Facies and depositional settings of the Middle Eocene-Oligocene carbonates in Kutch

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ABSTRACT
Middle Eocene Fulra Limestone and Oligocene Maniyara Fort Formation represent platform carbonate deposits of Kutch at the north-western margin of India. These carbonates contain larger benthic foraminifera, including Alveolina, Assilina, Discocyclina, Lepidocyclina, Miogypsina, Nummulites and Spirocyclus. This study presents paleodepositional and paleobathymetric interpretations for both formations using benthic foraminifera in combination with lithological association, sedimentary structures and early diagenetic features. The six carbonate facies comprising the Fulra Limestone indicate a depositional spectrum ranging from bar-lagoon to mid-ramp depositional conditions. It records several shallowing upward cycles, leading to emergence and formation of paleokarst. The four carbonate facies of the Maniyara Fort Formation represents deposition within the inner ramp setting in bar-lagoon and patch-reef environment, while intervening fine siliciclastics correspond to episodes of relative sea level fall. Nummulitic accumulations form low-relief bars within the fair weather wave base in both the formations. The depositional setting of the Paleogene carbonate in Kutch broadly resembles Eocene platformal deposits in the circum-Tethys belt.

1. Introduction
Nummulitic accumulations form significant hydrocarbon reservoirs in the Paleogene of offshore Tunisia and Libya while these are the potential exploration targets in Egypt, Italy, Oman and Pakistan (Racey, 2001; Racey et al., 2001). Inner- to outer-ramp-originated nummulitic accumulations occur all along the continental margin of Tethys. These are dominated by larger benthic foraminifera (LBF), including nummulitid, orthorhaphminid and alveolinid (Adabi, Zohdi, Ghabeishavi, & Amiri-Bakhtiyyar, 2008; Beavington-Penny, Wright, & Racey, 2006; Buxton & Pedley, 1989; Racey, 2001). Study of larger foraminifera in the nummulitic accumulations provides crucial evidences for paleoenvironmental settings of Paleogene carbonates (Bassi, Nebelsick, Pugaernabéu, & Luciani, 2013; Beavington-Penny & Racey, 2004; Hadi, Mosaddegh, & Abbassi, 2016; Jorry, Davaud, & Caline, 2003; Papazzoni & Trevisani, 2006). The origin of nummulite accumulations is widely debated as these may form anywhere on the shelf (Adabi et al., 2008; Bassi et al., 2013; Beavington-Penny & Racey, 2004; Jorry et al., 2003, 2008; Papazzoni & Trevisani, 2006; Racey et al., 2001). A detailed study involving microfacies, sedimentary structures and early diageneric features of nummulite accumulations is necessary to infer the depositional settings of such carbonates. A thorough petrographic study of these carbonates is useful to infer the heterogeneity of nummulitic carbonate reservoir.

Facies, depositional setting and evolution of carbonate platform in Kutch remains poorly documented notwithstanding excellent outcrops. Chattoraj, Sarkar, Chakraborty, Banerjee, and Saraswati (2012) provided preliminary reports on the middle Eocene nummulitic accumulations in the Fulra Limestone and interpreted inner ramp-middle ramp setting. Recently Srivastava and Singh (2017, 2018) provided more information regarding mineralogical and chemical characterization of the constituent formations and depositional conditions. However, all these studies lack a detailed facies analysis of the Paleogene carbonates. The origin of nummulitic accumulations and foraminiferal assemblage are largely ignored. This study presents facies, depositional environment and paleogeography of carbonate platforms in the Paleogene of Kutch and highlights the evolution of the carbonate platform in a well-constrained stratigraphic framework. Further, it explains the origin of nummulite banks on the basis of facies analysis and distribution of foraminifera.

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2. Geological and Stratigraphic Framework of Carbonates

Resting unconformably on Mesozoic sedimentary rocks and Deccan Trap the Cenozoic sediments of Kutch crop out as a semi-circular band parallel to the present day coastline (Figure 1). The entire Cenozoic succession is almost 900 m thick of which around 100 m consists of Paleogene sediments. The Paleogene carbonates are exposed on the banks of mostly N-S or NE-SW flowing rivers including Berwali, Kakdi and Kapurasi (Figure 1).

Carbonates occur within the Naredi Formation, Harudi Formation, Fulra Limestone and Maniyara Fort Formation (Figure 2). The predominantly siliciclastic Naredi Formation contains two meter-thick, *Assilina*-bearing limestone beds alternating with red and green shale (Chattoraj, Banerjee, & Saraswati, 2009; Saraswati, Banerjee, Sarkar, Chakraborty, & Khanolkar, 2016; Sarkar, Banerjee, & Saraswati, 2012; Srivastava & Singh, 2017). The Harudi Formation essentially consists of fine siliciclastics, containing three cm-scale coquina beds (Banerjee, Chattoraj, Saraswati, Dasgupta, & Sarkar, 2012a). The bottom part of the Harudi Formation is dominated by a lagoonal shale containing foraminifera in low abundance. The deposition of a glauconitic green shale with abundant planktic and benthic foraminifera at the top of the Harudi Formation indicates a sharp rise in relative sea level. Planktic/benthic ratio steadily increases from the bottom to the top of this green shale indicating continuous rise in seawater depth (Banerjee et al., 2012a; Chattoraj et al., 2009). The transgressive trend continues up to the base of the Fulra Limestone (Figure 3(a)). The latter represents an overall shallowing upward trend (Chattoraj, Banerjee, Saraswati, & Bansal, 2016; Saraswati et al., 2016). A prominent paleokarst surface marks the boundary between the Fulra Limestone and the Maniyara Fort Formation (Figure 3(b)) (Banerjee, Chattoraj, Saraswati, Dasgupta, & Sarkar, 2012b; Chattoraj et al., 2016). The bottom part of the Maniyara Fort Formation records a transgressive deposit consisting of glauconitic shale and nummulitic grainstone (Banerjee et al., 2012b). The Coral Limestone and the Bermoti Member consisting of *Spiroclpeus* Limestone represents the major carbonate deposit of the Maniyara Fort Formation. Siliciclastic sediments occur at the upper part of the Maniyara Fort Formation. The unconformity at the top of the Maniyara Fort Formation represents a significant eustatic sea level fall at the end of the Chattian Stage (Haq, Hardenbol, & Vail, 1987).

The sequence stratigraphic framework of the Paleogene sedimentary record of Kutch was presented in a few publications (2012b; Banerjee et al., 2012a; Chattoraj et al., 2009, 2016; Sarkar et al., 2012; Srivastava & Singh, 2017).
The Paleogene succession of Kutch rests unconformably on Deccan basalt in most places, consisting of three sequences, separated by four regional unconformities (Chattoraj et al., 2016) (Figure 2). The poorly fossiliferous Matanomadh Formation, comprising weathered basalts, lithic sandstone, siltstone and shale occur locally. The Naredi Formation marks the first marine transgression across the basin during the Eocene time and comprises the sequence 1. This sequence is defined by an unconformity UNC-1 above the Deccan basalt and is topped by another unconformity (UNC-2) at the top of the Naredi Formation. The Harudi Formation and the Fulra Limestone together comprises the sequence 2, which is topped by the paleokarst surface, marking the third sequence boundary (UNC-3). The Maniyara Fort Formation comprises the sequence 3. A prominent hiatus above the Maniyara Fort Formation defines the fourth unconformity UNC 4.

3. Methodology

Detailed field investigations were carried out along river sections to identify constituent facies and facies association based on lithology, texture, sedimentary structure, geometry and thickness of beds and nature of bed boundaries. Bioturbation, faunal content, grain size variation and other sedimentological details were represented in graphic logs. True thickness of the formations and facies constituents of each formation were measured from cliffs, river sections and road cuttings. Paleontological detailing of each formation were carried out, which include faunal identification (up to generic level), taphonomy, abundance and diversity with a focus on its foraminiferal constituents. Species level identification of some typical forms was carried out for relevant samples.

Thin sections were prepared by hardening samples using epoxy solutions within a Cast n’Vac 1000 (Buehler).

Figure 2. Lithofacies and paleobathymetric variations across the Paleogene succession of Kutch. Sequence boundaries, systems tracts and maximum flooding surfaces in the succession are indicated.

Figure 3. (a) Vertical section showing the contact between the Harudi Formation (below) and the Fulra Limestone (above). Note change in lithology marked by the colour contrast of rocks. (b) Vertical section showing the contact between Fulra Limestone and the Maniyara Fort Formation marked by a prominent palaeokarst surface.
vacuum impregnation unit at the Department of Earth Sciences, Indian Institute of Technology Bombay. The epoxy solutions were mixed with a pinch of blue dye (Orasol blue GN, Ciba Chemicals) for selected samples to observe the pores. Samples were cut by IsoMet Precision Saw. PetroThin (Buehler) thin sectioning system was used for precise sectioning and grinding of the impregnated samples. The hardened samples were then polished by using 220, 400 and finally 800 mesh carborundum powders. Thin sections were obtained using Dickson’s (1966) methodology to reveal the mineral contents. Petrographic observations were carried out using Leica DM 4500P polarizing microscope at the Department of Earth Sciences, Indian Institute of Technology Bombay using transmitted light.

The samples were dried in oven at 50–60 °C and a 20–30 gm of it was soaked in normal water for micropaleoentological investigations. Organic matter was removed by digestion with 30% H2O2, and cleaned with distilled water. The samples were slowly boiled in enamel saucepans for an hour with a pinch of washing soda (sodium bicarbonate, NaHCO3). The residue was cleaned by flushing out the finer material with water jet. The residue was then dried in an oven at about 50–60 °C for 3–4 h. The processed samples were kept on gridded tray for observation under Zeiss Stemi 2000 stereo zoom microscope. Micropaleoentological investigations, both qualitative and quantitative, were carried out on the sorted forms.

4. Facies analysis–Fulra Limestone

The Fulra Limestone comprises exclusively of carbonates unlike other Paleogene formations in Kutch. Facies analysis of the Fulra Limestone was carried out along five river sections viz. Rakdi, Berwali, Kundri, Sheh and Kapurashi. Each facies is distinct from the other on the basis of lithology, texture, microfossil content, and primary sedimentary structure. The Fulra Limestone comprises six facies, viz. orthophragminid mudstone, orthophragminid wackestone-mudstone alternation, orthophragminid wackestone-packstone alternation, nummulitic grainstone, nummulitic wackestone-packstone alternation and Alveolina wackestone-packstone alternation (Figure 4). Facies constituting the Fulra Limestone are described as follows.

4.1. Orthophragminid mudstone

This facies comprises dirty grey mudstone and it contains the larger benthic foraminifera Discocyclina (Figure 5(a) and (b)). With incorporation of more bioclasts it gradually passes over to wackestone in places (Figure 5(b)). The thickness of this facies varies from .75 to 1.5 m. The facies is repetitive in nature, occupying the basal part of the Fulra Limestone succession in most sections. Moderate bioturbation interrupts the original planar laminae. The burrows are horizontal to slightly inclined.

Allochems include intact bioclasts as well as nummulithoclasts (<1.3 mm fractions of broken fragments of larger benthic foraminifera). Nummulithoclasts comprise 5 to 15% of total allochems. The bioclasts are usually well preserved, ill-sorted and randomly oriented, ranging in size from a few microns to 8 mm on average. The planktic foraminifera consists of species of Acarinina, Subbotina, Jenkinsina and Streptochilus. Other invertebrates include giant gastropods (Bolis), echinoids, bivalves (Pectinids) and rare sponge spicules. Intra-particle and inter-particle pores are filled by blocky calcite cement. Some of the shell fragments show in situ breakage by mechanical compaction.

4.1.1. Interpretations

The dominance of micritic sediments indicates a low-energy depositional setting. The abundance of large and flat Discocyclina supports the low-energy depositional condition (Beavington-Penney et al., 2006; Racey et al., 2001; Sinclair, Sayer, & Tucker, 1998). Deposition of sediments might have taken place below the fair weather wave base. The quantitative analysis of autochthonous foraminiferal assemblage provides a mid-ramp depositional condition, at 50–60 m water depth. Moderate abundance of planktic foraminifera further supports the bathymetric interpretation. The nummulithoclasts in this low-energy facies is unlikely to reflect in situ fragmentation by abrasion. These are possibly related to predation by organisms such as echinoids, gastropods and fish (Beavington-Penney & Racey, 2004; Beavington-Penney et al., 2006). Alternatively, some of the nummulithoclasts could be allochthonous, derived from the associated higher-energy facies.

4.2. Orthophragminid wackestone-mudstone alternation

This facies exhibits cm-scale alternations between thin layers of mudstone and relatively thicker wackestone beds (Figure 6(a) and (b)). The average thickness of this facies is approximately .75 m. It is a non-repetitive facies occupying the lower part of the Fulra Limestone succession. The wackestone beds of 1 to 3 cm thickness display horizontal laminae. The degree of bioturbation varies from moderate to high.

The bioclasts of the facies include predominantly Discocyclina with subordinate Assilina and Nummulites. Associated benthic foraminifera include Operculina, Linderina, Lockhartia, Eoannularia, Glandulina, Bolivina, Bulimina, Brizalina, Reussella, Florilus, Nonion, Cibicides, Heterolepa, Rotalia, Asterigerina and Neoepiondus. The planktic foraminifera include Orbulinoides, Subbotina, Acarinina and Streptochilus. Both megalospheric (A form) and microspheric (B form) Nummulites are equally abundant. The proportion of nummulithoclasts may vary from 15 to 20%. Most of the forms are well preserved with only minor fragmentation. Fragments of bivalves and bryozoa also occur. Bioclasts are poorly-sorted and they
been documented from mid-ramp setting of Eocene carbonate platforms (Adabi et al., 2008; Beavington-Penney & Racey, 2004; Colombié & Strasser, 2005; Dupraz & Strasser, 2002; Racey, 1995; Sinclair et al., 1998).

4.2.1. Interpretations
The abundance of micrite suggests a low-energy depositional condition. Foraminiferal data of mudstone indicate somewhat shallower water-depths than the orthophragminid mudstone. Similar mud-rich matrix and microfaunal association dominated by discocyclinids have been documented from mid-ramp setting of Eocene carbonate platforms (Adabi et al., 2008; Beavington-Penney & Racey, 2004; Colombié & Strasser, 2005; Dupraz & Strasser, 2002; Racey, 1995; Sinclair et al., 1998).

4.3. Orthophragminid wackestone-packstone alternation
The facies is characterized by wackestone and packstone alternation of equal thickness (10 to 25 cm) (Figure 7).
Abundant nummulithoclasts in packstone beds are possibly allochthonous in nature, transported from the shallower part of the basin by moderately strong flows.

4.4. Nummulitic grainstone

This facies is dominated by larger benthic foraminifera which constitutes more than 75% of total rock volume. Asterocyclina may contribute up to 30% of total bioclasts (Figure 7(b)), which is followed by other larger benthic foraminifera Discocyclina, Operculina, Dictyconoides, small Nummulites, Lockhartia and Sphaerogypsina. Both wackestone and packstone beds exhibit crude planar laminae. Bioturbation is moderate to high, including fodinichnial trace Rhizocorallium. Crustacean burrows are observed within this facies.

The nummulithoclasts constitute 15 and 30% of the total rock in packstone beds. However, intact forms of discocyclinids and nummulitids are abundant. Other biogenic components include fragments of irregular echinoids, bryozoa and oysters. Sorting of the skeletal grains is usually poor. The skeletal particles vary in size from more than 1 cm to less than 500 μm. Pressure solution and fractured bioclasts occur in places.

4.3.1. Interpretations

Foraminiferal assemblage indicates a mid-shelf environment with a maximum water depth of about 40 m. The association Asterocyclina-Discocyclina-Operculina supports the bathymetric interpretation. Poor sorting of bioclasts, presence of micrite and good preservation state of foraminifera indicate a low-energy environment of deposition of wackestone beds. The presence of Rhizocorallium conforms the depositional conditions (Gaillard et al., 1994). Abundant nummulithoclasts in packstone beds are possibly allochthonous in nature, transported from the shallower part of the basin by moderately strong flows.

4.4. Nummulitic grainstone

This facies is dominated by larger benthic foraminifera which constitutes more than 75% of total rock volume. It is the most significant component of Nummulites accumulation in the Fulra Limestone. It consists of white to light yellow, coarse-grained limestone. The facies is repetitive in nature and its thickness varies from 1.1 to 5.25 m (Figure 4). Cross-stratifications, although cryptic in nature, are abundant within these grainstones (Figure 8(a)–(d)). These cross-stratified grainstones often alternate with up to 35 cm-thick planar laminated beds. The set thickness of cross-stratification varies from 20 to 65 cm. The cross-stratified beds exhibit a broadly convex-upward geometry. Although tabular cross-stratifications dominate, trough cross-stratifications also occur (Figure 8(b)–(d)). The foresets of the cross-stratifications are marked by the arrangement of flat bases of larger benthic foraminifera. Foresets may exhibit chevron up-building in places. Climbing ripple lamination occur locally. Paleocurrent data represents a broad unimodal pattern towards west to south-west direction. The burrows are of sub-horizontal to horizontal
The foraminifera tests reflect dissolution features close to the paleokarst surfaces.

4.4.1. Interpretations

The facies exhibits high diversity of foraminifera, indicating deposition in an open marine condition (Dupraz & Strasser, 2002). Good sorting, abundance of physical structures and the absence of micrite suggests high-energy depositional regime. The shape and scale of cross-stratifications relates them combined wave and tidal processes in shallow marine environment (Aurell, Bádenas, Bosence, & Waltham, 1998; Burchette, Wright, & Faulkner, 1990). An abundance of high-angle cross-stratified beds and absence of hummocky cross-stratification indicates deposition above the fair weather wave base. The west-ward directed foresets suggests dominance observed close to the paleokarst surfaces (Figure 10(c)). The foraminifera tests reflect dissolution features close to the paleokarst surfaces.

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of ebb tidal current. Chevron up-building of fore-sets indicates aggradation of bedforms under influence of waves (Allen, 1973). The lack of abrasion and abundance of intact forms reflect autochthonous to para-autochthonous accumulations of foraminifera. The broadly convex upward, cross-stratified grainstone represents deposition in shoals or bars above the fair weather wave base. These bars separate the open marine from the restricted environment. The paleokarst surfaces are marked by the presence of meniscus cements forming in the vadose zone (Flügel, 2004; Tucker & Wright, 2001). Intermittent local subaerial exposures corroborate the shallow water depositional condition. Similar nummulitic grainstones are reported from Paleogene successions of Oman and Egypt (Adabi et al., 2008; Aigner, 1982, 1983, 1985; Sinclair et al., 1998).

4.5. Nummulitic wackestone-packstone alternation

An alternation between packstone and wackestone characterizes this facies (Figure 11(a)). *Nummulites* is the most abundant constituent of this facies. The facies is commonly associated with nummulitic grainstone, particularly at the middle and upper portions of the Fulra Limestone succession (Figure 4). The thickness of packstone beds varies from 20 to 45 cm (Figure 11(a)–(d)). These beds have sharp bases and usually appears massive. Thickness of wackestone beds range from 10 to 30 cm. These beds exhibit poorly defined planar laminae. The original laminae are mostly disturbed by moderate to high degree of bioturbation. The overall thickness of this facies is approximately 0.8 to 2.2 m.

The second most dominant larger benthic foraminifera after *Nummulites* is *Discocyclina* (Figure 11(b)–(d)). A few large gastropods may occur locally in this facies (Figure 11(a)). The nummulithoclasts vary in proportion from 20% to 30%. Intact forms of nummulitids and discocyclinids are equally abundant in this facies. Other bioclasts include algae, echinoid spines and pectinid bivalves. Large size of *N. maculatus* and *N. vohrai* occur towards the upper part of the Fulra Limestone succession (Figure 11(b)). *N. vohrai* (B-form: 8 cm) appears to be the largest form of ebb tidal current. Chevron up-building of fore-sets indicates aggradation of bedforms under influence of waves (Allen, 1973). The lack of abrasion and abundance of intact forms reflect autochthonous to para-autochthonous accumulations of foraminifera. The broadly convex upward, cross-stratified grainstone represents deposition in shoals or bars above the fair weather wave base. These bars separate the open marine from the restricted environment. The paleokarst surfaces are marked by the presence of meniscus cements forming in the vadose zone (Flügel, 2004; Tucker & Wright, 2001). Intermittent local subaerial exposures corroborate the shallow water depositional condition. Similar nummulitic grainstones are reported from Paleogene successions of Oman and Egypt (Adabi et al., 2008; Aigner, 1982, 1983, 1985; Sinclair et al., 1998).

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Packstone beds are usually sharper than those in mudstones. The facies is poorly to moderately bioturbated. The packstone beds include 30–40% skeletal grains and 5–10% of nummulithoclasts (Figure 12(b)). Although Alveolina is the most distinguishing larger benthic foraminifera, it also contains a few small, flat forms of Assilina, Discocyclina, Nummulites, Operculina and Lockhartia. Some of the wackestone beds display monospecific Alveolina. Wackestone beds occasionally yield planktic foraminifera Acarinina and Subbotina. Bioclasts are generally not abraded and these are randomly arranged. Average size of the skeletal particles varies from more than 25 mm to smaller than few microns. Molluscs (mainly gastropods) and dasycladacean algae occur locally. Mollusc fragments are partially to completely dissolved and are filled by blocky and drusy calcite cements. Syntaxial overgrowth may occur around echinoid fragments. Micrite is partially recrystallized to microsparite in places.

4.6.1. Interpretations
The abundance of carbonate mud suggests a low-energy depositional environment. The presence of Alveolina corroborates a sheltered depositional environment (Adabi et al., 2008; Beavington-Penney & Racey, 2004). High bioturbation and high fossil diversity of this facies support the inner ramp condition (Colombié & Strasser, 2005). Abundant nummulithoclasts in this facies possibly derive from the main body of shoal made up of nummulitic grainstone. The presence of the Nummulites and the paucity of alveolinids and orbitolitids indicate deposition below the fair-weather wave base. The sharp bases of the packstone beds indicate stronger flows. The paleobathymetry of the facies appears to be intermediate between orthophragminid mudstone-packstone alternation and Nummulitic grainstone, within the range of 20–40 m.

4.6. Alveolina wackestone-packstone alternation
The facies is characterized by alternations between thin packstone (2 to 5 cm) and thick wackestone beds (Figure 12(a)). The thickness of this facies varies from 2.2 to 2.7 m. It occurs immediately above the cross-stratified nummulitic grainstone at specific levels in the Fulra Limestone succession (Figure 4). This facies is conspicuous by the presence of the larger benthic foraminifera Alveolina. Although wackestone beds are poorly laminated, packstone beds exhibit planar laminae in places. Bases of packstone beds are usually sharper than those in mudstones. The facies is poorly to moderately bioturbated.

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facies suggests a low-energy depositional environment. Further, the presence of *Alveolina* corroborates a sheltered lagoon environment on the back side of nummulitic bars (Adabi et al., 2008; Beavington-Penney & Racey, 2004; Dupraz & Strasser, 2002). Nummulitic grainstone and orthophragminid mudstone represents two end-members of depositional energy conditions for the remaining facies formed in an open marine setting. Nummulitic wackestone-packstone alternation represents a shoal flank facies. Orthophragminid wackestone-packstone alternation and orthophragminid wackestone-mudstone alternation forms more distally. The Fulra Limestone records repeated phases of shallowing and deepening as evidenced from paleobathymetric data and facies association. The lower part of the Fulra Limestone is comparatively deeper and is dominated by orthrophragminid-bearing mudstone and wackestone. The nummulitic grainstone records the shallowest deposits in the ramp depositional setting, often leading to exposure. Nummulitic grainstones are more frequent in the middle and upper portions of the Fulra Limestone, representing slow rise of accommodation space. The nummulitic grainstones mark the top of shallowing upward cycles within the Fulra Limestone.

5. Facies sequence, paleogeography and depositional environment of the Fulra Limestone

The Fulra Limestone consists dominantly of larger benthic foraminifera. The diversity and abundance of foraminifera in the Fulra Limestone are comparable to those in Eocene carbonate ramp systems around the circum-Tethys (Bassi, 2005; Ćosović, Drobne, & Moro, 2004; Racey, 1995, 2001; Romero, Caus, & Rosell, 2002). Figure 13 represents the depositional model for the Fulra Limestone displaying disposition of facies. Orthophragminid mudstone occupies the lower part of the Fulra Limestone succession (Figure 4). This facies contains abundant planktonic foraminifera and it records the deepest bathymetry (up to 60 m), corresponding to a mid-ramp setting (Adabi et al., 2008). While the nummulitic grainstone, occurring at the middle and upper levels of the Fulra Limestone succession represents deposition in inner ramp setting. The thoroughly cross-stratified nummulitic grainstone represents a high-energy deposit above the fair weather wave base. The cross-stratified beds with slightly convex-up geometries indicates formation of low-relief bars in shoal environment with lagoons behind them. The abundance of carbonate mud in the *Alveolina* wackestone-packstone facies suggests a low-energy depositional environment. Further, the presence of *Alveolina* corroborates a sheltered lagoon environment on the back side of nummulitic bars (Adabi et al., 2008; Beavington-Penney & Racey, 2004; Dupraz & Strasser, 2002). Nummulitic grainstone and orthophragminid mudstone represents two end-members of depositional energy conditions for the remaining facies formed in an open marine setting. Nummulitic wackestone-packstone alternation represents a shoal flank facies. Orthophragminid wackestone-packstone alternation and orthophragminid wackestone-mudstone alternation forms more distally. The Fulra Limestone records repeated phases of shallowing and deepening as evidenced from paleobathymetric data and facies association. The lower part of the Fulra Limestone is comparatively deeper and is dominated by orthophragminid-bearing mudstone and wackestone. The nummulitic grainstone records the shallowest deposits in the ramp depositional setting, often leading to exposure. Nummulitic grainstones are more frequent in the middle and upper portions of the Fulra Limestone, representing slow rise of accommodation space. The nummulitic grainstones mark the top of shallowing upward cycles within the Fulra Limestone.

![Figure 12](image-url) (a) Field photograph showing *Alveolina* wackestone packstone alternation (pen length = 12 cm, *Alveolina* marked by blue arrow); (b) Photomicrograph of *Alveolina* packstone under cross polars.

![Figure 13](image-url) Depositional model for Fulra Limestone.
succession (Figure 13). Saraswati et al. (2016) recognized up to seven shallowing upward cycles within the Fulra Limestone. The boundary between the Fulra limestone and the Maniyara Fort Formation is a sequence boundary marked by a prominent paleokarst surface (Figure 3(b)). The overall shallowing upward part of the Fulra Limestone represents a highstand systems tract (Figure 2). The overlying Maniyara Fort Formation unconformably rests with a sharp basal contact and is marked by the appearance of Oligocene reticulated *Nummulites*.

### 6. Facies analysis – Maniyara Fort formation

Lower and middle segments of the Maniyara Fort Formation are well exposed in Berwali river and Kharai, while its top part crops out near Waior and Bermoti. Unlike the Fulra Limestone, the Maniyara Fort Formation incorporates fine siliciclastics, particularly at the lower and upper levels (Figure 14). Four carbonate facies have been recognized in the Maniyara Fort Formation, viz. mudstone, nummulitic grainstone, *Lepidocyclina* packstone and *Spiroclypeus* packstone (Figure 7), which are described as follows.

#### 6.1. Nummulitic grainstone

The facies consists of a dirty grey, cross-stratified grainstone which is characterized by an abundance of larger benthic foraminifer *Nummulites* (Figure 15(a)–(c)). The facies is repetitive in nature and it occupies the lower and middle levels of the Maniyara Fort Formation. At the bottom part, it often alternates with red and green shales. The thickness of this facies varies from 1 to 1.25 m. Facies thickness remains more or less similar in strike-parallel sections. The set thickness of cross-stratification varies from 20 to 50 cm. The cross-stratifications include both planar and trough type. The paleocurrent data indicates broad westward direction. Crude planar or ripple lamination is observed in some places. Although both microspheric (B-forms) and megalospheric (A-forms) forms of *Nummulites* occur, usually one of the forms dominate in a particular bed (Figure 15(b)). The beds comprising dominantly of A-forms usually overlie beds dominated by the B-forms. Extensive bioturbation disrupts the primary sedimentary structures in most places. Three-dimensional maze of *Thalassinoidei* burrows is the most common type of bioturbation. Wavy, irregular and iron-stained paleokarst surfaces occur near the basal part of this facies.

The rock primarily consists of skeletal grains, which include abundant *Nummulites* (Figure 15(c)). Invertebrates including minor echinoids (*Clypeus*) and bivalves also occur. The diameter of flat, large benthic foraminifera ranges from a few mm to 2 cm. The proportion of nummulithoclasts ranges from 25 to 30%. Planktic foraminifera are completely absent.

#### 6.1.1. Interpretations

The limestone is characterized by concentrations of *Nummulites* and near absence of other larger benthic foraminifera. The well preserved and highly abundant *Nummulites* points to autochthonous to para-autochthonous origin (Adabi et al., 2008; Beavington-Penney & Racey, 2004; Beavington-Penney et al., 2006). Small-scale cross-stratifications and ripples indicates reworking by current actions. A high concentration of larger foraminiferal shells and segregation of small megalospheric and large microspheric forms of reticulate *Nummulites* corroborate actions of moderately strong currents. The scale of cross-stratifications in nummulitic grainstones suggests low-relief shoals or bars within the fair weather wave base, around 5–10 m depth. The presence of paleokarst surfaces corroborates the shallow marine origin of the facies and indicates intermittent exposure of the depositional substrate.

#### 6.2. Mudstone

This facies occurs below and above the nummulitic grainstone in Berwali and Bermoti river sections (Figure 14). The thickness of this facies is 3.6 m in the Bermoti section. It comprises loosely compacted mudstone and subordinate wackestone/packstone intercalations (Figure 16(a) and (b)). The mudstone beds may exhibit moderate to strong nodularity which obliterates primary bedding character in places. The original planar laminae are destroyed in many places by moderate degree of bioturbation. Most common burrows include *Thalassinoidei* and *Palaeophycus*. Leaf impressions may occur in places.

#### 6.2.1. Interpretations

The paucity of marine fossils, presence of leaf impressions and moderate bioturbation as well as low-energy depositional conditions indicate restricted to semi-restricted shallow lagoons (Colombié & Strasser, 2005). *Thalassinoidei* and *Palaeophycus* are reported from lagoonal to marginal marine settings (Kamola, 1984).

#### 6.3. Lepidocyclina Packstone

This facies is characterized by the presence of *Lepidocyclina*-bearing light grey packstones with minor mudstone alternation which enclose irregularly-shaped and laterally limited bioherm (Figures 17(a) and 18). The average thickness of the facies is 3.1 m. The facies is non-repetitive and is laterally continuous. The bioherms are mainly composed of corals (Figure 17(b)–(d)). These occur as patch reefs in Waior and Bermoti sections. Corals may either form colony or occur as solitary forms. Most of them belong to scleractinian variety, ranging in morphology from meandroid, dendroid to large fan-shaped. The foraminiferal assemblage comprises *Nummulites*,...
Lepidocyclina (Nephrolepidina), Lepidocyclina (Eulepidina) (abundant), Operculina, Heterostegina, Sphaerogypsina, Cibicides, (common), Anomalina, Rotalia, Discorbis (rare). Other bioclasts include pectinids, serpulids and echinoid spines. The shells are well preserved and they lack any preferred orientation.

6.3.1. Interpretations
The scleractinian corals form in shallow marine, clear tropical water (Frost, 1981; Hohenegger, Yordanova, Nakano, & Tatzreiter, 1999). A similar coral bioherm with high fossil diversity in wackestone/packstone may form in patch-reef sub-environment (cf. Colombié & Strasser, 2005). The patchy coral bioherms of the Maniyara Fort Formation possibly formed in an open lagoon behind a possible coral reef in the offshore as suggested by previous workers (Biswas & Deshpande, 1973; Ghose, 1982). The presence of serpulids corroborates the shallow marine interpretation (Dupraz & Strasser, 1999; Nalin & Massari, 2009). The foraminiferal association represents a paleoabathymetry up to 30 m.

Figure 14. Composite graphic log of the Oligocene Maniyara Fort formation in Kutch.
Figure 15. Field photographs showing (a) vertical section showing low angle cross-stratification in nummulitic grainstone (hammer length = 38 cm); (b) vertical section of nummulitic grainstone showing concentrations predominantly of B-form of *Nummulites* (pen length = 12 cm); (c) Photomicrograph of nummulitic grainstone under cross polars (scale bar = 2 mm).

Figure 16. (a) Field photograph showing vertical section of mudstone (hammer length = 38 cm); (b) Photomicrograph of mudstone under cross polars.

Figure 17. (a) Field photograph showing vertical section of *Lepidocyclina* packstone; (b) Field photograph of a patchy coral reef (pen length in (a) & (b) = 12 cm); (c) Sideview of a corallum coral (match stick length = 4.5 cm); (d) Bedding surface showing a compound coral (diameter of coin = 2.5 cm).
6.4.1. Interpretations
The low diversity of foraminifera indicates deposition in a restricted environment. The *Spiroclypeus*-rich horizons suggest a restricted lagoonal environment behind a bar (Hottinger, 1997). The foraminifera *Heterostegina* and *Lepidocyclina* support the lagoonal depositional environment (Colombié & Strasser, 2005; Kumar & Saraswati, 1997; Maragos, 1974; Munari & Mistri, 2008). The foraminiferal assemblage indicates paleobathymetry within 10 to 15 meters.

7. Facies sequence, paleogeography and depositional environment of the Maniyara Fort Formation
A distinct change in foraminiferal assemblage is observed at the base of the Maniyara Fort Formation. Larger benthic foraminifera records markedly reduced diversity from the Fulra Limestone to the Maniyara Fort formation. A highly diversified assemblage of *Nummulites*, *Discocyclina* and *Alveolina* in the underlying Fulra Limestone is replaced by almost monospecific assemblage of reticulate *Nummulites* at the lower part of the Maniyara Fort Formation. The foraminiferal diversity gradually increases at the upper part of the Maniyara Fort formation and *Nummulites* is accompanied by the species of *Lepidocyclina*, *Miogypsina*, *Sphaerogypsina* and *Operculina*. The depositional model for the Maniyara Fort Formation is presented in Figure 20.

The alternation between red shale and green shale on top of the paleokarst surface in the Kunrajpur section indicates deposition in lagoonal conditions (Banerjee et
The species of larger benthic foraminifera vary according to the water-depths and so do their morphology, test size and thickness. Study of these foraminifera, therefore, provides useful information regarding depositional conditions. Larger benthic foraminifera with relatively thin-ner tests like that of *Assilina* are common either in less transparent waters (Hottinger, 1983, 1997) or in deeper waters with low light intensity. Robust tests, ovate in shape like that of *Alveolina* are commonly found in shallow bathymetry. *Discocyclina* are observed in relatively deeper bathymetries. *Spiroclypeus* is generally found in restricted marine environments (Hottinger, 1997; Kumar & Saraswati, 1997). The cross-stratified nummulitic grainstone facies in both Fulra Limestone and Maniyara Fort Formation indicates shallow marine, high-energy depositional conditions. While, the abundance of mudstone and wackestone in some facies indicates low-energy depositional conditions, representing either lagoon or an environment below the fair weather wave base.

Nummulitic grainstones predominantly form as para-autochthonous deposits above the fair weather wave base as low-relief bars in both Fulra Limestone and Maniyara Fort Formation. Wave reworking as well as ebb tidal current transports some of the robust *Nummulites* as well as nummulithoclasts in the relatively deeper water settings. The consistent thickness and facies sequence of the Fulra Limestone across the western Kutch indicates the establishment of a broad carbonate ramp (Figure 13). The facies sequence of the Fulra Limestone reflects deposition in middle to inner ramp settings (cf. Burchette & Wright, 1992). The middle ramp, occurring between the fair weather wave base and the storm wave base, accumulates mud-dominated sediments (Figure 13). The inner ramp, between upper shore face and fair weather wave base, is affected by wave agitation. Sediments in this setting are dominated by grainstone and packstone (Figure 13). The facies constituting the Maniyara Fort Formation represents an overall low-energy, shallow
9. Conclusions

(i) The inner ramp to mid-ramp–originated Fulra Limestone consists of six carbonate facies which include, orthophragminid mudstone, orthophragminid wackestone-mudstone alternation, orthophragminid wackestone-packstone alternation, nummulitic grainstone, nummulitic wackestone-packstone alternation and Alveolina wackestone-packstone alternation.

(ii) The thoroughly cross-stratified, nummulitic grainstone with abundant well preserved Nummulites indicates para-autochthonous low relief bars forming above the fair weather wave base.

(iii) Maniyara Fort Formation represents deposition in the inner ramp environment in bar-lagoon and patch reef environment. Nummulitic grainstone and patchy corals form isolated bars, whereas Spirolypepus packstone and mudstone indicates lagoonal deposits. Lepidocyclina packstone forms in open marine condition.

(iv) Carbonate facies of both the formations are influenced by the rate of relative sea level variation. Seven sea level cycles characterize the overall shallowing upward Fulra Limestone. Paleokarst surfaces in the Fulra Limestone bear evidences of slow rate of relative sea level rise while fine siliciclastics in the Maniyara Fort Formation records relative sea level fall.

(v) The carbonate facies of both Fulra Limestone and Maniyara Fort Formation represents larger benthic foraminifera–dominated ramp environment, which is typical of most Paleogene carbonate sequences.

Acknowledgements

Authors thank Indian Institute of Technology Bombay for infrastructure facilities. Authors thank Shovan Lal Chattoraj, Urbashi Sarkar and Swarnava Chakraborty for their support in field and laboratory studies. Authors also thank many M.Tech. and M.Sc. students of the Department of Earth Sciences, Indian Institute of technology Bombay for taking part in the field work. The anonymous reviewer is thanked for offering useful suggestions to improve the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Department of Science and Technology, Government of India [Project number SR/S4/ES-281/2007].

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