Ecology of foraminifera during the middle Eocene climatic optimum in Kutch, India

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The shallow marine carbonates of Kutch temporally correspond to the globally recognised warming period called Middle Eocene Climatic Optimum (MECO) that extended from later part of planktic foraminiferal zone E11 to E12 and Shallow Benthic Zone (SBZ) 17. The present study aims to investigate how foraminifera responded ecologically to the warming event. It involves identification and distribution of foraminifera, and cluster and detrended correspondence analyses of the species distribution data. Selected samples across E11 and E12 were analysed for carbon isotopes. The major conclusions are: (i) bloom of Jenkinsina columbiana in zone E11, possibly marking the initiation of warming in a shallow, eutrophic sea, (ii) increased foraminiferal diversity, appearance of Orbulinoides beckmanni and Acarinina and a sharp rise in the sea level in the early part of E12 (iii) significant jump in diversity and abundance of larger benthic foraminifera in E12, signifying warm, clear-water oligotrophic seas, promoting the formation of platform carbonates, (iv) MECO does not seem to have adversely impacted the foraminifera in shallow seas, and larger benthic foraminifera were rather ultimately superior in their diversity, abundance, size and latitudinal distribution and (v) δ\textsubscript{13}C excursions up to 1.5‰ are noted in the upper parts of E11 and lower parts of E12.

Keywords: MECO; paleoclimate; biotic-response shallow marine foraminifera; carbon isotope excursions

Introduction

The history of the Earth in the Eocene epoch has generated considerable interest in the past decade for its dynamic climate that ranged from extreme greenhouse warming during the early Eocene to icehouse cooling in the late Eocene. The most extensively studied Eocene climatic event and its effect on biotic communities is the transient warming at the onset of the epoch known as Paleocene Eocene Thermal Maximum (Kennett & Stott, 1991; Lourens et al., 2005; Miller, Wright, & Fairbanks, 1991; Nicolo, Dickens, Hollis, \& Zachos, 2007; Stap, Sluijs, Thomas, \& Lourens, 2009; Zachos, 2001; Zachos, Dickens, \& Zeebe, 2008). The transitional middle Eocene, where the climate shifted from greenhouse to icehouse, is also called the doubt-house world (Miller et al., 1991), and has not been studied in greater depths. A reversal in the cooling trend occurred from ~40.6 to 40.0 Ma ago, known as the Middle Eocene Climatic Optimum (MECO) (Bohaty \& Zachos, 2003; Bohaty, Zachos, Florindo, \& Delaney, 2009; Sexton, Wilson, \& Pearson, 2006). Stratigraphically, MECO extended from the later part of planktic foraminiferal zone E11 to E12 (Edgar et al., 2010) and in shallow benthic zone (SBZ) 17 (Whidden \& Jones, 2012). The record of this event is now globally established but the response of biota to warming is known from very few sections. A turnover in eberdian, silicoflagellates and dinoflagellates has been observed during the MECO (Witkowski, Bohaty, McCartney, \& Harwood, 2012). The Alano section in NE Italy is among the few on land sections to have been well studied for the response of benthic foraminifera (Galazzo, Giuberti, Luciani, \& Thomas, 2013), planktic foraminifera (Luciani et al., 2010) and nannoplankton (Toffanin et al., 2011).

India was located in low latitudes during the Eocene times. The stratigraphic records of the late middle Eocene, the likely potential sections to have preserved the warming event, are exposed in Kutch in the west and Meghalaya in the east. These two regions are characterised by shallow marine carbonates formed during the Bartonian when a major transgression flooded several continental margin basins of India (Raju, 2008). These carbonates were dominantly made of larger benthic foraminifera that thrived in warm tropical seawaters estimated by the stable oxygen isotope analysis of the foraminiferal carbonates of Kutch to have a seawater temperature of 24–28 °C (Saraswati, Ramesh, \& Navada, 1993). Further, tropical angiosperm pollen assemblages and dinocysts suggestive of a warm and humid climate (Kar, 1985; Sharma \& Saraswati, 2015) dominate in lignite occurring below the carbonates. Here, we study the ecological aspects of the foraminiferal assemblages across the biostratigraphically constrained stratigraphic record of Kutch through the middle Eocene warming event.

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Location and stratigraphy

Kutch is located on the western margin of India (Figure 1). The outcrops of Mesozoic and Cenozoic rocks of this area constitute a part of the Kutch basin and extend offshore. The basin evolved as a pericratonic rift basin in the late Triassic–early Jurassic and as a passive margin basin in the Cenozoic. Mesozoic and Cenozoic age sediments are intervened by the Deccan Trap. The Cenozoic succession occurs as a semi-circular outcrop fringing the Deccan basalt and classified into eight lithostratigraphic units. The Eocene part of the succession comprises three formations (Table 1). The present study is limited to Harudi Formation and Fulra Limestone of late middle Eocene (Bartonian) age.

The Harudi Formation unconformably overlies the early Eocene Naredi Formation and passes gradationally to Fulra Limestone. It consists of grey shale and lignite in the lower part, shelly limestone (coquina beds) in the middle and green shale at the top. The lower and middle parts are practically devoid of foraminifera. It should be mentioned that lignite was formerly assigned to Naredi Formation and therefore early Eocene age (Biswa, 1992). Recent biostratigraphic studies indicate that the upper age limit of lignite may be Bartonian (Saraswati, Khanolkar, Raju, Dutta, & Banerjee, 2014; Sharma & Saraswati, 2015). The green shale consists of larger benthic foraminifera (Nummulites obtusus, N. spectabilis and N. vredenburgi) and planktic foraminifera (Orbulinoide Beckmanni, Acarinina rohri and Streptochilus martini) depending on which Bartonian age is assigned to the formation. The interval between the first occurrence and the last occurrence of O. beckmanni marks the planktic foraminiferal zone E12. The water depths varied from ~5 m in the lower part to about 60 m in the upper part of the formation (Banerjee, Chattoraj, Saraswati, Dasgupta, & Sarkar, 2012). The overlying Fulra Limestone is light coloured and moderately hard to compact limestone dominantly consisting of larger benthic foraminifera. It is a platform carbonate varying from mudstone to grainstone types. An unconformity between the Fulra Limestone and the overlying Maniyara Fort Formation is marked by the absence of late Eocene sediments. The section under study represents a depositional sequence in which the Harudi Formation corresponds to transgressive systems tract and Fulra Limestone to highstand systems tract.

Materials and methods

Sampling

The samples were collected from Harudi Formation and Fulra Limestone in the western part of Kutch. Thirty samples were collected from Harudi Formation on the banks of Rato River, of which only 27 contain foraminifera. The Fulra Limestone is exposed along the Berwal River. Out of 57 samples collected in this section, only 15 samples of wackestone and mudstone could be macerated satisfactorily to separate foraminifera for the quantitative study. The remaining samples were compact packstone and grainstone, hence hard to yield foraminifera for quantitative analysis. Forty-nine samples were collected from Panandhro lignite mine of which only 11 samples contained foraminifera. The lithologs and sample positions of all the investigated sections are shown in Figure 2.

Sample processing and identification

Foraminifera were extracted from shale, mudstone and wackestone by boiling 60 gm of the samples in water with two spoonfuls of sodium carbonate. The disaggregated samples were washed over a 44 μm (325 ASTM) sieve and the washed-residues were dried in oven at low heat. A representative split for quantitative analysis was obtained from the residue using a microsplitter.

Table 1. Eocene Formations in Kutch with shallow benthic zones (SBZ).

| Epoch/Age (Stage) | SBZ (Shallow Benthic Zone) | Formation            |
|-------------------|-----------------------------|----------------------|
| Oligocene         | Rupelian                    | SBZ 21               |
| Eocene            | Bartonian                   | SBZ 17               |
|                   | Ypressian                   | SBZ 5/6 – SBZ 11     |
|                   |                             | Maniyara Fort        |
|                   |                             | Fulra Limestone      |
|                   |                             | Harudi               |
|                   |                             | Naredi               |
The first 300 specimens were picked and counted from each of the washed residues. The relative abundances of the identified taxa were calculated. The foraminifera are well preserved and the tests do not exhibit breaking or dissolution features. Secondary calcite infilling is observed in larger benthic foraminifera. The most representative taxa are illustrated using a Scanning Electron Microscope model FEI QUANTA-200. The foraminifera were identified after Murray and Wright (1974), Kalia (1978), Loeblich and Tappan (1988) and Singh and Kalia (1970). Foraminiferal morphogroups have been widely used to determine paleo-depositional conditions based on the morphology of smaller benthic foraminifera (Nagy, 1992; Nigam, Mazumder, Henriques, & Saraswat, 2007; Preece, Kaminski, & Dignes, 1999; Reolid, Rodriguez-Tovar, Nagy, & Olóriz, 2008). Following these studies, we divided the smaller benthic foraminifera into the morphogroups as follows: (i) Rectilinear Benthic Foraminifera (RBF): comprising genera with biserial, triserial or uniserial chamber arrangement, or (ii) Rounded Benthic Foraminifera (RoBF): comprising genera with trochospiral or planispiral chamber arrangements. For biostratigraphic purpose, the planktic foraminiferal zonation (Pearson, Olsson, Hemblen, Huber, & Berggren, 2006) and shallow benthic zonation (SBZ; Serra-Kiel et al., 1998) are followed. Even though the Bartonian sections in Kutch are dominated by larger benthic foraminifera, it was not possible to quantify them in the samples of washed residues owing to their large size. Hence, we have given a qualitative description of larger benthic foraminifera found in these sections.

Quantitative analysis
The foraminiferal count data were analysed using the PAST package (Hammer, Harper, & Ryan, 2001) to calculate Fisher ($\alpha$) and Shannon–Weaver (H) indices. The relative abundance of common species (>5% in at least one sample) was subject to R-mode cluster analysis (CA) and Q-mode detrended correspondence analysis (DCA). The CA was used to recognise clusters of species supposedly of similar ecologic requirements. The DCA revealed relationships between the samples and the groups so recognised reflect biofacies.

Carbon isotope analysis
Stable carbon isotopes ($\delta^{13}$C) and total organic content (%TOC) were determined in 30 samples, were finely ground to <125 um and a portion of each sample was

Figure 2. Detailed lithologs with sample positions from (A) Rato river section (B) Berwali river section and (C) Panandhro lignite mine section.
treated with 1 N HCl for 24 h to remove the inorganic carbonate fraction. After neutralisation, samples were oven dried at 40 °C and weighed in duplicate into 6 × 4 mm tin capsules. Carbon isotopes and TOC were measured at the Stable Isotope Laboratory, GNS Science, Lower Hutt, New Zealand, using an Isoprime isotope ratio mass spectrometer, interfaced to an Euro EA elemental analyzer in continuous-flow mode (EA-IRMS).

Results were expressed in conventional delta notation as ‰, according to the following equation:

$$\delta^{13}C = \left[ \left( \frac{^{13}C}{^{12}C} \right)_{\text{sample}} - 1 \right] \times 1000$$

Blanks and reference materials were used to normalise the results to Vienna Pee Dee Belemnite for carbon (VPDB).

Results

The Bartonian section in Kutch is about 60 m thick. Except for the lower ~4 m of poorly fossiliferous interval, the complete successions is characterised by a diverse assemblage of foraminifera. Well-preserved, age-diagnostic planktic foraminifera has constrained planktic foraminiferal zone E11, seen by the diagnostic planktic foraminifera has constrained planktic foraminiferal zone E11, while the bulk of the carbonate was formed in zones E12 and E13. The larger benthic foraminifera such as N. obtusus, N. maculatus, N. acutus, N. beaumonti and Assilina exponens are indicative of SBZ 17. In an only section in Berwali river, the top few centimetres of the Fulra Limestone contain Pelletispira sp and Heterostegina sp. In Western Tethys, Heterostegina appears in SBZ 18A and the lower range of Pellatispira questionably extends to SBZ 18A (Less & Özcan, 2012). The associated assemblage of Alveolina sp, Nummulites biarritzensis and N. ptukhianii, however, assigns to SBZ 17, or at the most transitional to SBZ 18A. In either case, it represents Bartonian age.

The foraminifera are represented by all key types including small benthic, large benthic and planktic. The distribution of small benthic and planktic species and variation in α-diversity and Shannon–Weaver (H) index is shown in Figures 3 and 4. The larger benthic foraminiferal diversity could not be measured in the same samples due to their giant size compared with the other foraminifera. The published literature suggests that there is a marked jump in species diversity of Nummulites from 5 species in Harudi Formation to 22 species in Fulra Limestone (Samanta, Bandopadhyay, & Lahiri, 1990).

The cluster analysis recognised four clusters of foraminiferal species 1, 2, 3 and 4 (Figure 5) such that the species in each cluster have supposedly similar ecology. The known ecological significance of important taxa is given in Appendix 1. The detrended correspondence analysis assigned the samples to three distinct groups. (Figure 6). Axis 1 has a detrended eigenvalue of 0.5 and Axis 2 of 0.13.

The carbon isotopes across the section show a positive 1.8 ‰ shift in δ13C values followed by a negative shift of equal magnitude at biostratigraphically equivalent positions in planktic foraminiferal zone E11 (Figure 7). This negative δ13C shift of 1.5 ‰ coincides with the first occurrence of N. obtusus/N. spectabilis in the section.

Discussions

The climate

The formation of platform carbonates in Tethys in response to warming events of the early Eocene is well discussed by Scheibner and Speijer (2008). Corals and larger benthic foraminifera were the main producers of carbonates and dominated according to their tolerance of seawater temperatures. The larger foraminifera-dominated platform carbonates developed again in late middle Eocene in India at Kutch, Meghalaya and subsurface Mumbai offshore. They signified widespread climate change that further favoured flourishing of larger benthic foraminifera and promoted the development of carbonate platforms.

The carbonate succession of Kutch is almost exclusively made of larger benthic foraminifera Alveolina, Assilina, Asterocyclus, Discocyclina, Nummulites and Orbitoclypeus among several other genera. The distribution of modern larger foraminifera is limited by winter minimum isotherms between 15° and 20°C. The genera Nummulites, Operculina and Alveolina, which also occurred in Fulra Limestone, requires minimum temperatures of 24 °C for survival (Langer & Hottinger, 2000). The oxygen isotopic analysis of foraminifera estimates that seawater temperatures during the formation of Fulra Limestone varied from 24 to 28 °C (Saraswati et al., 1993) and was as high as 32 °C in middle Eocene in Tanzania, located about the same latitudes (Pearson et al., 2001). The palynofloral assemblages and biomarker studies of lignite suggest angiosperm-dominated vegetation as the key organic source, with a hot and humid tropical climate (Dutta et al., 2011; Kar, 1985; Sharma & Saraswati, 2015). The warming in the middle Eocene thus possibly was initiated with or was preceded by high precipitation. The micropaleontological and palynological evidence indicates that the Bartonian succession at Kutch represents a warmer climate co-relatable with the late middle Eocene warming event, the MECO.

Ecological assemblages of foraminifera

The DCA assigns the samples to three groups with distinct correspondence scores (Figure 6). The relative abundance of the four clusters of ecologically similar
species, 1 to 4, in each of the three groups of samples helped recognise the biofacies. While there are distinct distributions of clusters from 1 to 3 in the three biofacies, species of cluster 4 occurs uniformly in all biofacies. The scanning electron microscope (SEM) images of the representative taxa are given in Figure 8. The distinguishing characteristics of each biofacies are discussed below.
Biofacies A

This biofacies corresponds to the lower green shale unit of the Harudi Formation. It is dominated by faunal cluster 1 (varying from ~35 to 82%). *Jenkinsina columbiana* exhibits peak abundance of about 66% in this interval. The $\alpha$-diversity of foraminifera ranges from 6 to 24 and Shannon Weaver ($H$) varies from 1.5 to 3. On the DCA plot, the biofacies has high scores on Axis 1 and generally an intermediate score on Axis 2. The distinguishing characteristics of this biofacies are:

1. the first occurrence of larger benthic foraminifera in the section,

2. triserial planktic foraminifer *J. columbiana* constituting ~66% of the total foraminiferal count (80% of the planktic foraminifera count),

3. RBF abundance varying from 25 to 43% and

4. A negative excursion of 1.5 ‰ in $\delta^{13}C$ values of organic carbon.

The triserial planktic foraminifera are good tracers of unstable environments on shelf and marginal seas with high run-off and upwelling conditions (Ghosh et al., 2008; Kroon & Nederbragt, 1990). The dominance of *J. columbiana* foraminifer in green shale of the Harudi Formation supports high precipitation and eutrophic conditions.

Figure 5. Cluster analysis of Middle Eocene Foraminifera of Kutch.
Figure 6. Detrended Correspondence Analysis of Middle Eocene Foraminifera from Kutch.

Figure 7. Carbon isotopic variation in $\delta^{13}$Corg of (A) Rato and Berwali river section(combined) and (B) Panandhro lignite mine section.
Figure 8. The representative foraminifera from Middle Eocene sections of Kutch, Biofacies A: (1) External view of *N. obtusus*; (2) Equatorial section of *N. obtusus*; (3) External view of *Nummulites pinfoldii*; (4) *J. columbiana*; (5) *Streptochilus martini*; (6) *Chiloguembelina ototara*; (7) *Rotalia* sp; (8) *Brizalina* sp; Biofacies B: (9) *Miliammina* sp; (10) *Textularia halkyardia*; (11) *O. beckmanni*; (12) *Acarinina rohri*; (13) *G. ouachitaensis*; (14) *Praemurica lozanoi*; (15) *Halkyardia minima*; (16) *Linderina kutchiensis*; (17) *Discocyclina* sp; Biofacies C: (18) External view of *Alveolina* sp; (19) External view of *Nummulites stamineus*; (20) External view of *Assilina exponens*; (21) External view of *Nummulites maculatus*; (22) *Neoeponoides schrebersii*; (23) *Cibicides punjabensis*; (24) *Glabratella ubiqua*; (25) *Robulus* sp; (26) *Cibicides lobatulus*; (27) *Pijpersia coronaeformis*; (28) *Reusella* sp; (29) *Acarinina topilensis*; (30) *Trifarina advena rajasthanensis*; (31) *Nonionella* sp; (32) *Florilus* sp.
conditions during the initial warming of the middle Eocene. As stated elsewhere, the palynological remains found in the underlying lignite beds also suggest a humid environment at this time. Another upwelling indicator Streptochilus (Smart & Thomas, 2006) represented by S. martinii, similarly shows high abundance intermittently across this interval. The larger benthic foraminifera, characterising oligotrophic environment, are low in abundance and diversity. The assemblage comprises *N. obtusus, Nummulites vredenburgii, Nummulites spectabilis* and *Operculina*. The foraminiferal assemblage in this biofacies indicates an inner shelf, eutrophic environment. The biofacies corresponds to the transgressive systems tract of the sequence.

**Biofacies B**

This biofacies corresponds to the upper part of the green shale unit in the Harudi Formation. It mainly comprises cluster 2 (varying from 5 to 28%) and cluster 3 (varying from 29 to 60%). Cluster 1 species are low in abundance (maximum of 9%). *Miliammina* exhibits a peak abundance of 23% in this biofacies. It has a uniformly high α-diversity from 17 to 28 and Shannon Weaver (H) from 2.9 to 3.3. On the DCA plot, the biofacies has rather low scores on both the axes. The biofacies is characterised by:

1. the first occurrence of *Orbulinoides* and *Acarinina*.
2. first appearance of genus *Discocyclina* in this section.
3. abundance of agglutinated foraminifera.
4. fluctuating δ¹³C values with maximum positive excursion of 1.5‰.

The planktic foraminifer *O. beckmanni* is reported to be an excursion taxon coinciding with the MECO event (Edgar et al., 2010). *Acarinina* is a symbiont-bearing planktic foraminifer indicative of warm tropical seawater and oligotrophic conditions (Luciani et al., 2010). *Acarinina* species show good abundance at certain levels in this interval but further diversify and become abundant in the overlying carbonates. The distribution of ecologically sensitive planktic foraminifera thus indicates that the eutrophic environment of the previous biofacies intermittently switched to oligotrophy during the deposition of the later part of the Harudi Formation. The larger benthic foraminifera consist of *Nummulites spectabilis, Operculina, Linderina, Halkyardia, Discocyclina sowerbyi* and *Discocyclina dispansa*. A moderately high abundance of RBF suggests somewhat low oxygen conditions but overall the environment was toxic. A sharp rise in water depth at the top signifies that sea level rise accompanied middle Eocene warming and was of regional extent, recorded as maximum flooding surface in several other basins in India during the Zone E12. A middle shelf environment, switching to oligotrophy is inferred for this biofacies. It corresponds to a maximum flooding zone.

**Biofacies C**

It corresponds to Fulra Limestone and it is dominated by cluster 3 (varying from 21 to 72%). High trochospiral taxa *Neoeponoides schrebersi* and *Cibicides punjabensis* exhibit peak abundance of 14 and 15%, respectively, in this biofacies. The α-diversity of foraminifera ranges from 13 to 47 and Shannon Weaver (H) values from 2.9 to 3.6. On the DCA plot, the biofacies has high scores on the second axis and somewhat lower scores on the first axis. The characteristics of the biofacies include:

1. high abundance and diversity of larger benthic foraminifera comprising *Alveolina, Assilina, Asterocyclina, Calcarina, Dictyococcloides, Discocyclina, Nummulites, Orbitoclypeus* and *Pellatispira* that constitutes the limestone.
2. high abundance of rounded trochospiral benthic species includes *Neoeponoides schrebersi* and *Cibicides punjabensis*.
3. continuation of *O. beckmanni* for the major part of the formation.
4. diversification of *Acarinina*.
5. low abundance of *Jenkinsina* and *Streptochilus*, except for the basal part of the formation.

There are more than 22 *Nummulites* species reported from Fulra Limestone (Samanta et al., 1990). The typical larger benthic foraminifera found in this biofacies include *Assilina exponens, Nummulites maculatus, N. acutus, N. beaumonti, Asterocyclina alticostata, Dictyococcloides cookie, Calcarina, Pellatispira* and *Alveolina elliptica*. There is thus a quantum increase in the abundance and diversity of larger benthic foraminifera in comparison to the underlying Harudi Formation. In general, larger foraminifera are K-strategists, but in shallow waters they are opportunistic strategists, which rapidly increase in numbers when conditions are favourable (Murray, 2008). High diversity and abundance of larger benthic foraminifera in Fulra Limestone suggest favourable environmental conditions during the major warming phase in planktic foraminiferal zone E12. The larger benthic foraminifera inhabit well-lit, clear waters of shallow seas to benefit (to feed as well as photosynthesize) from algal symbionts. Their mixotrophic diet gains an energy advantage of several orders of magnitude over purely autotrophic or heterotrophic diets in environments that are well-lit but have poorly dissolved nutrients (Pomar & Hallock, 2008). Algal symbiosis allows larger foraminifera to be mixotrophic (to feed as well as photosynthesize) and thus thrive in oligotrophic environment. Rounded oligotrophic benthic trochospiral foraminifera (Bernhard, 1986; Reolid et al., 2008) are commonly represented by a higher abundance of *Neoeponoides schrebersi* and *Cibicides punjabensis* in Fulra Limestone. In planktic foraminiferal zone E12, this oligotrophy is further supported by an increase in diversity and abundance of *Acarinina*. The depositional
Table 2. Summary of hyperthermal events in Kutch and Cambay basins and the corresponding foraminiferal assemblages.

| Thermal Events | Biozone | Isotopic Characteristics | Fisher (α) | Size of Nummulites (diameter) | RBF% | Biserial and Triserial Planktic (%) |
|----------------|---------|--------------------------|------------|-------------------------------|------|-----------------------------------|
| MECO           | E 12    | δ¹³Corg; -25.8‰ to -24.2‰ (This study) | 13-47      | N. vohrai; (A FORM): 6 – 7.5mm (B FORM); 8cm | 7–24 | 1–10                             |
|                | E 11    | Middle Eocene warming: δ¹³Corg; negative excursion of ~1.5‰ (This study); δ¹³Ccarboe; ~3.5‰ and δ¹⁸O values ~−0.5‰ (4) | 6–24       | N. obtusus; (A FORM): 0.21-0.39mm; (B FORM): 7.4–26.2mm | 25–43 | 27–70                           |
| EECO           | SBZ 11  | δ¹³Corg; negative excursion of ~2‰ (2) | 10–11      | N. burdigalensis cantabricus (A FORM) –1400µm; (B FORM) –2300µm | 10–20 | 10                               |
|                | SBZ 10  | δ¹³Corg; negative excursion of ~3‰ to 4‰ (3) | 1–3        | N. burdigalensis burdigalensis (A FORM) –1000µm; (B FORM) –1700µm | 50–70 | <5                              |
| ETM 2          | SBZ 8   | δ¹³Corg; negative excursion of ~1‰ (2) | 3–5        | N. burdigalensis kuepperi (A FORM); ~1000µm | 10–35 | <5                              |
| PETM           | SBZ 5/6 | δ¹³Corg; negative excursion of ~5‰ (1) | 2-4        | N. solitarius (A FORM) ~600µm | 10–40 | 60                             |

1Samanta et al., 2013; 2Saraswati et al., 2014; 3Clementz et al., 2011; 4Dutta 2007 (Unpublished M.Tech Thesis, IIT Bombay).
environment of this foraminiferal assemblage is suggestive of middle to inner shelf, with a warm water, oligotrophic ocean. It corresponds to the highstand systems tract.

Comparison with foraminiferal response to early Eocene hyperthermal events

Carbon isotope excursions corresponding to early Eocene hyper-thermal events have previously been recorded in the stratigraphic sections of western India (Clementz et al., 2011; Samanta et al., 2013, and Saraswati et al., 2014) and foraminiferal assemblage responses to these events have been studied (Khanolkar & Saraswati, 2015). Unlike the PETM and other hyperthermal events of the early Eocene, the middle Eocene warming event was not accompanied by a carbon isotope excursion (Bohaty et al., 2009). However, the Kutch section shows a 1.5% negative shift in $\delta^{13}C$ in the later part of planktic foraminiferal zone E11, coinciding with the first appearance of N. obtusus/ N. spectabilis. It has been postulated that the characteristic negative $\delta^{13}C$ excursion in early Eocene hyperthermal event was caused by a large volume of methane released due to dissociation of clathrates, while the middle Eocene event was caused by enhanced degassing of CO2 from magmatic sources, or by extensive metamorphic decarbonation which occurred during Himalayan orogeny (Bohaty et al., 2009; Pearson, 2010).

During the PETM and ETM 2, foraminifera in equatorially placed India were typically characterised by (i) low diversity and dwarfism (ii) RBF abundance up to 40% but in some parts of the early Eocene it was up to 70% (iii) high abundance of triserial planktic foraminifera that are known indicators of high run-off and eutrophy (Khanolkar & Saraswati, 2015). In comparison, during the middle Eocene warming, the foraminifera in the same sections were typified by (i) moderate to high diversity, (ii) larger benthic species reach giant size up to 8 cm, (iii) RBF abundance rarely exceeding 40% and (iv) a good abundance of triserial planktics in the upper part of planktic foraminiferal zone E11 and the lower part of zone E12 (that is, the early warming phase) (Table 2). The stressed environments typical of the hyperthermal PETM and ETM 2 events ameliorated in later part during the EECO when foraminifera attained normal size and larger benthic genera were more diversified and abundant. The present study indicates that warming in middle Eocene commenced with high precipitation and eutrophy, but soon warmer and oligotrophic conditions prevailed that provided an optimum environment for larger benthic foraminifera to flourish and form the major platform carbonates. Globally, larger foraminifera had greater latitudinal diversity in the middle Eocene and several taxa including Nummulites and orthophragminids attained highest diversity during this period (Adams, Lee, & Rosen, 1990; Whidden & Jones, 2012). The well-studied, deep water Alano section in Italy suggests prevalence of eutrophic conditions in the MECO that is characterised by a marked increase in triserial and biserial planktic foraminifera Jenkimensa, Streptochilus, Chiloguembelina and Zeauvigerina (Luciani et al., 2010). There was also an increase in biserial and triserial benthic foraminifera indicating an increase in supply of less refractory organic material from increased primary productivity in the overlying surface waters (Galazzo et al., 2013).

It is evident from the ecological response of Kutch foraminifera that the PETM exerted the most impact, and warming during the EECO and MECO did not have much effect on shallow marine species, the oligotrophic hyperthermal events rather promoted the success of larger benthic foraminifera.

Conclusions

The Bartonian section of Kutch biostratigraphically corresponds to the globally recognised warming period called Middle Eocene Climatic Optimum (MECO). The present study focuses on the ecological aspects of the foraminiferal assemblage and concludes that:

1. A bloom of triserial planktic foraminifer J. columbiana and a low abundance of larger benthic foraminifer Nummulites characterise the later part of planktic foraminiferal zone E11, possibly marking the initiation of warming in a shallow, eutrophic sea.

2. Increase in foraminiferal diversity, a relatively high abundance of agglutinated foraminifera and the appearance of planktic foraminifera O. beckmanni and Acarina characterise the early part of planktic foraminiferal zone E12. It also marks a sharp rise in the sea level and transitions from a eutrophic to oligotrophic sea.

3. The high diversity and abundance of larger benthic foraminifera characterises most of the planktic foraminiferal zone E12. They flourished in a warm and clear-water oligotrophic sea that promoted the formation of platform carbonates.

4. In comparison to the hyperthermal events of the early Eocene, the foraminifera in shallow seas do not appear to have been impacted by the middle Eocene warming. The larger benthic foraminifera were ultimately superior in their diversity, abundance, size and latitudinal distribution during the middle Eocene warming (Table 2).

5. $\delta^{13}C$ isotopic excursions of 1.5 ‰ are noted in the upper part of planktic foraminiferal zone E11 and at the bottom of the planktic foraminiferal zone E12.

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No potential conflict of interest was reported by the authors.

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**Appendix 1. Important foraminiferal genera in Middle Eocene sections, Kutch and their ecology.**

| Foraminifera | Ecology |
|--------------|---------|
| *Asterigerina* | Epifaunal, free, herbivore, 0–100 m, inner shelf (Murray, 2006) |
| *Brizalina* | Infaunal, free, detritivore, marginal marine-bathyal (Murray, 2006) |
| *Quinquelocula* | Epifaunal, free/clinging, herbivore, hypersaline lagoons, marsh and shelf (Murray, 2006) |
| *Jenkinsina* | Eutrophic, low oxygen indicator, upwelling indicator, high organic content |
| *Nonionella* | Epifaunal, free; mud; detritivore, 10–1000 m; shelf-upper bathyal (Murray, 2006) |
| *Florilus* | Epifaunal, Rounded, Oligotrophic (Bernhard, 1986) |
| *Nonion* | Infaunal, free, herbivore, 0–180 m; shelf (Murray, 2006) |
| *Cibicides* | Epifaunal, attached, passive suspension; 0–2000 m; shelf-bathyal (Murray, 2006) |
| *Robultus* | Epifaunal, free; shelf to bathyal, oligotrophic (Murray, Murray, 2006) |
| *Triloculina* | Epifaunal, free/clinging, herbivore-detritivore, hypersaline, inner shelf, inner shelf (Murray, 2006) |
| *Miliammina* | Infaunal-Epifaunal, free, detritivore, brackish-hypersaline (Murray, 2006) |
| *Textularia* | Epifaunal, free, clipping, detritivore, 0–500 m bathymetry, lagoons, shelf – bathyal (Murray, 2006) |
| *Acarinina* | Oligotrophic, warm indices, surface dwellers, symbiont bearing (Luciani et al., 2010) |
| *Reussella* | Elongated, tapered, infaunal, low oxygen (Bernhard, 1986) |
| *Eponides* | Epifaunal, free/clinging, detritivore, shelf-abysal (Murray, 2006) |
| *Glabratella* | Epifaunal, attached, herbivore, 0–50 m; hypersaline marshes, lagoons, inner shelf (Murray, 2006) |
| *Neoep Nationes* | Trochospiral, rounded, epifaunal, oligotrophic (Bernhard, 1986) |
| *Discorbis* | Epifaunal, attached, herbivore, 0–50 m; bathymetry; inner shelf (Murray, 2006) |
| *Tetragona* | Infaunal, free, detritivore, 0–400 m; bathymetry; shelf-upper bathyal (Murray, 2006) |