Bartonian reticulate Nummulites of Kutch
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Nummulites with reticulate septal filaments stratigraphically span from the Bartonian to the Rupelian Stages. The size of the proloculus of the megalospheric forms of reticulate species helped recognise N. fabianii – N. fichteli lineage in western Tethys. Unlike the species of this lineage, N. ptukhiani, described from Armenia, is characterised by an unusually large proloculus. A possibly second lineage of reticulate species comprising N. ptukhiani is recently reported from Lutetian – Bartonian succession of Tanzania. The present study examines reticulate species from palaeogeographically adjacent Bartonian succession of Kutch. The statistical analysis of the biometric data suggests the presence of three distinct species, referred to Nummulites ptukhiani, N. aff. hormoensis and N. acutus. The reticulation starts developing in N. acutus that ranges from P13 to P14 in its type locality, Kutch. We infer that Nummulites ptukhiani and N. aff. hormoensis possibly evolved from N. acutus in Zone P14. A binary tree model based on Classification and Regression Tree is proposed to statistically discriminate the three reticulate species.

Keywords: biometry; CART; larger benthic foraminifera; Eocene

Introduction
In the planispirally coiled foraminiferal genus Nummulites the septa continue over the lateral surfaces of the test as septal filaments. The septal filament traces are categorised as primary (arising directly from the septa), secondary (originating from the primary septa) and tertiary (derived from both primary and secondary septa) (Adams, 1988). The 3-D reconstruction by micro-CT however has revealed that all three originate similarly as traces of the primary septal filaments (Renema & Cotton, 2015). In radiate or striate forms of the genus, the septal filaments are primary, straight to curved and converge towards the poles. The secondary filaments occur in sub-loculi, recurvate to reticulate forms. In reticulate Nummulites there is a complex network of secondary filaments and the primary filaments are partially or wholly lost. The reticulate species of Nummulites are of chronostratigraphic value in shallow marine successions of Bartonian – Rupelian age. The N. gargaricus – N. hormoensis – N. fabianii – N. fichteli – N. bormidiensis lineage is well established in the western Tethys (Less & Özcan, 2012). The lineage, extending from the Zone SBZ17 to SBZ22, is characterised by progressively increasing diameter of the proloculus from 100 – 140 μm in N. gargaricus to 200 – 300 μm in N. fabianii – N. fichteli and 300 – 450 μm in N. bormidiensis. Apart from this lineage is N. ptukhiani described from Armenia by Kacharava (1969), having a large proloculus of up to 600 μm. It is further recognised in eastern Turkey (Less & Özcan, 2012) and very recently in Tanzania (Cotton, Pearson, & Renema, 2016). In India, Nummulites fabianii and N. fichteli are widely reported from Priabonian – Rupelian sections (Dasgupta, 1970; Nuttall, 1925; Shukla, 2008). Samanta, Bondhopadhyaya, and Lahiri (1990) reported Nummulites hormoensis for the first time from the late Middle Eocene of Kutch. Shukla (2008) reported two more reticulate forms, Nummulites sp. cf. N. ptukhiani from uppermost Middle Eocene of Surat-Broach area and N. fabianii forma primitive from the Middle Eocene of Kutch and Cambay Basin. Biometric data of the species from India are very limited, however, the size of proloculus recorded in some of the studies suggest that the embryos of the recorded species are larger compared with that of the corresponding species in western Tethys. The proloculi of the reported N. hormoensis and N. fichteli are two times that of the respective species in the western Tethys (Table 1). Does it imply that (i) the eastern Tethys developed an independent lineage of reticulate Nummulites and, (ii) there are multiple lineages evolving contemporaneously in a region? There is a need to re-examine the reticulate species of this region in the biometric framework of the modern taxonomy to compare with the taxa of the western Tethys. We therefore attempt this study to examine the earliest reticulate forms occurring in the Bartonian succession of Kutch and carry out a detailed biometric analysis to distinguish them by multivariate statistical analysis.

Samples and methods
The samples for the present study are from a borehole and an outcrop section in Kutch (Figure 1).
Stratigraphically, they belong to Fulra Limestone of Bartonian age, referred by Samanta (1970) to Zones Orbitoclypeus beckmanni – truncorotaloides rohri (P13-P14). The planktonic foraminifera comprise Acarinina rohri, A. topilensis, Globigerina linaperta, G. officinalis, Globorotalia centralis, G. lehneri, Globorotalita ovachitaensis and Orbitoclypeus beckmanni among others (Mohan & Soodan, 1970; Samanta, 1970; Saraswati, Khanolkar, Raju, & Banerjee, 2016). The larger benthic foraminiferal assemblage includes Alveolina elliptica, Assilina exponens, Asterocyclina alictostata, A. sireli, Calcarina sp., Dictyoconoides cooki, Discocyclina dispansa, D. sowerbyi, Nummulites acutus, N. maculatus, N. stamineus and Orbitoclypeus haynesi, (Ismail-Lattrache et al., 2013; Özcan, Saraswati, Hanif, & Ali, 2016; Samanta & Lahiri, 1985; Samanta et al., 1990; Saraswati, Patra, & Banerjee, 2000). The two types of reticulate species reported in this paper are confined to the upper part of the Fulra Limestone (Figure 1). It may be mentioned that the reticulate species are low in abundance and not-so-well preserved. A relatively good number of specimens could be obtained only from borehole samples. We also re-examined our previous collection of Nummulites from Fulra Limestone in Berwali river section (Saraswati et al., 2000) for the morphometric data of N. acutus.

The reticulate Nummulites were separated into morphotypes based on external characters. Diameter and thickness of selected specimens were measured prior to preparations of their equatorial sections for biometric measurements (Figure 2). We tried to study them by micro-CT but except for a few specimens the results were not satisfactory due to calcite infilling.

The biometric data were subject to cluster analysis by paired group method using the PAST package (Hammer, Harper, & Ryan, 2001). We attempted to apply discriminant function, successfully used in an earlier study to discriminate species of Nummulites (Saraswati & Patra, 2000), but the biometric data of the studied populations were not multivariate normal (as per Mardia’s multivariate normality test). A non-parametric method, Classification and Regression Tree (CART), was therefore employed using Statistical Analysis Software. Saraswati and Sabnis (2006) discussed the methodology of CART and its application in the taxonomy of Nummulites.

### Results

The following two morphotypes of reticulate Nummulites are visually distinguished on their external characters (Pls.1-2):

Type-1: small and lenticular; reticulate; granular, granules spirally arranged and some granules merging at the poles.

Type-2: small and inflated (compared with Type-1); reticulate; coarsely granulated and a prominent polar knob.

The diameter and thickness of the tests and the internal measurements in equatorial sections of the two morphotypes and that of N. acutus are given in Table 2. The bivariate plot of diameter and thickness of the tests shows that all the three examined taxa have inflated lenticular tests (Figure 3). The bivariate plots of length and height, respectively, of the chambers in the last whorl express the shape of the chambers that are longer than high (Figure 4).

| Table 1. Reticulate species of Nummulites reported from India. |
|-------------------|-------------------|-------------------|
| Species           | Age               | Proloculus diameter in A forms (μm) | Surface features                                      |
| N. fichteli<sup>a</sup> | Oligocene         | 290–370 | Reticulate; surface smooth                                      |
| N. clypeus<sup>b</sup>  |                  | 250–360 | Reticulate; apical mamelon (polar plug)                           |
| N. hornoensis<sup>c</sup> | Middle Eocene    | 400   | Sinuous septal filaments in A forms but crude reticulate structure reported in B forms; coarse, spirally arranged granules; |
| N. cf. fichteli<sup>d</sup> | Oligocene         | 600–800 | Reticulate; surface smooth                                      |
| N. fabianii forma fabini<sup>e</sup> | Late Eocene      | 220–500 | Reticulate; no pustules                                         |
| N. fabianii forma primitiva<sup>f</sup> | Middle Eocene    | 400–700 | Primitive reticulation; no pustules, sometimes small polar pillars |
| N. fichteli forma fichteli<sup>g</sup> | Oligocene         | 400–750 | Reticulate; no pustules or polar plug                           |
| N. fichteli forma clypeus<sup>g</sup> |                 | 350–800 | Reticulate; raised polar plug                                   |
| N. fichteli forma granulata<sup>g</sup> |                  | 400–600 | Reticulate; small pustules near polar region; no polar plug     |
| N. sp cf. N. pukhian<sup>h</sup> | Uppermost Middle Eocene | 200–500 | Primitive reticulations at periphery; small granules, pillars in polar region |

<sup>a</sup>Nuttall, 1925.  
<sup>b</sup>Samanta et al., 1990.  
<sup>c</sup>Sengupta, 2000.  
<sup>d</sup>Shukla, 2008.
The cluster analysis of the biometric data distinctly classifies all the specimens of the two reticulate species in to their respective morphogroups (identified on external characters only), except for misclassification of a specimen of Type-2 with Type-1 (Figure 5). It signifies the two types of reticulate taxa are not only externally distinguishable but also quantitatively distinct in terms of their various internal morphological characters. The phenogram of the two types and *N. acutus* (that somewhat resemble externally) is presented in Figure 6. The spiral diagrams (Figure 7) suggest that spires are tighter in Type-1 compared with Type-2. The coiling of *N. acutus* falls between the two types. Although not all comparable parameters of the Tanzania samples are available, cluster analysis on common data in both Kutch (Type-2 populations) and Tanzania (data from stratigraphically equivalent Zone P14) was carried out for comparison (Figure 8). Notwithstanding few data, Kutch and Tanzania populations of reticulate *Nummulites* are closely clustered, sharing high similarity coefficients.

**Discussion**

The Middle Eocene reticulate *Nummulites* of Kutch were reported for the first time in Bartonian Fulra Limestone by Samanta et al. (1990), and referred them...
to *N. hormoensis*. Both A and B-forms were reported, characterised by coarse, spirally arranged granules and sinuous septal filaments in A forms and crude reticulate structure in B forms. Biometric data are not given in the publication to statistically compare it with the Type-1 in the present study. Roveda (1970) provided some measurements on diameter and thickness of the tests and diameter of the proloculus of the topotypes of the species in Sedgwick Museum (UK). The Type-1 is smaller, inflated and have less number of whorls and significantly larger size of the proloculus compared with *N. hormoensis* (Table 3). At this stage, we refrain from giving a new name to the Kutch species and assign Type-1 to *N. aff. hormoensis*.

The Type-2 in the studied assemblage differs distinctly from the Type-1 both qualitatively and statistically. The Type-1 tends to be lenticular, have more reticulation as well as granulation and smaller proloculus compared with Type-2. The Type-2 is more inflated and has a prominent polar knob. The average diameter of the proloculus in Type-2 is 600 μm, significantly larger than the average diameter ~400 μm in Type-1. The spire is high and opens rapidly in Type-2 compared with tighter coiling in Type-1 (Figure 7). Statistically, the specimens of the two groups cluster separately in the phenogram (Figure 5). This validates the differentiation of the two types based on external characters. The inflated tests, pronounced polar knobs and large proloculii (P2: 465–750 μm, average 600 μm) in Type-2 are comparable with Armenian *N. ptukhiani* (A-form) as discussed by Papazzoni (1998). The Type-2 form closely resembles the recently reported *Nummulites ptukhiani* (population TDP4) from Tanzania (Cotton et al., 2016). The inflated lenticular test, comparable size of the proloculus, number of whorls, coarse granulations, presence of polar knob and similar nature of spire opening (Figure 7) make the two populations from India and Tanzania remarkably similar. This is also reflected in cluster analysis (Figure 8) in spite of limited quantitative data. We therefore assign Type-2 to *Nummulites ptukhiani*. The species chronostratigraphically lies at similar position in Zone P14 in India and Tanzania.

Sowerby (1840) described *Nummulites acutus* from Lakhpat (Kutch). Samanta (1982) studied the only remaining syntype specimen of the species at NHM, London, and observed gently wavy and irregularly branching septal filaments producing a subreticulate septal pattern on the surface of the microspheric form. We have re-examined our previous collections (Saraswati et al., 2000) and find that the A-forms of the species are characterised by reticulate pattern on the peripheral parts and somewhat resemble *Nummulites ptukhiani* (Type-2) in their inflated tests, large proloculi and polar knob. *N. acutus* however is comparatively larger and thicker, have sharp margin and distinctly larger chambers compared with *N. ptukhiani*. The cluster analysis of the combined data distinguishes the three species and, as explained below, *N. acutus* is clustered partially with both Type-1 and Type-2 (Figure 6). *Nummulites acutus* occurs throughout the Fulra Limestone (Zones P13–P14).

There are general external similarities in the Bartonian reticulate *Nummulites* discussed in the
present study. The small size, inflated lenticular tests, granular surface, and reticulation of varying degree are common external features of the three species. The internal morphology in equatorial sections varies. It is reflected in the cluster analysis as discussed before. The phenogram unambiguously distinguishes N. ptukhiani from N. aff. hormoensis. Interestingly, some specimens of N. acutus cluster at higher similarity coefficient with N. ptukhiani while the others cluster with N. aff. hormoensis. It is likely indicator of

| Sample | PI | P2 | WD | W1 | W2 | W3 | W4 | D | T | D/T | CW1 | CW2 | CW3 | LI | HI | LL | HL | M | LI/HI | LL/HL |
|--------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|----|----|----|----|---|-------|--------|
| Type-1 | 131 | 21.20 | 795 | 795 | 1150 | 1535 | 2060 | 1430 | 1.9 | 336 | 403 | 371 | 460 | 284 | 26 | 29 | 57 | 63 | 52 | 98 | 46 |
| Type-2 | 316 | 359 | 288 | 315 | 330 | 310 | 388 | 434 | 446 | 773 | 802 | 3468 | 3468 | 1990 | 1.9 | 5 | 9 | 15 | 9 | 6 | .3 | 1.1 |
| N. acutus | 319 | 695 | 795 | 1150 | 1535 | 2060 | 1430 | 1.9 | 336 | 403 | 371 | 460 | 284 | 26 | 29 | 57 | 63 | 52 | 98 | 46 |

Figure 3. Bivariate plots of diameter and thickness of the three species of *Nummulites*. The tests of Type-1 and Type-2 samples fall in the field of inflate lenticular tests and *N. acutus* are inflate lenticular to sub-globular.
evolution of both N. ptukhiani and N. aff. hormoensis from N. acutus in Zone P14. In the suggested N. ptukhiani lineage of Tanzania, the Lutetian population does not show reticulation (Cotton et al., 2016). The reticulation develops in the population of Zone P13 in Tanzania and the reticulated N. acutus in Kutch ranges down to Zone P13. A future study may be important and interesting to compare the materials of the two regions to find out if this part of the eastern Tethys was the cradle of evolution of N. ptukhiani lineage.

We have attempted to statistically distinguish the Bartonian reticulate Nummulites of Kutch by CART. The majority of tree models in CART analysis were built on two key variables, height of chambers in the first whorl (HI) and horizontal proloculus height (P2). A binary tree model (Figure 9) of the training data-set assigned all the specimens to the correct groups as N. acutus and N. ptukhiani but two (of the nine) specimens of N. aff. hormoensis were wrongly assigned to N. ptukhiani. All specimens in the validation data-set were correctly referred to their respective groups.
Figure 7. Spiral diagram of the three species. It shows tighter coiling in Type-1 compared with Type-2. Coiling of *N. acutus* falls between the two types. The sample from Tanzania (TDP 4; Cotton et al., 2016) falls in the broader field Type-2.

Figure 8. Cluster analysis of Type-2 and Tanzania samples suggesting close similarities of most specimens from the two regions.

Figure 9. A binary tree model of *N. acutus*, *N. ptukhiani* and *N. aff. hormoensis* discriminating the three taxa on the basis of height of chambers in the first whorl (HI) and diameter of the protoconch (P2).

Table 3. Comparison of morphometric data of Type-1 reticulate species of Kutch with *N. hormoensis*. The data of *N. hormoensis* are after Roveda (1970).

| Characters                  | Type-1       | *N. hormoensis* |
|-----------------------------|--------------|-----------------|
| Diameter (mm)               | 1.8–3.5      | 3.0 – 4.45      |
| Thickness (mm)              | 0.9–1.9      | 1.0 – 1.60      |
| D/T                         | 1.7–1.9      | 2.4 – 3.7       |
| Diameter of proloculus (μm) | 312–521      | 132 – 185       |
| Number of whorls            | 3–4          | 6               |
| Shape of chambers in last whorl | 1.0–1.4     | Sub quadrate or slightly longer than higher |
| (expressed as length/height ratio of chambers for Type-1) |               |                  |
Plate 1. Photomicrographs of *N. aff. hormoensis* (external view: A, B, C; side view: E; equatorial section: D, F, G; axial section: I) and *N. ptukhiani* (external view: H). Scale bar: 1000 μm. A, B, D, E, I: borehole 21.20 m; F, G: borehole 21.55 m; H: borehole 31.88 m depth; C: outcrop sample.
Conclusions
Three species of reticulate *Nummulites* are recognised in the Bartonian succession of Kutch. These are referred to *Nummulites ptukhiani*, *N. aff. hormoensis* and *N. acutus*. It is observed that reticulation starts developing in *Nummulites acutus*, particularly visible in the A-forms of the species. We infer that *Nummulites ptukhiani* and *N. aff. hormoensis* possibly evolved from *N. acutus* in Zone P14. A binary tree model based on CART is proposed to statistically discriminate the three reticulate species.

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Disclosure statement
No potential conflict of interest was reported by the authors.

Plate 2. Photomicrographs of *N. ptukhiani* (external view: A; equatorial section: C, D; axial section: B, D) and *N. acutus* (external view: E; equatorial section: F, H; axial section: G). Scale bar: 1000 μm. A, B, C: borehole 21.55 m; D, E, F, G, H: outcrop.
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