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Biostratigraphy and Foraminiferal Paleoecology of the Early Eocene Naredi Formation, SW Kutch, India

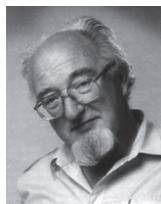
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Abstract : The Naredi Formation in southwestern Kutch overlies the last Deccan Trap deposited during the early Paleocene. The lower part of the Naredi Formation (2.8-4.2 m from base) is of early Eocene (Ypresian) age (SBZ8, E4) based on larger foraminifera and rare planktic foraminifera, whereas the upper part (9.3-11 m, including the *Assilina* limestone) is of late early Eocene age (SBZ11, E6). There is no age control for the basal 0-2.8 m and between 4.2-9.3 m because microfossils are rare or absent. Small benthic and rare planktic foraminifera are common in three short intervals and indicate deposition in a brackish to normal marine inner shelf environment (SBZ8, E4), brackish environment (middle of section, no age control) and inner shelf to marginal marine environment (SBZ11, E6). Two phases of marine transgressions can be identified with the maximum transgressions in each phase coincident with the lower and upper foraminiferal assemblages. A paleosol indicated by root traces and burrows (5.9 m) represents a regression and possibly sequence boundary.



This study is dedicated to Dr. Lukas Hottinger (1933-2011), who passed away before this study was completed. We remember him for his invaluable contributions to the biostratigraphy, taxonomy and paleoecology of larger Foraminifera and his generous ever cheerful willingness to teach, advise and share his immense knowledge and expertise. We will miss him.

INTRODUCTION

The last Deccan Traps of the early Paleocene are exposed along the base of the Kadi River near the village of Nareda (Lat: N23°34.602'; Long: E68°38.628') in the Kutch District, State of Gujarat in western India (Fig. 1). At this locality about 11 m of predominantly argillaceous sediments disconformably overlie the Deccan Traps and are topped by a limestone rich in *Assilina* species. These sediments have been classified as the Naredi Formation (Biswas and Raju, 1972; Biswas, 1992) and the Kadi River area is known as the Naredi type locality. Sediments consist of shallow marine deposits that are intermittently fossiliferous containing larger foraminifera (e.g., Biswas, 1992; Raju et al., 1970; Puneekar et al., 2010; Saraswati et al., 2000, 2012), small benthic and rare planktic foraminifera (Tandon et al., 1980; Jauhri and Vimal, 1978), and calcareous nannofossils (Singh and Singh, 1991; Jafar and Rai, 1994; Saravanan, 2007). Microvertebrate

fossils include teeth, scales and otoliths of shallow marine fishes including sharks, rays and bony fishes, found together with the freshwater gar fish (*Lepisosteus*), and aquatic snakes (collections made by S. Bajpai). Despite all these studies a precise age has remained elusive, although most workers suggest an early Eocene (early Ypresian) age based on the first calcareous fossil assemblages above the basalt. A recent study on dinoflagellates (Garg et al., 2011) confirmed an early Ypresian age for the Naredi section.

This study contributes to the biostratigraphy and paleoecology of the Naredi Formation based on rare planktic foraminifera, abundant small and larger benthic foraminifera and stable isotopes. The main objectives of this study include: a) analysis of planktic foraminifera to obtain good age control—this objective was not fully reached because planktic foraminifera are very rare; b) analysis of small benthic foraminifera to determine their potential for age control and paleoecological interpretations; c) examine larger benthic

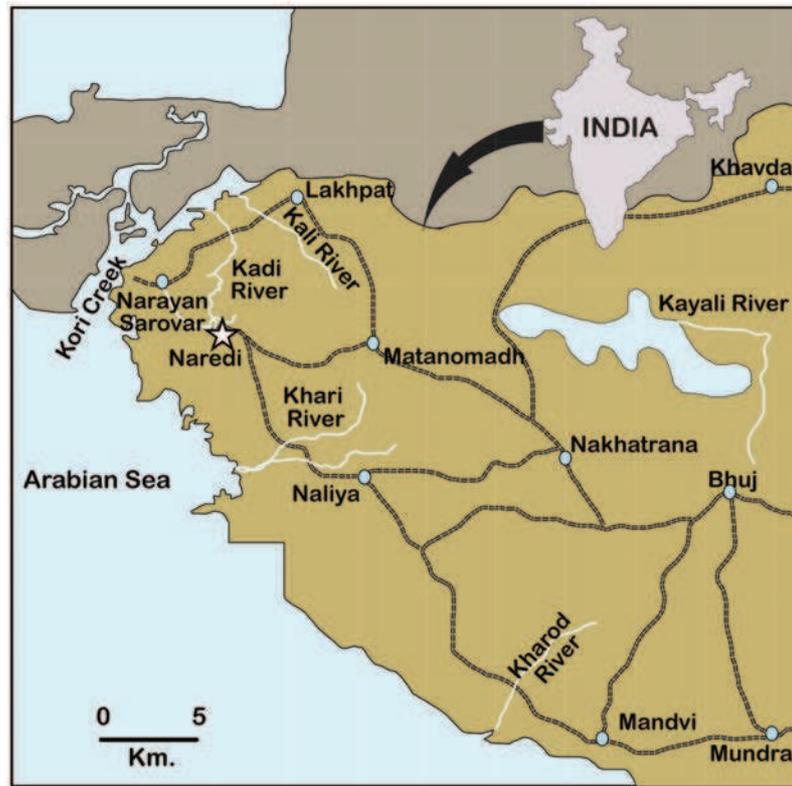


Fig.1. Geological map of the Naredi area with Location of the studied Naredi section (modified after Garg et al., 2011).

foraminifera as age indicators and correlate these to small benthic and planktic assemblages; and d) correlate and integrate age control of microfossil assemblages with the stable $\delta^{13}\text{C}$ isotope curves of carbonate and organic carbon to obtain better age constraints of the Naredi section. A companion study by Khozyem et al., (this vol.) details the lithology, mineralogy, major and trace elements and stable isotopes of the same outcrop and the same sample set.

METHODS

The Naredi Formation was sampled along the Kadi River at the type locality. In order to expose fresh rock and avoid contamination of sediments, a section was trenched from the base of the limestone layer near the top of the outcrop down to the river base and Deccan Traps and the latter was also traced to nearby localities. The trenched section was sampled at 10 cm intervals spanning a sequence of 11 m. Samples were processed for microfossils by standard methods (Keller et al., 1995) and washed through a 63 μm screen. Benthic foraminifera were observed primarily in the 63-100 μm size fraction and assemblages tend to be dominated by one or two species. Preservation is very good and shells are not recrystallized. All major species are illustrated by Scanning

electron microscopy (SEM; Tescan Mira/LMU) based on gold and carbon coated specimens.

Carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) analyses were conducted on bivalves, bones and teeth with a Thermo Fisher Scientific (Bremen, Germany) GasBench II preparation device interfaced to a Thermo Fisher Scientific Delta Plus XL continuous flow isotope ratio mass spectrometer (IRMS) (Revesz et al., 2001). Analytical uncertainty (2σ), monitored by replicate analyses of the international calcite standard NBS-19 and the laboratory standards Carrara Marble and Binn Dolomite, are no greater than $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}_{\text{carb}}$.

Organic carbon isotope analyses was performed on decarbonated and oven-dried bulk sediment samples by flash combustion on a Carlo Erba 1108 elemental analyser connected to a Thermo Fisher Scientific Delta V isotope ratio mass spectrometer that was operated in the continuous helium flow. The $\delta^{13}\text{C}_{\text{org}}$ values are reported relative to VPDB. The reproducibility was better than 0.1 ‰ (1 σ). Stable isotope results are fully discussed in Khozyem et al., (this vol.).

LITHOLOGY

At the Naredi Formation type locality Biswas (1992) subdivided sediments into three main members:

(1) Gypsiferous Shale Member at the base with grey, brown and olive green glauconitic claystones and shales, including gypsum, limonite and siderite concretions; (2) *Assilina* Limestone Member of bedded limestone and yellow-grey marls rich in *Assilina* shells; (3) Ferruginous Claystone Member at the top with grey-brown iron-rich claystone. This study examined the lower two members of the Naredi Formation.

Figure 2 shows our detailed outcrop observations of the lithology in the lower two members of the Naredi Formation. In general, sediments consist of glauconitic and phosphatic claystone and siltstones with intervals rich in bivalves, oysters and larger foraminifera. Naredi Formation sediments unconformably overlie a paleosol that developed at the top of the weathered basalt that represents the last phase of Deccan

volcanism in the early Paleocene. At the base is a grey-green silty claystone rich in fossils (~0.3 m) followed by a green-brown to red silty claystone with only rare fossils (up to 1.1 m, Fig. 2). Sediments between 1.1 m to 4.2 m consist of dark grey-green to olive-green claystones and silty claystone with pyrite nodules at the base and intermittently fossil-rich. Overlying this interval is a pale brown silty claystone (4.2-4.5m) followed by 1 m of dark brown fissile, silty claystone with gypsum veins and iron oxide. A 30 cm thick red-brown clayey siltstone with burrows and roots at the top (5.5-5.8 m) marks a paleosol and unconformity (Fig. 2). This interval likely represents a non-deposition and/or erosion surface and may correspond to a sequence boundary.

Above the root-bearing (paleosol) horizon is a 50 cm

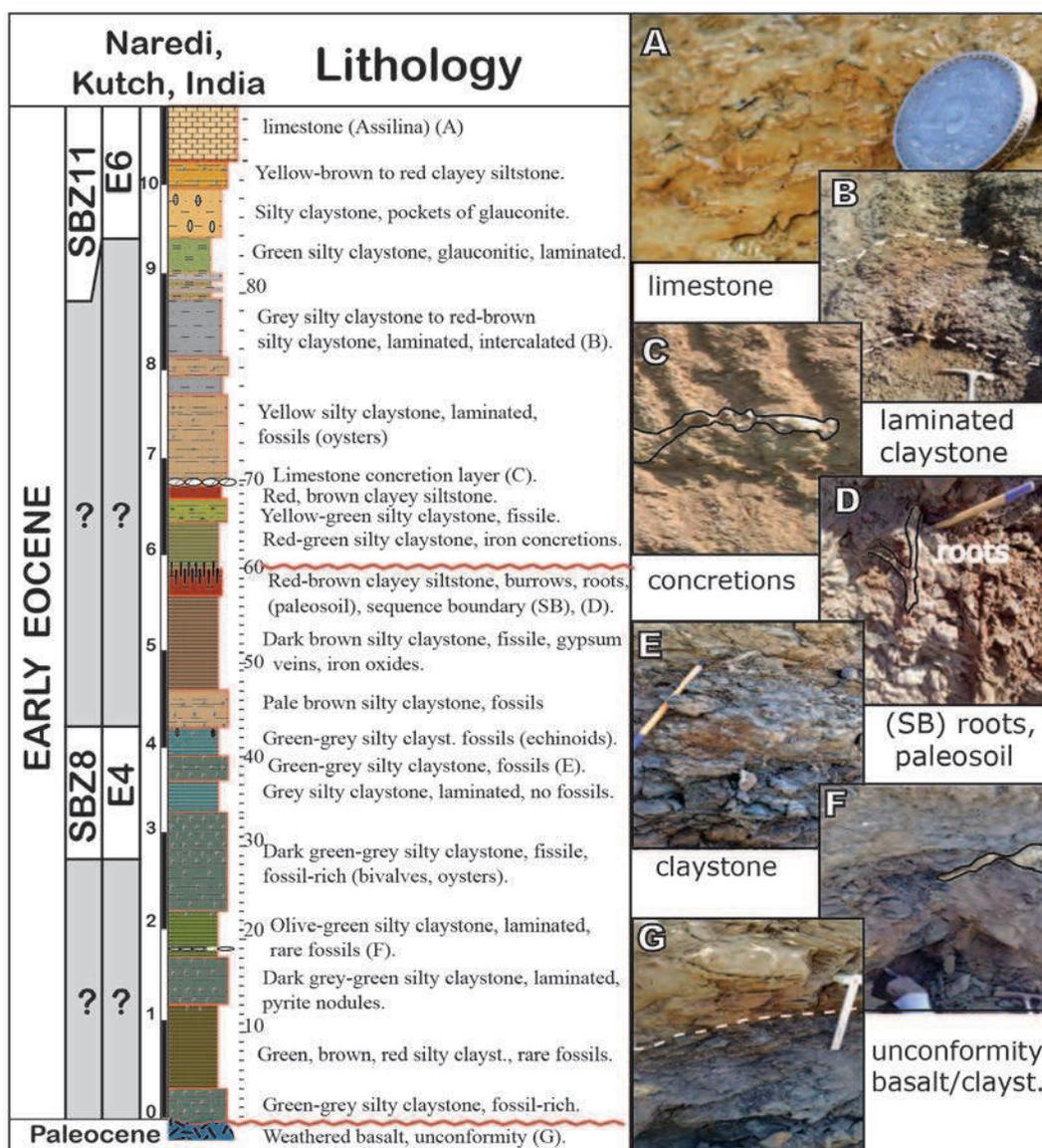


Fig. 2. Lithostratigraphy, description of lithology and photo illustrations of key lithologic horizons of the studied Naredi section.

thick red-green silty claystone devoid of fossils but with iron concretions. This interval is overlain by yellow-green and red-brown silty claystone to clayey siltstone layers also devoid of fossils and followed by a limestone concretions level at 6.8 m. The overlying laminated yellow silty claystone contains oysters and dwarfed foraminifera indicating a return to marginal marine conditions. From 7.8 m to 9.0 m sediments consist of intercalated grey to red-brown silty claystones devoid of fossils, followed by glauconitic claystone. Between 9.5 to 10.2 m silty claystones contain common macro- and microfossils marking a return to marginal marine conditions. At the top of the sampled interval is the (*Assilina*) limestone rich in larger foraminifera (mostly nummulites) (Fig. 2).

BIOSTRATIGRAPHY

At the type locality of the Naredi Formation marine microfossil bearing horizons with good assemblages are restricted to three short intervals (2.8-4.1 m, 6.5-7.2 m, 9.8-11 m), with an additional two intervals with larger foraminifera (1.5 m, 4.5 m) (Fig. 3). Macrofossils (primarily bivalves) are

distributed more broadly through the section. Foraminiferal assemblages consist mainly of small (63-100 μm) shallow water benthic species. Larger benthic species are common particularly at the top and bottom fossiliferous intervals. Planktic foraminifera are very rare with just a few mostly long-ranging species, which makes age determination difficult. For this reason we integrate biostratigraphic information from planktic foraminifera and small and larger benthic foraminifera with the stable isotopes ($\delta^{13}C_{org}$, $\delta^{13}C_{biv+bones}$) in order to obtain a relative age assignment for the Naredi Formation (Fig. 3). The biostratigraphic scheme used in this study is illustrated in Figure 4.

Larger Benthic Foraminifera

Larger benthic foraminifera are common in the three fossiliferous intervals of the Naredi section with rare and mostly dwarfed specimens in two other intervals (Fig. 3). Samples bearing larger foraminifera were sent to the late Dr. Lukas Hottinger for analysis. Because Dr. Hottinger passed away before this study was completed the correspondence is reported here. Hottinger (Jan. 26, 2007) reported: "The nummulites sent

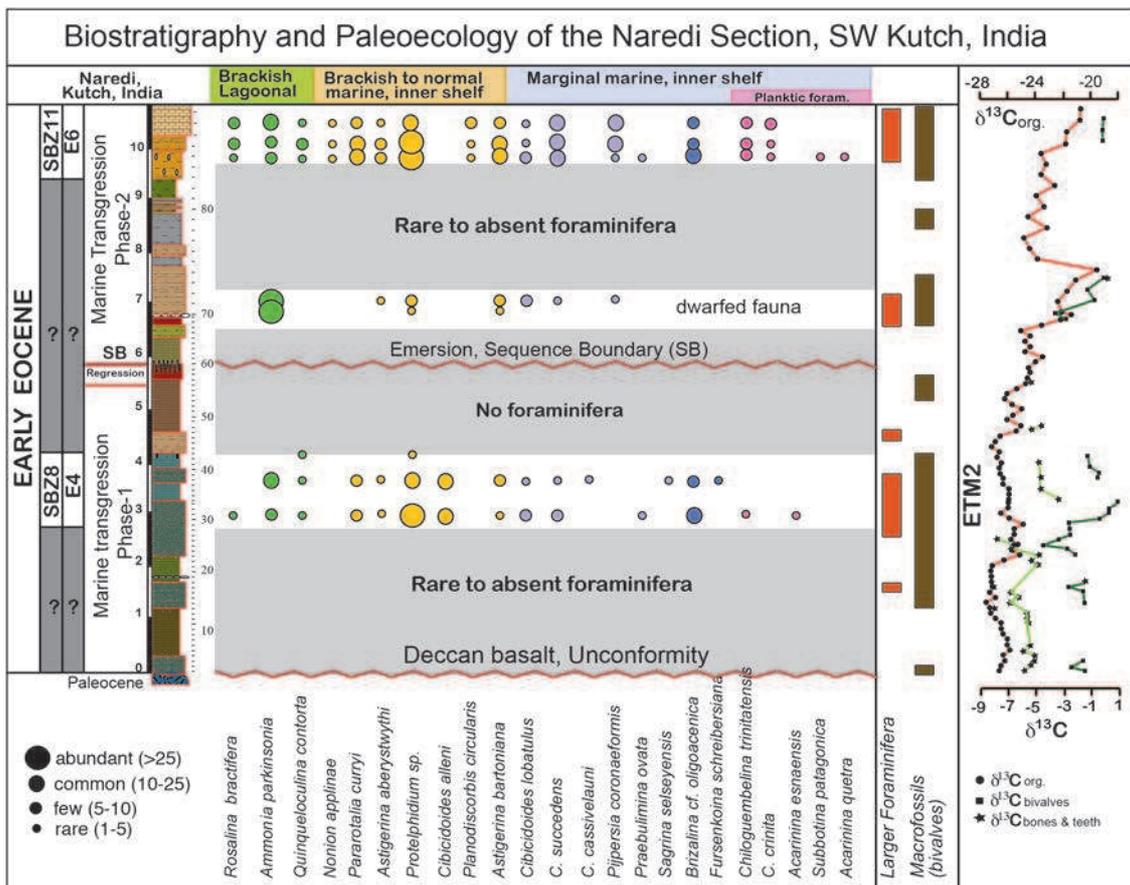


Fig. 3. Biostratigraphy, qualitative abundance of small benthic and planktic foraminifera, occurrences of larger foraminifera and macrofossils, and stable isotope curves based on $\delta^{13}C_{org}$, $\delta^{13}C_{biv}$ and $\delta^{13}C_{bones}$ at the Naredi section, Kutch.

by Thierry Adatte contain *Nummulites globulus nanus* Schaub, 1981. This species comes from SBZ8, which corresponds to planktic foraminiferal zone P6 (= E3-E4, Fig. 4). More Details are available in Serra-Kiel et al., (1998). It could have a somewhat broader range because of its extreme habitat, which is not represented at all ages in Europe. The nummulite population is monospecific with only a San-partner of an odd pair [suggesting] much environmental stress: deep and/or dark with lots of turbidity, fine grained mud with some nutrients (some shells are filled with pyrite), which indicates that estuaries are not too far away.”

Nummulites globulus nanus is illustrated in Figure 5. Hottinger noted: “This species is exceptionally small and therefore escapes notice when associated to a “normal” nummulite assemblage. So far, it was described only from the Treppe area in the Pyrenees where it marks SBZ8 (Ypresian, middle Ilerdian) according to Serra-Kiel et al. (1998). There might be another, larger species but I have only a single specimen that I hesitate to cleave.” When asked whether the small, dwarfed nummulites reflect high stress environmental conditions similar to planktic and benthic foraminifera in this

section and elsewhere, Hottinger answered (Jan. 24, 2008): “Yes, I think so. However, there are different kinds of stress. These small sizes seem to be depth-related. I have the same problem with assiliniids in the Gulf of Aqaba at the lower end of the photic zone. There I do not know if I have to consider the dwarfed forms as separate species or not. *Nummulites nanus* in the Treppe basin is also in the deepest position where larger forams are still present. The relation with symbiosis (stress by low light levels) remains unclear and in my view improbable. I would rather see a shift in reproduction strategy away from seasonal dependence”.

Based on Hottinger’s analysis the larger foraminiferal assemblage of the lower part of the Naredi section indicate an early Eocene SBZ8 age, which is equivalent to planktic foraminiferal zone E4 (=P6b) as shown in the summary of zonations in Figure 4. Hottinger’s age determination and faunal observations are in good agreement with studies by Saraswati et al., (2000, 2012), though Shukla (2008) suggested a late Paleocene age. Saraswati et al., (2012) report larger foraminifera, particularly *Nummulites globulus nanus* from the basal 4 m of the Naredi section overlying the basalts and

AGE		Planktic Zones		Nanno. Zones	Shallow Benthic Zones (SBZ)	Age of Naredi Formation: basalt to first limestone cliff					
		Pearson et al., 2006 Berggren et al., 1995		Aubry et al., 2000	Serra-Kiel et al., 1998 Scheibner & Speijer, 2009	<i>Larger Foraminifera planktic</i>					
middle Early Eocene	Ypresian Ilerdian	E8	P10	NP15	a	SBZ13	Naredi core B3/4		Naredi Naredi		
				NP14	b		SBZ12				
						NP13		a	SBZ11	SBZ11	SBZ11
				E7	P9	NP12	SBZ10	SBZ 9-10?	SBZ 9-10?	?	
				E6	P8						
				E5	P7	NP11	SBZ9	SBZ8	SBZ8	SBZ8	SBZ8
				E4	P6b						
				E3	P6a	NP10	SBZ8	SBZ8	SBZ8	SBZ8	E4
				E2							
				E1	P5	NP9	SBZ7	SBZ7?	SBZ7?		
		Late Paleocene	Thanetian Seland.	P5		NP9	b	SBZ6	SBZ6	SBZ6	PETM
P4c	P4c			SBZ5	SBZ5			SBZ5			
P4b				NP7/8	a	SBZ4	SBZ4				
P4b	P4b					SBZ3	SBZ3				
P4a				NP6							

Fig. 4. Correlation of late Paleocene to middle Eocene biozones based on planktic foraminifera (after Pearson et al., 2006; Berggren et al., 1995), nannofossils (Aubry et al., 2000) and larger shallow water benthic foraminifera (Serra-Kiel et al., 1998 and Scheibner et al., 2005), and the age of Naredi Formation based on larger foraminifera (Sarawati et al., 2012) and this study.

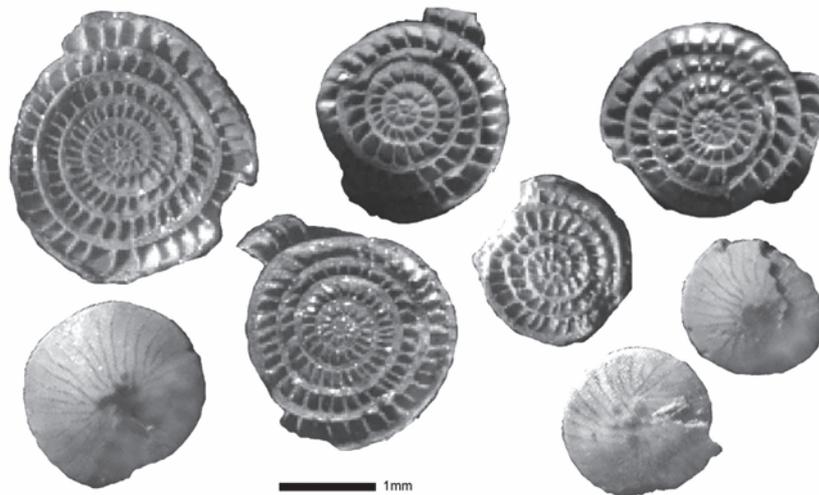


Fig. 5. Micrographs of the external views and equatorial sections of monospecific *Nummulites globulus nanus*.

assigned this interval to SBZ8, which is equivalent to the interval analyzed by Hottinger as SBZ8 (Figs. 3 & 4). Above this interval Saraswati et al. (2012) report a generally barren zone questionably interpreted as SBZ9-10 containing a short interval with only small foraminifera. At this level we observed dwarfed foraminifera and Hottinger noted “exceptionally small” *Nummulites*. The age of this assemblage is unknown. Near the top of the section, Hottinger (this study), Punekar and Saraswati (2010) and Saraswati et al., (2012) observed a diverse assemblage of *Nummulites burdigalensis cantabricus*, *Assilina laxispira*, *A. spinosa* and *Lockhartia*, which was assigned to zone SBZ11, equivalent to planktic foraminifera zones E6 to E7 (formerly P8-P9) and hence Ypresian (uppermost Ilerdian, Fig. 4). Based on larger foraminifera the 11 m overlying the Deccan basalt at the Naredi type locality is of (early to middle) Ypresian age.

In a borehole about 10 km to the southwest of the Naredi section, Saraswati et al., (2012) recovered a considerably expanded sequence between the basalt and the limestone cliff with similar assemblages and barren intervals as at Naredi. The first 9 m above the basalt are identified as SBZ6 (= lower part of E2, Fig. 4). This is followed by a 14 m interval with rare or no foraminifera, which they questionably identify as SBZ7? At 25 m above the basalt is a second *Nummulites* horizon attributed to SBZ8 (Saraswati et al., 2012). The upper part with the limestone layer has a diverse assemblage of larger foraminifera indicative of SBZ11, similar to Naredi. This suggests that the lower part of the borehole section (SBZ6-SBZ7?) is basal Ypresian in age. This interval appears to be missing at the Naredi outcrop we examined.

Planktic Foraminifera

Planktic foraminifera are rare, except for

chiloguembelinids, and all are present primarily at the base and top of the section. Just five species were identified and all but one are long ranging: *Acarinina quetra* (zones E3-E6), *Acarinia esnaensis* (zones P4-E5), *Chiloguembelina crinita* (early Paleocene to E8), *Chiloguembelina trinitatensis* (zones P5-E3), *Subbotina patagonica* (zones P4-E8) (ranges from Pearson et al. 2006). These rare planktic species can provide only tentative age determinations. The presence of *A. quetra* near the top of the section indicates an age no younger than E6, correlative with the larger benthic zone SBZ11 (Figs. 3 & 4). At the base of the section the presence of *Acarinina esnaensis* suggests an early Eocene age possibly of zone E4 or lower E5, but an older late Paleocene (P4-5) age cannot be excluded. *Chiloguembelina trinitatensis* with a reported upper range limit of zone E3 (Pearson et al. 2006) is relatively common at the top of the section, which suggests that this stress-tolerant species has a longer range than previously reported.

No triserial planktics were observed although they have been reported in Chatteraj et al. (2009) and Saraswati et al. (2000, 2012). Tandon et al. (1980) reported *Globorotalia trinitatensis*, *G. inconstans*, *G. rex* and *G. prolata* from the lower part of the Naredi Fm. This assemblage has not been observed to date by other workers, including this team.

PALEOENVIRONMENT

Small Benthic Foraminifera

Small benthic species are generally long ranging and therefore not good age indicators. However, they are excellent environmental proxies as species adapt to changes in sea level, salinity, oxygen, nutrients and substrate. In the Naredi section small benthic foraminifera are relatively common and well

preserved in the small size fraction (63-100 μm) in the same three horizons as larger foraminifera and separated by long barren zones (Fig. 3). These barren zones are partly due to mechanical corrosion, which is most severe in the glauconitic and phosphatic intervals. Dissolution effects in the clayey layers could be related to outcrop weathering. Species assemblages are generally of low diversity with a total of just 18 species. All species have small or dwarfed morphologies characteristic of high stress shallow water environments.

Species identification can be difficult because few well-illustrated records of very small species (<100 μm) in shallow water environments exist. Publications on small benthic species from the Naredi section or other Paleocene-Eocene shallow water environments in India are rare (e.g., Punekar and Saraswati, 2010). A study of shallow water benthic foraminifera by Murray and Wright (1974) based on Eocene sections from the Paris basins, the English Channel and Hampshire, England, was most helpful. Many of the species in the Naredi section are also present in Eocene assemblages of these European sequences, including larger foraminifera suggesting similar environments. We used Murray and Wright (1974) as well as Murray et al. (1989) as guide to the shallow water assemblages from Naredi. All common species from the Naredi section are illustrated in Figures 6-8 and their occurrences and relative abundances recorded and grouped based on known environmental affinities from brackish lagoonal to normal marine inner shelf and marginal marine environments (Fig.3).

Paleoecology

Chattoraj et al. (2009, see also Raju, 2008; Khozyem this vol.) interpreted deposition of the Naredi Formation in a subtidal setting with barren intervals representing supratidal settings. In such shallow water environments faunal assemblages tend to be highly stressed due to fluctuations in salinity, oxygen and nutrients. Species generally adapt to high stress conditions by dwarfing, early sexual maturation and rapid reproduction with many offspring improving chances for survival. Only few species adapt successfully which leads to low diversity assemblages dominated by one or two species. At Naredi the most dominant species are *Ammonia aff. beccarii* and *Protelphidium* sp. 4 (Fig. 3). Common species include *Cibicidoides succedens*, *Astigerina bartoniana*, *Pararotalia curryi*, *Pijpersia coronaeformis* and *Brizalina*. Different assemblages dominated the fossil-bearing horizons suggesting changing environmental conditions. In this study species associations are grouped into brackish lagoonal, brackish to normal marine inner shelf and marginal marine inner shelf environments (Fig. 3) based on known and inferred affinities from recent analogs and particularly from the extensive

Paleogene studies of shallow water environments by Murray and Wright (1974) and Murray et al. (1989).

Ammonia parkinsoniana morphotype assemblage

Ammonia parkinsoniana (*A. beccarii parkinsonia* of some authors) is a well-known opportunistic species (similar to *A. beccarii*) that thrives in shallow saline to brackish environments (e.g., Colburn and Baskin 1998; Almogi-Labin et al., 1995) and may live in surface sediments, on hard substrates or attached to macrobenthos in brackish marine or nearby rivers and lakes (Takata et al., 2009). Colburn and Baskin (1998) observed that *Ammonia parkinsoniana* is one of the most widely distributed and abundant foraminiferans living in nearshore environments of the north-west Gulf of Mexico as well as in Neogene sediments of the Gulf Coast. They have variable test morphologies presumed to be adaptations to environmental changes. Colburn and Baskin (1998) found salinity to be the most important factor affecting morphology. Specimens collected at times of higher salinity (50 ppt) differed from those collected at lower salinity (14 ppt) by having a larger proloculus and fewer chambers in whorls 1 and 2, a smaller umbo diameter and fewer total chambers. Experimental studies on *Ammonia* sp. by Le Cadre et al., (2003) determined that prolonged exposure to low pH results in test dissolution, whereas return to normal pH induces test deformation. Experimental studies by Nigam et al., (2005) and Panchang et al., (2006) exposed species to low oxygen, which revealed a rapid decline in most species, including *A. beccarii* with *Fursenkoina* and *Nonion* species more adaptive.

In the Naredi section a morphotype similar to *A. parkinsonia* (Fig. 6, No. 9-12) dominates a low diversity (8 species) assemblage in a short interval 7 m above the basalt at the base (Fig. 3). Marginal marine species (e.g., *Cibicidoides lobatulus*, *C. succedens*, *C. cassivelauni*, Fig. 6, No. 15-17; Fig. 7 No. 5-7, 9-10) and brackish to normal inner shelf species (e.g., *Astigerina bartoniana*, *A. aberystwythi*, *Protoelphidium* sp. 4, Fig. 6, No. 1-5) are few to rare varying from <5 to <10 specimens). All species in this assemblage are dwarfed. In addition, a nearly monospecific assemblage of very small specimens of the larger foraminifer *Nummulites globulus nanus* is present and also indicates a high stress environment (Hottinger, written communication, 2008). Based on these assemblage observations we interpret a brackish lagoonal environment. Sediments in washed residues are rich in phosphate suggesting high nutrient influx and possibly dysoxic conditions.

Protelphidium sp. 4 assemblage

This relatively low diversity assemblage (13 species) is

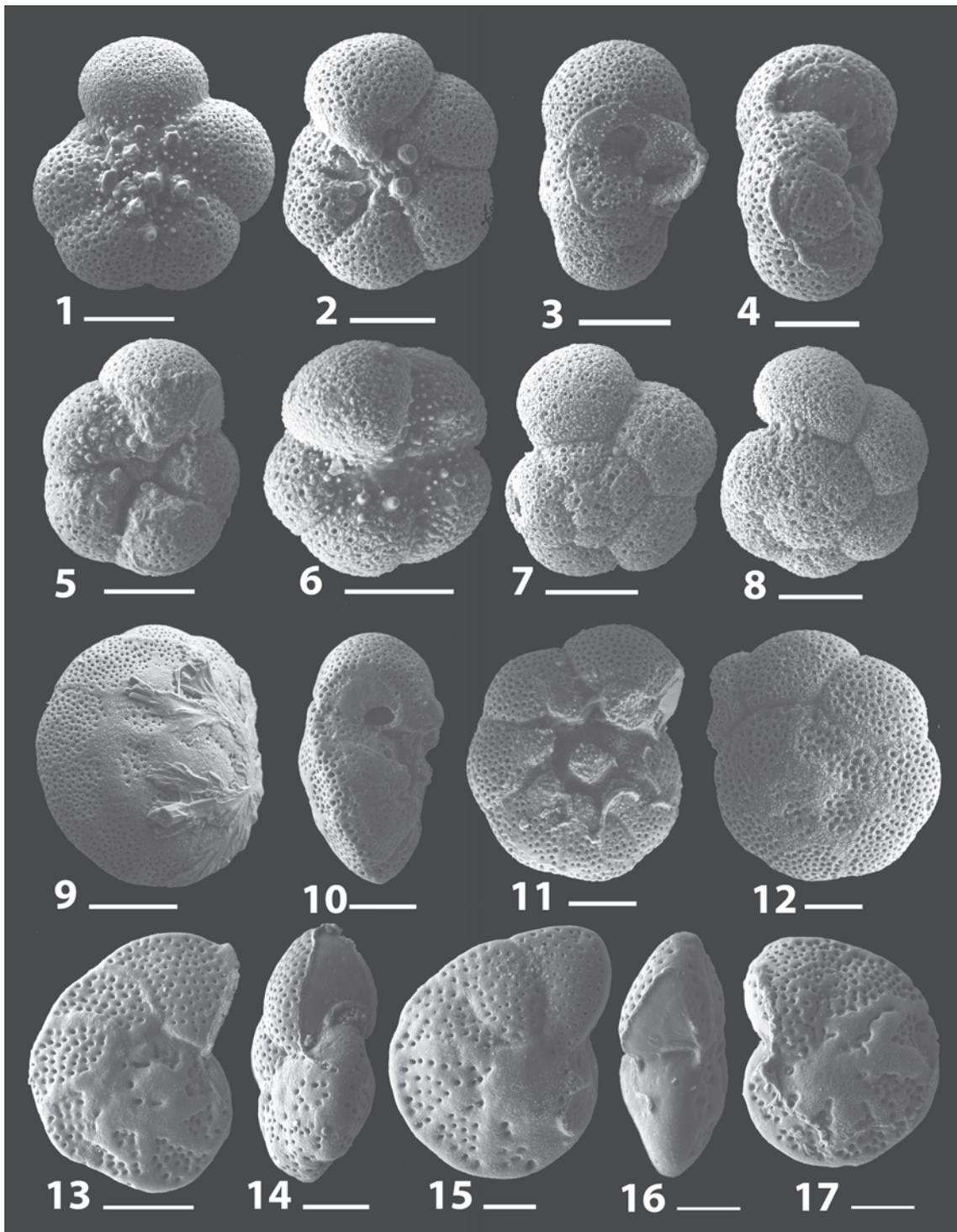


Fig. 6. Benthic foraminifera from the Naredi section of Kutch, India. Scale bar=50 μ m. **1-5.** *Protelphidium* sp. 4 of Murray and Wright 1974, Naredi sample NE-32. Description: test planispiral, inflated chambers, rounded, lobate periphery, 5- 6 chambers in Naredi specimens, depressed sutures, umbilicus ornamented with tubercles, aperture interiomarginal row of pores; wall coarsely perforate except on apertural face. Paleogeology; brackish to normal marine, estuarine and lagoonal; **6-8.** *Protelphidium* sp. Naredi sample NE-32. Similar to sp. 4, but 4-5 chambers, less ornamented umbilicus, aperture interiomarginal slit. Paleogeology: brackish to normal marine, shelf, muddy substrate; **9-12.** *Ammonia parkinsonia* (d'Orbigny), sample NE-32; **13-14.** *Cibicides alleni* (Pummer), sample NE-32. Paleogeology: marine middle to inner shelf; often associated with current activity; **15-17.** *Cibicides succedens* Brotzen, sample NE-32. Paleogeology: marginal marine to middle shelf, may be tolerant of poorly aerated mud bottom.

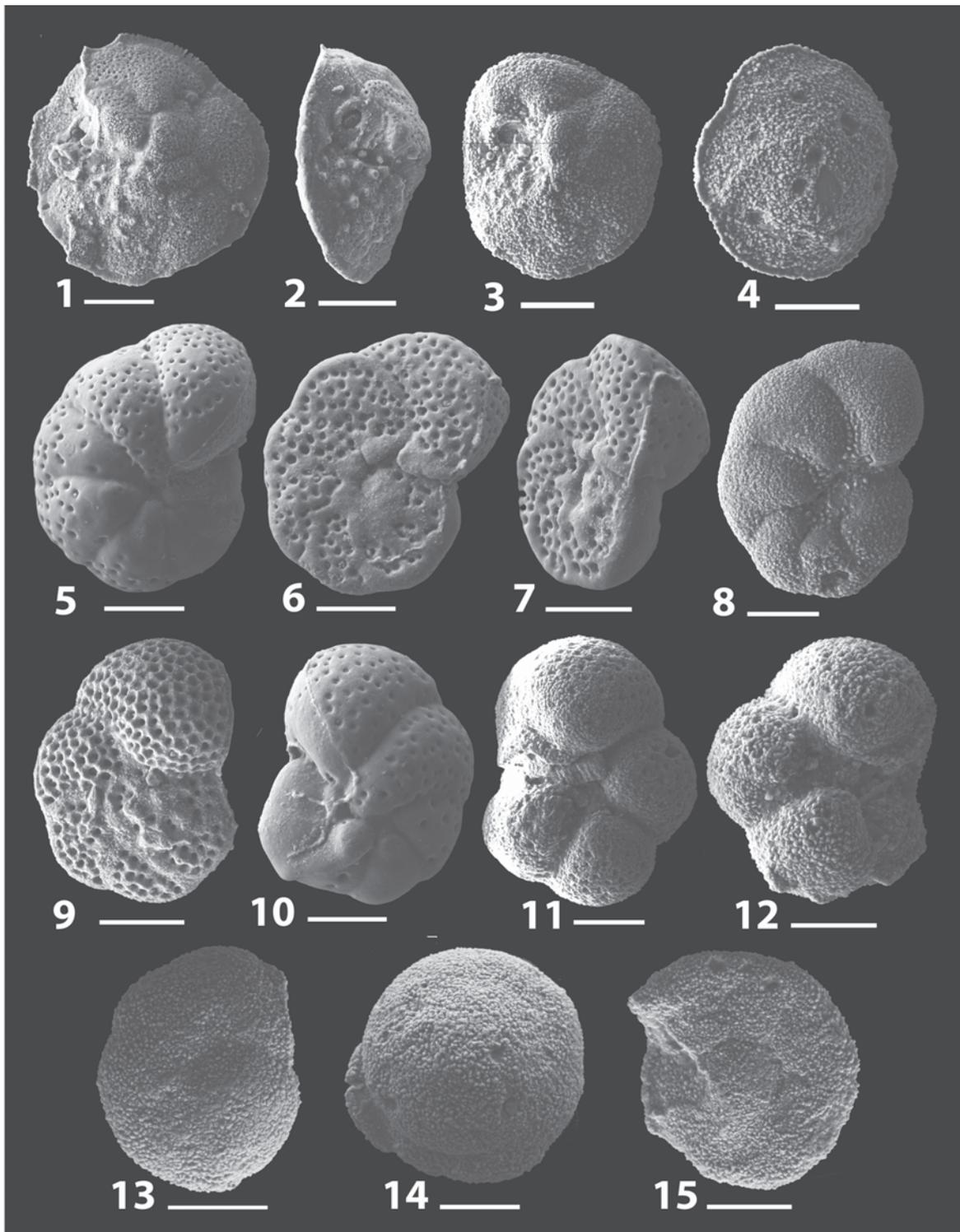


Fig. 7. Benthic foraminifera from the Naredi section of Kutch, India. Scale bar=50 μm . **1-2.** *Astigerina bartoniana* (Ten Dam), sample NE-44. Paleoecology: normal marine, inner shelf; **3-4.** *Astigerina aberystwythi* Haynes, sample NE-87. Paleoecology: normal marine, ? brackish, inner shelf; **5-7.** *Cibicidoides lobatulus* (Walker and Jacob), sample NE-32. Paleoecology: brackish to normal marine, inner to mid shelf, varied substrates; **8.** *Nonion applinae* Howe and Wallace, sample NE-32; **9-10.** *Cibicides cassivelauni* Haynes, sample NE-39. Paleoecology: normal marine inner to middle shelf; **11-12.** *Pararotalia cf. curryi* Loeblich and Tappan, sample NE-86. Specimens less compressed with more rounded periphery than type specimens. Paleoecology: mainly brackish but extending into normal marine inner shelf; **13-15.** *P. circularis*, sample NE-86.

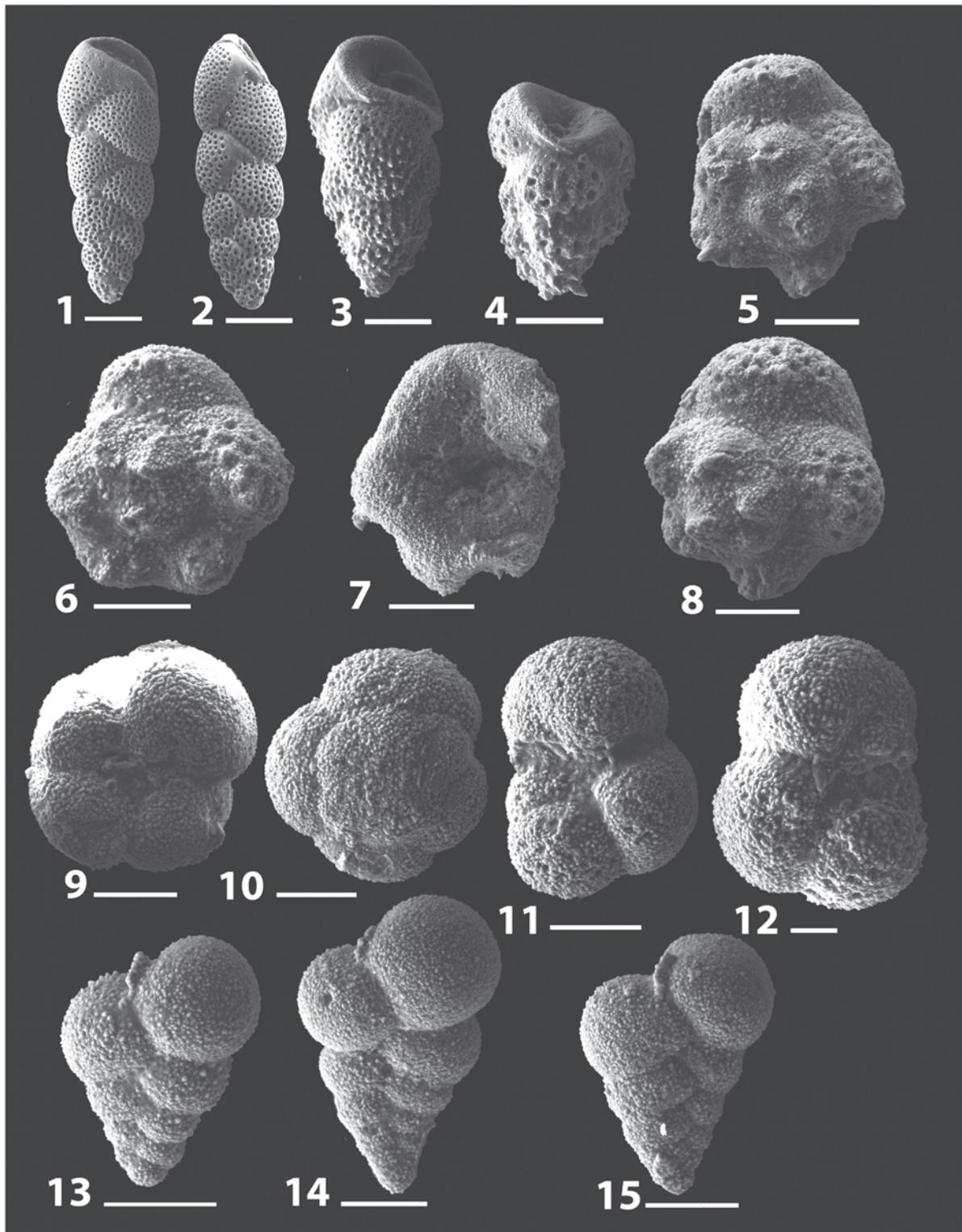


Fig. 8. Benthic and planktic foraminifera from the Naredi section of Kutch, India. Scale bar=50 μ m for figs. 1-12 and 20 μ m for figs. 13-15. **1-2.** *Brizalina oligoacenic* (Spandel), sample NE-32, Fig. 2. specimen from Vastan lignite mine. Paleoeology: Normal marine shelf, mud substrate; **3-4.** *Praebulimina spinata* (Cushman & Campbell), samples NE-32, NE-39. Sliter 1968, pl. 12 p. 85; **5-8.** *Pijpersia coroneiformis* (Pijpers), sample NE-88; **9-10.** ? *Protelphidium* sp. or *Rosalina bractifera*? Sample NE-88; **11-12.** *Subbotina patagonica* (Todd and Kniker), sample NE-86; **13-15.** *Chilogembelina trinitatensis* (Cushman and Renz), sample NE-86; Paleoeology: planktic foraminifera, stress tolerant, inner shelf to open marine.

dominated by small 5-6 chambered species with a row of small apertures at the base of the last chamber (Fig. 6, No. 1-5). Two of the three foraminifer horizons at Naredi are dominated by *Protelphidium* sp. 4 (Fig. 3). The species was described by Murray and Wright (1974) as one of several morphotypes abundant in low diversity assemblages of the Paris Basins, English Channel and Hampshire. They interpreted the *Protelphidium* sp. 4 assemblage as indicative of an abnormal environment, possibly hyposaline such as a lagoon or estuary. In the Naredi section a similar environment may have prevailed in the first foraminifer horizon between 2.8-4 m above the basal basalt. At this horizon *Protelphidium* sp. 4 coexists with other brackish to normal marine inner shelf species, including common *Cibicoides alleni* and *Brizalina cf. oligoacenic* (Fig. 6, No. 13-14; Fig. 8, No. 1-2). All other species are few to rare (Fig. 3). Low diversity larger foraminiferal assemblages are also present and dominated by *N. globulus nanus*. However, since sediments are rich in glauconite with minor phosphate this suggests a palaeodepth of about 5-10 m with a more open sea connection, rather than a lagoon or estuary.

Protelphidium sp. 4 – *Cibicoides succedens* assemblage

The uppermost foraminiferal horizon differs from the two lower ones by higher species diversity (18 species), presence of marginal marine inner shelf benthics with common *C. succedens*, *C. lobatulus*, *Brizalina cf. oligoacenic* and *Pijpersia coronaeformis* (Figs. 6-8). Planktic foraminifera are few to rare, including *C. trinitatis* (Fig. 8, No. 13-15), *C. crinita*, *Subbotina patagonica* (No. 11-12) and *Acarinina quetra*. The brackish to normal marine inner shelf benthic assemblage is still common and dominated by *Protelphidium* sp. 4, *Pararotalia curryi*, *Astigerina aberystwythi* and *A. bartoniana* (Figs. 6, 7). *Ammonia aff. beccarii* is present but significantly reduced in abundance. Most species are larger than in the lower two horizons, suggesting less environmental stress. Larger foraminifera are common and diverse. Sediments are more calcareous with decreased glauconite and phosphate suggesting more oligotrophic conditions. Murray and Wright (1974) interpreted a similar early Eocene assemblage in the European sections as inner shelf with moderate water depth (20-50 m) and slightly hyposaline. The relatively rare and low diversity of planktic foraminifera suggests sluggish connection with the open sea.

DISCUSSION

The difficulty in determining the precise age of the Naredi Formation is due to the shallow depositional environment and consequently absence of diverse planktic foraminiferal assemblages that provide excellent age control in marine sequences. Larger shallow benthic foraminifera currently

provide good age control indicating an early Eocene Ypresian age (shallow benthic zones SPZ8 to SPZ11), although their intermittent presence leaves age dating at the base of the section and between zones SPZ8 and SPZ11 uncertain (Fig. 4). A recent study by Garg et al., (2011) based on dinoflagellates confirmed an early Eocene age for the Naredi section, but also recovered age diagnostic species in the basal part of the section overlying basalt that indicate a very early Ypresian age (e.g., *Muratodinium fimbriatum*, *Heterolaucacysta granulata*, *Operculodinium severinii* and *Gingiodinium palaeocenicum*).

Age resolution can be further refined by integrating all microfossil data and compare and correlate the results with the high-resolution carbon isotope curve of the Naredi section that can be correlated with the global isotope record. This was the main objective of this study and the companion study on geochemistry by Khozyem et al. (this vol.). The carbon isotope curve of the Naredi section is based on $\delta^{13}\text{C}_{\text{org}}$ with additional $\delta^{13}\text{C}$ measurements from bivalves, bones and teeth where available through the Naredi section (Fig. 3). The data are discussed in detail in Khozyem et al. (this vol.) and briefly summarized here.

The $\delta^{13}\text{C}_{\text{org}}$ curve shows predominantly negative values (-24.9 and -27.6‰) in the basal 4.5 m of the section with minimum values between 1.0-1.8 m and 3-4.2 m (Fig. 3). At the top of this interval (2.8-4.2 m) are the first planktic and benthic foraminiferal assemblages that indicate an early Eocene age (early Ypresian) based on biozones SBZ8 and E4 (Fig. 3) (Saraswati et al., 2012, this study; see also Chatteraj et al., 2009). This foraminiferal and macrofossil-rich assemblage records a strong positive $\delta^{13}\text{C}$ excursion in macrofossil shells, bones and teeth. Microfossils and macrofossils suggest a sea level transgression resulting in a brackish to more normal marine inner neritic environment as indicated by benthic and rare planktic foraminifera and abundant glauconite. In the basal 2.8 m of the section $\delta^{13}\text{C}$ values of bones, teeth and macrofossils show the same negative trend as $\delta^{13}\text{C}_{\text{org}}$. No age diagnostic foraminifera species are present. However, dinoflagellates in this interval indicate an early Ypresian age (Garg et al., 2011). The warm early Ypresian climate of the first 4.5 m of the Naredi section may be correlative to the early Eocene climatic optimum (ETM2 at 53.7 Ma) (Zachos et al., 1994; Sloan and Huber, 2001; Slujs et al., 2007; Woodburne et al., 2009).

Within this interval and correlative with the first relatively diverse marine assemblages is a major positive $\delta^{13}\text{C}$ excursion measured in bivalves, bones and teeth and to a lesser extent in $\delta^{13}\text{C}_{\text{org}}$. Similar excursions coincide with the other two foraminiferal marine assemblages in the upper part and at the top of the Naredi section (Fig. 3). These positive $\delta^{13}\text{C}$

excursions are likely linked to mixed sources of organic matter or a change toward increased marine organic input (Calvert et al., 1987).

Between 4.5 m and 6.5 m of the Naredi section $\delta^{13}\text{C}_{\text{org}}$ values increase fluctuating between -26 to -24‰. This interval is barren of foraminifera and contains rare bones and fish teeth showing a similar positive trend. The major positive excursion in $\delta^{13}\text{C}_{\text{org}}$ (6.5-7.6 m) culminates (-19.6‰) in the fossiliferous claystones (Fig. 3). Benthic foraminifera in this interval are strongly impoverished with just seven species dominated by a morphotype similar to *Ammonia parkinsonia*, which indicates a brackish to lagoonal environment. In the interval above a rapid negative $\delta^{13}\text{C}_{\text{org}}$ excursion occurs in an interval devoid of fossils. Between 7.8-9.8 m $\delta^{13}\text{C}_{\text{org}}$ values gradually increase (-26.3 to 24‰) then rapidly reach 20.7‰ at the top of the section (Fig. 3). This rapid $\delta^{13}\text{C}_{\text{org}}$ increase occurs in the interval of the most diverse foraminiferal assemblages, which suggest a marginal marine inner shelf environment. Benthic foraminifera are dominated by *Protoelphidium* sp. 4, which indicates brackish to normal marine inner shelf environment.

Lithology, foraminifera and stable isotope data thus suggest deposition occurred in a shallow marine environment that varied from brackish to normal marine inner shelf environments. Two transgressive trends are apparent – one in the lower part of the section culminating with the first diverse foraminiferal assemblage and the second in the upper half culminating near the top of the section with the most diverse foraminiferal assemblages (see also Chattoraj et al., 2008). In between these transgressive trends is a root zone horizon representing a paleosol at 5.9 m that indicates a regression and possibly a sequence boundary (Fig. 3) (see Khozyem et al., this vol. for a detailed discussion and lithology). The intervals with rare and mechanically corroded foraminifera suggest supratidal environments as also indicated by the presence of glauconite.

CONCLUSIONS

The Naredi section is intermittently fossiliferous with bivalves, echinoids, ostracods and larger foraminifera more frequently present than smaller benthic and planktic foraminifera, which are restricted to three intervals. Associated microvertebrates are dominated by teeth, scales and otoliths

of shallow marine fishes (sharks, rays, teleosts) and a few aquatic snakes. Based on faunal assemblages and stable isotope data ($\delta^{13}\text{C}_{\text{org}}$, $\delta^{13}\text{C}_{\text{biv+bones+teeth}}$) the following age and environmental interpretations can be reached.

1. *Age and Biostratigraphy*: The lower part of the Naredi section is of early Eocene (Ypresian) age (SBZ8, E4) based on larger foraminifera and rare planktic foraminifera in assemblages between 2.8-4.2 m from the base of the section. The top of the section (including the limestone) is of late early Eocene (SBZ11, E6) age (Fig. 3). There is no biostratigraphic age control for the lower 2.8 m and between 4.2-9.3 m.

2. *Paleoenvironment*: Small benthic and rare planktic foraminifera are common in three short intervals: the lower assemblage (SBZ8, E4) is indicative of brackish to normal marine inner shelf environments; the middle assemblage represents a brackish environment; the top assemblage (SBZ11, E6) is the most diverse and indicates an inner shelf to marginal marine environment.

3. *Sea level changes*: Two phases of marine transgressions can be identified with the maximum transgressions in each phase marked by the lower and upper foraminiferal assemblages. A paleosol indicated by root traces and burrows (5.9 m) represents a regression and possibly a sequence boundary.

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