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MICROFACIES AND DEPOSITIONAL ENVIRONMENT OF THE GAJ FORMATION (MIOCENE) EXPOSED NEAR BHATIA, DISTRICT JAMNAGAR, SAURASHTRA

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ABSTRACT

Complex tectonic features surround the Saurashtra Peninsula of the Gujarat state on the western extremity of India, a consequence of the breaking up of Gondwanaland in the Triassic. The arching up of the Saurashtra peninsula was a result of pre-Eocene thermal expansion of the crust while moving northeastward over the Reunion hot spot. This, together with lower eustatic sea level during the Eocene in comparison to higher global sea level in the Miocene, has resulted in the absence of Eocene sediments from the Saurasthra upland. The oldest sediments deposited at the northwestern coast of Saurasthra, which forms the Palaeogene-Neogene pericratonic sedimentary basin, belong to the Miocene. These Miocene sediments of Saurashtra have been, lithostratigraphically, grouped into the lower Ashapura Clay Member and the upper Ranjitpur Limestone Member of the Gaj Formation. Fossil records suggest a marine environment of deposition, however, rapid temporal change of facies can be attributed to fluctuating depositional environments. In the present paper, a 1.5 m thick section of the Ranjitpur Limestone Member exposed along a ridge near Bhatia, district Jamnagar, Saurashtra, has been investigated and interpreted to represent nearshore to subtidal environments.

Keywords: Gaj Formation, Saurashtra, depositional environment, microfacies, molluscs

INTRODUCTION

The tectonic framework of the Saurashtra Peninsula on the western extremity of India (Fig. 1) is related to the evolution of the whole of the state of Gujarat, which was initiated sometime in the Triassic with the breaking up of Gondwanaland. The subsequent geological history including Deccan Volcanism is related to the northward drift of the Indian subcontinent. The Saurashtra Peninsula with its coastal margins, although situated away from the plate boundary and sometime considered a passive area (Mathur, 1999; Mathur and Pandey, 2002), witnessed periodic earthquakes as a result of a complex tectonic features within and around the state of Gujarat (Biswas, 1987). The development of the Cambay and the Kachchh grabens can be traced, along with the western Ghat uplands, back to the splitting up of Gondwanaland. These features have developed as a result of rifting between Madagascar and India. While moving northeastward, the Indian Plate passed over the Reunion hot spot (Fig. 2). As a result of thermal expansion of the crust, the arching of Western Ghat uplands, Saurashtra and Kachchh took place (Courtillot *et al.*, 1986). The radial drainage observed in Saurashtra is the result of such arching. The uplift of the Saurashtra Peninsula can be dated as pre-Eocene, because Eocene and Oligocene marine sediments are missing on the Saurashtra upland (not Lower Miocene as postulated by Radhakrishna, 1993). The global sea level during Eocene has been suggested to be lower than that in the Miocene (Lincoln and Schlanger, 1991). The outcrop distributions of marine Eocene and Miocene sediments are not similar. This is because of difference in sea level and also perhaps due to change in the degree of arching up of the Saurashtra Peninsula during Eocene-Miocene epochs. The marine Eocene sediments have been recorded from the western coast of Gujarat Mainland, and the Kachchh, Jaisalmer, Bikaner-Nagaur basins on the northwestern part of Indian craton, whereas the Miocene sediments have been recorded from the western Saurashtra and Kachchh basins only (Fig. 1).

STRATIGRAPHY

The deposition of oldest marine sediments in the pericratonic-shelf basin at the fringe of the Trappean highlands of Saurashtra (Fig. 1), started at the beginning of the Neogene (early Miocene). These sediments have been grouped into the Gaj Formation (Shrivastava, 1963). Lithostratigraphically, the Gaj Formation has been divided into the lower Ashapura Clay Member and the upper Ranjitpur Limestone Member (Bhatt, 2000; Kachhara *et al.*, 2000) (Table 1). The Ranjitpur Limestone Member is rich in both micro- and macro-invertebrate fossils. Both sediments and faunal elements provide a good opportunity for palaeoenvironmental studies. Earlier records suggest a marine depositional environment as indicated by the abunaance of foraminifers such as *Lepidocyclina* and *Miogypsina*, echinoids, molluscs, etc. (Mathur *et al.*, 1988; Kachhara *et al.*, 2000; Jain, 2002). However, rapid temporal facies changes suggest fluctuating conditions characteristic of the shallow shelf. Only a few good outcrops of the formation exist. One of them investigated here is an exposure of the lower part of the Ranjitpur Limestone Member (Lower Miocene) exposed along a ridge crossing the road to Dwarka about 10 km east of Kuranga village near Bhatia, district Jamnagar, Saurashtra (Fig. 1). The present paper deals with the microfacies and depositional environment of the lower part of the Ranjitpur Limestone Member at that locality.

The Gaj Formation

The highly fossiliferous Gaj Formation (early to middle Miocene) occupies a wide area of about 300 km² in the district of Jamnagar, Saurashtra. However, the best exposures are in

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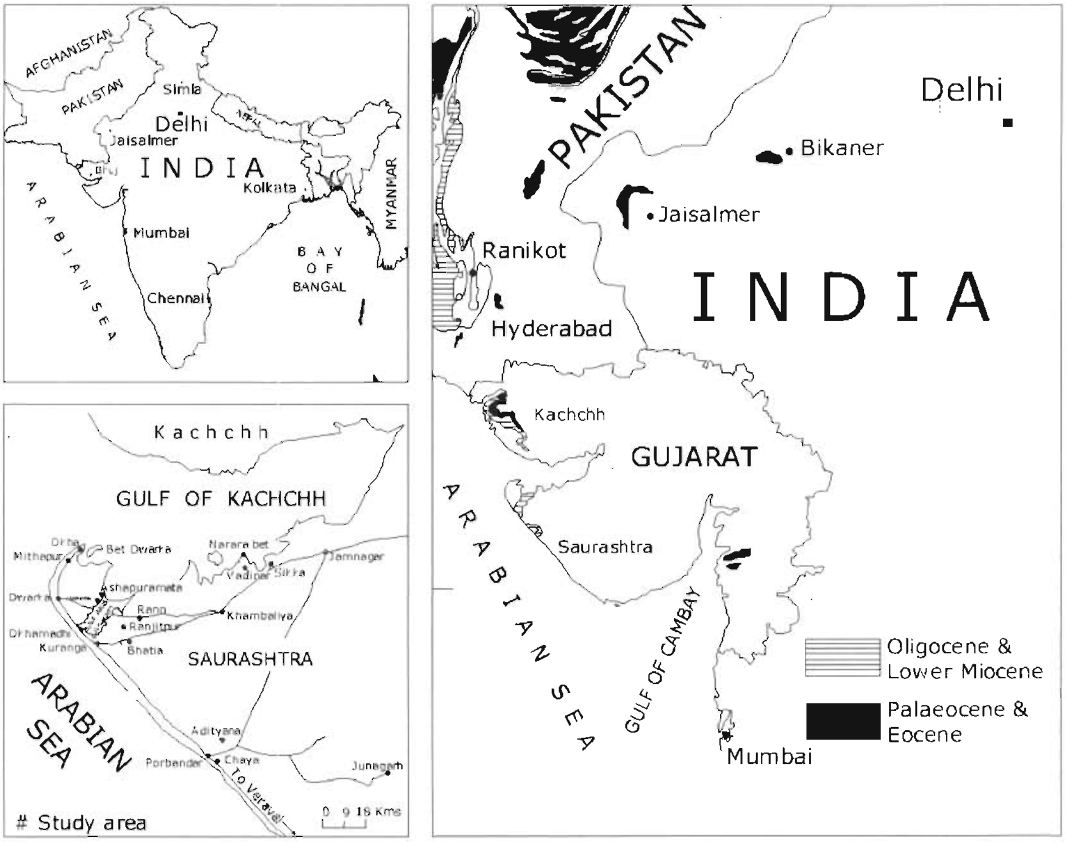

Fig. 1. Outline map of northwestern part of Indian craton showing outcrops of marine Eocene and Miocene sediments (after Krishnan, 1982). Note the location of the study area (northern Saurashtra).

the western margins of the Okha Rann. The sediments consist predominantly of ash-grey to variegated mudstone in the lower part, the Ashapura Clay Member, and shelly limestone in the upper part, the Ranjitpur Limestone Member (Bhatt, 2000). Jain (1997; 2002) measured several sections of the Gaj Formation and described several bivalves, gastropods and echinoids. Kachhara *et al.* (2000), on the basis of molluscs, recognized at least three biozones within the Gaj Formation. The Dwarka Formation disconformably overlies the Gaj Formation. Locally, a conglomerate bed here included in the Dwarka Formation marks the contact.

Ashapura Clay Member: The type section of this unit is at the Ashapura temple (22°17′N, 69°10′E), 1 km east of the village of Khatumba. An average thickness of about 90 m can be estimated for this unit, which increases in thickness towards the west. Lithologically, it consists of thinly laminated clays of variegated colours overlain successively by thin calcareous sandy clays, bioturbated sandstones, pale-reddish to yellow sandy clays and marls, and dolomitic siltstones. Fossiliferous bands with casts of gastropods (*Turritella, Natica, Cerithium, Cypraea* and *Conus*) and bivalves (*Ostrea, Acila,* and *Venus*) occur at different levels.

Ranjitpur Limestone Member: The distinctly calcareous member is best exposed at a low mound about 1.5 km east of the village Ranjitpur (22°11′ N, 69°13′ E). The limestone beds are yellow to brown or grey, compact, cross-bedded and fossiliferous. The beds are extensively bioturbated and contain recrystallised shells mainly of *Acila, Arca, Pecten, Ostrea* and fragments of corals. Pectinid-rich bands characterize the member near Okhamadhi. In addition, larger foraminifera of the family Miogypsinidae also occur in the Ranjitpur Limestone Member.

The fauna of the Ashapura Clay and the Ranjitpur Limestone members is similar. On the basis of the occurrence of the larger foraminifers *Lepidocyclina (Nephrolepidina), Miogypsina,* and *Pseudotaberina malabarica*, an early Miocene (Burdiglian) age has been suggested for the Gaj Formation (Bhatia and Mohan, 1959), whereas later workers, based on molluscs and foraminifers, assigned an early to middle Miocene age to the formation (Kachhara *et al.*, 2000).

Ridge Section of the Gaj Formation

The section is situated on the eastern side of the Okha Rann along a ridge (about 10 km east of Kuranga village, near Bhatia, crossing the road going from Jamnagar to Dwarka). About 1.5 m thick section (Table 2, Fig. 3) consists of thinly bedded, low angle cross-bedded, partly bioturbated, ooid-bearing, bioclastic calcareous mud- to packstones. They belong to the lower part of Ranjitpur Limestone Member. In the field, different limestone beds can be easily differentiated on the basis of sharp, erosional, uneven bases, primary sedimentary structures, and degree of bioturbation (Pl. I, figs. A-B). The present study concentrates on the microfacies, molluscan fauna and depositional environments of this section.

MICROFACIES

The rock units of the Gaj Formation exposed in the ridge section near Bhatia village have been studied under a microscope (Tables 2 and 3). For carbonate sediments, the

Table 1: Lithostratigraphy of Cenozoic of Saurashtra (modified after Mathur et al., 1988; De, 1989; Jain, 1997; Bhatt, 2000 and Pandey et al., 2007).

Stratigraphic unit			Lithology	Age
Group	Formation	Member		
Unconsolidated sediments				Middle -Late Holocene
Unconformity				
Porbandar Group	Chaya Formation	Porbandar Calcarenite Member	Semi consolidated to consolidated calcarenite with megafossils (pack to grainstone/rudstone	Late Pleistocene to Early Holocene
		Aramda Reef Member	Coral-algal reef, coral bafflestone and algal rudstone with micro and mega- fossils	
		Okha Shell Limestone Member	Cross- bedded pack to rudstone, bioturbated shell limestone with mega-fossils	
			Polymictic fossiliferous conglomerate	
	Miliolite Formation	Adatiana Member	Pelletoid limestones (Calcarenites)	Middle Pleistocene
		Dhobaliya Talav Member	Alternating sequence of pelletoid Limestones and fine grained limestone (micrtites)	
	Unconformity			
	Dwarka Formation	Kalyanpur Limestone Member	Recrystallised fossiliferous limestone and arenaceous limestone	Middle Miocene (?) to Lower Pliocene
		Shankhodar Sand-Clay Member	Sandy clays and sandstones	
		Positra Limestone Member	Bioclastic and coralline limestones with few dolomite bands	
	Disconformity			
	Gaj Formation	Ranjitpur Limestone Member*	Hard, compact, fine grained limestone with abundant foraminifers, gastropods, bivalves, echinoids etc.	Middle Miocene
		Ashapura Clay Member	Variegated clay with gypsiferous bands	
	Nonconformity			
	Deccan trap Formation		Basalt and other derivatives covered at places by laterite and bauxite	Upper Cretaceous to Eocene

* Sample collection

classifications of Folk (1959, 1962) and Dunham (1962) have been used.

The basal bed (Bed no. 1; thickness 10cm) is a wacke- to packstone (biopelmicrite: (Pl. II, figs A; Pl. III, fig. B) with diverse bioclasts, peloids and black extraclasts. Quartz grains are absent. The grain boundaries are sharp. Bioclasts consist predominantly of foraminifers such as *Miogypsina*, *Lepidocyclina*, *Pseudotaberina*, and rotaliids, coralline algae, ostracods and shell fragments.

The overlying unit (Bed no. 2; thickness 15cm) is also a wacke- to packstone (biomicrite). The grain boundaries are not clear. Peloids are less common than in the underlying bed. Foraminifers include *Miogypsina*, *Lepidocyclina* and rotaliids. Other common bioclasts are ostracods, coralline algae, echinoderms, and shell fragments.

The next bed (Bed no. 3; thickness 22cm) has a more uniform texture and is a packstone (biopelmicrite) (Pl. III, fig. A) with rare angular quartz grains. The grain boundaries of the allochems are sharp with point contact. The micritic groundmass contains iron impregnations. Bioclasts include *Miogypsina*, *Lepidocyclina*, *Pseudotaberina*?, miliolids, rotaliids, ostracods, articulated coralline algae (*Amphiroa*), echinoderm spines, and fragments of bivalves and gastropods.

The overlying bed (Bed No. 4; thickness 32cm) is also a packstone (biomicrite) with no quartz grains. The micritic

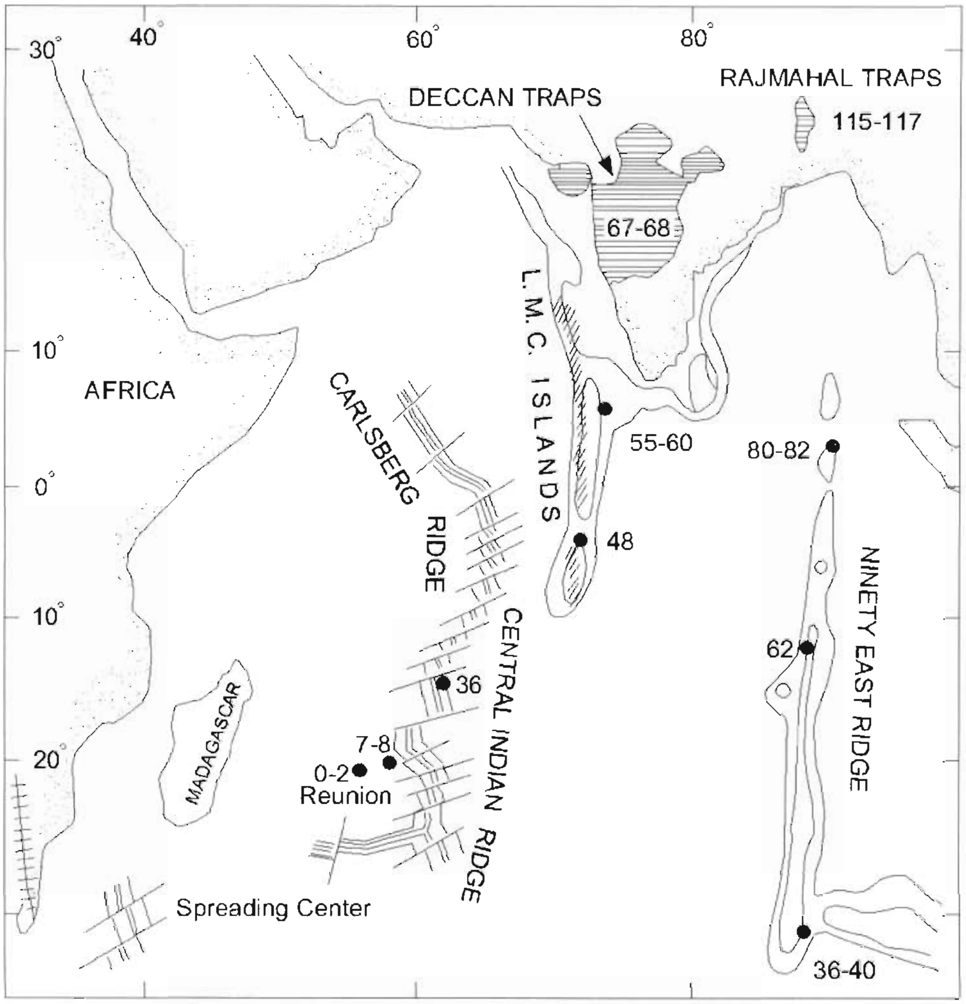

Fig. 2. Map showing location of Reunion hot spots and northerly shift of spreading axis resulting in uplift of Western Ghat, Saurashtra and Kachchh Highlands (modified after Courtillot *et al.*, 1986); Position of the continent (in million years) before present over the Hot spots (numbers indicate ages in my).

groundmass contains iron impregnations. The outline of the allochems is unclear. Foraminifers include *Miogypsina*, *Lepidocyclina*, and *Pseudotaberina*. Ostracods, coralline algae, gastropods other shell fragments are common. Some of the shell fragments are larger than 4 mm in size.

Bed No. 5 (thickness 1cm) is a mudstone to wackestone (intramicrite) with up to 3% mostly angular quartz grains. The boundaries of the allochems are unclear. There are abundant ferruginous micritic to sparitic intraclasts. Bioclasts are less common with rare foraminifers, shell fragments, and echinoid fragments.

The next overlying bed (no. 6; thickness 30cm) is a wacke- to packstone (biomicsparite) (Pl. II, fig. B; Pl. III, figs. C, E & F). The original micritic matrix is partially washed out and the secondarily developed cavities are filled up with the sparitic groundmass. Radial ooids are present. Grain boundaries are not clear. *Miogypsina*, *Lepidocyclina*, miliolids, and rotaliids are common foraminifers, while other bioclasts include echinoids and ostracods. Due to the abundance of *Lepidocyclina*, this bed is called the *Lepidocyclina* Bed.

The youngest bed (bed no. 7; thickness 34cm) of the

EXPLANATION OF PLATE I

A. Field photograph showing about 1.5 m thick section of the Ranjitpur Limestone Member of the Gaj Formation exposed on the eastern side of the Okha Rann along a ridge (about 10 km east of the Kuranga village, near Bhatia) crossing the Jamnagar-Dwarka Road road. Here, the member dominantly consists of thinly bedded, partly low angle cross-bedded, bioturbated, ooids bearing bioclastic packstone with sharp uneven bases. Note the burrow tube, marked by an arrow in the photograph, for scale geological hammer.

B. Photograph showing burrow tubes assembled in the field, range in length about 4.5 – 10.5 cm and in diameter from 3 to 4 cm. Note straight, curved to sinuous tubular burrow fragments, some of which are similar to cf. ***Spongeliomorpha*** sp., for scale geological hammer.

Plate I

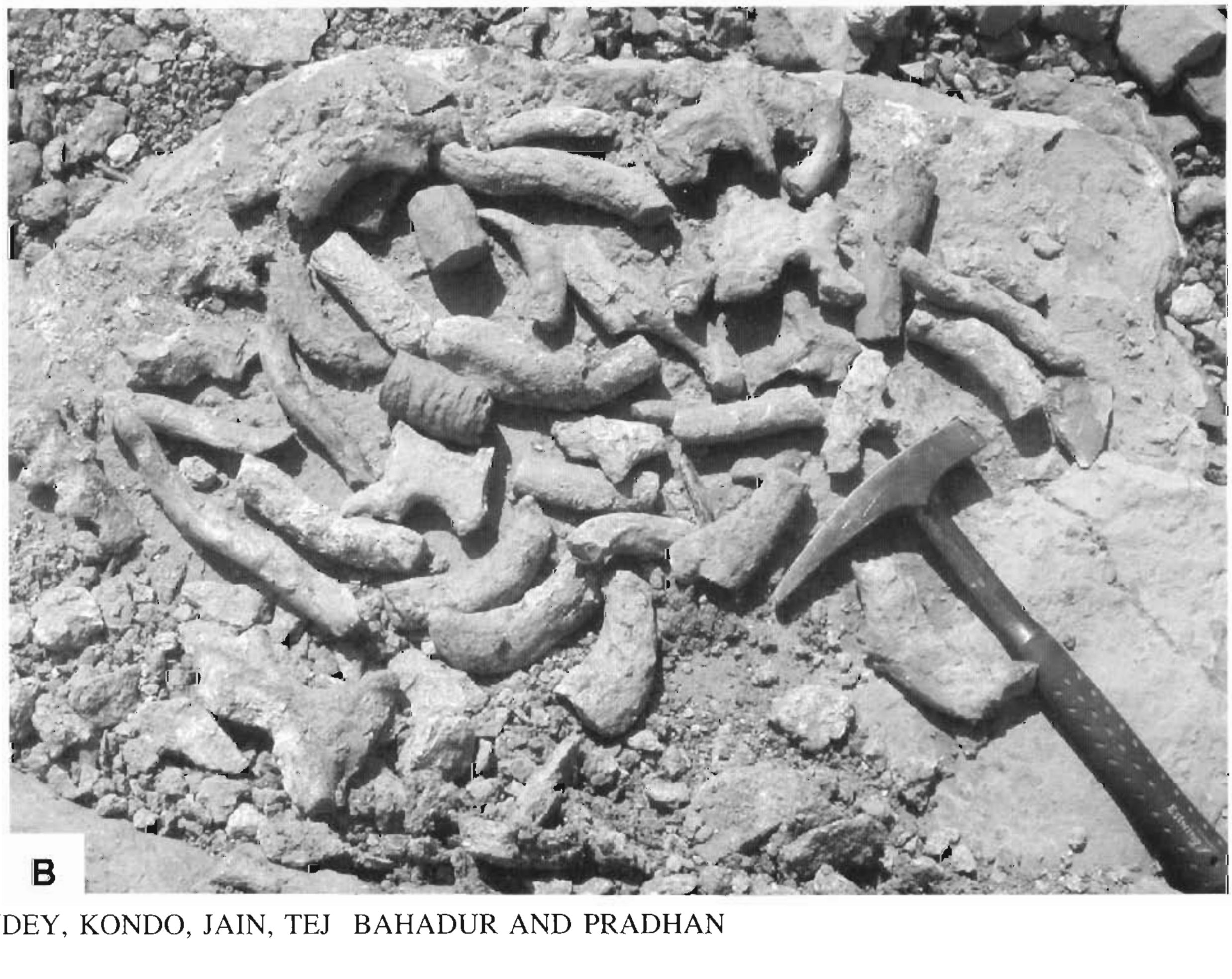

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Table 2: Field description of the lithic units of the Gaj Formation exposed along a ridge (about 10 km east of Kuranga village, near Bhatia) crossing the road going to Dwarka from Jamnagar.

Bed No.	Sample no.	Th. in cm	Description	Shell fragments/microfossils as seen under microscope
7	RUC20031 151	34	Thinly bedded, compact ferruginous packstone with black extraclasts of igneous origin, scattered burrow fill structures, poorly preserved bioclasts (some >7 mm in size), rootlets up to 25 mm. Uneven base and top	Bored shell fragments (c), foraminifers: *Miogypsina* (c), *Lepidocyclina* (c), rotalids (r), articulated coralline algae (o), echinoderm spines (o), ostracods (o).
6	RUC20031 150	30	Bioturbated packstone to wackestone with black extraclasts of igneous origin (5%), abundant recrystallised bioclasts up to 20 mm, solution cavities.	Shell fragments (a), foraminifers: *Miogypsina* (c), *Lepidocyclina* (a), milliolids (r), rotalids (r), echinoderm plates (r), ostracods (c),
5	RUC20031 152 & RUC20031 153	1	Ferruginous mudstone to wackestone with quartz grains up to 0.5 mm.	Shell fragments (r) upto 0.8 mm foraminifers: *Miogypsina* (r), gastropod shells (o), echinoderm plates (o).
4	RUC20031 149	32	Bioturbated, ferruginous packstone with bioclasts >5 mm in size and burrow fills.	Gastropod shell fragments up to 2 mm and other shell fragments (c), foraminifers: *Miogypsina* (c), *Lepidocyclina* (c), *Pseudoaberina*? (r), coralline algae (r), ostracods (o).
3	RUC20031 148	22	Packstone, bioclasts up to 3 mm	Bivalve shells (r), gastropod shells (r), shell fragments (c), foraminifers: *Miogypsina* (c), *Lepidocyclina* (c), rotalids (c), echinoderm plates (r), ostracods (o), coralline algae (*Amphiroa*) (r), echinoderm spines (o).
2	RUC20031 147	15	Bioturbated packstone to wackestone with rare ooids.	Shell fragments (c), foraminifers: *Miogypsina* (r), *Lepidocyclina* (r), rotalids (r), echinoderm plates (o), ostracods (c), coralline algae (r).
1	RUC20031 146	10	Bioturbated packstone to wackestone with bioclasts up to size 2 mm and pelloids.	Shell fragments (a), foraminifers: *Miogypsina* (r), *Lepidocyclina* (a), milliolids (r), *Pseudoaberina*? (r), rotalids (r), ostracods (c), coralline algal fragments (*Amphiroa*) (c).

(o)-occur, (r)-rare, (c)-common, (a)-abundant.

sequence is also a poorly washed packstone (biosparite). Quartz grains are absent. The outline of allochems is hazy. Bioclasts are diverse and include foraminifers such as *Miogypsina Lepidocyclina*, rotaliids and ostracods, coralline algal fragments, echinoid and shell fragments. Shell fragments are bored (Pl. III, fig. D).

Fauna

In general, each bed of the ridge section is fossiliferous (Table 2). However, islolated macro-invertebrate fossils were collected from a poorly cemented marly unit, stratigraphically a few meters below the ridge section, exposed in a ditch near the road. The macro-invertebrates collected from the scree of this unit are bivalves and gastropods (bivalves - *Chlamys* (*Chlamys*) sp., *Chlamys* (*Argopecten*) *alexandri* Vredenburg, *Chlamys* (*Argopecten*) *soomrowensis* J de c. Sowerby, *Hyotissa hyotis* (Linné), *Ostrea latimarginata* Vredenburg, *Ostrea khamirensis* Cox, *Nemocardium (Discors)* sp., *Tellina (Lyratellina)* sp., *Paphia* (*Callistotapes*) *virgatus* (J. de C. Sowerby), *Antigona mekranica* (Vredenburg), *Clementia* (*Clementia*) *papyracea* (Gray), gastropods - *Strombus* sp., Cypracid gastropod, *Conus* sp.). The bivalves include infaunal suspension-feeders: *Paphia* (*Callistotapes*), *Venus*, and *Nemocardium*, infaunal deposit-feeder: *Tellina*, deep-burrowing bivalves: *Clementia* and epibyssate suspension-feeder: *Chlamys*.

In addition, shell debris predominantly belonging to bivalves, gastropods, coralline algae (*Amphiroa* sp.), foraminifers, bryozoans, echinoderms, ostracods, etc. have

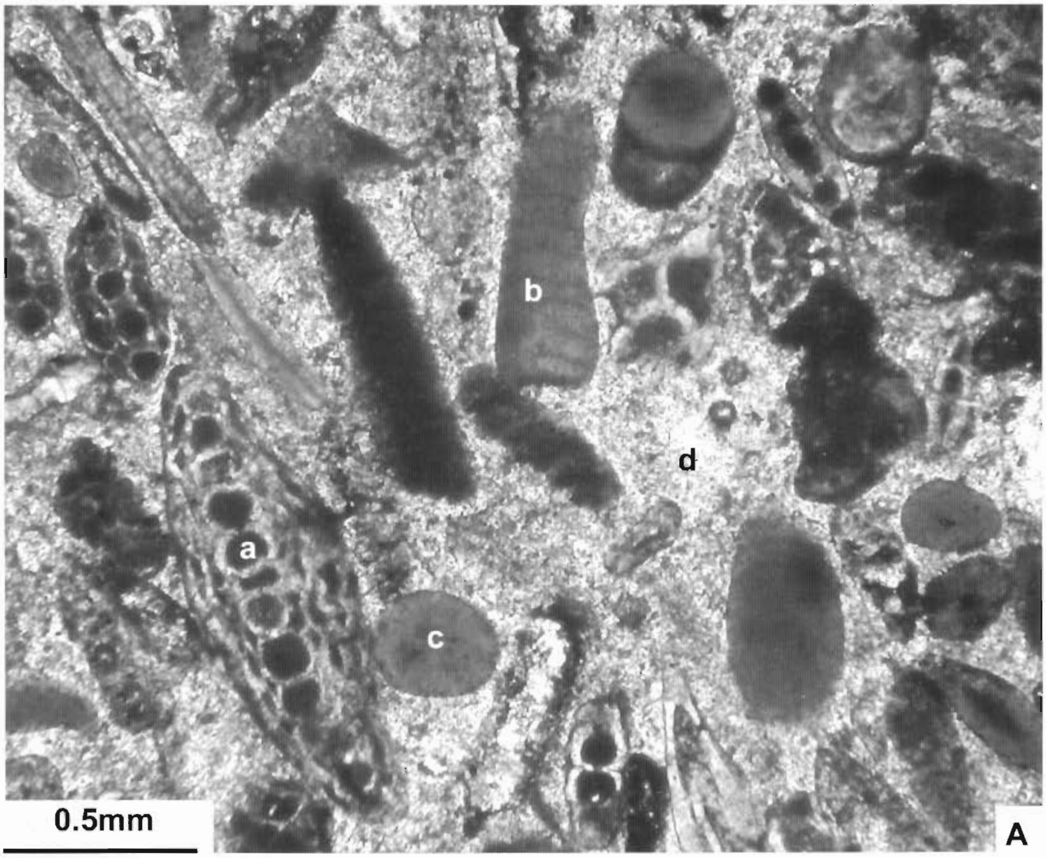
EXPLANATION OF PLATE II

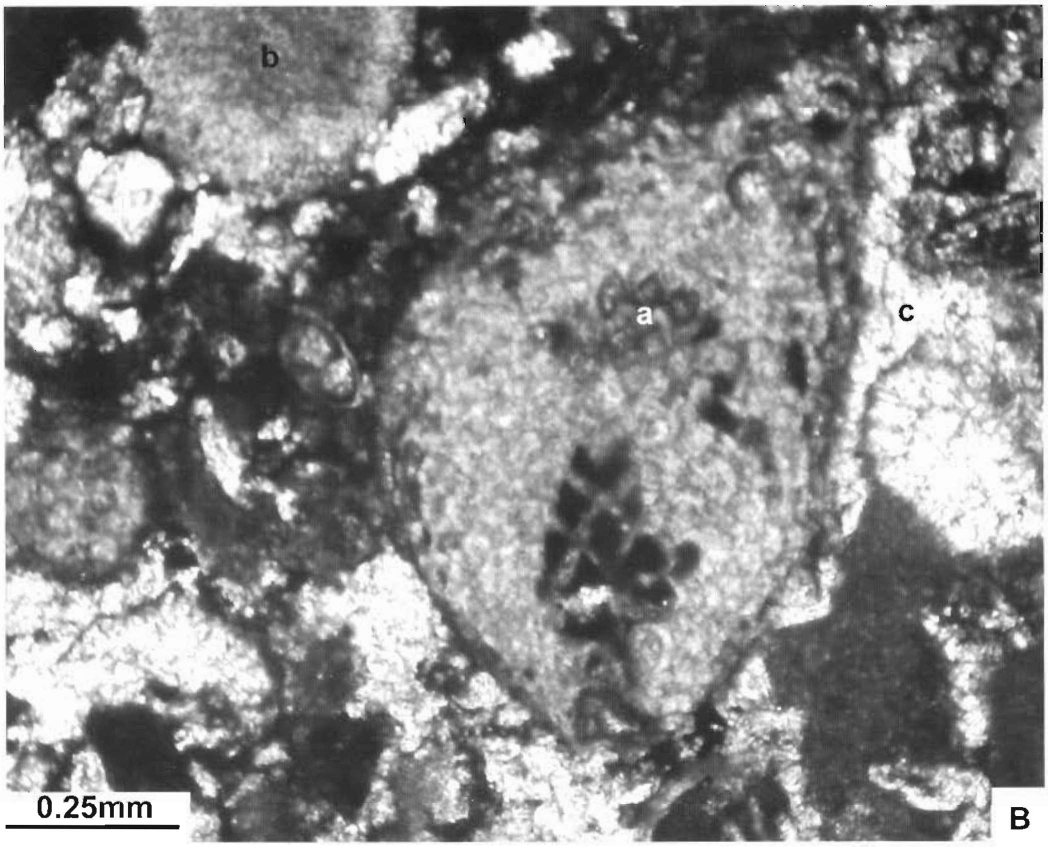
Photomicrographs of the Gaj Formation seen along the Bhatia section (Table 3), exposed along a ridge (about 10 km east of Kuranga village, near Bhatia) crossing the Jamnagar-Dwarka Road, (in plane polarized light).

A. (Bed no. 1; biopelmicrite). The bed mostly consists of diverse bioclasts with sharp outline but heavy iron impregnation. Note the axial sections of the foraminifer genus ***Lepidocyclina*** (a), an articulated coralline algal fragment (b) and a peloid (c) in the micritic groundmass (d).

B. (Bed no. 6; biosparite). In terms of biodiversity the bed is similar to bed no. 1, however, the micritic ground mass is partially washed and the voids are filled up with sparry calcite. Note the equatorial section of the foraminifer genus ***Miogypsina*** (a) and sieve-like structure of an echinoderm plate (b) within a recrystallized sparitic groundmass (c).

Plate II





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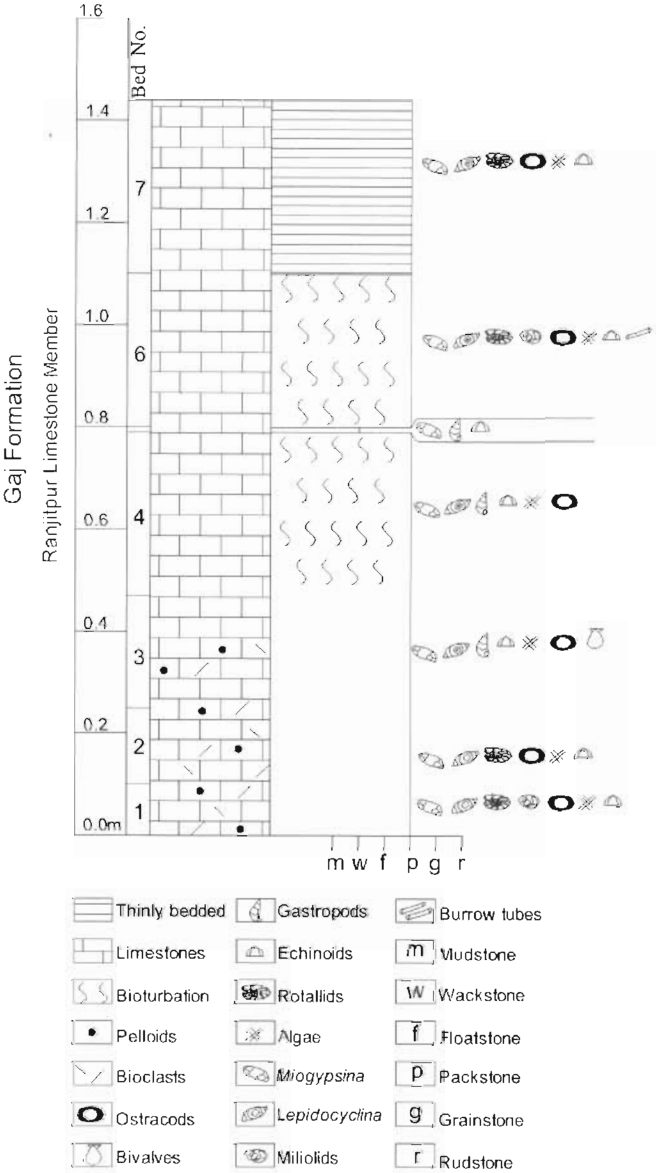


Fig. 3. Ridge section (about 10 Km before Kuranga village, near Bhatia) crossing the road going to Dwarka from Jamnagar.

also been observed in thin-sections. The dominant foraminifers observed in thin-sections include *Miogypsina* and *Lepidocyclina*, rotaliids and miliolids, in descending order of abundance. Most of the fossils seem to be allochthonous as is indicated by their abraded nature and borings found in shell fragments.

SYSTEMATIC DESCRIPTION

In the present work, the systematic classification given by Moore (1960; 1969; 1971), has been adopted. References for taxonomic classification are not included here to limit the number of pages. Please refer to the "Treatise on Invertebrate Paleontology edited by Moore, R. C. (1964 - 1971), for such references.

Class **Bivalvia** Linné, 1758
Subclass **Pteriomorpha** Beurlen, 1944
Order **Pterioida** Newell, 1965
Suborder **Pteriina** Newell, 1965
Superfamily **Pectinacea** Rafinesque, 1815
Family **Pectinidae** Rafinesque, 1815
Genus ***Chlamys*** Röding, 1798

Type Species: *Pecten islandicus* Müller, 1776; SD, Herramannsen, 1847, Recent, North Atlantic.

Chlamys (*Chlamys*) sp.
(Pl. IV, figs. A-E)

Material: Six specimens; three articulated bivalve specimens, two disarticulated right valve specimens and one fragment, from a poorly cemented marly unit of the Gaj Formation (RUC2005I 23-28).

Remarks: Shell small to moderately large, thin, compressed, higher than long. Anterodorsal and posterodorsal, anterior, posterior and ventral margins form an even curve. Auricles unequal, anterior one larger than the posterior one and characterized by a moderately deep byssal notch. Anterior auricle ornamented with radial riblets of equal prominence. Shell valve ornamented with 18-35 primary radial ribs, of which each primary rib exhibits furrow, which becomes a narrow groove towards the ventral margin.

Chlamys quilonensis: Dey (1961, p. 43, Pl. II, figs. 8, 9) from the Miocene of Quilon, Kerala is the closest ally to the present species, but the former exhibits simple rounded ribs. The ornamentation resembles that of *Chlamys (Chlamys) rubida* (Hinds) (MacNeil, 1967, p. 21, Pl. XX, fig. 7) from the Cenozoic of Alaska, but the latter has more number of radial ribs. The present specimen resembles *Chlamys* (*Chlamys*) *bhatiyaensis* described by Jain (1997: 60), however, unpublished.

Suborder **Ostreina** Ferussac, 1822
Superfamily **Ostreacea** Rafinesque, 1815
Family **Gryphaeidae** Vyalov, 1936
Subfamily **Pycnodonteinae** Stenzel, 1959
Genus ***Hyotissa*** Stenzel, 1959

Type species: *Mytilus hyotis* Linné, 1758.

Hyotissa hyotis (Linné, 1758)
(Pl. IV, fig. Q)

Material: Three specimens from a poorly cemented marly unit of the Gaj Formation (RUC2005I 06-8).

Remarks: Of the three specimens, one is articulated with almost equal valves and the other two are fragmentary. The external surface of both valves is covered with conspicuous, irregular, radial plicate ribs crossed by squamae, which at places developed into prominent spines.

Family Ostreidae Rafinesque, 1815
Subfamily **Ostreinae** Rafinesque, 1815
Genus ***Ostrea*** Linné, 1758

Type species: *Ostrea edulis* Linné, 1758; SD, Recent, England.

Ostrea latimarginata Vredenburg, 1908
(Pl. IV, figs. Sa,b, T)

Material: Five specimens; two isolated left valves and three right valves from a poorly cemented marly unit of the Gaj Formation (RUC2005I 01-05).

Remarks: Both the left valve specimens show long unequal, rounded radial ribs interrupted by frilled delicate growth squamae on the external surface and a ligament groove along the ventral margin of the dorsal part in the internal surface. Both the specimens agree well with the species with respect of ornamentation and suborbicular outline. The other closely comparable species is *Ostrea angulata* J. de C. Sowerby, which differs from the present species in its postero-lateral angulation of the left valve. The right valves are thin, small and exhibit

Table 3 : Petrographic description of lithic-units of the Gaj Formation exposed along a ridge (about 10 km east of Kuranga village, near Bhatia) crossing the road going to Dwarka from Jamnagar.

Bed no.	Quartz (Size, Shape, %)	Allochems (size, shape & %)			Contact/ Grain boundary	Groundmass / Porosity	Fossils	Texture / Descriptive name
		Bioclasts	Intraclasts/ Extraclasts	Coated grains/ Pelloids				
7	-	0.7 - 3mm. up to 50%, few >7mm and bored	Sparitic up to 20%. (0 5mm-1mm in size)	Pelloids (up to 0.4mm) (r)	Hazy	Micritic. poorly washed. filled with sparite. cavities up to 2mm	*Miogypsina* sp. (c). *Lepidocyclina* sp. (c). rotalids (r). ostracods (o), coralline algae (o). echinoderm spines (o). bored shell fragments (c)	Packstone /Biosparite
6	-	0.5mm-3mm. up to 50%	Intraclasts are sparitic up to 1mm. extraclasts are micritic up to 2mm	Radial ooids up to 3mm	Hazy	Micritic. poorly washed. filled with sparite	*Miogypsina* sp. (c). *Lepidocyclina* sp. (a). miliolids (r). rotalids (r). ostracods (r). echinoderm plates (r)	Packstone- Wackestone/ Biosparite
5	0.1-0.5mm. angular. up to 3%	0.2 -1.1mm, up to 1%	Ferruginous, micritic to sparitic 0.5-2.2mm (>5mm), up to 30-40%	-	Hazy	Micritic	*Lepidocyclina* sp. (r), shell fragments (r). up to 0.8mm. echinoderm spines (o)	Mudstone-Wackestone/Bio-micrite
4	-	0.8mm-3.5mm (>4mm occur)	Intraclasts iron impregnated, sparitic, (0.5mm-1mm) up to 1%	Pelloids (0.5mm) up to 1%	Hazy	Micritic with iron impregnation	*Miogypsina* sp. (c). *Lepidocyclina* sp. (c), *Pseudotaberina* sp (r). ostracods (r), bryozoans (r). coralline algae (r). gastropod shell fragments (2mm), shell fragments >4mm (c)	Packstone /Biomicrite
3	0.1mm. angular. <1%.	0.5-2.5mm (>5mm), up to 50%	Intraclasts sparitic (0.5mm) up to 1%	Pelloids (0.5mm). up to 20-30%	Point/ sharp outline	Micritic	*Miogypsina* sp. (c). *Lepidocyclina* sp. (c). *Pseudotaberina* sp. (c), miliolids (c). rotalids (c). ostracods (r). amphiroa (algae) (r). coralline algae (c), echinoderm spines (r). bivalve shells (r). gastropod shells (r), shell fragments (c)	Packstone/ Biopelmicrite
2	-	0.5mm-2mm. up to 50-80%	Sparitic (up to 0.3mm). up to 10%	Pelloids (0.2mm). up to 3%	Hazy	Micritic	*Miogypsina* sp. (r), *Lepidocyclina* sp. (r), ostracods (c). coralline articulated algae (r). rotalids (r). echinoderm plates (o), shell fragments (c)	Packstone-Wackestone/ Biomicrite
1	-	0.5 - 3mm. up to 50 - 80%	Sparitic. iron impregnated. (up to 0.5mm), up to 1%	Pelloids (0.2mm). up to 20-30%	Point/ sharp outline	Micritic	*Miogypsina* sp. (r), *Lepidocyclina* sp. (a). *Pseudotaberina* (r). articulated coralline algae (c), rotalids (r). ostracods (c). shell fragments (a)	Packstone-Wackestone/ Biopelmicrite

(r)-rare. (o)-occur. (c)-common. (a)-abundant.

fine concentric ornamentation.

Ostrea khamirensis Cox, 1936
(Pl. IV, figs. Ra, b)

Material: Seven specimens from a poorly cemented marly unit of the Gaj Formation (RUC2005I 09-15).

Remarks: Out of the seven specimens, one is complete, one is left valve, a right valve, the rest are fragmentary. The valves are thick, almost equal in size and exhibit fine lamellar ligament grooves along the anterior and posterior margin. The specimens match well with *Ostrea khamirensis* (Cox, 1936, p. 35-36, Pl. V, figs. 2-4).

Subclass **Heterodonta** Neumayr, 1884
Order **Veneroida** Adams and Adams, 1856
Family **Cardiidae** Lamarck, 1809
Subfamily **Protocardiinae** Keen, 1951
Genus ***Nemocardium*** Meek, 1876

Type species: *Cardium semiasperum* Deshayes, 1858 ; SD, Sacco, 1899, Eocene, France.

Subgenus ***Discors*** Deshayes, 1805,

Type species: *Cardium discors* Lamarck, 1805.

Nemocardium (Discors) sp.
(Pl. IV, fig. L)

Material: Single articulated specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 17).

Remarks. The lone specimen is poorly preserved; however, the remnants or ornamentation suggest the subgenus *Discors*. The radial ornamentation is incised and conspicuous only on the concentric ribs; consequently, the concentric ribs appear broken and giving appearance of rectangular granules. *Nemocardium* (*Discors*) *triforme* (J. de C. Sowerby) (1840, Pl. XXII, fig. 11) is the closest comparable species in shape and proportionate dimensions; however, the umbones are median in the present specimen. The poor state of preservation does not allow for specific identification.

Superfamily **Tellinacea** de Blainville, 1814
Family **Tellinidae** de Blainville, 1814
Subfamily **Tellininae** de Blainville, 1814
Genus ***Tellina*** Linné, 1758

Type species: *Tellina radiata* Linné, 1758; SD, Children, 1823; Recent, West Indies.

Subgenus ***Acropegia*** Brown, 1827

Type species: *Tellina* (*Acropegia*) *crassa* 1777; SD, Recent, Mediterranean.

Tellina (*Acropegia*) sp.
(Pl. IV, fig. H)

Material: One poorly preserved specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 16).

Remarks: The lone specimen in the present collection is of medium size, thin and subelliptical in outline with acutely rounded anterior margin and obtusely rounded posterior margin. Umbones less pronounced, prosogyrate. Lunule small, well defined and escutcheon elongate. External surface ornamented with very faint concentric ribs.

Thin shell, faint ornamentation and nature of umbones suggest an assignment of the present specimen to *Tellina* (*Acropegia*). The poor preservation does not allow any further identification.

Family **Veneridae** Rafinesque, 1815
Subfamily **Tapetinae** Rafinesque, 1815
Genus ***Paphia*** Röding, 1798

Type species: *Paphia alapapilionis* Röding 1798; SD, Dall, 1902, Recent, West Pacific.

Remarks: *Paphia* is similar to *Tapes*, however, *Tapes* ranges from the Pleistocene to Recent only (Davies, 1971).

Subgenus ***Callistotapes*** Sacco, 1900

Type species: *Venus vetula* Basterot, 1825; OD

Remarks: *Callistotapes* differs from *Paphia* s.s. with respect to the presence of concentric ornamentation (Davies, 1971).

Paphia (*Callistotapes*) *virgatus* (J. de C. Sowerby, 1840)
(Pl. IV, figs. F a-b, G)

Material: 14 articulated specimens from a poorly cemented marly unit of the Gaj Formation (RUC2005I 42-55).

Remarks: All the specimens in the present collection are articulated bivalves. Therefore, it is not possible to observe the dentition. The two species of *Paphia* (*Callistotapes*) described by Jain (1997) differ from each other on the basis of ornamentation and shape. *Paphia* (*Callistotapes*) *virgatus* (J. de C. Sowerby) exhibits distinct, fine, deeply incised, concentric ornamentation, whereas the external surface of *Paphia* (*Callistotapes*) *pseudoliratus* Vredenburg (1928) shows indistinct concentric ornamentation. In addition, the shell outline of *pseudoliratus* is transversely ovate in contrast to the subtrigonal outline of *virgatus*. The outline is dictated by the position of umbo, which in many Jurassic to Recent bivalve genera vary from median to subterminal or even terminal position (Kanjilal, 1980).

Subfamily **Venerinae** Rafinesque, 1815
Genus ***Antigona*** Schumacher, 1817

Type species: *Antigona lamellaris* Schumacher, 1817; OD,

EXPLANATION OF PLATE III

Photomicrographs of the Gaj Formation seen along the Bhatia section (Table 3), exposed along a ridge (about 10 km east of Kuranga village, near Bhatia) crossing the Jamnagar-Dwarka Road, (in plane polarized light).

A. (Bed no. 3; biopelmicrite). A transverse section of a crinoidal plate impregnated with opaque material (iron oxide). The sieve-like structure of the original plate can be seen.

B. (Bed no. 1; biopelmicrite). A close view of an articulated ostracod filled with micritic groundmass. The slightly different size of the two valves is evident.

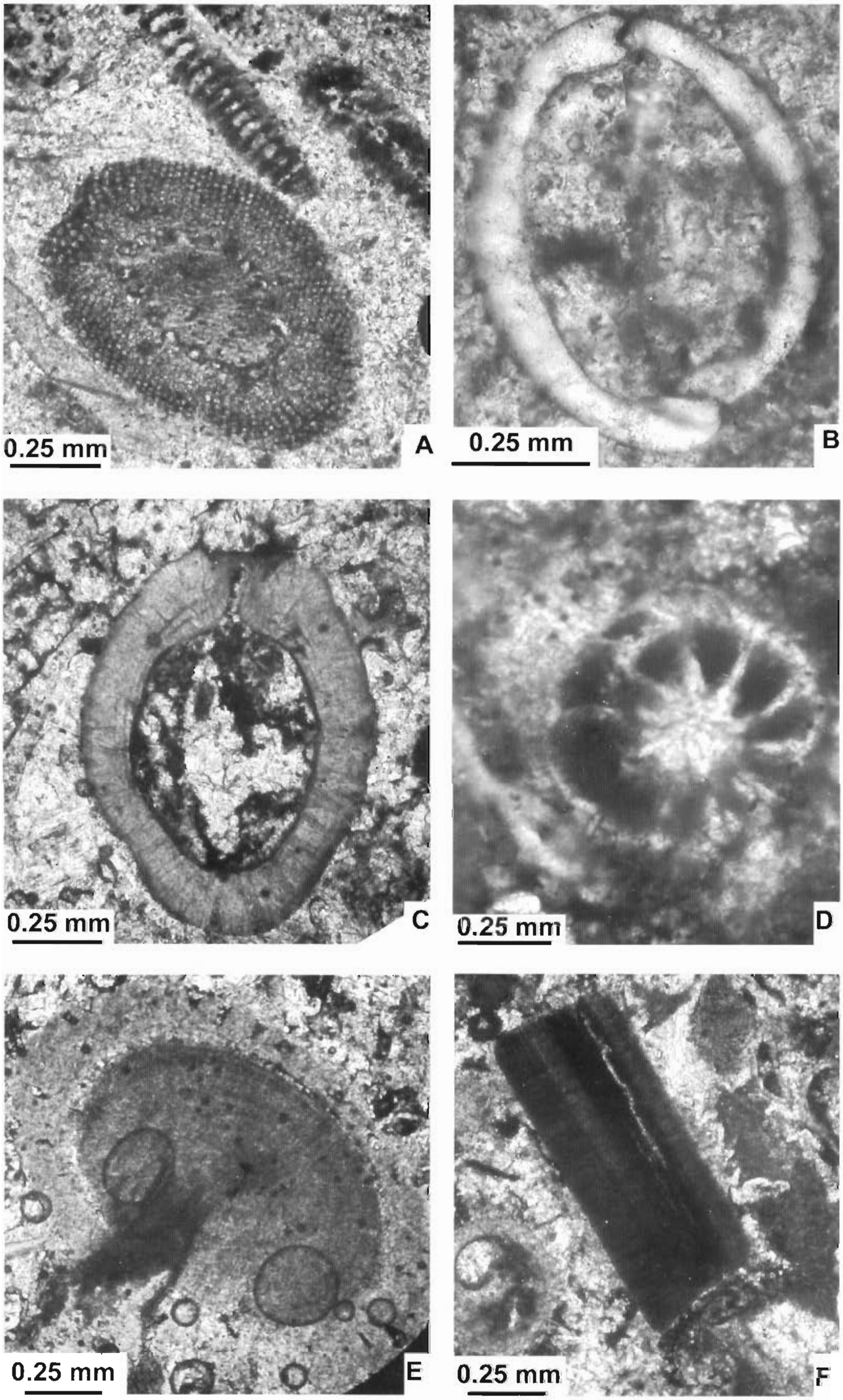
C. (Bed no. 6; biosparite). A close-up view of an articulated ostracod carapace. Note the traces of radial pore canals.

D. (Bed no. 7; biosparite). A close-up view of a rotalid (circular in outline with heavy iron impregnation. Note the planispiral arrangement of chambers.

E. (Bed no. 6; biosparite). A close-up view of a radial ooid, with sample indistinct concentric rings.

F. (Bed no. 6; biosparite). A close-up view of a longitudinal section of an echinoderm spine embedded in recrystallized micritic groundmass. The hollow center as well as the pore spaces are filled up with iron oxide.

Plate III



Recent, East Indies.

Antigona mekranica (Vredenburg, 1928)
(Pl. IV, fig. M)

Material: One articulated specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 18).

Remarks: One of the commonly occurring genera in the Gaj Formation of Saurashtra is represented by two species. *Antigona granosa* Sowerby (Jain, 1997, p. 138) differs from the present species in the presence of distinct and regular concentric ornamentation and granules at the intersection of radial and concentric components of the ornamentation. In addition, *mekranica* is more orbicular and the concentric lines are less uniform.

Subfamily **Clementiinae** Fizzell, 1936
Genus ***Clementia*** Gray, 1842

Type species: *Venus papyracea* Gray, 1825; SD, Gray, 1847, Recent, Pacific.

Remarks: *Clementia* from the Miocene of Saurashtra are more posteriorly elongated than their corresponding Recent forms (Davies 1971: 255, fig. 586c)

Clementia (*Clementia*) *papyracea* (Gray, 1847)
(Pl. IV, figs. I-K)

Material: 11 articulated specimens from a poorly cemented marly unit of the Gaj Formation (RUC2005I 19, 29-41).

Remarks: Externally, *Clementia* distinguished from *Paphia* described above by its coarse commarginal corrugations. The external surface exhibits 18 to 20 concentric ribs. Jain (1997, p. 149) described a new species *Clementia* (*Clementia*) *lowraliensis* on the basis of smaller number of concentric ribs (16) more or less of the same size. In addition, *lowraliensis* is more equilateral and taller.

Class **Gastropoda** Cuvier, 1797
Subclass **Prosobranchia** Milne Edwards, 1848
Order **Mesogastropoda** Thiele, 1925
Family **Strombidae** Refinesque, 1815

Genus ***Strombus*** Linné, 1758

Type species: *Strombus pugilis* Linné; SD, Montfort, 1810.

Strombus sp.
(Pl. IV, fig. P)

Material: One specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 21).

Remarks: The lone poorly preserved specimen is an internal cast, which exhibits conical spire and large body whorl. The stromboid notches or nodes are not preserved.

Family **Cypraeidae** Refinesque, 1815
Genus ***Cypraea*** Linné, 1758

Type species: *Cypraea tigris* Linné, 1758; SD, Montfort, 1810. Recent, Indo-Pacific.

A Cypraeid gastropod
(Pl. IV, fig. N)

Material: One specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 20).

Remarks. The ovate shape, medium size, feebly rostrate anterior and posterior, moderately convex ventral and dorsal margins are well discernible in the specimen.

EXPLANATION OF PLATE IV

Macro-invertebrate fossils collected from a poorly cemented marly unit stratigraphically few meter lower than the ridge section of the Ranjitpur Limestone Member of the Gaj Formation exposed along a ridge (about 10 km east of the Kuranga village, near Bhatia) crossing the Jamnagar-Dwarka Road; scale bar 10mm.

7A-E. ***Chlamys (Chlamys)*** sp. (RUC2005I 23-24, 26-28). Note 18-35 simple rounded ribs with equal interspaces.
- A (RUC2005I 26), external view of a juvenile right valve
- B (RUC2005I 27); (a) external view of right valve. Note anterior auricle exhibiting deep sulcus, (b) dorsal view of an articulated bivalves shell.
- C (RUC2005I 28), external view of left valve of an articulated bivalves.
- D (RUC2005I 24), external surface. Note tripartite nature of ribs.
- E (RUC2005I 23), external view of right valve. Note unequal auricles, anterior one larger than the posterior one, the primary radial ribs exhibiting a furrow.

7F-G. ***Paphia (Callistotapes) virgatus*** (J. de C. Sowerby, 1840) (RUC2005I 42-43), articulated bivalves showing distinct fine deeply incised concentric ornamentation
- F (a) dorsal view, (b) external view of right valve.
- G external view of left valve.

7H. ***Tellina (Acropegia)*** sp. (RUC2005I 16), external view of right valve showing very faint concentric ribs.

7I-K. ***Clementia (Clementia) papyracea*** (Gray, 1847) (RUC2005I 29-31), articulated bivalve specimens showing 18 to 20 concentric ribs.
- I external view of left valve.
- J (a) external view of right valve, (b) dorsal view.
- K external view of left valve.

7L. ***Nemocardium (Discors)*** sp. (RUC2005I 17), external view of left valve of an articulated specimen. The radial ornamentation is incised and conspicuous only on the concentric ribs, consequently the concentric ribs appear broken the giving appearance of rectangular granules (not visible in the photograph).

7M. ***Antigona mekranica*** (Vredenburg, 1928) (RUC2005I 18), external left valve view showing orbicular outline.

7N. A **Cypraeid gastropod** (RUC2005I 20), note ovate shape, medium size and feebly rostrate anterior and posterior.

7O. ***Conus*** sp. (RUC2005I 22), note conical shape, flat spire and long and narrow aperture of the shell.

7P. ***Strombus*** sp. (RUC2005I 21) an internal cast showing conical spire and large body whorl.

7Q. ***Hyotissa hyotis*** (Linne', 1758) (RUC2005I 6), external left valve view of an articulated bivalve shell showing conspicuous, irregular, radial plicate ribs crossed by squamae, which at places developed in to prominent spines.

7R. ***Ostrea khamirensis*** Cox, 1936 (RUC2005I 9), an articulated bivalve shells, the valves are thick and almost equal in size (a) – external left valve, (b) - external right valve.

7S-T. ***Ostrea latimarginata*** Vredenburg, 1908 (RUC2005I 01-05).
- S (a) RUC2005I 1; external left valve view showing long unequal, rounded radial ribs interrupted by frilled delicate growth squamae, also note suborbicular outline, (b) internal left valve view showing ligament groove along the ventral margin of the dorsal part in the internal surface
- T RUC2005I 2; external view of left valve.

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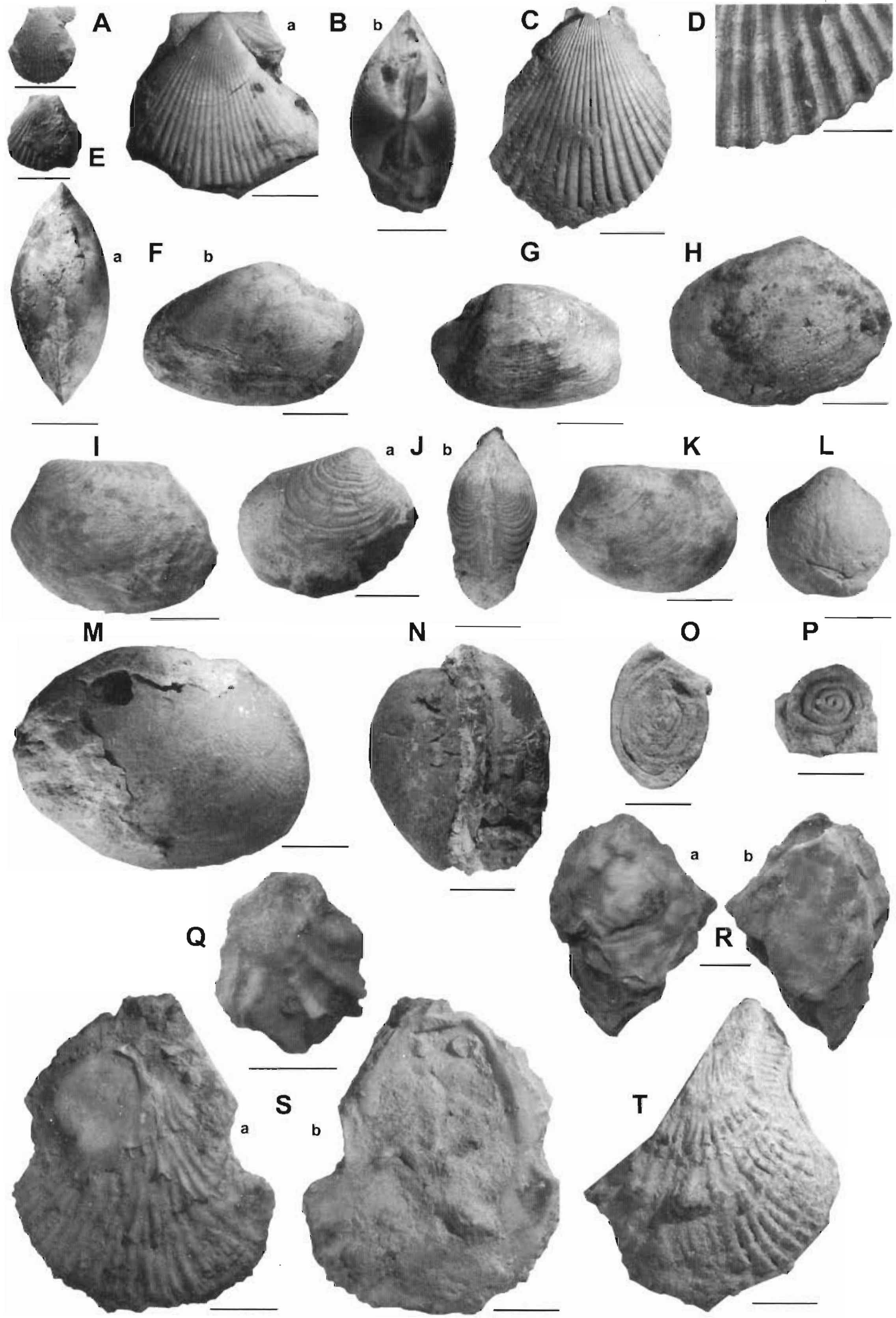
Plate IV



PANDEY, KONDO, JAIN, TEJ BAHADUR AND PRADHAN1

Family **Conidae** Fleming, 1822
Genus ***Conus*** Linné, 1758.

Type species: *Conus marmoreus* Linné, 1758 ; SD, Children, 1823.

Conus sp.
(Pl. IV, fig. O)

Material: One specimen from a poorly cemented marly unit of the Gaj Formation (RUC2005I 22).

Remarks: The conical shape, flat spire and long and narrow aperture of the shell allow the present specimen to be assigned to *Conus*. In view of the poor preservation, no further identification is possible.

DEPOSITIONAL ENVIRONMENT OF THE GAJ FORMATION

The Gaj Formation of the Bhatia section represents an advanced phase of the first marine transgression of the sea during the Neogene onto the Saurashtra Peninsula at the beginning of the Miocene. The earliest sediments of this transgressive event are not exposed in the section. The later phases of the transgression are characterized by erosional surfaces between successive units. Near the basin margin, in shallow water above the fair weather wave base, one would generally expect features indicative of high-energy conditions such as cross-stratification, pebbles, and terrigenous sediments, etc. during the transgression. Such features are absent in the exposed succession, which represents environments near to or below the fair weather wave-base. Alternatively, the erosional surfaces could be explained by storm action. However, no features characteristic of tempestite could be found in the section.

Clementia papyracea is a species still living in muddy or sandy bottom of shallow waters, often found at the depth of 28-87 m in the Indo-West Pacific (Zhongyan, 2004). *Hyotissa hyotis* is also found living on coral reefs in shallow waters in Hainai Province of China, Philippine and Japan (Zhongyan, 2004).

The measured section begins with a packstone (biopelmicrite), with a moderately high diversity of bioclasts. The presence of a micritic groundmass, suggests a low-energy environment. *Miogypsina* and *Lepidocyclina* are characteristic of marine environment. The radial ooids, although not in-situ, point to low-energy environment. The absence to very low percentage of terrigenous quartz suggests an offshore area, only little influenced by terrigenous sediments. The dominance of bioturbated units, absence of any sedimentary structures indicative of low-energy conditions also support the conclusion that the sediments were deposited below fair-weather wave-base in an offshore area.

In general, the remaining beds are similar to the basal bed except that bioturbation is more evident (see Pl. I, fig. A) and the diversity of the bioclasts is low. Bed no. 5 conspicuously differs from the remaining units. The common faunal components such as *Miogypsina*, *Lepidocyclina*, ostracods, coralline algae, rotaliids, *Pseudotaberina*, etc., are absent from this unit. Moreover, this bed is an intramicrite. The sudden change of allochems from bioclasts to intraclasts indicates winnowing of semi-lithified sediments possibly during a transgressive event. Temporal variation of textures, i.e. from wacke- to packstone (bed no. 1) to packstone with larger shell fragments >4mm (bed no. 4) and from mud- to wackestone (bed no. 5) to packstone (bed no. 7) suggests at least a twofold change of energy level from low (bed nos. 1 and 5) to moderately high (bed nos. 4 and 7). The grain boundaries are not as sharp as in the lower part of the section. Iron impregnation of the bioclasts including foraminiferal tests refers to reworking and low rates of net sedimentation during the deposition of the lower part of the section. The presence of black extraclasts of igneous origin in the top beds of the upper part of the section (Bed nos. 6 & 7), thinly bedded nature of the topmost unit (Bed no. 7) with scattered burrow fill structures, poorly preserved bioclasts (some >7 mm in size), occurrence of rootlets up to 25 mm and articulated coralline algae suggest shallow, well-lit, rather protected water conditions very near to the shore.

The mixed bivalve species composition (including pectinids and infaunal bivalves - listed above and illustrated on Fig. 7) and their abundance, in the poorly cemented marly unit, stratigraphically a few meters below the measured ridge section, indicates sediment-starved condition in maximum flooding zone (MFZ) on the continental shelf below fair-weather wave base. This may correspond to the first sequence cycle, where sediments corresponding to transgressive systems tract (TST) and that of high stand systems tract (HST) are either not exposed or could not be preserved. The successive changes in the lithology and fossil contents in the overlying units (Bed nos. 1-5) have been interpreted as to represent transgressive systems tract and highstand systems tract (Bed nos. 6 & 7) of the second sequence cycle. The Bhatia Ridge Section is thus interpreted to represent parts of two sequence cycles.

AGE

The Gaj Formation is characterized by rich assemblages of molluscs and foraminifera. The foraminifera were studied by Chatterji *et al.* (1953), Mohan and Chatterji (1956) and Bhatia and Mohan (1959). They noted presence of age-diagnostic species of larger foraminifera, e.g. *Pseudotaberina malabarica* (Carter), *Austrotrillina howchini* (Schlumberger), *Miogypsina* (*Lepidosemicyclina*) *polymorpha* Rutten, *Miogypsina* (*Lepidosemicyclina*) *thecideaeformis* Rutten and *Miogypsina irregularis* (Michelotti). These workers considered the Gaj Formation to be of Burdigalian age on the basis of above foraminiferal species.

These species have now been examined in terms of precise biochronostratigraphic framework by Adams (1984) and Boudagher-Fadel and Banner (1999). Their revised correlations indicate correspondence between Letter Stages of the Far East and Neogene planktic foraminiferal zones correlated to European stages. *Miogypsina* (*L.*) *polymorpha* (Rutten) and *Miogypsina* (*L.*) *thecideaeformis* are long-ranging Miocene species, i.e. Te5 to Tf2 Letter Stages, corresponding to planktic foraminifera Zone N5 to Zone N7/8, ? N12 (Aquintanian-Serravallian). *Pseudotaberina malabarica* and *Austrotrillina howchini*, however, are useful marker species. The correlation by Boudagher-Fadel and Banner (1999) indicate precise biostratigraphic position of these taxa. *Pseudotaberina malabarica* ranges from Zone N5 to Zone N7, i.e. the latter part of Upper Te to Lower Tf1, and *Austrotrillina howchini* appears at the base of the Zone N7 and extends to the top of Zone N9, i.e. Lower Tf1 to Upper tf1. The age assignment based on occurrence together of the two taxa suggests that the Gaj Formation in the study area corresponds to the latter part of uppermost Upper Te to Lower Tf1 Letter stages; in terms of planktic foraminiferal biochronology, it would correspond to N6-N7, i.e. late Burdigalian.

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