Paleogene stratigraphy of Kutch, India: an update about progress in foraminiferal biostratigraphy

Pratul Kumar Saraswati, Sonal Khanolkar, and Santanu Banerjee

ABSTRACT

The Paleogene sections of Kutch are the reference for the regional chronostratigraphic units of India. The ages of these dominantly shallow marine carbonates are mainly based on larger benthic foraminifera (LBF). The taxonomic revisions of the LBF and the progressively refined shallow benthic zonations (SBZ) have necessitated the present study on updating the stratigraphy of the area. The sedimentation in Kutch commenced with the deposition of volcaniclastics in terrestrial environments in the Paleocene. The marine transgression in SBZ 5/6 deposited finer clastics and carbonates, designated as Naredi Formation, in early Eocene. There is no evidence of marine Paleocene in Kutch. A major hiatus spanning SBZ 12 to SBZ 16 was followed by the development of a carbonate platform and deposition of Harudi Formation – Fulra Limestone during the Bartonian, SBZ 17. The hiatus corresponds to a widespread stratigraphic break in Pakistan and India to Australia, referred as the ‘Lutetian Gap’. The Maniyara Fort Formation is assigned to SBZ 22 B and SBZ 23, and its age is revised to Chottian. Climate played a major role in building up of the Paleogene stratigraphic succession of Kutch, the carbonates formed during the warming intervals and the stratigraphic gaps were in the intervening cooling periods.

1. Introduction

The Kutch basin formed a pericratonic rift basin on the western continental margin of India at the time of separation of the Indian plate from the rest of the Gondwanaland. The rifting took place in early Jurassic along the westerly swing of the NE-SW Delhi orogenic trend (Biswas, 1999). The limits of the basin are defined by Nagar Parkar uplift in the north, Radhanpur – Barmer arch in the east and Saurashtra uplift in the south (Figure 1). The syn-rift succession comprises marine sediments of Jurassic age and fluvial-deltaic sediments of early Cretaceous age (Biswas, 1981). They occupy a large part of the mainland and constitute all islands from Patcham in the west to Chorad in the east. The rift history ended in late Cretaceous when Deccan volcanic spread over the western part of the Indian craton and also covered the Jurassic-Cretaceous sediments of Kutch. The subsequent sedimentation occurred in the passive margin setting during the Cenozoic (Figure 2). An NNE-SSW trending subsurface basement ridge, named Median High, had a strong influence on the sediment facies and thickness (Biswas, 1992). The Cenozoic succession is nearly 700 m thick on the mainland and thickens to about 4500 m in offshore (Mitra et al., 1983).

The geological investigation of Kutch dates back to 1840 when Colonel Grant prepared the first report providing details of the rock types along with a geological map of the area. The invertebrate fossils collected by Grant were studied by Sowerby (1840), and it is the earliest work on mollusks, echinoderms, and foraminifera from this region. He reported several new species of foraminifera including Nummularia (=Nummulites) acuta, Nummularia obtusa, Fasciolites elliptica and Lycophis (=Discocyclina) dispersus. Later, Archiac and Haime (1853–1854) described and illustrated 18 species of Nummulites and Assilina from Kutch and Sind. Biswas (1965) and Biswas and Raju (1971) proposed the presently followed chronostratigraphic and lithostratigraphic classifications respectively of the Cenozoic succession. Later, Biswas (1992) presented a modified and an integrated litho-, chrono- and bio-stratigraphic classification of the Kutch Basin. Revisions in taxonomy and stratigraphic ranges of several species of larger benthic and planktic foraminifera, on which the ages assigned to various stratigraphic units are based, has necessitated a re-look at the Paleogene stratigraphy of the area. Developments in planktic foraminiferal zones and shallow benthic zones and their integration continually update the geologic time scale, the latest being the Geologic Time Scale 2012 (Gradstein, Ogg,
age to the stratigraphic units and in the correlation of Kutch and Sind successions. Nuttall's (1926) study made a significant conclusion that the Oligocene beds unconformably overlie the middle Eocene beds in Kutch. These monographic works are landmark contributions in the early stratigraphic investigations of this region.

The succession of Sind remained a reference for the correlation of the Cenozoic succession of India until a major initiative on geological mapping of Kutch was taken in the 1960s. The outcomes of the initiatives were chronostratigraphic (Biswas, 1965) and the lithostratigraphic classifications (Biswas & Raju, 1971) of the Cenozoic succession that continues to be the framework of all geological studies in this area. Biswas (1992) gave an updated version of the classifications (Figure 3) based on inputs gained since their first publications. The Paleogene succession overlying the Deccan basalt is classified as Matanomadh Formation, Naredi Formation, Harudi Formation, Fulra Limestone and Maniyara Fort Formation respectively. These were assigned Thanetian, Thanetian – Ypresian, Lutetian, Lutetian – Bartonian, and Rupelian – Chattian ages respectively. Most researchers in the past five decades have followed this classification except for a few who attempted to present a different view, particularly for the early part of the Paleogene sedimentation. Ray et al. (1984) recognized three units in the Paleogene and named them as Clastic-Evaporite (CE) Suite, White Limestone and Marl (WLM) Suite and Coralline Limestone and Marl with Clastics (CLMC) Suite of sediments, pending their formal nomenclature for observations in additional sections. According to this, the Matanomadh, Naredi and Harudi Formations were combined as Clastic Evaporite Suite. A significant conclusion of the study was that sedimentation in Kutch

Schmitz, & Ogg, 2012). The chronostratigraphy needs to be amended given the revisions in the systematics of foraminifera and the timescale. In this paper we present a brief historical development in the stratigraphy of Kutch, review the foraminiferal biostratigraphy and discuss the updated stratigraphy of the Paleogene in current stratigraphic understanding.

2. A review of stratigraphy of the basin

Grant (1840) initiated a geological study of Kutch with the identification of various rock units including syenite, quartz-rocks, trappean volcanic rocks, sandstone, clay beds with coal, nummulitic limestone and marl. Their order of succession is not properly defined, but he prepared the very first geological map of this region. Carter (1853) provided the order of superposition of the rocks and their geological ages. Wynne (1872) until date remains the most comprehensive work on the geology of Kutch. It provides a detailed account of the geology of the area including the description and distribution of rocks and fossils and a classification of the Tertiary sediments and a geological map that continued to be the most dependable map for the workers in later years. Simultaneously, Blanford (1879) was working on the classification of the Tertiary succession of Sind, which was adopted by later workers as a standard stratigraphic scheme for the Indian subcontinent. Four stratigraphic units namely, Ranikot, Laki, Kirthar, and Nari were recognized in the Paleogene. Medlicott and Blanford (1879) found that the stratigraphic units of Kutch correspond very closely to those in Sind. The works of Vredenburg (1906, 1907) and Nuttall (1925, 1926) on the zonal distribution of larger foraminifera aided in assigning the age to the stratigraphic units and in the correlation of Kutch and Sind successions. Nuttall's (1926) study made a significant conclusion that the Oligocene beds unconformably overlie the middle Eocene beds in Kutch. These monographic works are landmark contributions in the early stratigraphic investigations of this region.

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commenced in middle Eocene or at the earliest in late early Eocene. Biswas (1986) refuted it in a rejoinder, and more recently, Saraswati, Sarkar, and Banerjee (2012) provided biostratigraphic zonation of the Naredi Formation in support of the early Eocene age. Some other workers also had contrary views on the early part of the post-Deccan sedimentation. Sen Gupta (1964) noted that early Eocene sediments are absent in Lakhpat region. Saraswati and Banerji (1985) gave another lithostratigraphic classification in which the lignite-bearing succession (referred to Naredi Formation by Biswas & Raju, 1971) is named as Panandhro Formation and considered it as undifferentiated Madh, Naredi and possibly a part of the Harudi Formation. In the absence of age indicator taxa, it was assigned a doubtful Paleocene-early Eocene age. They were also of the view that early Eocene sediments equivalent of the Naredi Formation are missing in Lakhpat and surrounding areas. As stated before, the presence of early Eocene is now unequivocally established in Kutch. The uneven topography of the Deccan country possibly caused facies variation and discontinuous marine sediments in the lower parts of the Cenozoic succession that misled several workers whose observations were confined to local sections. The views of Sen Gupta (1964) and Ray et al. (1984) about the absence of early Eocene in Kutch and the alternative classification of Saraswati and Banerji (1985) are not valid and stand corrected.

A systematic biostratigraphic zonation of Kutch began with the works of Sen Gupta (1964) in Lakhpat region. He identified seven faunal zones based on larger foraminifera, mollusks, and corals but described them informally as Zone 1 to Zone 7. He assigned the succession to Lutetian to Burdigalian and identified two major unconformities, between Eocene and Oligocene and Oligocene and Miocene respectively. Sen Gupta’s (1964)
Saxena (1980) reported and sketched four species of planktic foraminifera of supposedly Paleocene and early Eocene age from Naredi locality, but the assemblage has not been recorded by any subsequent worker till date. Keller et al. (2013) and Khanolkar and Saraswati (2015) recorded *Acarinina quetra*, *A. esnaensis*, *Chiloguembelina trinitatensis*, *C. crinita*, *Subbotina patagonica* and *Jenkinsina columbiana*.

Raju (1974) initiated a significant study on the morphology and phylogeny of Miogypsinidae of India that in later years became a standard for the chronostatigraphic subdivisions of the Oligocene – Miocene in India stratigraphy. Based on the morphometric limits of the miogypsinids Waiorian (late Oligocene), Aidaian and Vinjhanian (early Miocene) Stages were established with their stratotypes in Kutch (Raju, 2013). In reference to the miogypsinid scale, he proposed the Paleogene/Neogene boundary at the mean values of $X = 11$ in the Miogypsinidae.

3. Issues in Paleogene stratigraphy

The Paleogene sediments were deposited on a stable shelf punctuated by mild tectonics in late early Eocene, late Eocene, and late Oligocene as evidenced by unconformities (Biswas & Deshpande, 1983). The sedimentation was confined to the west of the Median High, the
outcrops of which occur in coastal margin fringing the Deccan trap. The eastern part of the mainland and the islands in the Rann do not have marine Paleogene sediments. The volcaniclastic and other terrigenous sediments formed above the Deccan basalt sometime after the volcanism (69–63 Ma; Pande, 2002) and before the first marine transgression of the Cenozoic in early Eocene (Zone SBZ 5, Saraswati et al., 2012). The marine transgression in the early Eocene laid down finer clastics and carbonates in shallow lagoons with water depths up to 30 m (Sarkar, Banerjee, & Saraswati, 2012). A hiatus from the later part of early Eocene to a part of the middle Eocene separates these sediments from the overlying carbonate dominated succession.

A major marine transgression in Kutch occurred in the late middle Eocene (Bartonian). It was a regionally extensive, transgressive event in India, which flooded several pericratonic basins on the west coast (Raju, 2008). These basins record the maximum flooding surface corresponding to Zone P13 (=E12, Berggren & Pearson, 2005). The warming event, globally recorded during Zone P13 and known as middle Eocene Climatic Optimum (MECO), was ecologically favorable for larger benthic foraminifera (LBF), found today in tropical-subtropical regions. They became abundant and primary producers of shelfal carbonate in the western margin of India, including the Kutch Basin. Embayment and protected lagoons until this time were favorable locales for deposition of shale, minor carbonates, and lignite. The Bartonian transgression filled them all forming an extensive carbonate platform. The water depths reached to about 60 m during the deposition of the middle Eocene sediments (Banerjee, Chattoraj, Saraswati, Dasgupta, & Sarkar, 2012). The fall in sea level in late Eocene marks a hiatus in the outcrops of Kutch, but sediments of this age are recorded in offshore wells (Mehrotra, 1989).

The shallow marine, foraminiferal carbonates of the Oligocene formed over the karstic surface of the Bartonian carbonates. It is characterized by glauconitic and nummulitic limestone and shale in the lower part, coral limestone in the middle and foraminiferal limestone at the top. Patchy coral reefs in the middle suggest deposition in shelf lagoons behind the marginal reef (Kumar & Saraswati, 1997). A hiatus, spanning early Aquitanian (Raju, Peters, Ravi, & Kumar, 2005), separates the Oligocene sediments from the overlying mixed clastic-carbonate succession of the early Miocene.

The classification of the Cenozoic succession proposed by Biswas (1992) continues to provide the stratigraphic framework for all geological investigations in Kutch. Studies by later workers, developments and changes in the concept of Shallow Benthic Zones and revised stratigraphic ranges of some age-indicator species of foraminifera have raised issues that are of implications to the stratigraphy of Kutch. The major questions on the Paleogene stratigraphy are as follows:

1. The age of the Naredi Formation: Is it late Paleocene to early Eocene or exclusively early Eocene?
2. The age of the Harudi Formation and Fulra Limestone: Lutetian and/or Bartonian?
3. The age of lignite deposits (referred so far to early Eocene Naredi Formation): early Eocene or middle Eocene?
4. Is late Eocene present in Kutch?
5. What is the status of Oligocene reticulate Nummulites in reference to the biometrically defined N. fabiani – fichteli lineage in western Tethys and, how does it impact the age of the Oligocene sediments of Kutch?

Most stratigraphic studies in Kutch conform with the lithostratigraphic classification of Biswas (1992). A layer-cake stratigraphy along river sections allows easy recognition and tracing of the lithostratigraphic units. The deviations are local and, as explained before, possibly due to the paleogeography of this marginal part of the basin. We, therefore, attempt to answer the above-raised questions in the presently followed lithostratigraphic framework and provide an updated description and amended ages of the lithostratigraphic units (Figure 4). The field photographs of the described formations are given in Figures 5, 6 and selected foraminifera are illustrated in Figures 7 and 8.

4. Description of the Lithostratigraphic units

4.1. Matanomadh Formation

A highly heterogeneous sequence of trap-pebble conglomerates, volcaniclastics, laterites, bentonites, clays and sandstones with thin layers of carbonaceous shale occurs prominently in Matanomadh, after which the formation derives its name. Chronostratigraphically the succession is named Madh Series (Biswas, 1965). The formation occurs discontinuously over the Deccan trap and in several places, it is represented only by laterite or trap-pebble conglomerate intervening the Deccan basalt and the overlying marine Naredi Formation. Foraminifera and the other age-diagnostic fossils are absent in the formation. The relative stratigraphic position and presence of spore-pollens suggest a probable Paleocene age (Mathur, 1966).

4.2. Naredi Formation

The Naredi Formation in its designated type locality at Naredi overlies the Deccan basalt and trap-pebble conglomerate. It comprises alternations of green shale and red shale in the lower part, calcareous mudstone and limestone in the middle and ripple laminated sandstone at the top. Laterite and paleosol separate the Naredi Formation from the overlying Harudi Formation. A similar
succession in a borehole has an extended thickness of the lower shale that is older than the outcrop section. The Eocene strata are designated as Berwali Series, comprising the Kakdi Stage of early Eocene age and the Babian Stage of middle Eocene age. The Naredi Formation corresponds to the Kakdi Stage.

*Nummulites solitarius*, *N. fraasi*, and *N. burgidalensis kuepperi* characterize the lowermost beds of the Naredi Formation (Saraswati et al., 2012). This assemblage is found only in the subsurface while the lower beds in the outcrop contain the assemblage *N. burgidalensis kuepperi* and *N. globulus nanus*. The assemblage *N. burgidalensis burgidalensis*, *N. burgidalensis cantabricus*, *Assilina laxispira* and *Assilina spinosa* characterize shale and limestone in the middle. *N. solitarius* and *N. fraasi* range from SBZ 5 to SBZ 6 in the shallow benthic zonal scheme of Serra-Kiel et al. (1998). According to Scheibner and Speijer (2009), the Zones SBZ 5 and SBZ 6 are indistinguishable because of the co-occurrence of the two species in both the biozones. It is also established now that the first appearance of *N. fraasi* is coeval with the Paleocene – Eocene boundary (Pujalte et al., 2009). The base of the Naredi Formation is thus referred to undifferentiated SBZ 5/SBZ 6. The presence of *N. globulus nanus* demarcates SBZ 8, and the assemblage of *N. burgidalensis cantabricus* and *Assilina laxispira* constrains the upper part of the formation to SBZ 11. The planktic foraminifera in the formation are small, rare, long-ranging and mostly comprises *Chiloguembelina trinitatensis*, *C. crinita*, and *Jenkinsina columbiana*. The Sr isotopic values indicate an early Eocene age spanning from 50 to 55 ± 1.5 Ma (Anwar, Choudhary, & Saraswati, 2013).

Several previous workers (including Biswas, 1992; Pandey & Ravindran, 1988; Shukla, 2008) assigned a late Paleocene age to the lower part of the Naredi Formation exposed in the type locality. It was based on the reported occurrence of *N. indicus*, a species originally described as a new variety of *N. globulus* by Davies (1927) from the uppermost Ranikot beds in Pakistan. Saraswati et al. (2012) found the specimens of *N. globulus* of the Naredi Formation morphologically distinct from *N. indicus* and assigned them to *N. globulus nanus*. Also, the age of the upper beds of Ranikot Formation, from which *N. indicus* was first reported, is revised to Ypresian (Wakefield & Monteil, 2002).

The biostratigraphic data do not support the presence of marine Paleocene at least in onshore Kutch. The offshore is presently an active area of exploration.
that mark the top of the Naredi Formation (Banerjee et al., 2012). The upper contact of the formation with the Fulra Limestone is gradational. All commercial deposits of lignite in Kutch were referred to the lower and middle parts of Naredi Formation and therefore early Eocene age. The type locality of the Naredi Formation does not contain lignite, and the successions containing lignite do not contain foraminifera corresponding to the Naredi Formation. Saraswati, Khanolkar, Raju, Dutta, and Banerjee (2014) carried out the biostratigraphic study of the two active mines in the area and observed that lignite is gradationally overlain by a marine shale containing an assemblage of larger foraminifera comparable to Harudi Formation in one mine (Panandhro) and that of Fulra Limestone in the other (Matanomadh). It is highly probable that lignite was formed in embayment and restricted sub-basins during the middle Eocene notwithstanding a complete lack of published biostratigraphic data. In an earlier drilled well, *Miscellanea miscella – Nummulites deserti* Zone was identified at the bottom by which Paleocene age was assigned (Mehrotra, 1989). Given the discussion above, the presence of Paleocene in the offshore needs to be re-examined. The unconformable contact between the late Paleocene and the early Eocene, however, is of regional nature recorded both in Kutch offshore and western offshore areas (Mehrotra, 1989).

4.3 Harudi Formation

The formation comprises about 14 m succession of gray shale with lenses of lignite and interbedded coquina in the lower part and glauconitic green shale in the upper part. It overlies lateritic paleosol with abundant rootlets that mark the top of the Naredi Formation (Banerjee et al., 2012). The upper contact of the formation with the Fulra Limestone is gradational. All commercial deposits of lignite in Kutch were referred to the lower and middle parts of Naredi Formation and therefore early Eocene age. The type locality of the Naredi Formation does not contain lignite, and the successions containing lignite do not contain foraminifera corresponding to the Naredi Formation. Saraswati, Khanolkar, Raju, Dutta, and Banerjee (2014) carried out the biostratigraphic study of the two active mines in the area and observed that lignite is gradationally overlain by a marine shale containing an assemblage of larger foraminifera comparable to Harudi Formation in one mine (Panandhro) and that of Fulra Limestone in the other (Matanomadh). It is highly probable that lignite was formed in embayment and restricted sub-basins during the middle Eocene.
transgression and co-relatable with the lower part of the Harudi Formation. The economic deposits of coal/lignite occur dominantly in the TST of high-frequency sequences, and these are up-dip time-correlative rocks to flooding surfaces (Flint, Aitken, & Hampson, 1995). The lignites of Panandrho and Matanomadh are likely to have similarly formed and co-relatable with the thin, lensoidal beds of lignite in the lower parts of the transgressive Harudi Formation.

A middle Eocene age of the Harudi Formation is well-established. The debate is on its assignment to Lutetian Stage or Bartonian Stage. Mohan and Soodan (1970) reported *Truncarotaloides topilensis*, *T. rohri*, and *Orbulinoides beckmanni* among others from the Harudi Formation and assigned it to the Lutetian Stage. Biswas and Raju (1971) while proposing a new lithostratigraphic classification suggested a Lutetian age of the Harudi Formation. Samanta (1970) correlated Fulra Limestone with *Orbulinoides beckmanni* Zone and *Truncorotaloides rohri* Zone respectively and referred the former to upper Lutetian and latter to Biarritzian. The stage name Bartonian was not in common use during this time, and Berggren (1972) used it as an alternative to the Priabonian in late Eocene. The middle Eocene consisted only of the

*Figure 6*. Field photographs of the Paleogene stratigraphic units of Kutch. (a) a general view of the buff-colored nummulitic limestone of Fulra Limestone, Naliya – Narayan Sarovar road; (b) a close-up view of the Fulra Limestone with concentrated A & B forms of *Assilina exponens*; (c) karstic surface marking the unconformable contact between Fulra Limestone and Maniyara Fort Formation in Kharai, the demarcated zones on the section indicate the missing stratigraphic interval; (d) a close-up view of the Basal Member of the Maniyara Fort Formation in Kharai showing concentrated A & B forms of *Nummulites bomidiensis*; (e) patch coral in Coral Limestone Member, near Waier village; (f) Bermoti Member exposed near Bermoti village; the fossiliferous upper part is assigned to SBZ 23.
the Harudi Formation is of Bartonian age, but due to the absence of age-diagnostic taxa in the basal layers, the lower age may questionably be extended to latest Lutetian.

(2) The calcareous nannofossils refer it to Discoaster saipanensis Zone, NP17, and upper part of Discoaster tani-nodifer Zone, NP16 based on which Bartonian age was inferred (Jafar & Rai, 1994).

(3) The shells of coquina beds in the basal part of the formation were measured for \(^{87}\)Sr/\(^{86}\)Sr (Ravikant & Bajpai, 2010). Notwithstanding a large variation in age of about 5 m. Yrs., except for two samples (ages 42.5 and 42.8–45.7 Ma respectively), the remaining samples estimate age from 40.8 to 41.6 ± 2 Ma. Based on this data, the authors concluded late Lutetian age of the formation. We estimated 41.6 ± 0.5 Ma for the shells in the coquina beds at the bottom and 40.8 ± 0.5 Ma for the N. obtusus at the top of the formation (unpublished data). The Lutetian – Bartonian age boundary is at 41.2 Ma (Gradstein et al., 2012), and Sr-isotope data of Harudi Formation converge about this value.

(4) Both planktic foraminifera and the calcareous nanoplankton data reconcile with the Bartonian age of the upper fossiliferous part of Lutetian, and the Zone *Orbulinoides beckmanni* was referred to this stage. Hardenbol and Berggren (1978) found that the type section of Bartonian contains planktic microfossils considered of middle Eocene age and therefore amended this view to mark middle and late Eocene boundary between Bartonian and Priabonian Stages. It is adapted since then in the Geologic Time Scale, including the current version, GTS-12 (Gradstein et al., 2012). In spite of the revision of the middle Eocene time stratigraphy, the Harudi Formation continues to be assigned to Lutetian by most workers, except the nanoplankton biostratigraphers as discussed later. There are several arguments as follows to favor the Bartonian age of the formation:

(1) The planktic foraminifera *Truncorotaloides rohri* and *Orbulinoides beckmanni* occur in the upper half of the Harudi Formation. The foraminiferal data have indicated a sharp increase in water depths at this level (Banerjee et al., 2012). It is likely, therefore, that the first occurrences of *Orbulinoides beckmanni* (FAD P13 base, Berggren, Kent, Swisher, & Aubry, 1995; E12base, Berggren & Pearson, 2005) and *Truncorotaloides rohri* (FAD P12 base, Berggren et al., 1995; E10 base, Berggren & Pearson, 2005) may be ecological and not represent their respective first appearance datums (FADs). Given this, Saraswati et al. (2014) opined that

![Figure 7. The planktic foraminifera in Eocene sections of Kutch (a,b) Naredi Formation; (c) Naredi and Harudi formations; (d-j) Harudi Formation and Fulra Limestone (a) Chiloguembelina trinitatensis, (b) Chiloguembelina crinita, (c) Jenkinsina columbiana (d) Jenkinsina triseriata (e) Streptochilus martini (f) Acarinina rohri (g) Subbotina gortani (h) Orbulinoides beckmanni (i) Acarinina topilensis (j) Globoturborotalita ouachitaensis.](image)
Figure 8. Selected species of LBF from the Paleogene of Kutch. (a,b) N. solitarius, Naredi Formation; (c,d) N. burdigalensis burdigalensis, Naredi Formation; (e,f) N. globulus nanus, Naredi Formation; (g,h) N. burdigalensis cantabricus, Naredi Formation; (i,j) N. burdigalensis kuepperi, Naredi Formation; (k) Heterostegina assilinoides, Basal Member, Maniyara Fort Formation; (l–o) N. bormidiensis, Basal Member, Maniyara Fort Formation; (p) Calcarina, Fulra Limestone; (q,s) Pellatispira, Fulra Limestone; (r) N. obtusus; (t) Nephrolepidina ex. interc. morgani – praemarginata, Coral Limestone Member, Maniyara Fort Formation; (u) Eulepidina ex. interc. dilatata – formosoides, Coral Limestone Member, Maniyara Fort Formation; (v,w) N. ptukhiani, Fulra Limestone.
the formation and do not rule out the possibility of the downward extension of the respective Zones into the underlying marginal marine strata devoid of datable marine microfossils. The clustering of Sr-ages at about 41 Ma further argues that the basal part of the formation is also of Bartonian age. Moreover, there is no biostratigraphic or chronostratigraphic evidence so far to indicate the Lutetian age of the formation.

(5) A major transgression, known as the Kirthar transgression in the India–Pakistan region (Nagappa, 1959) and Wilson Bluff in Australia occurred isochronously in the vicinity of upper Zone P12 (McGowran, 1977, 1979). The biostratigraphy of the Harudi Formation conforms with this regional event in the Indo-Pacific region.

The micropaleontological evidence and Sr isotope data suggest that the middle Eocene transgression in Kutch commenced about the Lutetian/Bartonian boundary. The Lutetian age of the Harudi Formation in current literature (Biswas, 1992) is, therefore, revised to Bartonian.

4.4. Fulra Limestone

The middle Eocene transgression in Kutch, initiated with the deposition of finer clastics of the Harudi Formation, gradually developed into a carbonate platform. It deposited a monotonous succession of about 50 m of light-colored foraminiferal limestone made dominantly of nummulitids and orthophragmines. Twenty-two species of Nummulites are reported from Fulra Limestone (Samanta, Bandopadhyay, & Lahiri, 1990; Saraswati, Patra, & Banerji, 2000). Kutch is the type locality of N. acutus, N. maculatus, N. neglectus, N. stamineus, N. vohrai, N. obtusus, N. spectabilis and N. vredenburgi and, except for the last three species that occur in Harudi Formation, the remaining are confined to Fulra Limestone. The orthophragmines are also equally abundant and diverse, comprising of Discocyclina dispensa, D. augustae, D. discuss, D. kutchensis, Orbitoclypeus haynesi, Asterocyclus alticostata and A. sireli (Ismail-Lattrache et al., 2013; Özcan, Saraswati, Hanif, & Ali, 2016; Samanta & Lahiri, 1985). The other characteristic taxa readily identifiable in the field are Alveolina elliptica, Assilina exponens, and Dictyoconoides cooki. The type locality of the formation is Fulra village in the north of Panandhro lignite mine. The lower contact of the formation with the Harudi Formation is gradational, and the upper contact with the Maniyara Fort Formation is marked by a karstic surface (Plate–2). The Harudi Formation and Fulra Limestone together correspond to the Babian Stage.

The Fulra Limestone was initially assigned to an upper part of Lutetian (Biswas & Raju, 1971). In the subsequent publication (Biswas, 1992) the age is cited differently in text and figures, possibly causing different interpretations. Ray and Chaki (1997) reported Pellatispira at the top of the Fulra Limestone and therefore argued for the presence of late Eocene in Kutch. We find Calcarina, Alveolina, Heterostegina, Pellatispira and N. ptukhiani in the topmost bed of the formation. The stratigraphic distribution of these genera is as follows: the last occurrence of Alveolina is in SBZ 17 or questionably in SBZ 18A, and the first occurrence of Heterostegina is in SBZ 18A (Less & Özcan, 2012); the first occurrence of Pellatispira in Bartonian Zone P13 (Mukhopadhyay, 2003); Calcarina ranges from SBZ 17 to SBZ 18 (Serra-Kiel et al., 1998). N. ptukhiani occurs in Bartonian, and it is reported in Tanzania from Zone P14 (Cotton, Pearson, & Renema, 2015). The assemblage refers the topmost bed to the Zone SBZ 17. Therefore with Orbulinoides beckmanni at the bottom and the above discussed larger foraminiferal assemblage at the top, the Fulra Limestone is confined to Bartonian.

The Priabonian hiatus is thus established onshore Kutch. The offshore indicates the presence of late Eocene sediments, unconformably overlying the middle Eocene sediments and unconformably overlain by the early Oligocene sediments (Mehrotra, 1989). Pellatispira was considered a late Eocene marker in Indian stratigraphy possibly until Mukhopadhyay (2003) showed it to range down to late middle Eocene. A re-examination of the earlier data from Kutch offshore is required to conclude on this major hiatus.

4.5. Maniyara Fort Formation

The Fulra Limestone is para conformably overlain by a succession of glauconitic shale, claystone, coral limestone, glauconitic sandstone and foraminiferal limestone designated as Maniyara Fort Formation. The contact between the two formations is recognizable by the presence of glauconite of the Maniyara Fort Formation or by a karstic surface of the Fulra Limestone. There is, however, a contrasting difference in larger foraminifera across the two formations; the highly diverse assemblage of larger foraminifera in the Fulra Limestone is replaced by only surviving Nummulites in the overlying Maniyara Fort Formation. The upper contact with bioturbated shale/siltstone of the overlying Khari Nadi Formation is marked by a feeble unconformity in which upper part of Chattian sediments are missing (Raju, 2008). The formation is divided into four members: Basal Member, Lumpy Clay Member, Coral Limestone Member and Bemroti Member respectively from the base to the top. A diastem separates the Coral Limestone Member from the overlying Bemroti Member.

In Indian chronostratigraphy, the Maniyara Fort Formation corresponds to the Bermoti Series, classified into Ramanian Stage (early to middle Rupelian) and Waiorian Stage (late Rupelian to Chattian). The Ramanian Stage is defined by the total range of Nummulites fichteli,
and the Waiorian Stage is defined as the interval between LAD of *Nummulites fichteli* to a level of *Miohypsinoides* with a mean value of $X = 11$ (Raju, 2013). In recent years the morphometry of reticulate species in western Tethys has redefined the Bartonian to Chattian taxa and established the phylogeny of *N. fabianii* – *N. fichteli* lineage (for example, Özcan et al., 2010). Further, shallow benthic zonation scheme of Cauhzac and Poignant (1997) provides better biostratigraphic control for the oligocene. Reuter, Pillar, Harzhauser, and Kroh (2013) first refuted the Rupelian age of the Coral Limestone Member and assigned it to early Chattian (SBZ 22B). Our morphometric study of the reticulate *Nummulites* from Maniyara Fort Formation refers them to advanced form *N. bormidiensis* and, not to the so far typologically identified *N. fichteli* (Less et al., this volume). The association of *N. bormidiensis*, *N. kescskemetii*, and *Heterostegina assilinoides* assigns the Basal Member to SBZ 22B. It implies that the oldest Oligocene strata of Kutch are of early Chattian age. The Basal Member, Lumpy Clay, and Coral Limestone Member are therefore referred to SBZ 22B. The upper part of the Ber Member contains *Miohypsinoides complanatus* – *formosoides* (Kumar & Saraswati, 1997; Raju, 1974) and *Spirolyceus margaritatus* that represent SBZ 23.

### 5. A regional perspective

Nagappa (1959) synthesized the Cretaceous – Eocene succession of the Indian subcontinent and interpreted three major transgressions in this region, Ranikot (Paleocene), Laki (early Eocene) and Kirthar (middle Eocene). Later biostratigraphic studies have revised the ages of these stratigraphic units that were defined in Sind by Blanford (1879) and used by other workers in a time-stratigraphic sense for the successions in Kutch and other parts of the subcontinent. It is now established that the Ranikot Formation extends to lower parts of early Eocene Ypresian Stage and the upper parts of the Laki Formation are of middle Eocene Lutetian Stage (Afzal, Williams, & Aldridge, 2009; Wakefield & Monteil, 2002). According to Nagappa (1959), Ranikot, Laki, and Kirthar began with a transgression and ended with a regression; the most important and widespread of all the transgressions in the region being the Kirthar transgression.

In the Paleogene succession of Kutch, the volcanioclastics and carbonaceous shale, overlying the Deccan basalt are referred to Paleocene age due to their relative stratigraphic position and presence of spore-pollen. Marine Paleocene rock is absent in Kutch. The supposedly late Paleocene *Miscellanea miscella* – *Nummulites deserti* Zone in the offshore needs to be re-evaluated due to the revised ranges of the two species. Samanta’s (1974) review of marine Paleocene in India–Pakistan region indicated that, (i) there is no satisfactory foraminiferal evidence of marine early Paleocene, (ii) the middle Paleocene planktic foraminiferal assemblages are reported from several regions but documented only from the Sulaiman Range, and (iii) the late Paleocene is widely distributed and it is rich in both planktic and LBF. The late Paleocene witnessed building up of a carbonate platform in Greater Indus Basin (Afzal et al., 2009) in Pakistan and Meghalaya in eastern India (Jauhari & Agarwal, 2001). The Lockhart Formation (Upper Indus Basin) and the upper Dungan Formation (Lower Indus Basin) in Pakistan and the Lakadong Limestone in Meghalaya are characterized by *Miscellanea miscella*, *Ranikothalia sindensis*, *Lockhartia conditi* and *Glomalveolina primaeva*.

The first marine transgression in Kutch occurred in early Eocene, with the deposition of sediments referred to the Naredi Formation. The dominant shale succession is characterized by *Nummulites solitarius*, *N. deserti* and *N. globulus* in the lower parts and *N. burdigalensis cantabricus*, *Assilina laxispira* and *Lockhartia* in the upper parts. The faunal assemblage refers the formation to Zones SBZ 5/6 to SBZ 11. There is a significant change in the foraminifernal assemblage from the Zones SBZ 5/6 to SBZ 11. The assemblage in SBZ 5/6 to SBZ 10 interval is typically characterized by low diversity and dwarf foraminifera, rectilinear benthic foraminifera, and biserial and triserial planktic foraminifera that are known to survive in areas of high runoff, upwelling, and eutrophic conditions. There is a significant increase in abundance and diversity of foraminifera and the dominance of K-strategists in SBZ 11, signifying a shift from eutrophic to an oligotrophic environment (Khanolkar & Saraswati, 2015). The succession in the Indus Basin dominated by shale with subordinate sandstone, limestone and coal is referred to Ghazij/Laki formations (Afzal et al., 2009) and assigned to Zones P7 to P9 (Samanta, 1973). The early Eocene succession is dominantly constituted of carbonate in Jaisalmer and Meghalaya. The global sea level was at its highest of the Cenozoic at ~125 m above the present-day sea level in the early Eocene (Miller et al., 2005).

Lateritization and clastic, influx recorded above the marine sediments assigned to SBZ 11 or 12, mark the end of the early Eocene in Kutch, Jaisalmer, and Meghalaya. After a major hiatus, the next marine transgression in late middle Eocene, named Kirthar transgression, was the most widespread transgression in this region (Nagappa, 1959). It is recorded in Zone P12 in all the regions. The calcareous nannofossil data assigns the corresponding formations in Kutch, Jaisalmer, and Meghalaya to Zone NP17 (Jafar & Rai, 1994; Rai & Garg, 2009; Rai, Singh, & Gulati, 2014; Singh, 1980) and thus to Bartonian Stage, in conformity with the foraminiferal data. The biostratigraphy unambiguously suggests a stratigraphic gap in Lutetian. The Indus Basin also experienced a major marine regression at about this time in the Zone P9 but it had different effects in different parts of the basin. The southeastern Upper Indus closed, and the Lower Indus became shallower as evidenced by the deposition of
evaporate and coal-bearing beds (Afzal et al., 2009). The Sulaiman Range had a somewhat different sedimentation history, depositing the Domanda Formation in Lutetian in regressive global third order sequence (Jones, 1997) under three cycles of flooding and shallowing (Gingerich, Ul-Haq, Khan, & Zalmout, 2001).

The back stripped subsidence curve in Himalaya documents early Eocene marine regression and recorded a minimum uplift of 460 m during the earliest stages of India–Asia collision (Sciunnach & Garzanti, 2012). The regression in late early Eocene and transgression in middle Eocene are thus manifested variously as biostratigraphic gaps in Kutch, Jaisalmer, and Meghalaya in India and Indus Basin in Pakistan. McGowran (1977, 1979) studied the Eocene sections of Australia and concluded that the Kirthar transgression was of an even wider extent and occurred both in India and Australia in the vicinity of Zone P12 (Figure 9). This circum-Indian Ocean marine transgression seemed to be a tectonic-eustatic response to the new crustal spreading regime, the rapid Australia – Antarctica separation in late middle Eocene Ocean spreading (McGowran, 2009).

The break in stratigraphic succession between the late early Eocene and late middle Eocene, recorded uniformly from several sections in Pakistan and India to Australia, was termed as ‘Lutetian Gap’ by McGowran, Holdgate, Li, and Gallagher (2004) who also provided a paleoceano-graphic explanation for the same. Carbonates accumulate in the neritic realm at the expense of the pelagic realm when the carbonate compensation depth (CCD) shoals. The neritic carbonates contract during glaciations and deepening of the CCD. The Mg/Ca-based thermometry suggest a long-term warming in early Eocene (54.8–49.0 Ma) and rapid cooling of 4 °C beginning at 48 Ma (Lutetian) in tropical regions (Tripathi et al., 2003). It is argued that CCD steadily deepened with early, transient glacial as global cooling progressed through most of the Lutetian (Tripathi, Backman, Elderfield, & Ferretti, 2005) resulting in the formation of carbonate in the deep sea and contraction of carbonate in neritic realm during this period. It is also hypothesized that a reduction in the atmospheric CO₂ beginning 45 Myr ago and culminating in a minimum 42 Myr ago resulted in a major glaciation, lowering of sea-level and decreased area for carbonate deposition on continental shelves (Tripathi et al., 2005).

There was a reversal of the global cooling in late middle Eocene (Bartonian), extending from the later part of Zone P12 (=E11) to P13 (=E12) (Edgar et al., 2010), known as the Middle Eocene Climatic Optimum (MECO). The stable isotope estimated temperatures during this time ranged from 24 to 28 °C in Kutch (Saraswati, Ramesh, & Navada, 1993) and were as high as 32 °C in about the same paleolatitudes in Tanzania (Pearson et al., 2001). A major transgression in the Indo-Pacific occurred at this time, known as the Kirthar transgression in the India–Pakistan region (Nagappa, 1959) and Wilson Bluff in Australia (McGowran et al., 2004). The warming was congenial to LBF, and it led to a sharp increase in their diversity and biogeographic expansion toward high latitudes. This had a major impact on neritic carbonate deposition in tropical regions where LBF is the main producers of carbonate. The Kirthar Formation in the lower Indus Basin, Harudi Formation – Fulra Limestone succession in Kutch, Bandah Formation in Jaisalmer, Prang Limestone in Meghalaya and co-eval successions in New Guinea and Australia contain a highly diverse assemblage of larger foraminifera comprising the species of Nummulites, Assilina, Discocyclina, and Alveolina. The global warming in late middle Eocene, the regionally extensive Wilson Bluff – Kirthar transgression and the consequent expansion of platform-builders LBF were all synchronous about the Lutetian/Bartonian Stage boundaries (Figure 10). There were other geological similarities of regional nature in India – Pakistan – Australia regions at this time. Glaucolite formed extensively in Tasmanian Gateway deep-sea sites at 41–42 Ma (Wei, 2004) and at the same time in Harudi Formation of Kutch (Banerjee et al., 2012). There was an expansion of coal swamps with Wilson Bluff transgression in Australia (McGowran et al., 2004) and formation of lignite during the late middle Eocene transgression in Kutch (Saraswati et al., 2014). The presence of two levels of lignite in Barmer Basin, corresponding to early Eocene Dhariy Dungar Formation and middle Eocene Akli Formation (Dolson et al., 2015) is further indicative of the more extensive development of lignite in the middle Eocene. A humid climate just preceded the middle Eocene warming in both India and Australia.

The late Eocene rocks are absent from the inland areas of Kutch. The unconformity at the top of the middle Eocene is reported to be extensive in Kutch, Jaisalmer and many western offshore wells. Mehrotra (1989) recorded a short-lived transgression represented by Pellatissipa madaraszi – Nummulites fabiian Assemblage Zone in Kutch offshore, with both its lower and upper boundaries marked by an unconformity. The Prang Limestone of Meghalaya is overlain by a dominant shale succession referred to the late Eocene Kopili Formation. It contains Pellatissipa and planktic foraminifera assigning the formation to Zones P15-P16 (Jauhri & Agarwal, 2001). The Tethys retreated gradually, and the Indus basin closed from north-northwestern part to south-southwest through late Lutetian to Bartonian and finally closed in the Priabonian. The Kirthar Formation is overlain in most places by the sediments of the Siwalik Group (Afzal et al., 2009; Wakefield & Monteill, 2002). The marine Oligocene sediments occur only the south of the Lower Indus Basin. The Australian region witnessed a shift from carbonate-rich to carbonate-poor, high nutrient environments at Bartonian – Priabonian transition and resumption of carbonate accumulation in Rupelian (early Oligocene) (McGowran, 2009).

The Oligocene transgression further deposited shallow marine, glauconitic shale and nummulitic limestone
Figure 9. Eocene stratigraphy of the circum-Indian Ocean region showing stratigraphic break during the early middle Eocene in Pakistan, India, and Australia, referred as the ‘Lutetian Gap’ by McGowran et al. (2004). Data compiled after, (1) Warraich and Nishi (2003), (2) Afzal et al. (2009), (3) Wakefield and Monteil (2002), (4) this study, (5) Rai et al. (2014), (6) Jauhri and Agarwal (2001), (7) McGowran (1979).
Figure 10. The formation of the Paleogene stratigraphic units of Kutch in relation to the biogeography of larger foraminifera (the major producers of carbonates in Kutch) and other global geologic events. Biogeographic distribution of LBF (McGowran et al., 2004), major paleoclimatic events (PETM – Paleocene-Eocene Thermal Maxima, EECO – Early Eocene Climatic Optimum, MECO – Middle Eocene Climatic Optimum, LOWE – Late Oligocene Warming Event), major intervals of oligotrophic environments (Hallock, Premoli Silva, & Boersma, 1991), India – Asia collision and Kirthar transgression.
in Kutch. The Oligocene climate was marked by cooling and rapid expansion of Antarctic continental ice-sheets in earliest Oligocene, persisting until the later part of the Oligocene when a warming trend reduced the extent of Antarctic ice (Zachos, Pagani, Sloan, Thomas, & Billups, 2001). The rare oligotrophic habitats of the late Eocene expanded in late Oligocene Zones P21–P22 (Hallock, Premoli Silva & Boersma, 1991). The Oligocene strata of Kutch, assigned to the Chattian Stage, belong to this paleoclimatic phase that promoted larger foraminifera. A larger foraminiferal assemblage similar to that of the Maniyara Fort Formation also developed in the Nari Formation of the Lower Indus Basin (Kureshy, 1984). The Oligocene sediments, unlike the widely developed Eocene carbonates, occur in limited areas in this part of the Indian subcontinent. The Oligocene deposits are absent in Jaisalmer Basin and most parts of the Greater Indus Basin. In eastern India, including Meghalaya and Upper Assam Shelf, the carbonate regime declined after the Bartonian and predominantly clastic sediments deposited since the Oligocene. During late Eocene – Oligocene the Indian and Asian continents were under collision and obduction of the oceanic material and ridging of the crystalline basement in the northern belt (Valdiya, 1984). It was one of the major phases in the tectonic evolution of Himalaya. Further, the sea level dropped by ~55 m in the earliest Oligocene (Miller et al., 2005) and did not match the highstands of the early and middle Eocene when major carbonates were developed. Both climate and tectonics possibly constrained the development of carbonates in early Oligocene that resumed in late Oligocene with an increase in oligotrophy and warmer climate.

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ORCID

Pratul Kumar Saraswati □ http://orcid.org/0000-0001-9115-8951
Sonal Khanolkar □ http://orcid.org/0000-0002-7911-1699

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