basin consists of the youngest thick limestone units, suggesting excessive precipitation in hypersaline lacustrine environment (Gallois et al., 2018) conditions.

4.6.2 CHOTILA BASIN

The Chotila Basin is developed adjoining to Ninama Basin, both the basins predominantly contain fine clastic sediments; the major difference was observed in chemically formed sedimentary rocks. The Ninama Basin comprises limestone and chert while Chotila Basin comprises of thick chert band. The sequence of the Chotila Basin is highly disturbed by the younger lava flow and occurs as intra-, and intertrappean. It comprises a thick, fine grain dominated sequence, mainly including mudstone, siltstone, mudshale, siltshale and shales along with thick, conspicuous, extensively developed bedded chert and thin bands of calcareous fossiliferous sandstone. The succession of the Chotila Basin is divided into three formal litho-stratigraphic units (Table 4.1), namely, Rangpar Formation, Chotila Chert and Bamanbor Formation in ascending order.

4.6.2.1 Rangpar Formation

Historical Background: The name of the formation is given after the village Rangpar (Fig. 2.1) on the Chotila-Wankaner highway. It is the oldest unit and the first time noticed on the northern side of the Rangpar GIDC.

Intent and Utility: This stratigraphic unit of the Chotila Basin is coeval with the Sukhbhadar Formation of the Ninama Basin, resting nonconformably over the Deccan volcanic rocks (Table 1). A fine-grained shale-dominated unit, easily differentiated from the overlying chert unit, has been found recently due to extensive quarrying activities around Rangpar GIDC (Plate 4.4d and 4.5), Chanpa (Plate 4.6a-c), Jalsika and Garida villages (Plate 4.4a-c).

Designation: It is characterized by thick, conspicuous shale and hence designated as a Formation.

Stratotype: This unit is well exposed in the small hill, north of the Rangpar GIDC (Plate4.5a) and is also observed near the Chanpa, Garida and Jalsika villages (Plate 4.4a).

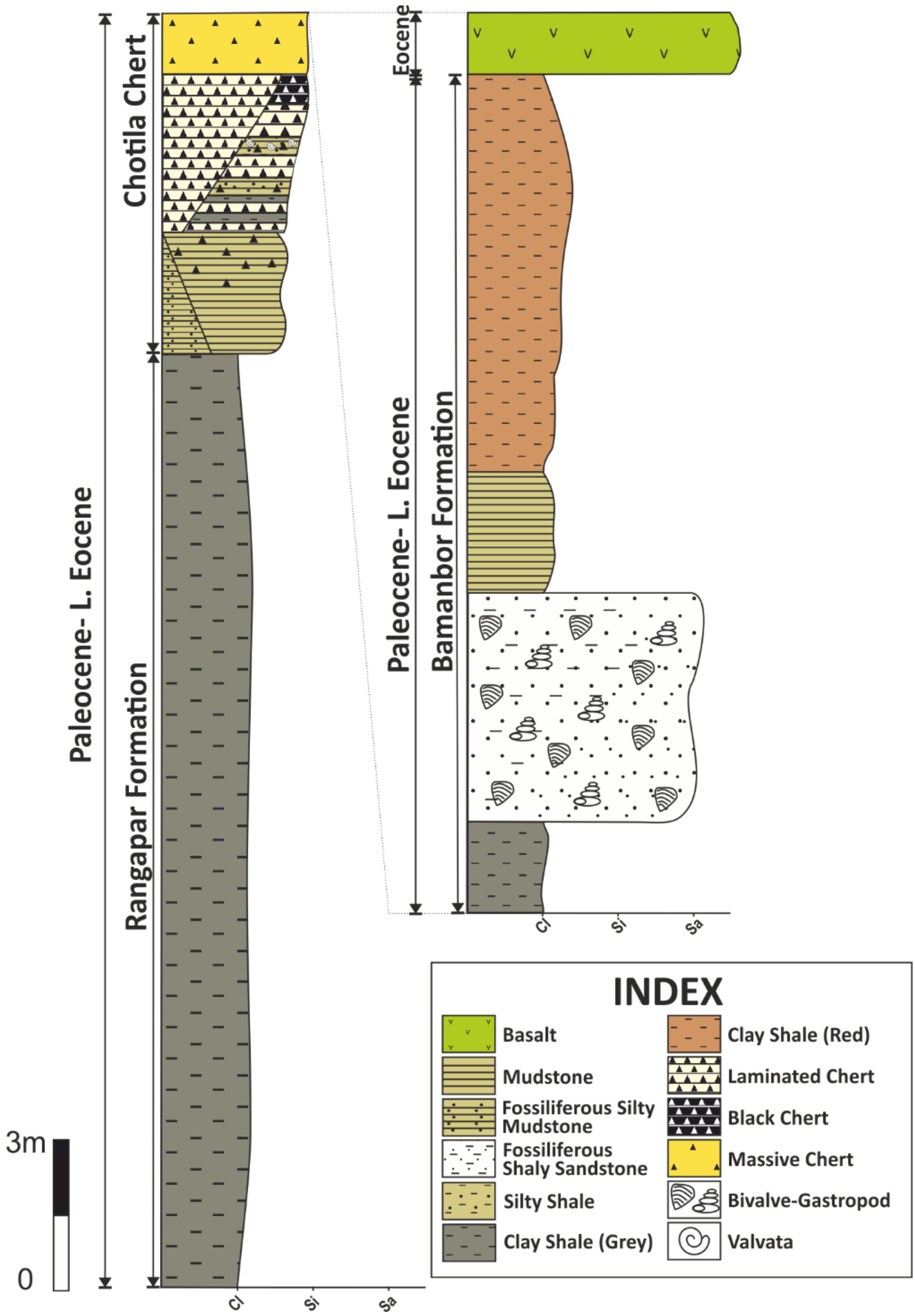

Fig. 4.3 Composite litholog representing lithofacies of Chotila Basin.

Unit description: This formation is well developed above the basalt and comprises a thick mudstone-dominated sequence interbedded with thin siltstone layers and embedded claystone nodules, attaining a maximum thickness of 6.5 m at the type locality (Plate 4.5). The mudstone is dark, earthy to greenish grey, highly fissile and crumbly, whereas siltstone layers are hard, compact and laminated. It is locally disrupted by discordant and concordant lava seams and shows variable attitudes (Plate 4.4d and 4.5c).

Boundaries: The lower boundary has nonconformable contact with igneous rocks while the upper boundary is conformable with Chotila Chert (Plate 4.4d).

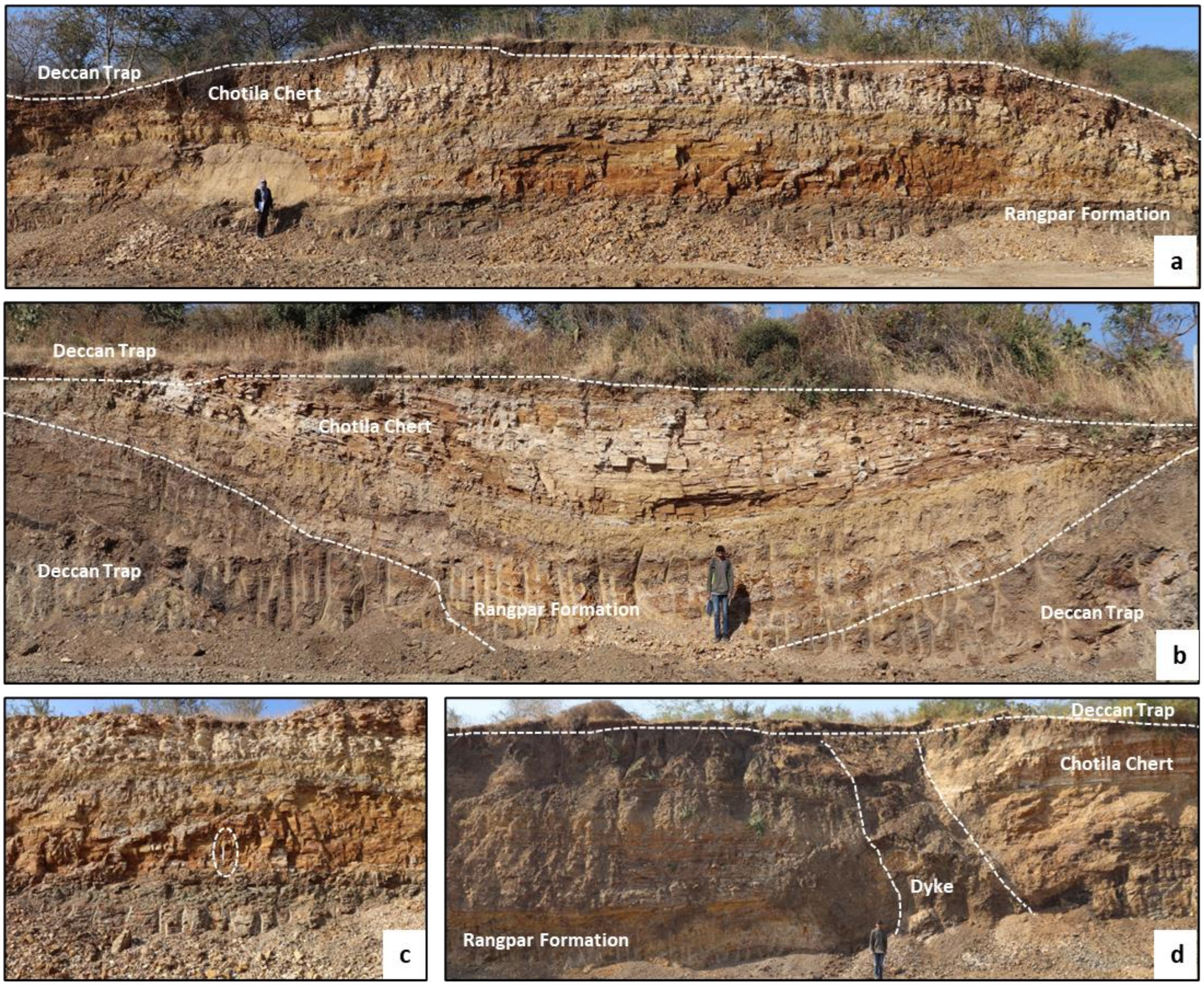

Plate 4.4 a. A freshly quarried section exposes the thick Chotila Chert with dark shale of the Rangpar Formation near Garida village. b. A freshly quarried section near Garida village shows an intratrappean sequence comprising a thick Chotila Chert and Rangpar shale sandwich between the younger lava flow, bending in the chert and shale beds is due to differential stress exerted from the different directions. c. Rangpar Formation and Chotila chert show the gradational contact near Garida village. d. Emplacement of the dyke in the Rangpar Formation and Chotila Chert has displaced the formations on either side.

4.6.2.2 Chotila Chert

Historical Background: The informal name Cherty beds was described by Fedden (1884), and later used by Borkar (1973), Samant et al. (2014) and Arratia et al. (2004). The chert layer is consistent in the Chotila Basin and observed in all the major sections. The name of the unit Chotila Chert is based on a well-developed succession at Chanpa Hill (Plate 4.6a).

Intent and Utility: Chotila Chert of the Chotila Basin is stratigraphic level equivalent to Ninama Limestone of the Ninama Basin and has distinct lithology. It is characterized by unique thinly bedded chert (Plate 4.6, 4.7 and 4.8) with homogeneous internal characters and may show lateral intercalations with shale (Plate 4.6c).

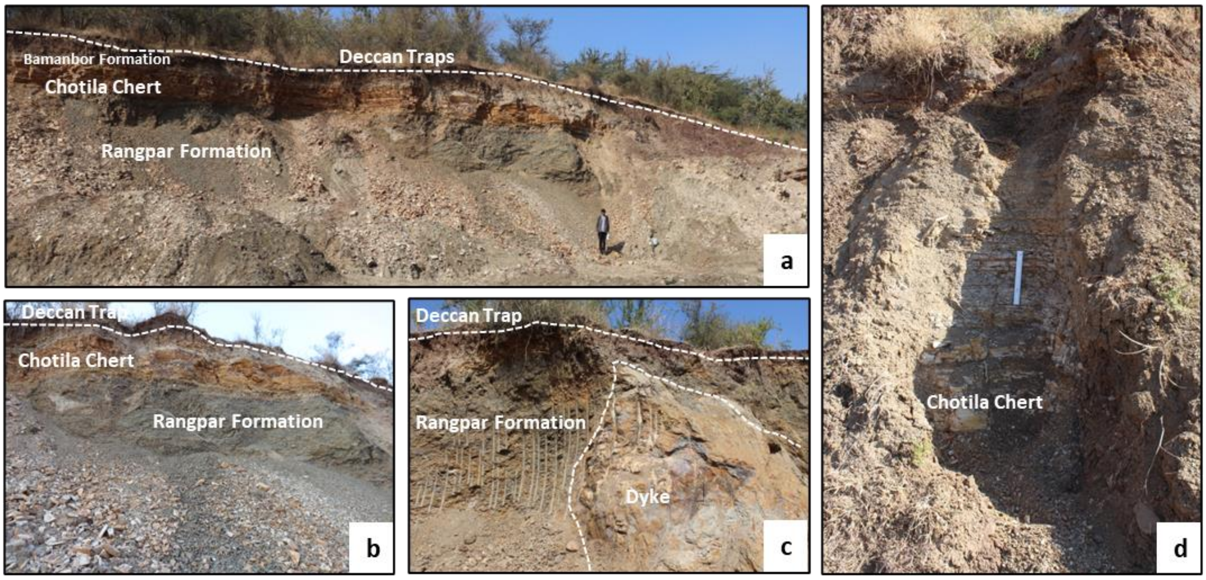

Plate 4.5 Photographs of the freshly quarried section near the Rangpar industry area. a. All three formations of the Chotila Basin are exposed on the northern side of the industry area. It is capped by the younger lava flow. b. Well-developed Rangpar Formation and Chotila Chert are capped by the lava flow. c. Discordant relationship between the shale of Rangpar Formation and dyke. d. Gradational contact between the Rangpar Formation, Chotila Chert and Bamanbor Formation.

Designation: Due to unique lithological characteristics, the lithological unit is designated as a Formation.

Stratotype: The stratotype of the formation is well exposed 3 km west of Chotila, on the Chanpa Hill, near Chanpa village and attains ~2.3 m thickness of the chert bed with 3-10 cm thick bands (Plate 4.6c). It is also observed near Bamanbor-Navagam (Plate 4.7 a and c, d-e), Redren industry, Rangpar (Plate 4.5a b and d), Garida (Plate4.4), Jalida, Vasundra (Plate 4.8 d) and Jalsika villages.

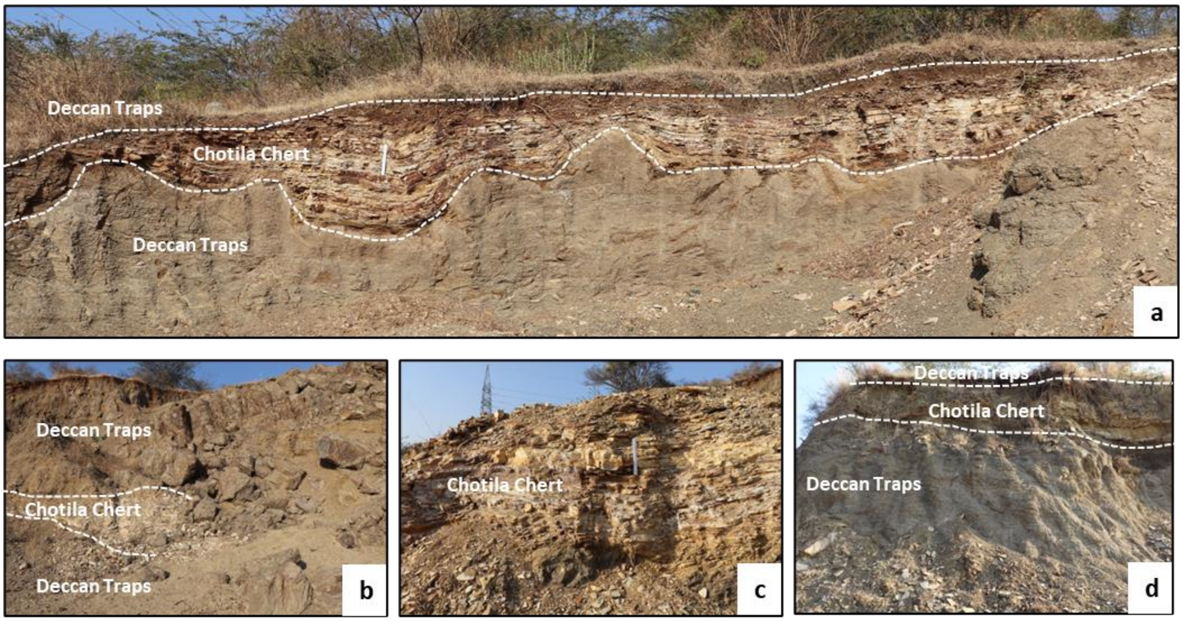

Plate 4.6 a. and b. Chanpa Hill Section, exposing the intratrappean consisting of mudshale and banded chert of Chotila Chert, sandwiched between the Deccan Traps. c. Thick banded chert and mudstone are exposed at the Chanpa Hill Section. d. The eastern part of the Chanpa Hill Section exposes the Chotila Chert, overlain and underlain by Deccan Traps.

Unit description: It mainly consists of light yellowish-beige to white, thinly to thickly banded chert and attains a thickness of 2.3 to 3.4 m in Chanpa Hill, (Plate 4.6 a-d), 3 m at Garida (Plate 4.4 a-d), 1.6 m at Redren Industry and 2.1 m around Bamanbor-Navagam village (Plate 4.7 a, e-f). The cherty layer is laterally intercalated with thick shale in the Chanpa Hill (west) (Plate 4.6 a-d) while with thin shale layers at Rangpar, Jalida, and Redren Industry (Plate 4.7 b, c). The nature of the chert is highly variable; cream, buff chert bands overlying the Rangpar Formation are porous, less dense, and thinly bedded in nature while the top chert layers are thinly laminated, massive, denser, and less porous due to recrystallization and consist microcrystalline and cryptocrystalline quartz, with alternate laminations of iron oxide and sparite veins. Chert beds are fossiliferous and contain fish fossil remains, *Indiaichthys bamanbornsis* (Arratia et al., 2004). They are deformed due to concordant and discordant igneous intrusions (Plate 4.6a, d and 4.7e).

Boundaries: The lower and upper boundary of the Chotila Chert is conformable with the underlying Rangpar Formation and overlying Bamanbor Formation (Table 1), respectively.

4.6.2.3 Bamanbor Formation

Historical Background: It was described by Fedden (1884), Borkar (1973, 1975, 1984, 1986) and Shringarpure (1985), who reported vertebrate remains and was recently measured by Samant et al. (2014). The name Bamanbor is invariably used by many workers for this intertrappean succession and thus priority is given and considered as the Bamanbor Formation which is the youngest unit of the Chotila Basin (Table 1).

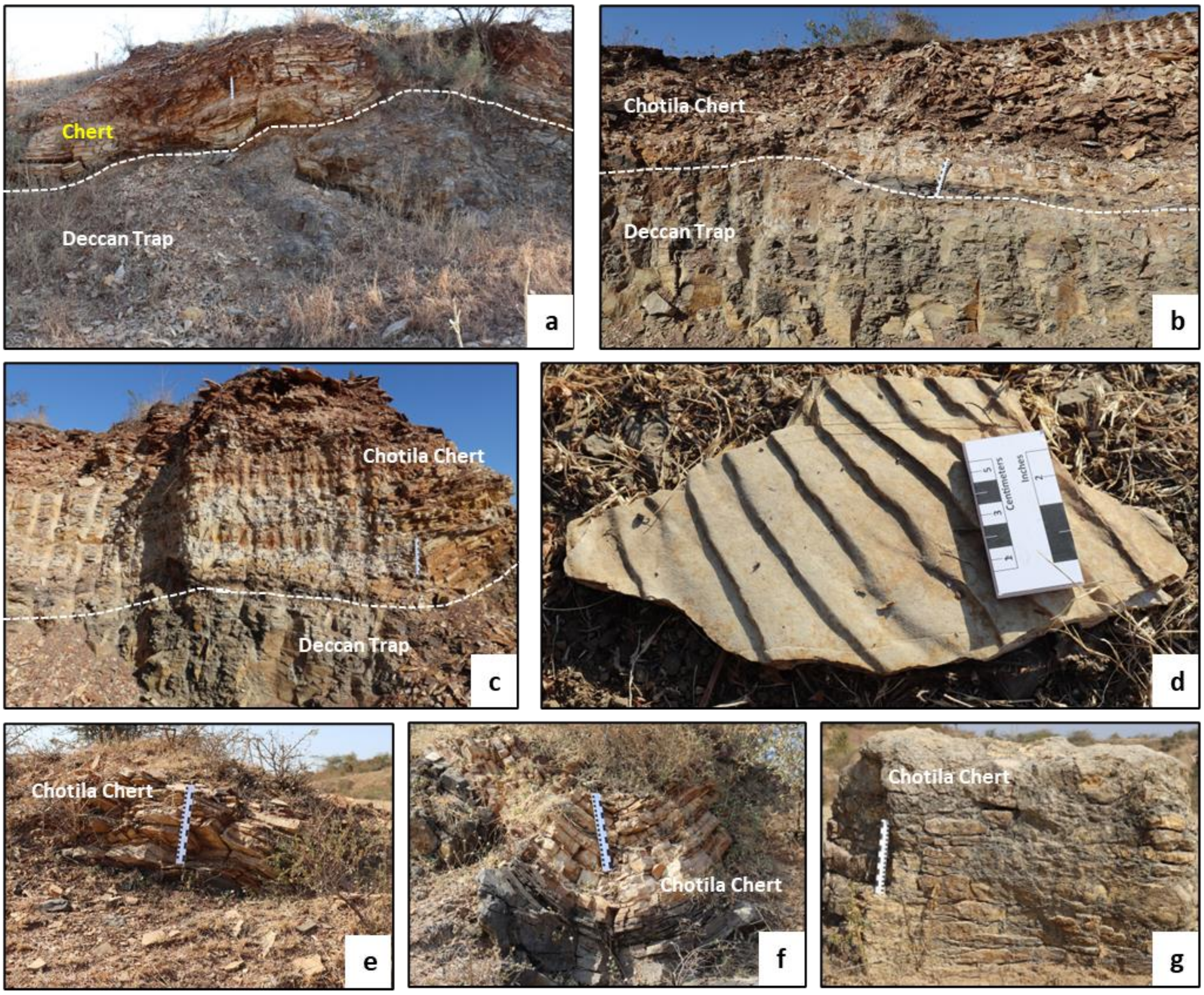

Plate 4.7 a. Photograph of chert belonging to Chotila Chert, exposed at the Bamanbor-Navagam Section, which is highly disturbed due to the intruded Deccan traps. b. and c. Thick 1-1.5m Chotila Chert exposed at Bhalgam Quarry section, and is exposed as intratrappeans. d. Pseudo ripples due to the Deccan lava flows preserved in the banded chert of Chotila Chert. e. and f. Highly deformed chert exposed at Bamanbor-Navagam Section. g. Thick unit of chert at Bamanbor-Navagam Section forming a yardang.

Intent and Utility: It has distinct lithology and mainly consists of mudstone, calcareous sandstone, and siltstone (4.5d, 4.8d and Plate 9a-f) with occasional thin chert layers (Plate

4.5d). It is the youngest unit of the Chotila Basin and its counterpart is not found in the Ninama Basin. It is differentiated based on lithological characteristics and also shows consistent nature in the basin, exposed at the Rangpar GIDC (Plate 4.5d), Garida, Redren Industry, and near Bamanbor (Plate 4.9 a-f).

Plate 4.8 a. b. and c. Exposed Chotila Chert in the Vasundhara Hill Section. d. Chotila Chert and Bamanbor formation exposed near the Actionwear Industry Section.

Designation: This section was earlier described as Bamanbor Intertrappean, now it is formalised as Bamanbor Formation.

Stratotype: The stratotype is 16.7m thick and observed at Bamanbor on the road cut section (Plate 4.9 a and c), 9 km west of the Chotila town, Chotila- Rajkot Highway. A 4.5 m thick bed is observed at Rangpar GIDC (Plate 4.5d) and is also exposed at Chanpa Hill, Redren Industry, Garida and Jalida villages.

Unit description: The thickest exposure is observed near the Bamanbor village, attaining 16.7m (Plate 4.9 a) thickness, also a 4.5 m thick near Rangpar GIDC and is overlying the Chotila Chert. It is characterized by mudstone, yellowish siltstone, greyish-shale, yellow-buff shale, and lenses of calcareous sandstone and is capped by the younger lava flow (Plate 4.9 a). The mudstone grades into siltstone at the bottom and yellowish grey shale, following upwards into grey shale and sporadically contains a thin bed of chert (Plate 4.5d) which is again overlain by red shale and grey shale at the top (Plate 4.5d and 4.9 a) with infrequent thin lenses of calcareous sandstone containing molluscan fossils (Plate 4.9 d-e). At place, moderately thick bands of the mudstone are noticed (Plate 4.9f). The calcareous sandstone consists of fine to medium, subrounded to subangular, moderately sorted mono-, polycrystalline quartz.

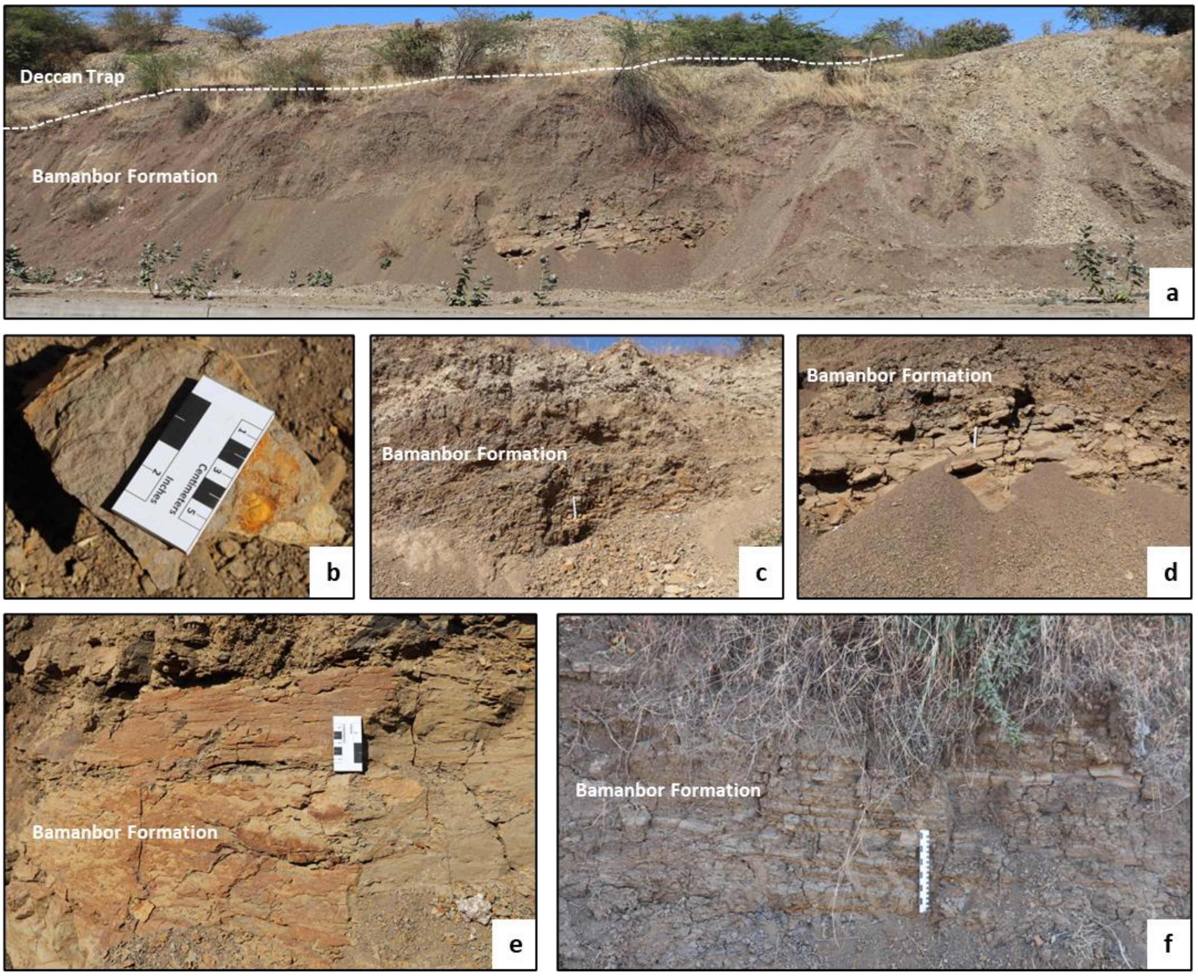

Plate 4.9 a. Bamanbor Road Section exposing the thick sequence of Bamanbor Formation, overlain by Deccan Traps. b. Physa containing sandstone of Bamanbor Formation. c. Thick shale unit of Bamanbor Formation. d and e. Sandstone unit of Bamanbor Formation consisting of gastropods and bivalves. f. Moderately thick bed of the Bamanbor Formation exposed at Bamanbor Road Section.

Boundaries: The lower boundary of the Bamanbor Formation is conformable with the Chotila Chert observed at Rangpar GIDC (Plate 4.9 a), Garida (Plate 4.9 a), Chanpa Hill (Plate 4.6c), and Redren Industry and Rangpar industry, the upper boundary is nonconformable with Deccan Traps (Plate 4.5 a-c).

4.6.2.4 Age and Environment of Deposition

The Rangpar (Plate 4.5 a, b and d), Garida and Chanpa sections expose the complete sequence of the Chotila Basin. Earlier, Samant et al. (2014) considered the Jalsika intertrappean at the lowest stratigraphic level for the intertrappean rocks and the Bamanbor– Wankaner road section at the highest stratigraphic level. Fedden (1884) recorded fragmentary fossil fish, Borkar (1973, 1975, 1984) reported *Paleopristolepis chiplonkari, Horaclupea intertrappean, Paleopristolepis feddeni, Perca* cf. *angusta*, and Arratia et al., (2004) reported *Indiaichthys bamanbornsis* and *Percromorpha* indet fishes from the Bamanbor area and assigned Paleocene age. The Ninama and Chotila basins consist of coeval deposits; hence, the fish remains and palynofossils assemblages (Samant et al., 2014) suggest the Paleocene- Eocene age.

The oldest Rangpar Formation characterised by fine-grained sediments suggests low energy conditions, but interbedded siltstone indicates an episodic fluctuation in energy, probably in a brackish water lacustrine environment. The Chotila Chert is characterised by thinly bedded and banded chert that corresponds to precipitation in alkaline (pH>9) conditions (Kuma et al., 2019) in the paleolake with a high amount of silica. The thinly laminated, compact, dense chert shows rhythmic banding of calcite and silica and is laterally intercalated with shale suggesting periodic changes in the sediment influx and presence of fish remains, a lacustrine environment condition is suggested (Fedden, 1884; Arratia et al., 2004). The youngest Bamanbor Formation is characterised by thick fine-grained sediments suggesting a change in the sediment influx in the calm conditions, with occasional moderate to high energy conditions interpreted based on the presence of siltstone and calcareous sandstones. The pristolepid fish remains (Borkar, 1973, 1975, 1984; Arratia et al., 2004), and the presence of bivalves and gastropods suggest a habitable freshwater lacustrine environment. Chotila Basin and Ninama Basin are closed systems with separate catchment areas. They received identical sediments in the beginning and later characterised by chert and limestone suggesting the brackish water lacustrine and hypersaline lacustrine environmental conditions, respectively.