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Nummulitids, lepidocyclinids and Sr-isotope data from the Oligocene of Kutch (western India) with chronostratigraphic and paleobiogeographic evaluations

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ABSTRACT

Due to its intermediate geographical position between the Mediterranean and W Pacific, the Oligocene shallow-marine sequence of Kutch (India) is of key importance in paleobiogeographical interpretations. Larger benthic foraminifera (LBF) are a fundamental link for the correlation between the Mediterranean shallow benthic zones (SBZ) and the W Pacific 'letter stages'. LBF were re-evaluated by morphometric studies of the internal test from five stratigraphic sections of the Maniyara Fort Formation. Based on their significant affinity to coeval fauna in the Mediterranean, they were assigned to W Tethyan SBZ zones, supported by Sr-isotope stratigraphy. In the Basal Member, traditionally considered as early Rupelian, we identified *Nummulites bormidiensis*, *N. kecskemetii* and *Heterostegina assilinooides* assigning it to the early Chattian SBZ 22B Zone. The Coral Limestone Member, previously considered as late Rupelian, is also assigned to this zone, for the presence of *N. bormidiensis*, *Eulepidina formosoides-dilatata* and *Nephrolepidina morgani-praemarginata*. Its early Chattian age (26.5–29 Ma) is further supported by Sr-isotope data. *Miogypsinoides complanatus* and *Spiroclypeus margaritatus* in the Bermoti Member (the top of the formation) document the late Chattian SBZ 23 Zone and the Sr-isotope data (22.5–24 Ma) place it close to the Oligocene–Miocene boundary.

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Introduction

The 30–35 m thick Oligocene succession of the Maniyara Fort Formation (Kutch Basin, western India) represents a mixed carbonate-siliciclastics sequence deposited in a shallow marine setting on the western margin of the Indian subcontinent. It is very rich in larger benthic foraminifera (LBF), whose distribution – according to most previous works (as summarized e.g. by Biswas, 1992; Raju, 2011 and Catuneanu & Dave, 2017) – covers almost the entire duration of the Oligocene period. Taking into account its intermediate geographical position between the peri-Mediterranean–European (Western Tethyan) and West Pacific realms (we use this term instead of the Indo-Pacific because this latter includes Kutch, whose paleobiogeographic affinity is one of the major issues of our paper), the Kutch Basin is a crucial link to establish a correlation between their LBF zonations, namely the Shallow Benthic Zone (SBZ) scheme proposed by Cahuzac and Poignant (1997) for the Western Tethys and the so-called 'East Indian Letter classification' for SE Asia (see Renema, 2007, for a recent revision).

According to Biswas (1992) and Saraswati, Khanolkar, and Banerjee (2018), the Maniyara Fort Formation overlies

paraconformably (in most cases but locally disconformably) the middle Eocene (Bartonian) Fulra Limestone Formation and is overlain by the Aquitanian Khari Nadi Formation, with a slight or inconspicuous erosional unconformity. The formation is subdivided into four members, which are, from bottom to top (thicknesses are those given by Biswas, 1992; although they are slightly variable, while fossil names are those used by Raju, 2011):

- The *Basal Member* (4–4.5 m thick), whose larger foraminiferal assemblages mainly consist of reticulate *Nummulites* (commonly assigned to *N. fichteli*), and subordinate *Heterostegina* (usually assigned to *H. borneensis*) and *Operculina* (*Op. complanata*).
- The locally missing *Lumpy Clay Member* (ca. 4.5 m thick), with only sporadic reticulate *Nummulites* or even totally barren of LBF.
- The *Coral Limestone Member* (about 10 m thick), with reticulate *Nummulites* (frequently with apical mamelon, described as *N. clipeus* by Nuttall, 1925) and *Operculina* (both continuing from the Basal Member), frequent *Eulepidina*, rare *Nephrolepidina* and no *Heterostegina*.

- (d) The ca. 12 m thick *Bermoti Member* (lying with erosional gap on the Coral Limestone Member), with common *Spiroclypeus* (assigned to *S. ranjanae*) and sporadic *Nephrolepidina* at the top and rare *Heterostegina* (*H. borneensis*) in the lower part. *Planolinderina* occurs throughout the vertical extent of this member, while *Miogypsinoidea* is only found in the upper two-third.

Biswas (1992) placed the lower three members into the regional Ramanian stage, which he correlated with the Rupelian, whereas the Bermoti Member corresponds to the Waiorian stage, which he correlated with the Chattian. The Biswas (1992) correlation is further detailed and slightly modified by Raju (2011), who placed the Rupelian/Chattian boundary in the lowermost part of the Waiorian. In the sequence stratigraphic interpretation by Catuneanu and Dave (2017), these two regional stages correspond to two unconformity-bounded third-order sequences.

The correlation of the regional stages of the Oligocene of the Kutch Basin with the standard chronostratigraphy by means of LBF is plagued by several problems. The Oligo-Miocene larger foraminiferal zonation for the Indian subcontinent by Raju (2011), which is largely based on morphometrically analyzed miogypsinids, cannot be fully applied, since there are no miogypsinids in the lower two-third of the Oligocene, during which nummulitids and lepidocyclinids are the most common LBF. Moreover, the Oligocene LBF of the Kutch Basin were mostly determined typologically (with the exception of *Nephrolepidina*, studied by van Vesse, 1978 and Saraswati, 1994, 1995), while the most widely used LBF biostratigraphic schemes are based on morphometrically defined chrono-species (see Pignatti & Papazzoni, 2017). Reuter, Piller, Harzhauser, and Kroh (2013) recently assigned the Coral Limestone to the early Chattian SBZ 22B Zone and the Bermoti Member to the late Chattian SBZ 23 Zone. However, they provided only a list of LBF with neither description nor illustration.

There is no comprehensive study on the LBF in the Oligocene of the Kutch Basin. The majority of previous works is concentrated on reticulate *Nummulites* (Dasgupta, 1970; Mohan, 1965; Nuttall, 1925; Sengupta, 2000, 2002; Sengupta, Sarkar, & Mukhopadhyay, 2011; Sengupta, Sarkar, & Syed, 2014; Sengupta, Syed, & Sarkar, 2015). Rare striate *Nummulites*, reported from the Basal Member by Shukla (2008) under the name of *N. vascus*, were later determined as *N. sp. aff. chavanesi* by Sengupta (2009). Saraswati (1994, 1995) and Muthukrishnan and Saraswati (2001) examined lepidocyclinids, while Tewari (1956) described *Spiroclypeus* from the top of the Bermoti Member under the name of *Sp. ranjanae*, which was followed by all the subsequent authors. Singh and Raju (2007) morphometrically described a single population of *Heterostegina borneensis* from the lower part of the Bermoti Member, while the

very common *Heterostegina* assemblages from the Basal Member have never been studied. Genus *Operculina* has also never been examined on morphometrical grounds. The paleoecology of Oligocene LBF from the Bermoti Member (and also from the Miocene sequence of Kutch) was studied in most details by Kumar and Saraswati (1997).

In addition to the problems posed by the incomplete knowledge of the LBF fauna, a major issue hindering the correlation of the Oligocene of Kutch with other regions is the absence of planktonic foraminifera, and the lack of studies on calcareous nannoplankton. Based on Raju (2011), the only available independent tie-point for the chronostratigraphic calibration of the LBF biostratigraphy is the presence of *Globigerinoides primordius* Blow & Banner in the level marked by the first appearance of *Miogypsina* (*Miogypsinoidea*) *bermudezi* Drooger (the forerunner of the main *Miogypsinoidea*-*Miogypsina* lineage of the Tethys – for more details see Drooger & Raju, 1978).

In the last decade, we applied the morphometric methods for nummulitids and lepidocyclinids in studying Oligocene and lower Miocene rocks of Turkey (Özcan & Less, 2009; Özcan, Less, Báldi-Beke, & Kollányi, 2010a; Özcan, Less, Báldi-Beke, Kollányi, & Acar, 2009a; Özcan, Less, & Baydoğan, 2009b), which allow us a correlation and comparison of the results with the Oligocene LBF from Kutch. The morphometrically defined *Nummulites fabianii* – *fichteli* lineage that has helped in assigning the shallow benthic zones of Serra-Kiel et al. (1998) and Cahuzac and Poignant (1997) in the Bartonian to early Chattian time span (Özcan et al., 2009a) in Western Tethys is still to be recognized in Indian subcontinent. As a result, while a more advanced (than *N. fichteli*) form is identified as *N. bormidiensis* with distinct biostratigraphic implications, the advantage of morphometrically splitting the two species is yet to be explored in Indian Oligocene successions.

In the present study, we perform a morphometric analysis of the nummulitids and lepidocyclinids from the Oligocene succession of Kutch and compare them with the assemblages of Western Tethys. In the absence of planktonic foraminiferal and calcareous nannoplankton data, Sr-isotope stratigraphy is applied as an independent tool of correlation and chronostratigraphic calibration between the Kutch and Western Tethyan Oligocene LBF assemblages.

Material

Morphometric analysis of LBF is based on samples coming from five sections (Kharai, Waior, Bermoti, Lakhpat and Walasara) (Figures 1 and 2), while Sr-isotope stratigraphy (SIS) was applied only in the first three sections, due to the lack of suitable material in the last two profiles.

The Kharai section (Figures 2(A–C) and 3), in which the disconformable deposition of the Maniyara Fort

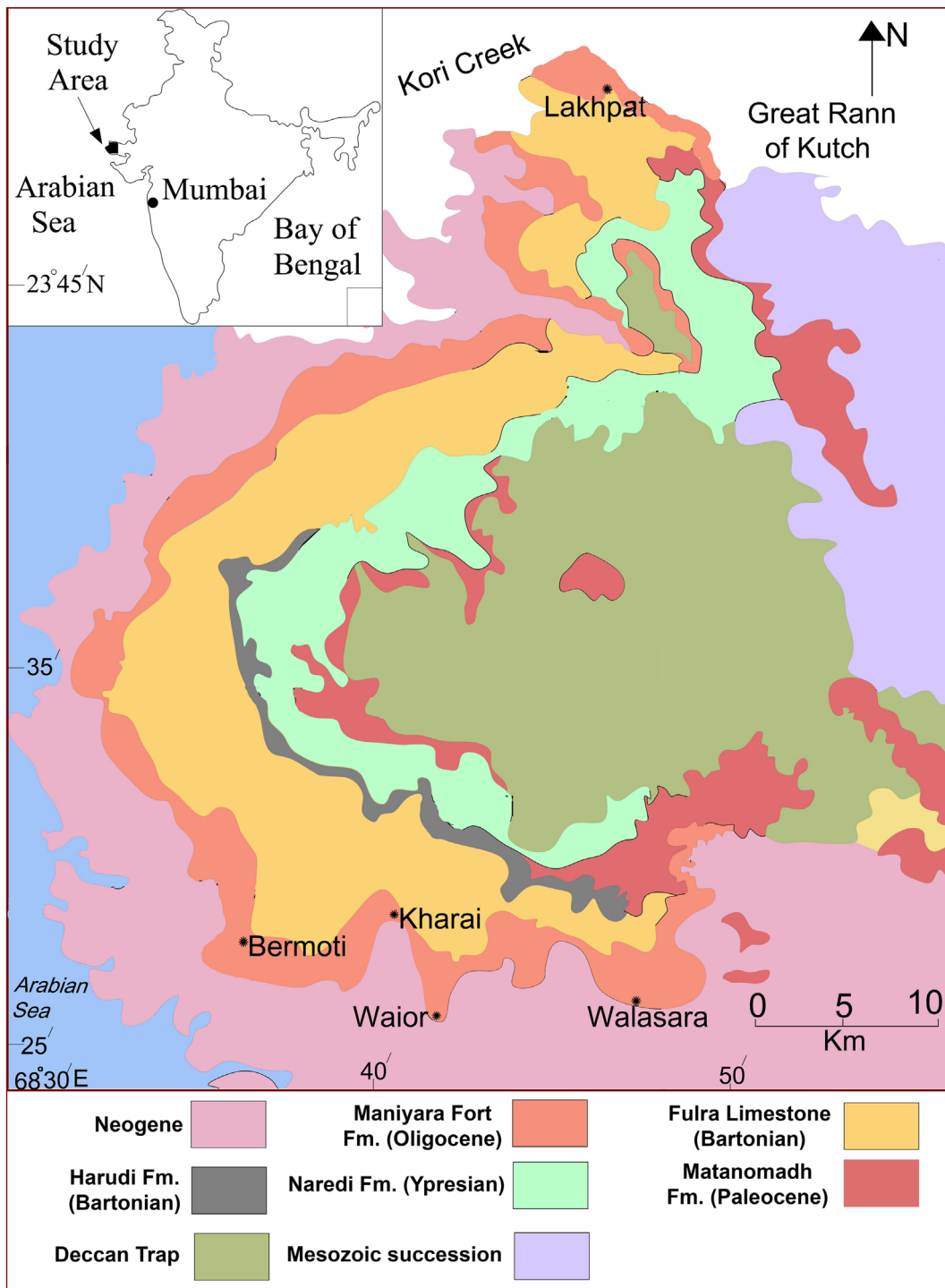


Figure 1. Geological map of the western part of Kutch (modified after Biswas, 1992) with the studied sections and localities.

Formation on the Bartonian Fulra Limestone can be well seen, covers the Basal Member (N: 23°28.846', E: 68°40.795'; samples Kharai 4, 5, 8–10), the Lumpy Clay (samples Kharai 11 and 12; same co-ordinates) and the lower part of the Coral Limestone (samples Kharai 13 and 15: N: 23°28.791', E: 68°40.697'). Samples for Sr-isotope study have been taken from both the Basal Member (samples Kharai 4 and 5) and the Coral Limestone (sample Kharai 13).

The Waior section (Figures 2(D–F) and 4) includes the Coral Limestone Member (N: 23°25.627', E: 68°41.961';

samples Waior 2–5 and 7–8) and the Bermoti Member (samples Waior 9, 11, 12). Sample for Sr-isotope dating has been collected from sample Waior 4 of the Coral Limestone Member.

All members of the Maniyara Fort Fm. are exposed in the Bermoti section (Figures 2(G–I) and 5). However, only a typological determination of LBF was possible, because the samples from this section do not contain enough specimens for morphometric studies. Samples Bermoti 1–2, Bermoti 3, Bermoti 4–5 and finally Bermoti 6–8 belong to the Basal Member, Lumpy Clay, Coral

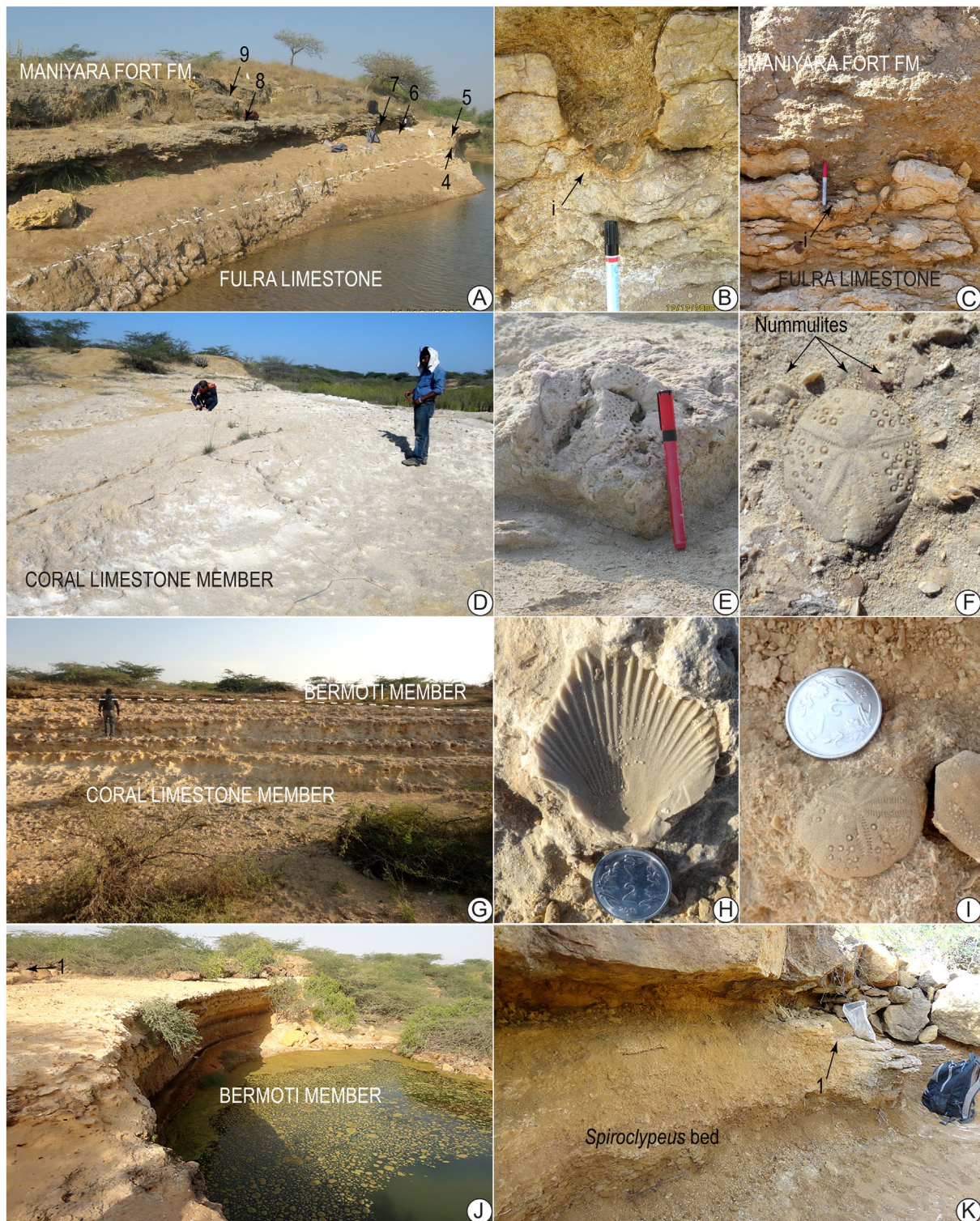


Figure 2. Field aspects of the studied stratigraphic sections: A–C: Disconformity between the Basal Member of Maniyara Fort Formation and Fulra Limestone in Kharai section, marked by karstic surface and cavities infilled by Chattian *Nummulites*-rich sediment (i) in Fulra Limestone. D–F: Coral Limestone Member in Waior section with large colonial corals (E), echinoids and scarce *Nummulites* (F). G–I: Coral Limestone and Bermoti Member of Maniyara Fort Formation in Bermoti section, with *Pecten* (H) and echinoid shells (I) from the Bermoti Member. J–K: Bermoti Member with abundant *Spiroclpeus* in Walasara section. Numbers in A and J–K refer to the sample numbers.

Limestone and Bermoti Member, respectively. Sample Bermoti 6 (N: 23°27.851', E: 68°36.121') from the Bermoti Member was also used for Sr-isotope stratigraphy.

The Lakhpat section (Figure 6), outside the north-eastern corner tower of the Lakhpat Fort (N: 23°49.568', E:

68°47.121'), includes the Basal Member (sample Lakhpat 1) and the Coral Limestone (samples Lakhpat 2–4). The Lumpy Clay cannot be recognized between them. No samples for Sr-isotope studies have been collected from this section.

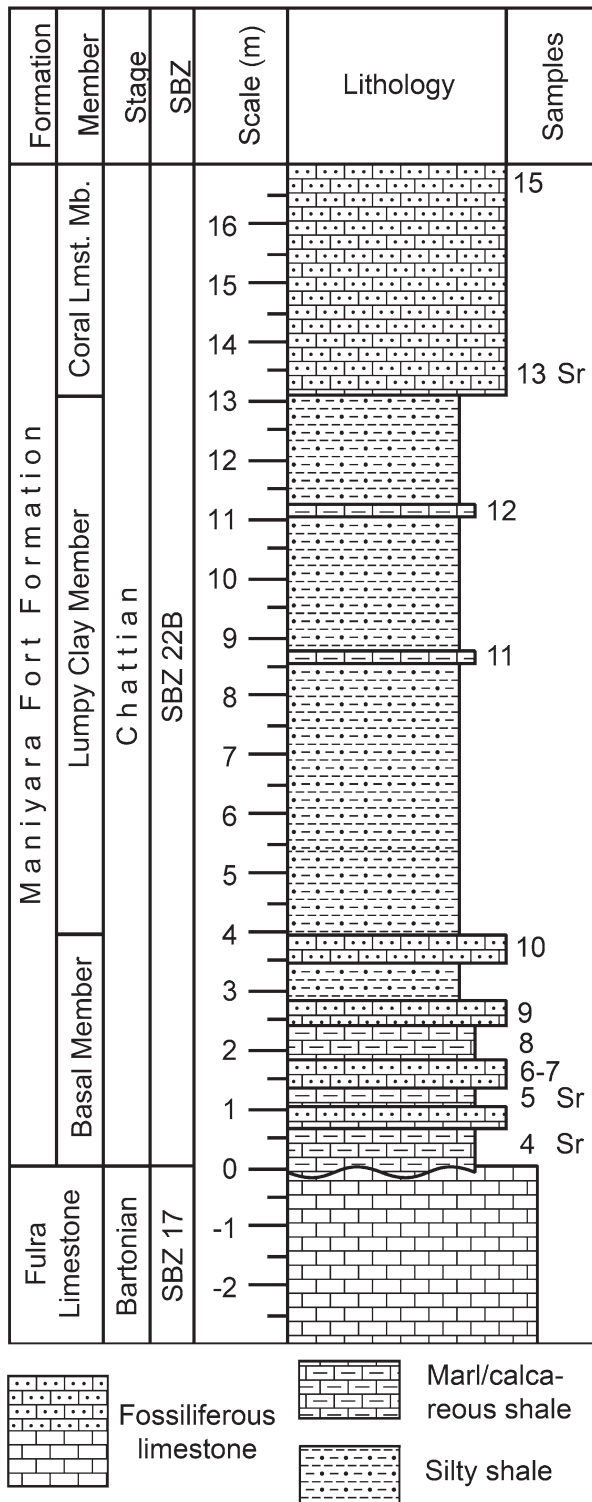


Figure 3. Simplified stratigraphic log of the Kharai section with position of the samples.

Finally, one single sample from the Bermoti Member (Walasara 1) has been studied from Walasara (Figure 2(J, K); N: 23°26.170', E: 68°46.963').

Figured specimens prefixed by 'Ö/' are stored in the Özcan collection of Department of Geology, İstanbul Technical University, while those marked by 'O.' are in the Oligocene collection of the Geological Institute of Hungary (Budapest).

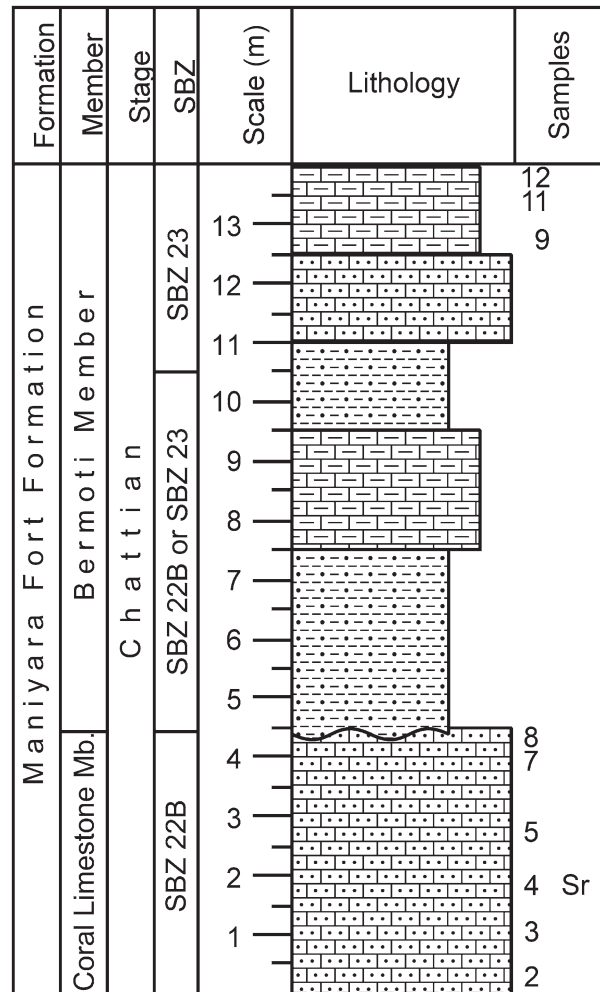


Figure 4. Simplified stratigraphic log of the Waior section with position of the samples.

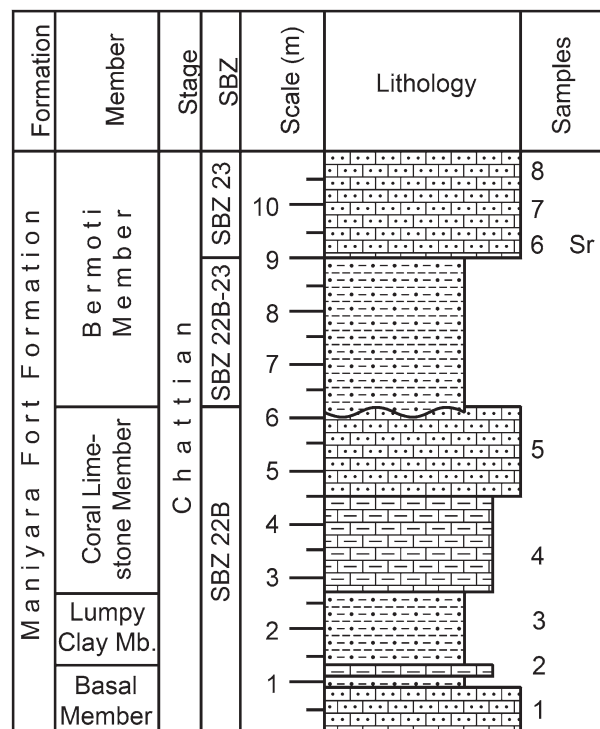


Figure 5. Simplified stratigraphic log of the Bermoti section with position of the samples.

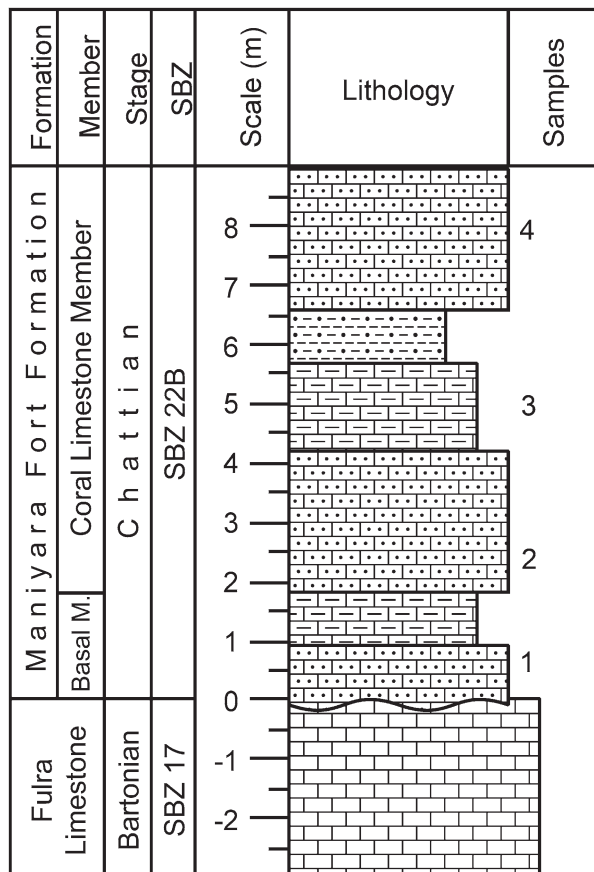


Figure 6. Simplified stratigraphic log of the Lakhpat section with position of the samples.

Methods

Morphometry of nummulitids and lepidocyclinids

External features of LBF have been studied typologically whereas their internal characteristics have been mostly investigated morphometrically in the equatorial plane of free specimens. We did not study the *Miogypsinoides* and *Planolinderina* from the Bermoti Member in the Waior section, because they have already been thoroughly described by Drooger and Raju (1978) and Raju and Drooger (1978).

Determination of *Nummulites* is based on both the surface characteristics and the features of the equatorial section. Since the microspheric (B) forms are much less common, we focused mostly on the megalospheric (A) forms. Based on Drooger, Marks, and Papp (1971), Less (1999) introduced a suite of measurements and parameters to characterize the equatorial section of A-forms. Seven parameters (explained in the header of Table 1; measurements and counts are shown in Figure 7(A)) are used to characterize the 339 megalospheric specimens of reticulate *Nummulites*; the statistical data are summarized in Table 1. Rare radiate *Nummulites* (previously determined as *Operculina complanata*) have not been morphometrically analyzed since their assignment to *N. kecskemetii* appears to be doubtless. Moreover, this

species does not show any significant morphological change across its whole stratigraphical range.

Since B-forms of nummulitids with secondary chamberlets (*Heterostegina* and *Spiroclypeus*) are very rare, too, we focused on the megalospheric forms also for these genera. Based on Drooger and Roelofsen (1982), Less, Özcan, Papazzoni, and Stöckar (2008) introduced the parameters and a measurement system to characterize the equatorial section of A-forms of the Western Tethyan late Bartonian and Priabonian *Heterostegina*. Here, we use the same morphometrical approach also for the Oligo-Miocene forms (Figure 7(B)) by adding one more parameter (S_{4+5}). Six parameters (explained in the header of Table 2) for 51 *Heterostegina* and 52 *Spiroclypeus* specimens are evaluated statistically by standard methods, considering all the specimens of a single sample as a population. The results are summarized in Table 2.

Adopting the terminology proposed by van der Vlerk (1959) and Drooger and Socin (1959), five parameters (explained in the header of Tables 3 and 4, while measurements and counts are shown in Figure 7(C)) for 97 *Eulepidina* and 34 *Nephrolepidina* megalospheric specimens are used to characterize the taxa. Statistical data are summarized in Tables 3 and 4. Adauxiliary chambers (parameter C) have not been counted for *Eulepidina* because according to Adams (1987) they are lying not normally in the equatorial (median) plane, and therefore, they are quite often invisible or indistinct in oriented sections. As a consequence, the distinction of true adauxiliary chambers from interauxiliary and closing chambers is problematic. In fact, only very few data are available in the literature, and they are partly incomparable: Parameter C was counted by van Heck and Drooger (1984), Less (1991) and also by Benedetti and D'Amico (2012), while van Heck and Drooger (1984) gave also data of all peri-embryonic chambers as well as Schiavinotto and Verrubbi (1996).

In Tables 1–4, samples containing the same assemblages, with similar morphometrical parameters, are evaluated both separately and jointly as a composite sample. However, the specific determination is given for the composite samples on the basis of the total number of specimens. These data are marked with bold letters. Reticulate *Nummulites* and species of the genera *Eulepidina* and *Nephrolepidina* are determined according to the morphometrical limits of species for populations detailed in the systematic part. If the mean value for a given population differs from the morphometrical limit between two neighboring species by less than one s.e., we use an intermediate denomination. In these cases, we adopt Drooger's (1993) proposal in using the notation 'exemplum intercentrale' (abbreviated as ex. interc.), followed by the names of the two subspecies on either side of the limit and putting that name into the first place to which the assemblage is closer.

Table 1. Statistical data of Oligocene reticulate *Nummulites* from Kutç (by bold), with some other populations for comparison (unpublished data for Cluj, Biarritz, Cassinelle, Gaas, Tuc de Saumon and Dego; for Dazkiri see Özcan et al., 2009a; for Kelereşdere see Özcan et al., 2010a), s.e.: standard error, * forms with external morphology referred to *N. clipeus* by previous authors.

Species	Sample	Proloculus										Index of spiral opening										Third whorl																	
		Diameter		Number of chambers		3./1-3. whorls		av. Length of chambers		av. Shape of chambers		rel. width of spiral cord		Diameter		Number of chambers		K = 100x(D-d)/(D-P)		L = dxπ/N (µm)		F = 100x(D-d)/(D-d+2L)		m = 100x(D-M)/(D-d)		Diameter		Number of chambers		E		K = 100x(D-d)/(D-P)		L = dxπ/N (µm)		F = 100x(D-d)/(D-d+2L)		m = 100x(D-M)/(D-d)	
		Range	Mean ± s.e.	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE						
<i>fichteli</i>	Cluj, Hoia (RO)	30	100-270	213 ± 8	960-1520	1225 ± 24	15-24	17.9 ± 0.4	28-38	34.7 ± 0.5	199-369	258 ± 8	43-60	51.2 ± 0.7	19-42	28.9 ± 1.0																							
	Biarritz, R. Vierge (F)	28	180-330	253 ± 6	970-1450	1218 ± 21	16-24	19.0 ± 0.4	25-37	31.6 ± 0.5	179-321	225 ± 6	44-55	49.8 ± 0.6	31-55	40.9 ± 1.1																							
	Kelereşdere 11+12 (TR)	45	190-410	261 ± 7	920-1360	1183 ± 18	16-21	18.3 ± 0.2	25-41	33.2 ± 0.4	192-329	249 ± 5	35-56	47.9 ± 0.5	15-47	23.5 ± 0.8																							
	Cassinelle (I)	28	225-360	275 ± 5	1150-1585	1295 ± 19	15-22	17.5 ± 0.3	26-42	34.1 ± 0.6	215-386	284 ± 6	37-61	48.2 ± 0.9	14-36	23.8 ± 1.1																							
	Gaas (FR)	21	205-415	289 ± 10	1015-1980	1403 ± 40	15-23	18.0 ± 0.4	29-36	33.3 ± 0.4	221-368	291 ± 8	45-55	48.8 ± 0.5	23-40	30.0 ± 0.8																							
	Kelereşdere 14 (TR)	34	200-510	289 ± 10	1010-1450	1190 ± 20	15-21	17.3 ± 0.2	28-37	32.2 ± 0.4	207-337	259 ± 6	39-50	45.4 ± 0.5	11-27	20.8 ± 0.7																							
	Tuc de Saumon (FR)	31	220-390	293 ± 7	1070-1715	1313 ± 24	15-20	17.6 ± 0.2	27-35	30.9 ± 0.3	227-369	291 ± 7	37-52	44.0 ± 0.6	20-42	31.0 ± 1.1																							
	Kelereşdere 16-20 (TR)	17	245-385	319 ± 10	1030-1470	1238 ± 25	14-20	17.8 ± 0.4	31-39	33.9 ± 0.6	226-369	292 ± 10	39-49	44.8 ± 0.7	12-36	21.2 ± 1.4																							
<i>bormidiensis</i>	Kharai 8-10 (IND)	68	235-595	380 ± 8	1045-2040	1559 ± 22	13-22	17.8 ± 0.2	17-47	31.2 ± 0.5	216-509	321 ± 6	33-69	45.5 ± 0.7	9-51	23.5 ± 0.9																							
	Kharai 8	23	255-455	360 ± 11	1045-1765	1496 ± 34	15-20	17.2 ± 0.3	24-35	30.8 ± 0.5	234-419	317 ± 10	33-55	44.5 ± 1.1	14-38	22.5 ± 1.3																							
	Kharai 9	19	305-545	399 ± 13	1205-1910	1562 ± 43	17-22	18.8 ± 0.4	17-47	31.2 ± 1.3	216-403	311 ± 12	35-69	45.6 ± 1.6	9-45	23.1 ± 1.7																							
	Kharai 10	26	235-595	385 ± 16	1320-2040	1612 ± 32	13-22	17.7 ± 0.4	27-38	31.6 ± 0.6	237-509	331 ± 11	39-56	46.3 ± 0.8	13-51	24.5 ± 1.5																							
	Lakhpatt 1 (IND)	27	250-540	403 ± 14	1390-2070	1659 ± 33	15-21	18.5 ± 0.3	11-35	28.7 ± 1.0	231-483	324 ± 11	21-52	43.7 ± 1.2	20-55	32.6 ± 1.9																							
	Kharai 11-12 (IND)	43	230-560	389 ± 13	1245-2050	1555 ± 28	15-21	17.2 ± 0.2	20-38	31.1 ± 0.5	234-416	334 ± 8	29-54	44.2 ± 0.6	11-42	20.8 ± 0.9																							
	Kharai 11	20	255-560	395 ± 18	1270-1810	1557 ± 34	15-19	17.1 ± 0.3	20-38	31.0 ± 0.8	249-416	339 ± 10	29-48	43.6 ± 1.0	15-42	21.9 ± 1.5																							
	Kharai 12	23	230-540	384 ± 17	1245-2050	1553 ± 43	16-21	17.3 ± 0.3	26-36	31.1 ± 0.5	234-405	329 ± 11	38-54	44.7 ± 0.7	11-30	19.8 ± 1.0																							
	Kharai 13 (IND)*	24	200-500	343 ± 11	1185-1910	1498 ± 36	16-21	17.8 ± 0.4	27-42	32.8 ± 0.8	211-420	319 ± 12	38-57	47.1 ± 0.9	15-36	23.2 ± 1.3																							
	Waior 3-8 (IND)*	93	190-560	336 ± 8	1010-1950	1450 ± 21	13-22	17.7 ± 0.2	15-47	31.6 ± 0.5	205-424	296 ± 5	25-66	46.4 ± 0.6	13-41	23.7 ± 0.7																							
	Waior 3*	7	245-510	344 ± 11	1230-1905	1463 ± 87	16-21	18.6 ± 0.7	28-36	31.8 ± 1.2	245-363	282 ± 14	44-51	47.8 ± 1.0	19-36	27.1 ± 2.1																							
	Waior 4*	22	235-440	326 ± 13	1110-1705	1456 ± 27	13-20	17.5 ± 0.4	25-47	31.8 ± 0.9	211-363	296 ± 8	38-62	47.2 ± 1.0	13-41	23.9 ± 1.5																							
Waior 5*	18	325-460	386 ± 11	1165-1860	1589 ± 42	15-20	17.8 ± 0.3	27-39	31.3 ± 0.7	252-424	333 ± 11	40-52	45.1 ± 0.8	16-23	19.6 ± 0.4																								
Waior 6*	24	210-560	344 ± 17	1110-1950	1457 ± 42	13-22	17.6 ± 0.5	28-47	32.9 ± 1.6	205-406	275 ± 16	38-66	49.1 ± 2.2	14-39	29.8 ± 2.2																								
Lakhpatt 2-4 (IND)	48	240-690	358 ± 11	1150-1860	1533 ± 25	15-23	17.9 ± 0.3	24-40	30.8 ± 0.4	221-404	309 ± 6	35-55	45.8 ± 0.5	19-47	31.9 ± 1.1																								
Lakhpatt 2	21	240-535	337 ± 15	1210-1770	1501 ± 36	15-20	17.5 ± 0.3	25-40	30.7 ± 0.7	226-404	301 ± 10	39-55	46.1 ± 0.9	19-46	28.4 ± 1.5																								
Lakhpatt 3	23	300-690	385 ± 16	1280-1860	1595 ± 34	15-23	18.0 ± 0.4	24-34	30.9 ± 0.6	221-390	323 ± 7	35-52	45.5 ± 0.7	21-44	34.2 ± 1.4																								
Lakhpatt 4	4	380-330	309 ± 6	1150-1465	1346 ± 60	16-21	18.8 ± 1.0	28-32	30.6 ± 0.8	242-278	264 ± 7	42-48	46.3 ± 1.3	28-47	36.6 ± 3.3																								
Dazkiri A7 (TR)	17	250-490	351 ± 13	1100-1700	1409 ± 41	16-20	17.8 ± 0.4	27-35	32.1 ± 0.5	236-411	291 ± 13	39-51	46.3 ± 0.9	16-38	26.8 ± 1.6																								
Dazkiri B5 (TR)	19	310-510	384 ± 13	1190-1710	1461 ± 32	15-21	17.4 ± 0.5	25-37	31.5 ± 0.7	234-400	311 ± 11	35-53	44.3 ± 1.2	15-27	21.1 ± 1.1																								
Dazkiri B1 (TR)	17	270-490	401 ± 13	1150-1700	1443 ± 29	14-20	17.5 ± 0.4	24-46	33.2 ± 1.1	243-385	303 ± 9	37-55	46.0 ± 1.1	18-36	25.0 ± 1.2																								
Dego, Costalupara (I)	24	300-550	401 ± 15	1165-1820	1523 ± 32	15-22	18.2 ± 0.4	29-42	34.2 ± 0.5	241-394	325 ± 10	42-55	47.4 ± 0.7	13-29	20.9 ± 0.9																								
<i>aff. bormidiensis</i>	Kharai 4 (IND)	36	315-800	522 ± 16	1210-2100	1698 ± 35	13-18	15.4 ± 0.2	25-44	30.8 ± 0.6	284-594	425 ± 10	31-54	38.1 ± 0.7	19-52	31.8 ± 1.2																							

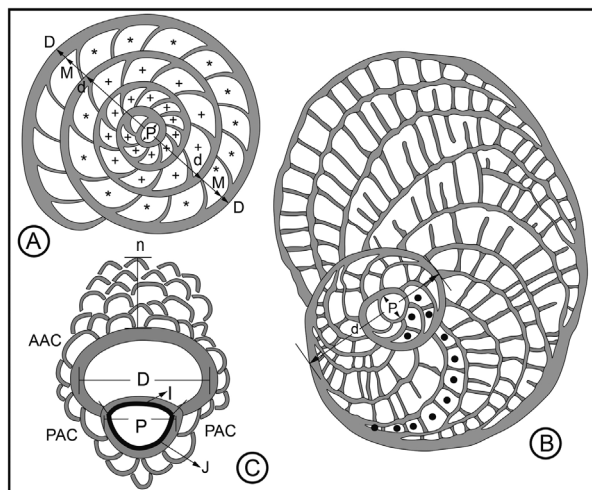


Figure 7. The measurement system for megalospheric larger foraminifera (most of the parameters are explained in the headers of Tables 1–4). (A) *Nummulites* (D and M: outer and inner diameter of the third whorl, $E = 19$, N (number of chambers in the third whorl) = 13), (B) *Heterostegina* and *Spiroclypeus* ($X = 1$, $S_{4+5} = 4$, $S_{14} = 8$) and (C) *Lepidocyclinidae* (AAC: adauxiliary chambers with direct stolon connection with the deuterococh, I and J: inner circumference of the protoconch embraced (I) and not embraced (J) by the deuterococh).

Sr-isotope stratigraphy

Strontium isotope stratigraphy (SIS) is a well established chemostratigraphic method (McArthur, 1994; McArthur & Howarth, 2004; McArthur, Howarth, & Shields, 2012) based on the empirical observation that the Sr isotope ratio of the ocean ($^{87}\text{Sr}/^{86}\text{Sr}$) has varied during the geological past and on the assumption (verified for the present ocean; Depaolo & Ingram, 1985) that at any moment the Sr isotope ratio of the ocean is homogeneous, because the residence time of Sr is much longer than the ocean mixing time. A database of the $^{87}\text{Sr}/^{86}\text{Sr}$ value of well-preserved and well-dated marine precipitates (carbonates and phosphates) has been used to build a marine reference curve for the past 590 Ma of geologic history, which is continuously updated and refined. (McArthur & Howarth, 2004; McArthur, Howarth, & Bailey, 2001; McArthur et al., 2012). Any marine precipitate can be dated with reference to this curve, provided that its pristine isotope ratio has not been substantially altered by diagenesis or changed by contamination (McArthur, 1994). Accurate chronostratigraphical dating and global correlation can be obtained by SIS for geological time intervals characterised by a steep marine Sr isotope curve. The Oligocene-Miocene is one of this favourable time intervals during which SIS may achieve resolution in the order of a few 10^5 years. The low-Mg biotic calcite of bivalve shells is one of the most appropriate materials for SIS, because it is resistant to diagenesis and its preservation can be adequately screened by petrographical and geochemical methods (McArthur, 1994; Ullmann & Korte, 2015).

For this work, several shells of bivalves (mainly pectinids and ostreids) were collected from the field and prepared in the laboratory, following the method described in Boix et al. (2011) and Frijia, Parente, Di Lucia, and Mutti (2015). The best preserved shells, based on visual inspection and optical petrography, were further screened for elemental composition of Mg, Sr, Mn and Fe, in order to get further information about possible diagenetic alteration and contamination. The elemental concentrations were determined on a Thermo Fisher Scientific iCAP6500 Dual View ICP-OES. Sr isotopes analyses were performed on a Finnigan MAT 262 thermal-ionization mass spectrometer and normalized to an $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194. All the geochemical analyses were made at the Institute for Geology, Mineralogy and Geophysics of the Ruhr-University (Bochum, Germany) (see Frijia et al., 2015; for details on analytical methods). The long-term mean $^{87}\text{Sr}/^{86}\text{Sr}$ of modern seawater (USGS EN-1), measured at the laboratory at the time when the samples were analysed, was 0.709162 ± 0.000002 (2 s.e.; $n = 257$). In order to correct for interlaboratory bias, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the samples were adjusted to a value of 0.709175 for the USGS EN-1 standard, to be consistent with the normalisation used in the compilation of the 'look-up' table of McArthur et al. (2001; version 5). This table, which is tied to the Geological Time Scale of Gradstein, Ogg, Schmitz, and Ogg (2012), was used to derive numerical ages from the studied samples. Minimum and maximum ages were obtained by combining the statistical uncertainty (2 s.e.) of the mean values of the Sr-isotope ratios of the samples with the uncertainty of the seawater curve. The numerical ages were then translated into chronostratigraphic ages and corresponding standard biozones by reference to the GTS2012. When less than four subsamples were available, we calculated the error of the mean using the long term standard deviation of the standards measured in Bochum. This procedure gives a 2 s.e. of 0.000032 for $n = 1$, 0.000023 for $n = 2$ and 0.000018 for $n = 3$. When there are two or more than two subsamples, the larger value is used between the one calculated from the subsamples and the one calculated from the standards. This procedure means that for less than 4 samples the precision (expressed as 2 s.e.) is never better than the precision of repeated measurements of the standards.

Results

Basal member

The larger foraminiferal fauna of this member (Table 5), which has been studied in the Kharai (samples 4, 5, 8–10), Bermoti (samples 1–2) and Lakhpat (sample 1) section, is rather uniform. It is composed of rock-forming reticulate and rare radiate *Nummulites* as well as common *Heterostegina*. All reticulate *Nummulites* belong to the *N. fabianii*-lineage and were previously determined in Kutch by most authors (Dasgupta,

Table 3. Statistical data of Oligocene *Eulepidina* from Kutch (by bold), with some other populations for comparison (unpublished data for Tuc de Saumon, Porto Badisco and Escornebéou; for S. Vicente de la Barquera see van Heck & Drooger, 1984; for Novaj and Csókás see Less, 1991; for Bey-Dağları and Dazkırı see Özcan et al., 2009a and for Kelerşdere see Özcan et al., 2010a). s.e.: standard error.

Parameters	Medium cross-diameter of the embryonic chambers										Degree of embracement of the protoconch by the deuteroconch				Number of annuli in 1 mm from the embryo's rim			
	Protoconch					Deuteroconch					A=100xI/(I+J)				n			
	Sample	Nº	Range	Mean ± SE	Nº	Range	Mean ± SE	Nº	Range	Mean ± SE	Nº	Range	Mean ± SE	Nº	Range	Mean ± SE		
<i>Eulepidina formosoides</i>	Tuc de Saumon (F)	32	310–645	456.4 ± 14.7	32	505–1215	741.1 ± 31.2	32	48.1–95.3	69.18 ± 2.17	32	11.0–18.0	14.67 ± 0.29					
	S. Vicente de la Barquera (E)	22	247–700	461.6 ± 25.7	22	363–1283	771.7 ± 50.3	22	50.0–91.0	68.90 ± 2.45	22	10.0–16.0	13.15 ± 0.31					
	Kelerşdere 3+7 (TR)	44	390–690	507.3 ± 10.8	46	630–1170	859.9 ± 18.2	38	51.6–92.5	72.32 ± 1.45	27	8.0–20.0	13.05 ± 0.37					
	Kelerşdere 11–12 (TR)	46	310–980	562.0 ± 21.3	49	505–1740	964.8 ± 34.5	44	60.4–92.9	77.87 ± 1.15	38	10.0–19.0	12.89 ± 0.51					
	Kelerşdere 14 (TR)	25	400–1120	738.2 ± 35.8	25	720–1760	1229.2 ± 48.6	22	62.4–100.0	80.46 ± 2.29	18	10.0–11.5	10.67 ± 0.28					
	Kharai 13+15 (IND)	6	620–1050	825.8 ± 58.8	6	1050–1540	1343.3 ± 77.5	6	73.9–87.7	79.91 ± 2.08	6	10.0–11.5	11.00 ± 0.31					
	Kharai 13	4	685–935	821.3 ± 44.6	4	1050–1515	1348.8 ± 90.0	4	74.9–87.7	80.07 ± 2.36	4	10.0–10.0	10.00					
	Kharai 15	2	620–1050	835.0	2	1125–1540	1332.5	2	73.9–85.3	79.59	2	10.0–10.0	10.00					
	Waior 3–8 (IND)	66	380–1330	680.8 ± 18.7	67	725–2080	1158.7 ± 25.5	66	50.3–94.3	78.51 ± 1.06	66	8.5–13.5	11.11 ± 0.15					
	Waior 3	9	445–855	672.2 ± 45.6	9	725–1415	1122.2 ± 67.9	9	71.6–89.0	79.47 ± 2.35	8	10.0–13.0	11.31 ± 0.31					
Waior 4	14	535–1330	770.0 ± 48.8	14	1015–2080	1262.1 ± 66.5	14	69.3–90.0	80.32 ± 1.76	14	9.5–12.5	10.79 ± 0.21						
Waior 5	16	470–960	682.2 ± 31.6	17	850–1530	1179.4 ± 44.8	16	65.1–94.3	82.27 ± 1.97	17	9.0–13.5	11.56 ± 0.30						
Waior 7	22	380–965	637.7 ± 27.0	22	730–1495	1102.7 ± 39.4	22	50.3–87.7	73.09 ± 1.91	22	8.5–13.5	10.91 ± 0.29						
Waior 8	5	515–915	632.0 ± 65.7	5	985–1360	1110.0 ± 61.5	5	80.6–88.2	83.55 ± 1.19	5	10.0–12.0	11.10 ± 0.41						
Lakhpāt 2–4 (IND)	25	445–1045	682.4 ± 27.8	25	665–1530	1124.6 ± 40.3	25	36.3–96.1	81.38 ± 2.32	25	9.5–13.0	11.54 ± 0.19						
Lakhpāt 2	20	445–950	685.3 ± 27.2	20	665–1530	1121.3 ± 46.7	20	36.3–96.1	81.69 ± 2.81	20	9.5–13.0	11.43 ± 0.21						
Lakhpāt 3	2	600–600	600.0	2	1040–1165	1102.5	2	69.4–88.5	78.95	2	11.0–13.0	12.00						
Lakhpāt 4	3	485–1045	718.3	3	925–1435	1161.7	3	78.8–83.0	80.96	3	11.0–13.0	12.00						
Dazkırı A7 (TR)	6	490–970	699.2 ± 69.7	6	990–1780	1328.3 ± 126.9	5	74.4–89.9	83.23 ± 2.75	6	9.0–14.0	11.50 ± 0.61						
Kelerşdere 16–20 (TR)	39	600–1430	895.3 ± 33.1	40	1060–2080	1477.6 ± 36.5	37	63.4–100.0	86.86 ± 1.46	35	8.0–12.0	9.97 ± 0.20						
Bey-Dağları (TR)	19	485–1800	933.7 ± 65.5	22	985–3460	1743.4 ± 100.9	16	62.1–100.0	86.21 ± 2.46	19	6.0–12.0	8.58 ± 0.33						
Porto Badisco 1–3a (I)	37	620–960	778.8 ± 13.8	37	1090–1680	1389.2 ± 24.3	37	72.6–100.0	89.99 ± 0.88	37	9.0–11.0	9.93 ± 0.12						
Escornebéou (F)	8	650–1080	780.6 ± 48.7	8	1275–1710	1427.5 ± 50.9	8	85.6–96.5	91.48 ± 1.47	8	8.0–11.5	10.06 ± 0.34						
Csókás (H)	59	430–1080	719.3 ± 17.2	63	870–1730	1293.3 ± 21.8	13	78.6–96.8	88.39 ± 1.67	56	8.4–14.5	11.62 ± 0.19						
Novaj – <i>Lepidocyclina</i> bed (H)	21	510–1380	911.2 ± 56.9	22	1065–2410	1590.2 ± 74.3	8	66.2–100.0	90.50 ± 3.82	18	8.3–13.5	11.18 ± 0.35						
Porto Badisco 1–3a (I)	60	320–735	510.5 ± 10.4	60	580–1165	860.8 ± 14.4	60	61.3–95.0	83.67 ± 1.04	60	11.0–16.5	13.03 ± 0.17						
Porto Badisco 4 (I)	20	390–745	585.3 ± 21.5	20	655–1185	948.0 ± 29.8	20	71.6–94.9	84.30 ± 1.37	20	11.0–15.0	12.43 ± 0.26						
Escornebéou (F)	16	380–740	572.5 ± 25.3	16	770–1150	977.8 ± 31.4	16	63.5–90.2	81.84 ± 1.87	16	10.0–13.0	11.46 ± 0.21						
Kelerşdere 29–34 (TR)	46	400–710	545.5 ± 12.4	56	640–1210	933.9 ± 17.3	46	76.1–96.3	88.23 ± 0.66	44	9.0–15.0	11.84 ± 0.21						
Kelerşdere 30 (TR)	4	1450–2625	1837.5 ± 230.6	6	2525–4225	3541.7 ± 244.8	4	84.7–100.0	93.57 ± 3.33	5	4.0–5.0	4.40 ± 0.22						

Table 5. Distribution of nummulitids, lepidocyclinids samples for Sr-isotope study in the Kutch samples.

Lithostratigraphic unit	Sample	<i>Nummulites bormidiensis</i>	<i>N. aff. bormidiensis</i>	<i>N. kecskemetii</i>	<i>Heterostegina</i>	<i>Eulepidina</i>	<i>Nephrolepidina</i>	<i>Spiroclypeus</i>	Sr-isotope studies
Bermoti Mb., <i>Spiroclypeus</i> beds	Walasara 1			×			+	+	
	Bermoti 6							×	Sr
	Waior 12							+	
	Waior 11							×	
Coral Lime-stone	Waior 9			×			+	+	
	Waior 8	+				+			
	Waior 7	+		×		+			
	Waior 5	+		×		+			
	Waior 4	+		×		+			Sr
	Waior 3	+				+			
	Waior 2	×				×			
	Lakhpat 4	×		×		+	+		
	Lakhpat 3	+		×		+	+		
	Lakhpat 2	+		×		+	+		
	Bermoti 4	×		×		×			
	Kharai 15	×		×		+	+		
	Kharai 13	+							
Lumpy Clay	Kharai 12	+							Sr
	Kharai 11	+							
Basal Member	Lakhpat 1	+		×	+				
	Bermoti 2	×		×	×				
	Bermoti 1	×		×	×				
	Kharai 10	+			+				
	Kharai 9	+							
	Kharai 8	+		×	+				
	Kharai 5	×		×	×				Sr
Kharai 4			+	+				Sr	

Notes: × present.

+ biometrically studied.

Table 6. Elemental composition and strontium isotope ratio of samples from the Maniyara Fort Formation in the Oligocene of the Kutch Basin.

Lithostratigraphy	Section	Sample	Component	P/A	Ca ppm	Mg ppm	Sr ppm	Fe ppm	Mn ppm	⁸⁷ Sr/ ⁸⁶ Sr	2 s.e. (*10 ⁻⁶)
Basal Member	Kharai	4	Pectinid	A	na	na	na	na	na	0.708295	5
		5A	Ostreid	A	384190	2459	824	972	125	0.708252	5
		5B	Ostreid	A	387960	1989	974	981	129	0.708288	5
		5C	Ostreid	A	382170	3911	685	708	241	0.708191	5
		5 M	Rock matrix	A	308130	9686	477	12750	291	0.708259	5
Coral Lime-stone	Waior	13A	Pectinid	P	na	na	na	na	na	0.708005	5
		13B	Pectinid	A	391420	2449	1090	825	173	0.708310	5
		4A	Ostreid	P	382240	1029	940	244	1160	0.708078	6
		4B	Ostreid	P	383120	785	772	416	1500	0.708064	5
		4C	Ostreid	P	381580	911	723	233	1290	0.708020	5
Bermoti Member (upper part)	Bermoti	6A	Pectinid	P	370010	2378	1108	1062	117	0.708215	5
		6B	Undet. bivalve	A	398090	3391	961	1362	222	0.708332	5
		6C	Undet. bivalve	P	396790	2562	1133	1250	126	0.708256	5

Note: P: preserved, A: altered, na: no analysis.

1970; Mohan, 1965; Nuttall, 1925) as *N. fichteli*. Based on their morphometrical values, the majority of the populations have been determined as *N. bormidiensis*. No morphometric trend has been recorded in samples from stratigraphically superposed levels. Surprisingly, the population from the lowermost sample, Kharai 4, turned out to be much 'more advanced', in terms of morphometric parameters (especially P, L and F), than those of the other samples. This population has been determined as *N. aff. bormidiensis* and interpreted as an extreme ecophenotypic variant of the former species. Radiate *Nummulites*, identified formerly as *Operculina*, have been determined as *N. kecskemetii*. *Heterostegina*, previously reported as *H. borneensis*, has been determined as *H. assilinoidea* (see more details in

the systematic part). In both cases, there is no evidence of morphometric evolution from the lowermost to the uppermost samples.

Samples Kharai 4 and 5 have been collected for SIS just above the unconformity marking the base of the Maniyara Fort Formation (Figure 3). We analyzed four shell fragments of pectinids and ostreids (Kharai 4 and Kharai 5A to C) and the matrix enclosing the shells of sample Kharai 5. The elemental concentrations and the ⁸⁷Sr/⁸⁶Sr ratios are given in Table 6. The shells are characterized by remarkably high Fe concentration (>700 ppm). Their Sr isotope ratio shows a rather large spread, from 0.708191 to 0.708295. Remarkably, with the exception of Kharai 5C, the shells have a Sr isotope ratio which is very close to that of the rock-matrix (Table 6).

Lumpy clay

The poor LBF from this member (Table 5) has been studied in the Kharai (samples 11 and 12) and Bermoti (sample 3) sections. The assemblage is monospecific and represented only by *Nummulites bormidiensis* populations with morphometrical parameters very similar to those of most samples from the Basal Member (samples Kharai 5, 8–10 and Lakhpat 1). Because of the lack of suitable material no sample for SIS has been collected from this unit.

Coral limestone

The LBF in this member (Table 5) have been studied in the Kharai (samples 13 and 15), Bermoti (samples 4–5), Lakhpat (samples 2–4) and Waior (samples 2–5, 7, 8) sections. The assemblages are quite homogenous and do not show any distinct morphometric trend from the base to the top of the unit. The main component of the assemblage, occurring in each sample, is the reticulate *Nummulites* (continuing from the lower members) that was determined in the literature as *N. fichteli* or *N. clipeus* (see below). Based on their morphometric parameters, all populations (with some uncertainty only for Waior 7, see details in the systematic part) belong to *N. bormidiensis*. As compared to the populations of the same species from the Basal Member and Lumpy Clay, they are slightly 'less advanced' but still within the morphometric limits of the above mentioned species. Moreover, the reticulate *Nummulites* specimens from the Coral Limestone commonly show an apical mamelon, which is not present in the specimens from the Basal Member and Lumpy Clay. Based on this character, Nuttall (1925) introduced *Nummulites clipeus* as a new species. Subsequent authors either followed this practice or disregarded it (see Sengupta et al., 2011, for a detailed review). We have found that specimens with apical mamelon are most common in the Waior samples and in samples Kharai 13 and 15, whereas this feature is completely missing in the Lakhpat samples. Since there is no significant difference in the internal morphological parameters of the populations with and without apical mamelon, we do not see the necessity of distinguishing two separate species of reticulate *Nummulites* in this member.

The second main component of the larger foraminiferal fauna of the Coral Limestone is *Eulepidina*, determined as *E. ex. interc. formosoides-dilatata*, which is present in all samples. *Nummulites kecskemetii* is also sporadically recorded in this member, with no significant difference of morphometric parameters as compared to the specimens from the Basal Member. *Nephrolepidina ex. interc. morgani-praemarginata* occurs sporadically; a significant number of specimens could only be found in sample Lakhpat 2. Very rare *Sphaerogypsina* have been found in two samples, Kharai 15 and Lakhpat 4. *Heterostegina*, occurring regularly in the Basal Member, is completely missing in the Coral Limestone.

Two samples have been collected for SIS in the Coral Limestone. From sample Kharai 13 (Figure 3), we analysed two shell fragments of pectinid bivalves (Kharai 13A and 13B), which gave very different Sr isotope ratio. Elemental concentration data are not available for Kharai 13A, while Kharai 13B is characterized by a very high Fe content (>800 ppm) (Table 6). From sample Waior 4 we analysed three shell fragments of ostreid bivalves (Waior 4A, 4B and 4C). The three shells are characterized by remarkably high Mn content (>1100 ppm) and by rather homogeneous Sr isotope ratios (0.708020–0.708078) (Table 6).

Bermoti member

LBF have been studied from seven samples (Table 5) of three sections (Waior, Bermoti and Walasara). All the samples come from the upper third of the Bermoti Member. They are dominated by a species of *Spiroclypeus* that has been mentioned in previous papers as *S. ranjanae* (introduced by Tewari, 1956). Based on the morphometric parameters, which are very similar in all the studied populations, we attribute this species to *S. margaritatus*. Reticulate *Nummulites* and *Eulepidina*, the dominant components in the Coral Limestone, are completely missing here. *Nummulites kecskemetii*, *Nephrolepidina ex. interc. morgani-praemarginata* and *Sphaerogypsina*, all continuing from the Coral Limestone Member, occur sporadically.

Information on the LBF of the lower two-third of the Bermoti Member is available in Drooger and Raju (1978) and Raju and Drooger (1978), who performed an exhaustive study of the genera *Miogypsinoidea* and *Planolinderina* from this member in the Waior section. They report the occurrence of a *Heterostegina* population from the lowermost part (sample K 27 in Drooger & Raju, 1978), which was later studied morphometrically by Singh and Raju (2007) under the name of *H. borneensis*. According to their data and photos, these forms do not differ too much from *H. assilinoidea* from the Basal Member. The lowest occurrence of the genus *Planolinderina* can also be found in this sample, and then it can be followed until the first mass occurrence of *Spiroclypeus*. Within this rather thin (<10 m) interval, two successive evolutionary steps of the genus (*P. freudenthali* and *P. escornebovensis*) were distinguished by Raju and Drooger (1978). The genus *Miogypsinoidea* occurs only in the upper two-third of the Bermoti Member in the Waior section. The populations from samples K 12 to K 8 of Drooger and Raju (1978) represent *Miogypsinoidea cf. bermudezi*, a species that is unknown in the Tethyan realm outside Kutch. The well-known Tethyan *Miogypsinoidea-Miogypsina* lineage, starting with *M. complanatus* and *M. formosensis*, is present in the upper third of the section (samples K6 to K3 of Drooger & Raju, 1978). An important *Nephrolepidina* population was described by van Vesseem (1978) from a level in the upper part of the section (sample K 4), just

below the interval marked by the mass occurrence of the genus *Spiroclypeus*. He stated that this population has a European affinity and determined it as *N. ex. interc. praemarginata-morgani*.

We studied for SIS one sample from the Bermoti section (Bermoti 6), collected from the levels with abundant *Spiroclypeus* in the uppermost part of the Bermoti Member (Figure 5). From this sample, we analysed three shells of pectinid and undetermined bivalves (Bermoti 6A, 6B and 6C). They are characterized by moderate Mn (ca. 100–200 ppm), high Fe content (>1000 ppm) and $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from 0.708215 to 0.708232 (Table 6).

Systematic description of nummulitids and lepidocyclinids

Family Nummulitidae De Blainville, 1827

All forms of nummulitids in Kutch without secondary chamberlets belong to genus *Nummulites* whereas those with secondary chamberlets are represented by two

genera, *Heterostegina* and *Spiroclypeus*, differing from each other in the absence or presence of lateral chamberlets, respectively. Genus *Operculina*, widely reported from the Oligocene of Kutch (Biswas, 1992; Reuter et al., 2013), has not been found.

Genus *Nummulites* Lamarck, 1801

Both radiate and reticulate *Nummulites* can be found in Kutch, however most of them belong to the *N. fabianii* lineage with reticulate surface, spanning at least from Bartonian to early Chattian (for possible Lutetian ancestors from N Africa and Arabia see e.g. Schaub, 1981; Racey, 1995 and Boukhary, Abd El Naby, Al Menoufy, & Mahsoub, 2015). The lineage has been revised and subdivided into species by using the criteria shown in Table 7 (Less, Özcan, & Okay, 2011; Özcan et al., 2009a, 2010a, 2010b), using the measurement and parameter system introduced by Less (1999). Figure 8 shows the distribution of Kutch populations on the P–L bivariate plot, in which other populations of reticulate *Nummulites* from the WTethyan Oligocene are also displayed. All the populations of reticulate *Nummulites* from Kutch, with

Table 7. Subdivision of the *Nummulites fabianii*-lineage in the Bartonian to early Chattian time-span (Özcan et al., 2010b with slight modification).

Taxon	P _{mean} (µm)	Surface	Stage	SBZ zone
<i>N. bullatus</i>	65–100	Granules, no reticulation	Late Lutetian to basal Bartonian	SBZ 16 to early SBZ 17
<i>N. garganicus</i>	100–140	Heavy granules + reticulation	Early to middle late Bartonian	late SBZ 17 to SBZ 18B
<i>N. hormoensis</i>	140–200	Heavy granules + umbo + reticulation	Late Bartonian	SBZ 18
<i>N. fabianii</i>	200–300	Weak granules + umbo + heavy reticulation	Priabonian to early Rupelian	SBZ 19–20
<i>N. fichteli</i>	200–300	Weak reticulation to irregular mesh	Late Priabonian to late Rupelian	SBZ 21–22A
<i>N. bormidiensis</i>	300–	Irregular mesh	Early Chattian	SBZ 22B

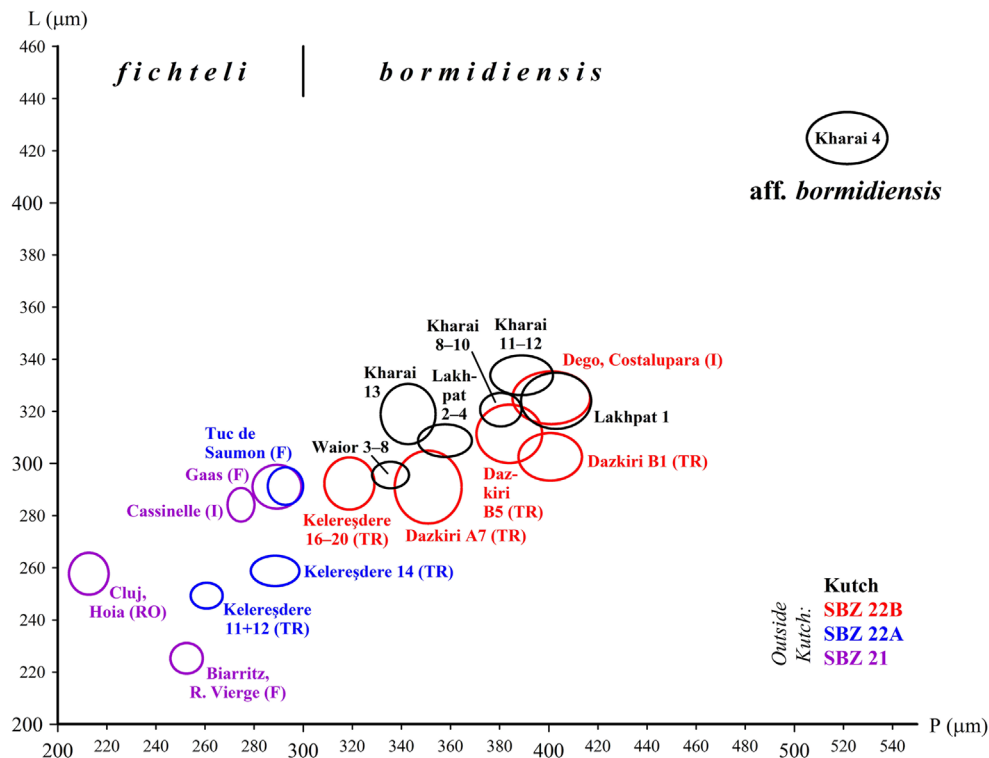


Figure 8. Bivariate P–L plot (proloculus diameter vs. chamber length in the third whorl) (mean values at the 68% confidence level) for Oligocene reticulate *Nummulites* populations from Kutch and some other localities (for numerical and source data see Table 1).

the exception of Kharai 4, form a distinct cluster, falling within the limits of *N. bormidiensis* (Figure 8). Population Waior 7, which has a P value slightly out of the morphometrical range of *N. bormidiensis*, is interpreted as an outlier and also ascribed to this species. Population Kharai 4, from the very base of the Basal Member of the Kharai section, shows morphometrical parameters that are, rather surprisingly, considerably larger than those from all the other, stratigraphically higher samples (see also Table 1). We interpret these parameters as probably controlled by environmental factors and use the name *N. aff. bormidiensis* for these forms. Several teratological phenomena are also described from this level by Sengupta (2000, 2002) and Sengupta et al. (2011, 2014, 2015).

All the rare radiate *Nummulites* present in our samples belong to *N. kecskemettii*, although they were traditionally determined as *Operculina complanata* (Biswas, 1992; Reuter et al., 2013). We did not find any *N. vasculus*, reported by Shukla (2008), or *N. sp. aff. chavannesi*, reported by Sengupta (2009). However, based on the illustrations provided in the above cited papers, they are clearly different from *N. kecskemettii*.

***Nummulites bormidiensis* Tellini, 1888**

Figs. 9/8–27

Nummulites intermedia var. *bormiensis* n. var. – Tellini, 1888, p. 219, pl. 8, Figs. 14a, b, 15, 17.

Nummulites bormidiensis Tellini – Özcan et al., 2009a; pp. 754–755, Figs. 17.1–5. (with synonymy); Özcan et al., 2010a, p. 479, pl. 4, Figs. 17–22.

Nummulites intermedius d'Archiac – Nuttall, 1925, pp. 662–664, pl. 37, Figs. 1–2.

Nummulites fichteli Michelotti – Nuttall, 1925, pp. 664–665; pl. 38, Fig. 1–2.; Dasgupta, 1970, pp. 160–162, pl. 1, Figs. 1, 2, 6, pl. 2, Figs. 1, 2, 7, 8.

Nummulites clipeus n. sp. – Nuttall, 1925, pp. 665–666; pl. 37, Figs. 3–5; Dasgupta, 1970, pp. 162–164, pl. 1, Figs. 3–5, pl. 2, Figs. 3–6.

Nummulites subclipeus n. sp. – Nuttall, 1925, p. 666, pl. 38, Figs. 3–5.

Material. Both A- and B-forms of this species occur in rock-forming quantity in almost all our samples coming from the Basal Member, Lumpy Clay and Coral Limestone (Table 7). In the lowermost sample (Kharai 4) of the Kharai section, *N. bormidiensis* is substituted by a form which bears externally the same features but differs considerably for the morphometric parameters of A-forms. We ascribed this form to *N. aff. bormidiensis* (see discussion above).

Remarks. By applying the modern nomenclature for *Nummulites* (thus using the same species name for A- and B-forms), reticulate forms from the Oligocene of Kutch have been described under three names, *N. fichteli* (+*N. intermedius*), *N. cf. fichteli* and *N. clipeus* (+*N. subclipeus*).

The mean inner proloculus diameter of the vast majority of reticulate *Nummulites* populations from Kutch exceeds 300 µm, the morphometric limit between *N.*

fichteli and *N. bormidiensis*. The application of the name '*bormidiensis*' for reticulate *Nummulites* with mean proloculus diameter over 300 µm (instead of '*sublaevigatus*' or '*fichteli*') is discussed in Özcan et al. (2009a). According to Table 1, all the other morphometric parameters of the Kutch populations are also closest to those of populations from Turkey and Italy that have been determined as *N. bormidiensis* based on the embryo size. Therefore, in our interpretation the vast majority of Kutch forms also belong to this species. The only exception is the population from sample Waior 7, which should be determined as *N. ex. interc. fichteli–bormidiensis*. Since reticulate *Nummulites* from both the under- and overlying samples (Waior 5 and 8, respectively) belong to *N. bormidiensis*, for the sake of simplicity this population is interpreted as an outlier and also ascribed to this species.

Reticulate *Nummulites* formerly described as *N. cf. fichteli* (Sengupta, 2000), occurring in our sample Kharai 4, have a considerably larger megalospheric embryo diameter (Table 1 and Figure 8). They are described below, separately, under the name of *N. aff. bormidiensis*.

Nummulites clipeus was introduced by Nuttall (1925) for reticulate forms with an apical mamelon on the surface of megalospheric specimens. Later, most authors (Mohan, 1965; Sengupta et al., 2011; see this latter paper also for more extended discussion) abandoned the distinction of *N. clipeus* from *N. fichteli*. A few of them (e.g. Dasgupta, 1970), however followed Nuttall (1925) and maintained the two species as distinct. Megalospheric forms with apical mamelon only occur in the Coral Limestone of the Kharai, Waior and Bermoti section; they are missing from the same lithostratigraphic unit in the Lakhpat section. Quantitative parameters of megalospheric forms are very similar to those without apical mamelon (only the proloculus is slightly smaller; see Table 1) and no considerable differences could be found in the microspheric forms, either. Therefore, we join to the majority of former experts in rejecting the validity of *Nummulites clipeus* and in interpreting the forms described under this name as an ecophenotypical variant of *N. bormidiensis*. We suppose that the presence or absence of apical mamelon is due to different paleoecological conditions, which we could not detect yet.

***Nummulites aff. bormidiensis* Tellini, 1888**

Figs. 9/1–7

Nummulites cf. *fichteli* Michelotti 1841 – Sengupta, 2000; pp. 673–677, pl. 1, Figs. 1–14.; Sengupta et al., 2014, pp. 193, 194, Figs. 3A–I (with synonymy)

Material. Both mega- and microspheric specimens of these forms occur in our material only in the lowermost part of the Basal Member in the Kharai section, where they can be found in rock-forming quantity and substitute the typical *Nummulites bormidiensis*.

Remarks. Sengupta (2000) was the first who distinguished reticulate forms with large-sized megalospheric embryo from typical ones, which were usually reported

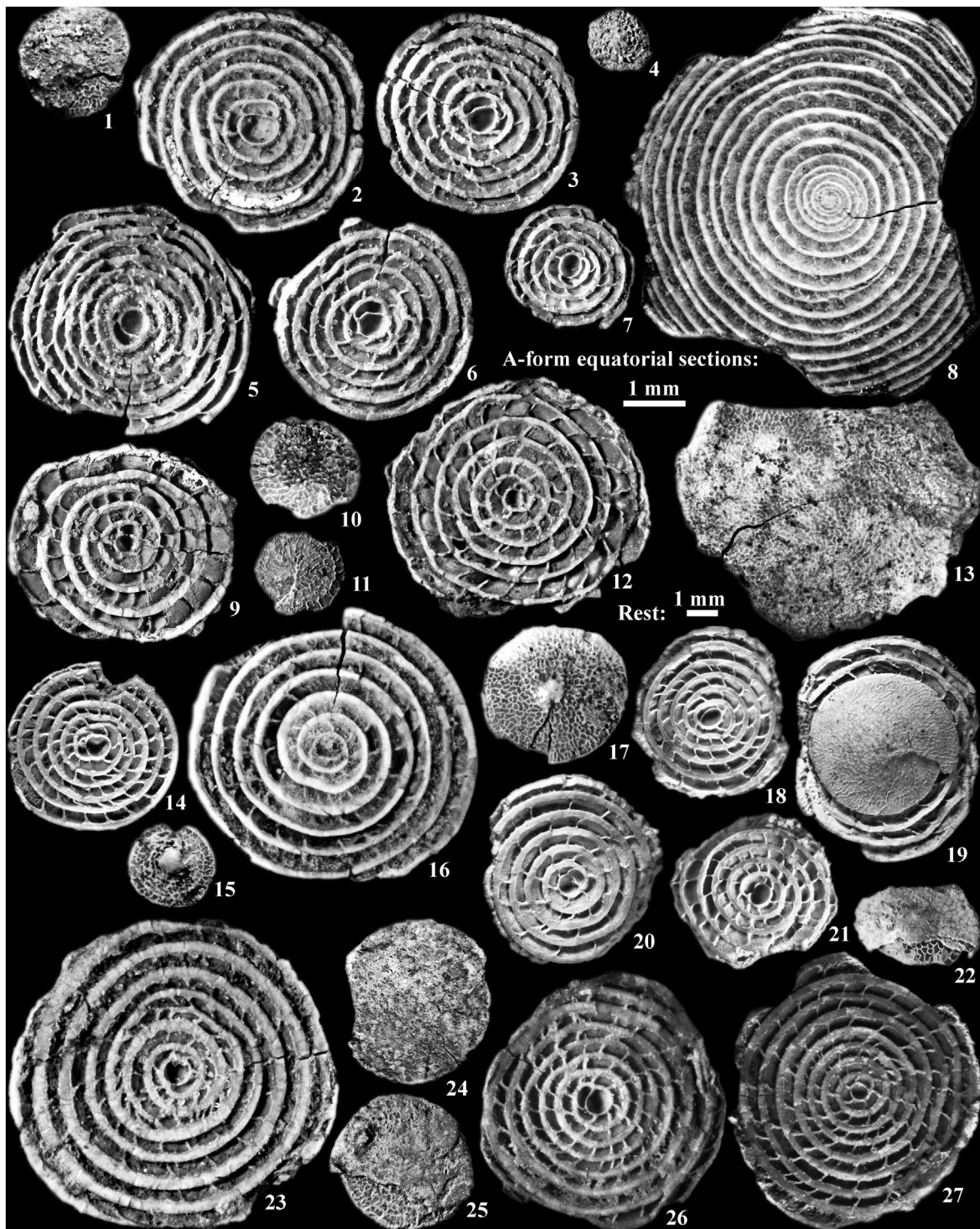


Figure 9. Reticulate *Nummulites* from the Oligocene of Kutch. 1–7.

Notes: *Nummulites* aff. *bormidiensis* Tellini, 1888 All from Kharai 4. 1, 4: A-form, external views; 2, 3, 5–7: A-form equatorial sections. 1, 2: O.2014.6.1; 3: O.2014.8.1; 4, 7: O.2014.7.1; 5: O.2014.5.1; 6: O.2014.9.1.

as *Nummulites fichteli* (and also as *N. clipeus/subclipeus* by Dasgupta, 1970; Nuttall, 1925). Sengupta (2000) noted another diagnostic feature of these forms (called by him *N. cf. fichteli*), namely the presence of intercalary whorls appearing in the middle and outer part of the spire of microspheric specimens. In this and also in subsequent publications (Sengupta, 2002; Sengupta et al., 2011, 2014, 2015), other unusual characteristics of these forms were described, like saddle-shape, change of

coiling of the spire and wall overgrowth. These features were interpreted as adaptations to different substrate conditions. Therefore, no new name for these forms has been introduced.

Our investigations confirm that these forms, found only in sample Kharai 4, are different from all the other reticulate *Nummulites* in Kutch (Table 1 and Figure 8). In our opinion, however, of the morphological traits described by Sengupta (2000, 2002) and Sengupta et

al. (2011, 2014, 2015), only the large-sized embryo and subsequent spiral characteristics can be considered as diagnostic. Intercalary whorls of microspheric *Nummulites* occur in all large-sized taxa exceeding 1 cm in diameter (Ferrández-Cañadell, 2012), and we also found this feature in reticulate *Nummulites* from other Kutch samples (Figure 9/8). This is also the case for the change in coiling direction (Figure 9/23). Saddle-shaped tests might be an adaptation to substrate conditions, while wall overgrowth is rather a pathological feature that can be explained by some unknown environmental stress.

Deviating paleoecological circumstances can also be responsible for the unusually large embryo size of the A-forms, because it only appears in the lowermost sample of the Kharai section. In all the other samples of Kutch, reticulate *Nummulites* fit well with *N. bormidiensis*. Thus, the appearance of reticulate *Nummulites* with abnormally large embryo has no stratigraphic significance. Since the exterior and the qualitative characteristics of both generations of reticulate *Nummulites* from sample Kharai 4 and from all the other Kutch samples fit well each to other, we agree with Sengupta (2000) that there is no need to introduce a new species name for the forms from sample Kharai 4. As in our interpretation reticulate *Nummulites* from all the other Kutch samples have to be called as *N. bormidiensis*, we apply the name of *N. aff. bormidiensis* for the forms from sample Kharai 4.

Benedetti, Di Carlo, and Pignatti (2010), Benedetti and Pignatti (2013) and also Eder, Hohenegger, and Briguglio (2017) suggested that the size of the embryo could be linked to the depth of water. In our case, however, there are not any indications for drastic difference in this condition between the layer of sample Kharai 4 and the overlying beds.

***Nummulites kecskemetii* Less, 1991**

Figs. 10/1–5

Nummulites kecskemetii n. sp. – Less, 1991; pp. 439–441, pl. 1, Figs. 1–6, pl. 2, Figs. 1–3; Özcan et al., 2009a; p. 755, Figs. 17.6–10 (with synonymy); Özcan et al., 2010a, p. 479, pl. 4, Figs. 23, 24.

Material. This species occurs throughout the Oligocene sequence of Kutch (Table 5) as an accessory element of the larger foraminiferal assemblage. Only A-forms have been found.

Remarks. In our opinion this species is identical with the one that was mentioned in the previous literature (Biswas, 1992; Reuter et al., 2013) as *Operculina complanata*, which, however, was neither described nor illustrated. Most probably the internal morphology of these forms has never been studied until now. Our investigations showed that the proloculus of these forms is much smaller (40–90 µm) than that characteristic for *Operculina complanata* (100–250 µm), and the number of whorls is usually three, instead of maximum two as in *O. complanata*. Curved septa are also characteristic rather for

Nummulites kecskemetii. Moreover, the septa of *O. complanata* consist of oblique stolons (see the photos in Less, 1991 and Benedetti et al., 2018), which are missing in *N. kecskemetii*. The absence of oblique stolons in *N. kecskemetii* is also justified in the studied material from Kutch. Where these two taxa co-occur (Hungary: Less, 1991; Turkey: Özcan et al., 2009a, 2010a), their distinction is unambiguous.

Nummulites kecskemetii is described and discussed in more details in papers listed in the synonymy list. Most probably it is an immigrant from the Western Hemisphere (Less, 1991) and its stratigraphic range in the Tethys is limited to the SBZ 22B and 23 Zones of the Chattian. During this time-span we could not observe any considerable evolution within this species. Therefore, and because its determination is not problematic, we did not perform detailed morphometric studies.

Genus *Heterostegina* d'Orbigny, 1826

This genus is known from the Oligocene of both the Mediterranean and W Pacific paleobiogeographic provinces. However, forms from these regions have been described under different names. In this paper we do not use the subgeneric subdivisions introduced by Banner and Hodgkinson (1991) for the reasons discussed in detail by Benedetti et al. (2018). Many populations from different Mediterranean sites were analyzed morphometrically in the last years (Benedetti et al., 2018; Less, 1991; Özcan et al., 2009a, 2010a). The results are summarized in Table 2 and Figure 11, which show that these populations can be grouped into three clusters, constituting three different species. The recently introduced *H. matteuccii* occurs very rarely in the early Oligocene of the Mediterranean realm (Benedetti, 2010; Benedetti & D'Amico, 2012; Benedetti et al., 2018). Population Csókás 4 from Hungary, which has not yet been formally described, differs very much from all the others found in the upper part of the Oligocene. In Less (1991) it was erroneously reported as *H. assilinooides*, which is the name that should be applied for the vast majority of populations from the upper part of the Oligocene. Numerical parameters of Kutch populations of *Heterostegina* fit well with those from the Mediterranean realm. However, they have been traditionally described under the name of *H. borneensis*, which is used for W Pacific forms from the upper part of the Oligocene (Te1–4, according to Renema, 2007). Unfortunately, no morphometric analyses are available from this realm. Based on the descriptions and photos by e.g. Banner and Hodgkinson (1991) and Racey (1995), we could not find any diagnostic features unequivocally separating *H. borneensis* from *H. assilinooides*. Since their stratigraphic ranges are also very similar, we think that they should be ascribed to the same species, which – considering the principle of priority – should be called *H. assilinooides*. Our interpretation matches that by Lunt and Renema (2014), who also joined these two nearly co-eval forms under one single name. However, they propose to

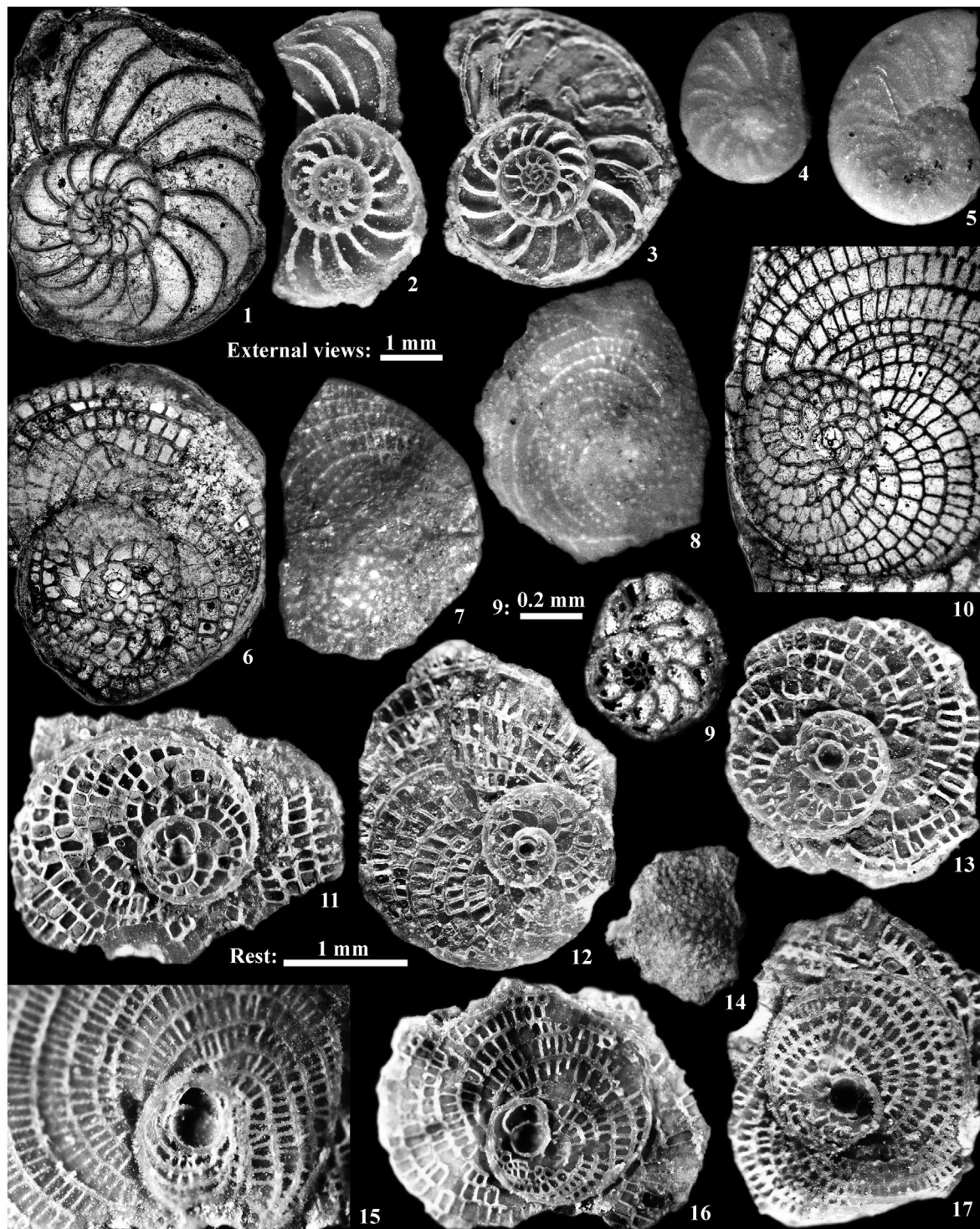


Figure 10. Radiate *Nummulites*, *Heterostegina* and *Spiroclypeus* from the Oligocene of Kutch. 1–5. *Nummulites kecskemettii* Less, 1991.

Notes: 1–3: A-form, equatorial sections. 1. Ö/Waior 4–11; 2. Waior 5, O.2017.9.1; 3. Kharai 15, O.2017.10.1. 4, 5: A-form, external views. 4. Ö/Waior 5–20; 5. Ö/Kharai 8–14. 6–13. *Heterostegina assilinoidea* Blanckenhorn, 1890 emend. Henson, 1937; 6, 10–13: A-form, equatorial sections. 6. Ö/Kharai 10–12; 10. Ö/Kharai 10–15; 11. Lakhpat 1, O.2017.11.1; 12. Lakhpat 1, O.2017.12.1; 13. Lakhpat 1, O.2017.13.1. 7, 8: A-form, external views. 7. Ö/Kharai 10–22; 8. Ö/Kharai 4–8. 9: B-form, equatorial section of the juvenarium, Ö/Kharai 10–20. 14–17. *Spiroclypeus margaritatus* (Schlumberger, 1902). 14. A-form, external view, Waior 12, O.2017.14.1. 15–17: A-form, equatorial sections. 15. Waior 9, O.2017.15.1; 16. Bermoti 6, O.2017.16.1; 17. Waior 12, O.2017.17.1.

use *H. borneensis*, which we consider a junior synonym of *H. assilinoidea* (see above).

***Heterostegina assilinoidea* Blanckenhorn, 1890 emend. Henson, 1937**

Figs. 10/6–13

Heterostegina assilinoidea – Blanckenhorn, 1890, p. 342; pl. 17, Fig. 5 (non Figs. 4, 6); Henson, 1937, p. 48; pl.

4, Figs. 1–5, pl. 6, Fig. 2; Banner & Hodgkinson, 1991, pp. 115–116; pl. 4, Figs. 4–6; Racey, 1995, p. 79; pl. 11, Figs. 1–2 (with synonymy), Özcan et al., 2009a; pp. 756–757, Figs. 20.5–9. (with synonymy); Özcan et al., 2010a; pp. 480–481, pl. 5, Figs. 1–4, 7.; Ferràndez-Cañadell & Bover-Arnal, 2017, pp. 96–97, Figs. 3G, 3H, 8A–8F, 8L, 8 M. (with synonymy)

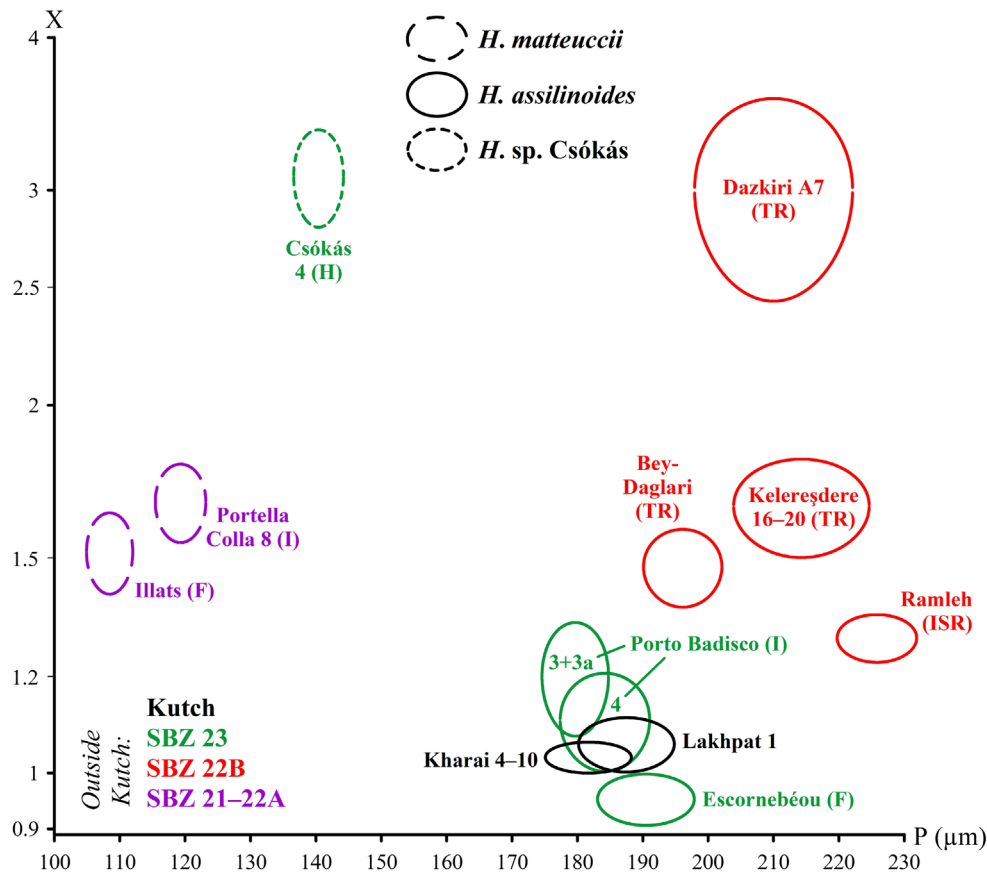


Figure 11. Bivariate P–X plot (proloculus diameter vs. number of post-embryonic pre-heterosteginid chambers; the scale for X is logarithmic) (mean values at the 68% confidence level) for Oligocene *Heterostegina* populations from Kutch and some other localities (for numerical and source data see Table 2).

Heterostegina borneensis – van der Vlerk, 1929; p. 16, Figs. 6a–c, 25 a–b; Racey, 1995, pp. 79–80; pl. 11, Figs. 3–4 (with synonymy); Matsumaru, 1996, pp. 94, 96, pl. 28, Figs. 1–7 (with synonymy)

Heterostegina (Vlerkina) borneensis – Banner & Hodgkinson, 1991, pp. 114–115; pl. 4, Figs. 1–3; Singh & Raju, 2007, p. 1254, pl. 1, figs. a–g.

Material. We found this species only in the Basal Member of the Maniyara Fort Formation (Table 5). It occurs in all three sections in which this member was studied. It is always present, but it is quantitatively subordinate to reticulate *Nummulites* (*N. bormidiensis* and *N. aff. bormidiensis* in sample Kharai 4). Most of the specimens turned out to be megalospheric, but a few microspheric specimens have also been found. Singh and Raju (2007) reported *Heterostegina borneensis* also from the lowest part of the Bermoti Member in the Waior section. Based on their detailed morphometric studies ($P_{\text{mean}} = 204 \mu\text{m}$ and $X_{\text{mean}} = 0.88$, based on 43 specimens) this population also belongs to *H. assilinoidea*, in our interpretation.

Remarks. We displayed all the available morphometric information on Tethyan Oligocene *Heterostegina* in Figure 11 and Table 2. *Heterostegina assilinoidea* from Kutch is closest to the populations from the late Chattian (SBZ 23) of Europe (Escornebéou and Porto Badisco). Our morphometrical data are still rather scattered and do not

support any distinct morphological trend. For this reason we believe that, for the time being, all the populations of *H. assilinoidea* plotted in Figure 11 have to be united into one single species. Detailed discussion on this species can also be found in Özcan et al. (2009a, 2010a).

Genus *Spiroclypeus* H. Douvillé, 1905

As concerns the Oligocene, this genus is known only from its upper part in both the Mediterranean (SBZ 23) and W Pacific realm (Te4). However, *Spiroclypeus* occurrences in these two paleo-bioprovinces are reported under different specific names. In the Mediterranean *Sp. blanckenhorni* is used uniformly, whereas in the West Pacific several names were erected, based mainly on minor differences in external features. According to Cole (1969, see also for detailed discussion), all these forms are synonymous and should be described as *Sp. margaritatus* Schlumberger (1902), by applying the principle of priority. Lunt and Renema (2014) agree in principle to use one single name for W Pacific *Spiroclypeus* (separated from *Tansinhokella*, introduced by Banner & Hodgkinson, 1991), but they propose the name of *Sp. orbitoideus* Douvillé, 1905. We agree with Cole (1969) in considering that the name '*margaritatus*' should be used as priority respect to '*orbitoideus*'.

For the Kutch forms, which can be found in enormous quantity in the upper part of the Bermoti Member, Tewari (1956) introduced a new name, *Sp. ranjanae*, which since

then has been used in all the subsequent papers on the stratigraphy of Kutch and other sedimentary basins of India. In accepting Cole's (1969) concept to unify all W Pacific *Spiroclypeus* from the latest Oligocene (and earliest Miocene) under the umbrella of *Sp. margaritatus*, the Kutch forms should be included here as well (based on both the Tewari, 1956, and our material). Therefore, *Sp. ranjanae* is considered here as the junior synonym of *Sp. margaritatus*.

According to our material from Turkey (Özcan et al., 2009b, 2010a), and based also on our still unpublished data from Escornebéou (France) and Porto Badisco (SE Italy), *Sp. blanckenhorni* does not exhibit any significant difference from the W Pacific representatives of the genus. Consequently, for priority reasons, *Sp. margaritatus* should be applied for all the late(st) Oligocene (and maybe also earliest Miocene) *Spiroclypeus*, from the W Mediterranean to the W Pacific, endowing this species with a considerable significance in terms of interregional stratigraphic correlation.

***Spiroclypeus margaritatus* (Schlumberger, 1902)**

Figs. 10/14–17

Heterostegina margaritata n. sp. – Schlumberger, 1902, p. 252, 253, pl. 7, Fig. 4.

Spiroclypeus margaritatus (Schlumberger) – Cole, 1969, p.; C8–10, pl. 2, Figs. 1–20; pl. 3, Figs. 9–14, 19 (with synonymy); Matsumaru, 1996, pp. 104, 106, 108, pl. 32, Figs. 1–8, pl. 33, Figs. 1–9 (with synonymy)

Spiroclypeus blanckenhorni – Henson, 1937, pp. 50–51; pl. 4, Fig. 7, pl. 5, Figs. 1–3; Özcan et al., 2009b; pp. 577–578, pl. 3, Figs. 27, 29, 30, 32–34 (with synonymy); Özcan et al., 2010a; pp. 481–482, pl. 5, Figs. 11, 14, 15, 17, 18;

Ferràndez-Cañadell & Bover-Arnal, 2017, pp. 97–99, Figs. 3I, 8G–8 K, 8 M–8O. (with synonymy)

Spiroclypeus ranjanae n. sp. – Tewari, 1956, p. 320, Figs. 1–4.

Material. This species occurs exclusively in the samples from the upper part of the Bermoti Member (Table 5), where it can be found in rock-forming quantity.

Remarks. Available morphometric information on Tethyan late Oligocene and early Miocene *Spiroclypeus* is summarized in Table 2 and Figure 12. They show that these populations can really belong to the same one single taxon, although (as in the case of *Heterostegina assilinoidea* – see discussion above) data from Kutch are closest to those from Europe (Escornebéou and Porto Badisco). A more detailed discussion on Oligo-Miocene *Spiroclypeus* can be found in Özcan et al. (2009b, 2010a), in which an independent origin of the Priabonian and late Chattian-Aquitanian representatives of the genus is proposed, and which is also well visible in Figure 12 (moreover Priabonian forms bear a tight spire while that of the Oligo-Miocene representatives is distinctly loose). Recently, this view has been strongly supported and confirmed by Lunt and Renema (2014). They also convincingly document the Indonesian roots (*Tansinhokella*) of Oligocene *Spiroclypeus*. Thus, the Tethys-wide expansion of *S. margaritatus* at the end of the Oligocene was originated most probably from the Far East.

Family Lepidocyclinidae Scheffen, 1932

Both Tethyan genera of this family can be found in Kutch. They can be distinguished typologically quite easily by four different characteristics: (1) externally, *Eulepidina* is significantly larger and looks thinner than

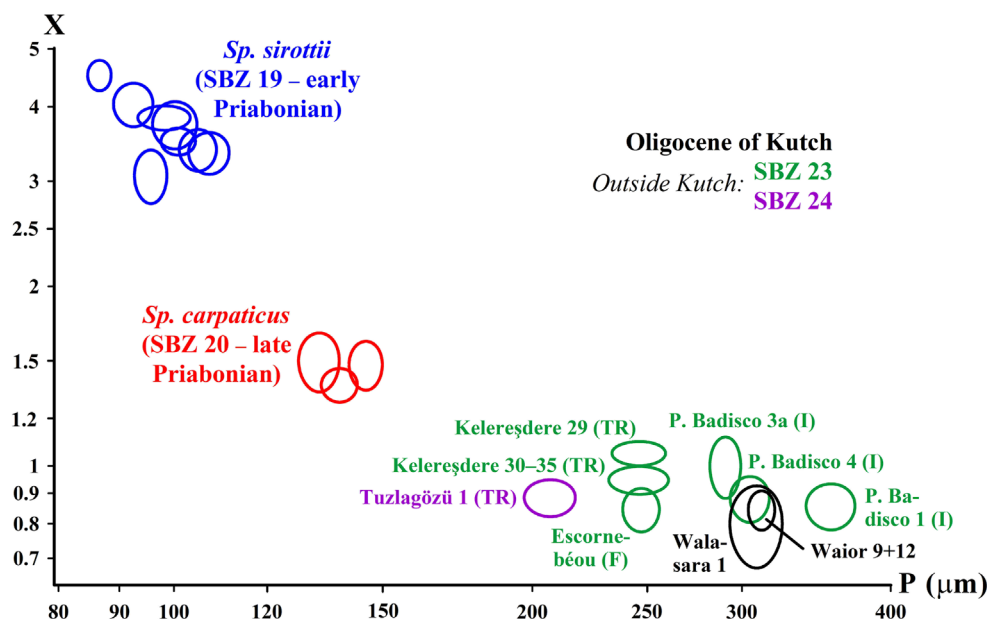


Figure 12. Bivariate P–X plot (proloculus diameter vs. number of post-embryonic pre-heterosteginid chambers; both scales are logarithmic) (mean values at the 68% confidence level) for Oligocene *Spiroclypeus* populations from Kutch and some other localities (for numerical and source data see Table 2).

Notes: Late Eocene *Spiroclypeus* populations from the Western Tethys are shown for comparison (for source data see Cotton et al., 2017; Less & Özcan, 2008; Less et al., 2011; Özcan et al., 2010b).

Nephrolepidina, which is rather inflated, (2) the megaspherical embryo of *Eulepidina* is much larger, (3) the degree of embracement of the protoconch by the deuterococonch is also much larger in the case of *Eulepidina* than for *Nephrolepidina*, and (4) the equatorial chamberlets of *Eulepidina* are also much larger than those of *Nephrolepidina*. The last three internal features can well be read from Tables 3 and 4 as well. The difference between the representatives of the two genera can be well detected morphometrically, too, as it was shown by Saraswati (1995) and Muthukrishnan and Saraswati (2001).

Genus *Eulepidina* H. Douvillé, 1911

The Oligocene representatives of this genus are much better known from the Mediterranean than from the W Pacific realm. Data from the latter region are rather scattered (no synthesis is available), many different names are used, and the stratigraphic control is also very poor in several cases. Morphometric studies of the internal morphology are completely missing. Thus, we agree with Drooger (1993) Özcan et al. (2009a, see also for a more detailed discussion) that W Pacific *Eulepidina* need a detailed taxonomic and stratigraphic revision at the species level. Pending this revision, we prefer to avoid the use of W Pacific names. For this reason, we do not use here *E. ephippioides*, the name applied by Saraswati (1995) and Muthukrishnan and Saraswati (2001) for the Kutch forms of *Eulepidina*.

Nevertheless, our general impression is that coeval Oligocene *Eulepidina* from the W Pacific have

considerably smaller embryos than those from the Mediterranean, and the evolution of this genus was mainly parallel but different in the two bioprovinces, as already suggested by BouDagher-Fadel and Price (2010). Temporary exchange of *Eulepidina* between the two provinces, however, could happen, as shown by Özcan et al. (2009a, 2009b, 2010a) and Özcan and Less (2009) to explain the records of *Eulepidina anatolica* in the upper Chattian and *E. aff. formosa* in the Burdigalian of Turkey.

Based on the data by van Heck and Drooger (1984), Less (1991), Özcan et al. (2009a, 2010a) and also on our still unpublished ones from Porto Badisco (S Italy), Tuc de Saumon and Escornebéou (both SW France), the evolution of Mediterranean *Eulepidina* cannot be described by the one single *E. formosoides-dilatata* lineage, as suggested by Drooger (1993). In the late Chattian SBZ 23 Zone, two other forms, *E. elephantina* and *E. anatolica* (a possible immigrant from the W Pacific, as suggested by Özcan et al., 2010a) can also be distinguished (Figure 13 and Table 3). As to the Kutch forms of *Eulepidina*, their morphometrical parameters best fit to the main *E. formosoides-dilatata* Mediterranean lineage (see Figure 13 and Table 3).

***Eulepidina ex. interc. formosoides* Douvillé, 1925 et *dilatata* (Michelotti, 1861)**

Figs. 14/1–6.

Material. The occurrence of this taxon is limited to the Coral Limestone. In almost all samples coming from this lithostratigraphic unit (Table 5) it occurs in rock-forming quantity.

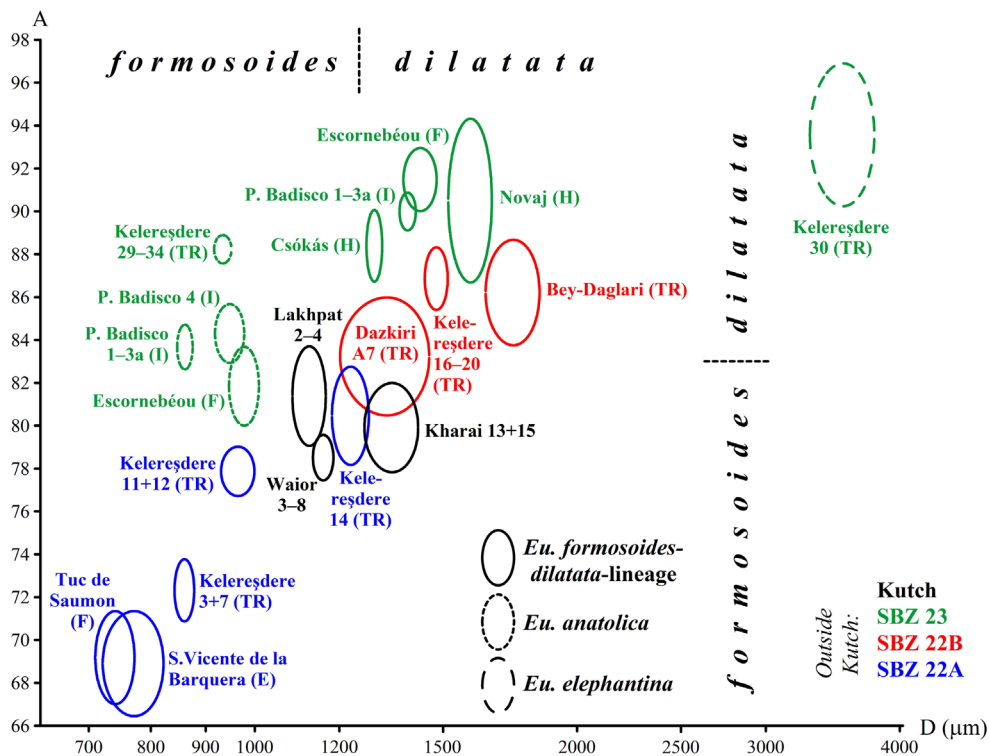


Figure 13. Bivariate D–A plot (deuterococonch diameter vs. degree of embracement of the protoconch by the deuterococonch; the scale for D is logarithmic) (mean values at the 68% confidence level) for Oligocene *Eulepidina* populations from Kutch and some other localities (for numerical and source data see Table 3).

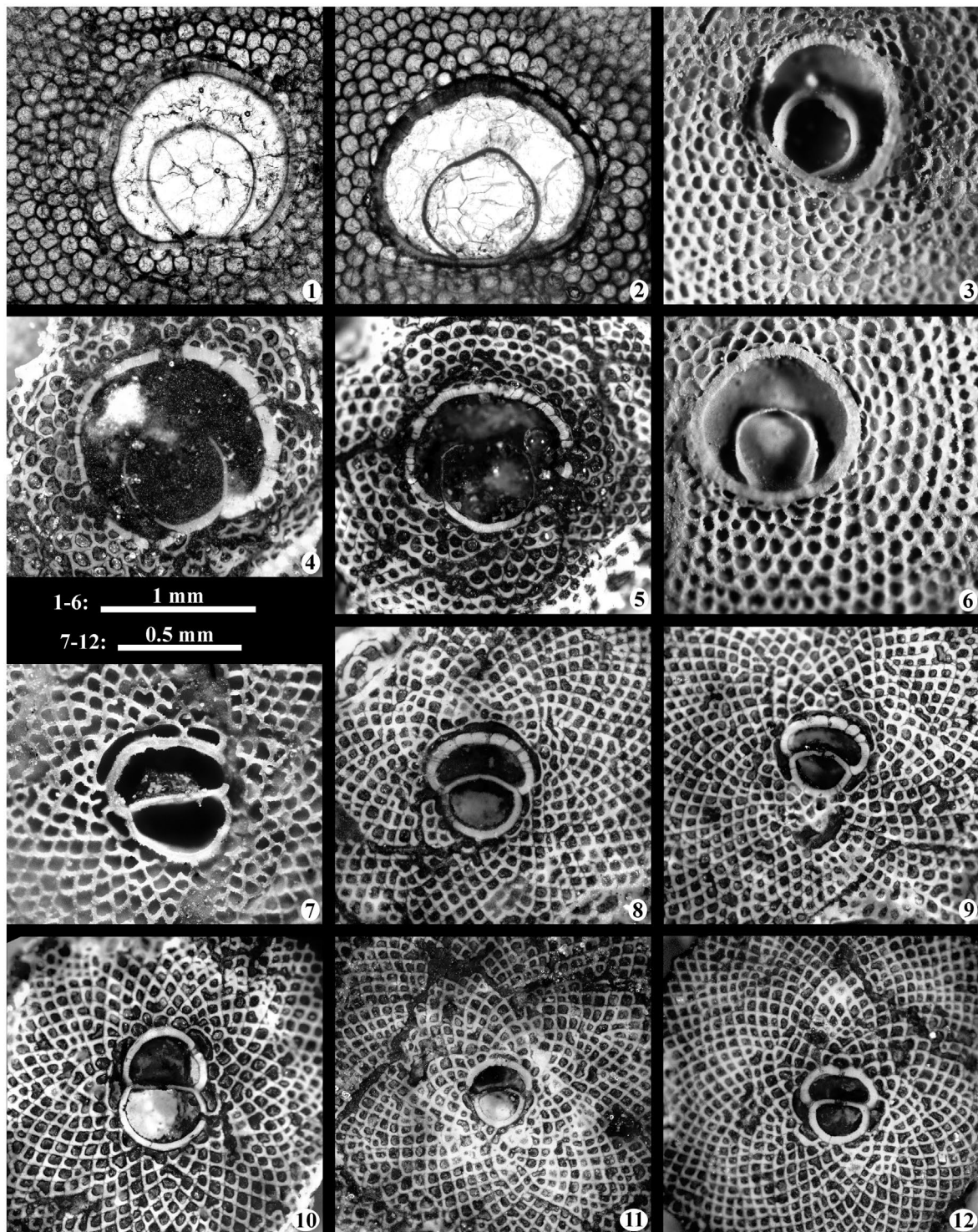


Figure 14. Lepidocyclinids from the Oligocene of Kutch. 1–6.

Notes: *Eulepidina* ex. interc. *formosoides* Douvillé, 1925 et *dilatata* (Michelotti, 1861). All A-form equatorial sections. 1. Ö/Waior 4–14; 2. Ö/Waior 5–10; 3. Waior 8, O.2017.18.1; 4. Lakhpat 2, O.2017.19.1; 5. Lakhpat 3, O.2017.20.1; 6. Waior 8, O.2017.21.1. 7–12. *Nephrolepidina* ex. interc. *morgani* Lemoine et Douvillé, 1904 et *praemarginata* R. Douvillé, 1908. All A-form equatorial sections. 7. Kharai 15, O.2017.22.1; 8. Lakhpat 2, O.2017.23.1; 9. Lakhpat 2, O.2017.24.1; 10. Lakhpat 3, O.2017.25.1; 11. Lakhpat 3, O.2017.26.1; 12. Lakhpat 4, O.2017.27.1.

Remarks. Özcan et al. (2009a, 2010a) proposed $A_{\text{mean}} = 83$ and $D_{\text{mean}} = 1250 \mu\text{m}$ to delimit the two successive species of the *Eulepidina formosoides-dilatata* lineage from each other. Considering these arbitrary limits, according to Table 3 the Kutch populations are closer to *E. formosoides*. However, Figure 13 shows that they rather fit to the group of *E. dilatata* populations, calling for a redefinition of the above mentioned morphometric

limits. Until that, we place the *Eulepidina* populations from Kutch in an intermediate position between *E. formosoides* and *E. dilatata*. The absence of *Eulepidina* in the Basal Member of the Maniyara Fort Fm., and its sudden appearance at the base of the Coral Limestone with forms that do not belong to the most primitive Mediterranean representatives, clearly indicate a migration/colonization event (most probably from the Western Tethys).

Genus *Nephrolepidina* H. Douvillé, 1911

This genus occurs both in the Mediterranean and W Pacific realms. According to Drooger (1993) – based on the data by de Mulder (1975) and van Vessem (1978) – its evolution followed different paths in these two paleobiogeographic provinces. The main difference, as it can be concluded from van Vessem's (1978) data, is that the embryo of the co-eval forms is significantly larger in the Mediterranean than in the W Pacific. He also concluded, based on a detailed discussion (van Vessem, 1978, pp. 107–108, 112–115, 117–119 and text-Fig. 77 on p. 106), that his only Oligocene sample (K4), from the Bermoti Member of the Waior section of Kutch, belongs to the Mediterranean *Nephrolepidina*-lineage (see also Drooger, 1993, p. 130; Fig. 79), whereas the lower Miocene sample, from the Khari Nadi section of this area, already represents the W Pacific lineage of the genus. On the contrary, Saraswati (1994) concluded that all Oligo-Miocene *Nephrolepidina* from the western part of India (Kutch, Saurashtra and Quilon) belong to the W Pacific *Nephrolepidina isolepidinoides-sumatrensis* group. Raw morphometric data (that are not detailed in Saraswati, 1994), based on 9 specimens from a sample of the Coral Limestone Member in Lakhpat ($P_{\text{mean}} = 231 \mu\text{m}$, $D_{\text{mean}} = 335 \mu\text{m}$, $A_{\text{mean}} = 40$ and $C_{\text{mean}} = 1.7$; for the explanation of symbols see the header of Table 4), are quite similar to ours from Kutch (see Table 4), with the

exception of the somewhat lower value of parameter C considered by Saraswati (1994).

Our new data, from both the Coral Limestone and Bermoti Member, fit well with those by van Vessem (1978), and, therefore strengthen his views since the embryo of the Kutch forms from the Oligocene are considerably larger than that of both *N. isolepidinoides* and *N. sumatrensis* from the W Pacific Oligocene and early Miocene. Thus, we believe that *Nephrolepidina* populations from Kutch should be placed within the W Tethyan lineage, which is subdivided by de Mulder (1975) into three species by applying the following morphometric limits:

$$N. \textit{praemarginata} \quad 1 < C_{\text{mean}} < 3.35 < A_{\text{mean}} < 40$$

$$N. \textit{morganii} \quad 3 < C_{\text{mean}} < 5.25 \quad 40 < A_{\text{mean}} < 45$$

$$N. \textit{tournoueri} \quad C_{\text{mean}} > 5.25 \quad A_{\text{mean}} > 45$$

It should be noted that Özcan et al. (2010a) reported a parallel Mediterranean *Nephrolepidina* (*N. musensis*), with considerably larger embryo and equatorial chamberlets. However, according to Table 4 the Kutch forms clearly do not belong to this parallel lineage.

Nephrolepidina ex. interc. *morganii* Lemoine & Douvillé, 1904 et *praemarginata* R. Douvillé, 1908

Figs. 14/7–12

Material. This taxon occurs sporadically in some samples of the Coral Limestone and Bermoti Member (Table 5). It seems to be more common in Lakhpat than in the

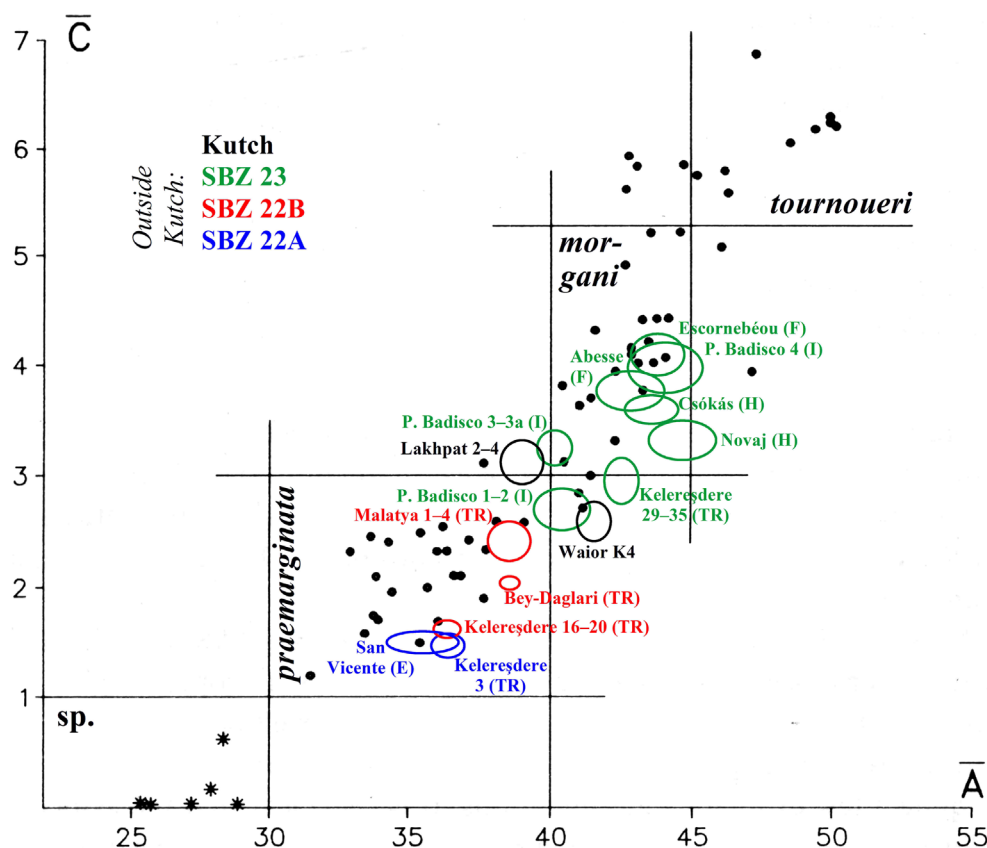


Figure 15. Distribution of *Nephrolepidina* populations from the the Oligocene of Kutch and some other localities (for numerical and source data see Table 4), marked by ellipses of the mean values at the 68% confidence level, in the $A_{\text{mean}} - C_{\text{mean}}$ bivariate plot for Western Tethyan nephrolepidinid populations (their means are marked by dots, while the means of *Lepidocyclus* sp. of Freudenthal, 1972 by asterisks), according to Drooger (1993).

other sections. In our material, only the population from sample Lakhpat 2 (Coral Limestone) was suitable for morphometric evaluation. These data can be completed with those from sample K4 (Waior section, Bermoti Member, Table 4) by van Vessem (1978).

Remarks. Based on their morphometric data (Table 4, Figure 15), the Kutch forms from both lithostratigraphic units occupy an intermediate position between *Nephrolepidina praemarginata* and *N. morgani*. According to Table 4 and Figure 15, similar populations from the Mediterranean are characteristic mostly for the SBZ 23 Zone. It should be noted, however that there is a large temporal overlap between the successive species of the main *Nephrolepidina* lineage introduced by de Mulder (1975).

Discussion

Chronostratigraphy and biostratigraphy

There exists a general agreement among Indian stratigraphers (e.g. Biswas, 1992; Raju, 2011) that the lower three members of the Maniyara Fort Formation belong to the Rupelian, whereas the Bermoti Member is generally referred to the Chattian. The only minor difference is that Raju (2011) places the Rupelian/Chattian boundary slightly higher, within the Bermoti Member, at the lowest appearance of miogypsinids. This partition reflects the tripartite division of Oligocene in India, and corresponds to the Tc (*Nummulites fichteli* with no lepidocyclinids), Td (*N. fichteli* and *Eulepidina*) and Te (lepidocyclinids with no *N. fichteli*) W Pacific (East Indian in Renema, 2007) letter stages. It is a very convenient way for professional geologists to correlate the sections across the basins.

However, in the recent paper by Reuter et al. (2013), which includes also the Bermoti section, the Coral Limestone is assigned to the early Chattian SBZ 22B Zone of Cahuzac and Poignant (1997), whereas the Bermoti Member is assigned to the late Chattian SBZ 23 Zone. These latter ages are based exclusively on LBF. *Nummulites* aff. *vascus*, *N. fichteli*, *N. sublaevigatus*, *Operculina complanata* and *Eulepidina dilatata* are reported from the lower part of the Coral Limestone, whereas the dominance of biconvex discoidal *Eulepidina dilatata* (2 cm Ø) is reported from the upper part of the Bermoti Member. None of the reported LBF is either described or illustrated in Reuter et al. (2013). For this reason, determination of the LBF fauna of the lower part of the Coral Limestone should be considered with caution. Also the determination of *Eulepidina dilatata* as the dominant form in the upper part of the Bermoti Member is at least doubtful, as we are afraid that these forms represent indeed *Spiroclypeus*.

Nevertheless, our studies support more the chronostratigraphic subdivision by Reuter et al. (2013) than that of Biswas (1992), which is followed in Indian stratigraphy and most recently also by Catuneanu and Dave

(2017). Based on our studies, mostly from Turkey (Özcan et al., 2009a; 2010) but also from some still unpublished sites (Tuc de Saumon, SW France; Dego-Costalupara, NW Italy), the characteristic larger benthic foraminiferal assemblage (*Nummulites bormidiensis*, *N. kecskemetii* and *Heterostegina assilinoidea*) of the Basal Member marks the SBZ 22B Zone, even in the absence of lepidocyclinids, because *N. bormidiensis* can only be found in this zone whereas *N. kecskemetii* and *H. assilinoidea* do not occur in the older zones. The coincidence of the SBZ 22A/B boundary with the Rupelian/Chattian boundary, suggested by Cahuzac and Poignant (1997), is still under debate. We cannot exclude that the zonal boundary is slightly older than the chronostratigraphic boundary between the two stages, but this still needs further studies. The occurrence of *N. aff. bormidiensis* in sample Kharai 4 is probably due to some extreme ecological factors, which is marked also by other unusual teratological phenomena (Sengupta et al., 2011, 2014).

Unfortunately, our Sr-isotope data from the Basal Member of the Kharai section do not provide a reliable age. All the bivalve shells of samples Kharai 4 and 5 have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that would translate into a numerical age much younger than the age obtained from the sample Kharai 13, collected from the overlying Coral Limestone in the same section. The most plausible explanation is that the pristine marine Sr isotope ratio of the bivalve shells of samples Kharai 4 and 5 has been substantially altered by diagenesis and or contamination. This conclusion is also supported by the fact that the Sr-isotope ratios of the shells are very close to the value obtained from the rock-matrix enclosing the shells (see Table 6).

Although the Lumpy Clay consists only of *Nummulites bormidiensis*, it is also ranked into the SBZ 22B Zone where both the under- and overlying lithostratigraphic units are placed.

Based on the occurrence of *Nummulites bormidiensis*, the Coral Limestone still belongs to the SBZ 22B Zone. This age is also consistent with the other three components of the larger foraminiferal fauna of this member. In fact, *N. kecskemetii* is characteristic for the SBZ 22B and 23 Zones, and lepidocyclinids, represented by *E. ex. interc. formosoides-dilatata* and *N. ex. interc. morgani-praemarginata*, are together most characteristic for the early Chattian.

Strontium isotope data for the Coral Limestone Member are available from the upper part of the Kharai section (sample Kharai 13; Figure 3) and from the lower part of the Waior section (sample Waior 4). Of the two pectinid shells of sample Kharai 13, we discarded Kharai 13B. His much higher Sr isotope ratio and high Fe content are suggestive of contamination by clay minerals bearing radiogenic Sr. The $^{87}\text{Sr}/^{86}\text{Sr}$ value of Kharai 13A, after correction for inter-laboratory bias, translates into a numerical age of 28.65 Ma, which is very close to the

Table 8. Strontium isotope stratigraphy of samples from the Maniyara Fort Formation in the Oligocene of the Kutch Basin. The Sr isotope ratios have been corrected for interlaboratory bias (see text for further details). Numerical ages are from McArthur et al. (2001; look-up table version 5). Minimum (min) and maximum (max) ages are obtained by combining the analytical error with the statistical error associated with the reference curve.

Litho-stratigraphy	Section	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$ corrected	$^{87}\text{Sr}/^{86}\text{Sr}$ mean	2 s.e. ($\times 10^{-6}$)	SBZ	Numerical Age (Ma)			Chronostratigraphic Age
							Min	Preferred	Max	
Coral Limestone Member	Kharai	13A	0.708018		30	22B	27.55	28.62	29.85	Rupelian-Chattian boundary
		Waior	4A	0.708091	0.708067	35	22B	25.95	27.25	28.45
		4B	0.708077							
		4C	0.708033							
Bermoti Member	Bermoti	6A	0.708228	0.708250	42	23	22.20	23.15	24.10	Latest Chattian
		6C	0.708271							

Rupelian-Chattian boundary according to the Geological Time Scale of Gradstein et al. (2012: GTS2012). Actually, the minimum age, obtained by combining the analytical uncertainty with the uncertainty of the reference curve, is 27.55 Ma, which is in the earliest Chattian (Table 8). An early Chattian age is also strongly supported by the Sr isotope ratio of sample Waior 4. The SIS data are quite robust, because the three bivalve shells from this sample have $^{87}\text{Sr}/^{86}\text{Sr}$ values that differ by less than 60×10^{-6} (Table 6). Internal consistency of values from different subsamples from the same sample or stratigraphic level is considered one of the best arguments for preservation of the original Sr isotope ratio of seawater (McArthur, 1994; McArthur et al., 2004), which is a prerequisite for correct application of SIS. After correction for interlaboratory bias, the mean $^{87}\text{Sr}/^{86}\text{Sr}$ value of the three bivalve shells of Waior 4 translates into a numerical age of 27.25 Ma (Table 8), which is in the early Chattian according to the GTS2012. This age is also within error with the age given by sample Kharai 13A.

Since the first occurrence of *Miogypsinoides complanatus-formosoides* is well documented within the Bermoti Member in the Waior section (Drooger & Raju, 1978), the age of the lower two-third of this member may be interpreted as still belonging to the upper part of the SBZ 22B Zone. Instead, according to our results, the *Spiroclypeus* beds of the upper part of the Bermoti Member already represent the SBZ 23 Zone. Not only *Miogypsinoides complanatus-formosoides* is exclusive for this zone but also the Tethys-wide expansion of *Spiroclypeus margaritatus* westward, that can be traced from SE Spain (Ferrández-Cañadell & Bover-Arnal, 2017) through SW France (Escornebéou and Abesse), Porto Badisco in S Italy (Benedetti & Briguglio, 2012 and also our still unpublished data), Turkey (Kelereşdere: Özcan et al., 2010a) and Kutch to SE Asia and the Western Pacific, marks the same horizon. The presence of accessorial LBF (*Nummulites keckemetii* and *Nephrolepidina* ex. interc. *morgani-praemarginata*) does not contradict to this age-determination.

Strontium isotope data from the *Spiroclypeus* beds are available from the Bermoti section (sample Bermoti

6). Out of the three subsamples analysed from this sample, we discarded Bermoti 6B. Its lower Sr concentration, higher Fe and Mn content and distinctly more radiogenic Sr isotope ratio, compared to the other two subsamples, call for a substantial alteration of the pristine isotopic value by diagenesis. The age obtained from the average value of samples Bermoti 6A and 6C, after correction for interlaboratory bias, is 23.15 ± 0.95 Ma (Table 8). This age is significantly younger than that obtained for the Coral Limestone but also surprisingly close to the Chattian/Aquitanian boundary. However, this is also the case for other SBZ 23 sites (Escornebéou, Abesse, Porto Badisco, Csókás, Novaj) of the Western Tethys (for preliminary data see Less, Parente, Frijia, & Cahuzac, 2015). Most probably the SBZ 23/24 Zone boundary already slightly extends into the Aquitanian.

Paleobiogeographic evaluation

Since all elements of the larger foraminiferal fauna from Kutch can also be found in the Mediterranean realm, the SBZ zonation (Cahuzac & Poignant, 1997) based on them can also be applied here. At the same time the lack of *Operculina complanata* commonly occurring in Europe (and in Turkey, too) is a significant difference. Until now, we could not find *Cycloclypeus* either, but this can also be due to the general rarity of this genus in the Tethys. Finally, lepidocyclinids are absent in the Basal Member. Their first representatives in the Coral Limestone are significantly more developed than the primitive forms appearing in the SBZ 22A Zone in Europe and in Turkey. This means that the first appearance of these forms in Kutch is a much younger event than that in Europe and Turkey. Summing up, the Oligocene LBF-fauna of Kutch is a slightly reduced Mediterranean one. This is in good agreement with the results of Harzhauser et al. (2009), who documented a similar Western Tethyan affinity of Oligocene gastropods from Kutch. The first westward migration, the Tethys-wide expansion of *Spiroclypeus margaritatus* from the Far East could happen only at the very end of the Oligocene.

Table 9. Correlation of Oligocene western Tethyan larger benthic foraminiferal zones (SBZ of Cahuzac & Poignant, 1997) and SE Asian letter stages (Renema, 2007) with standard chronostratigraphic units. Biostratigraphic markers and tentative numerical ages of boundaries are also shown. FO: first occurrence, LO: last occurrence.

Stage/sub-stage	SBZ	Letter stage	Boundary event	Num. age (Ma)
Aquitanian	24	Te5	FO <i>Miogypsina gunteri</i>	≈22.5
Late Chattian	23	Te4	FO <i>Spiroclypeus margaritatus</i>	24.5–25
Early Chattian	22B	Te1–3	FO <i>Miogypsinoidea</i>	
Late Rupelian	22A	Td	FO <i>Heterostegina assilinoidea</i>	≈29
Early Rupelian	21	Tc	FO <i>Eulepidina</i> FO <i>Nummulites fichteli</i>	30–31 ≈34
Priabonian	18 (p.)-20	Tb	LO orthophragmines LO <i>Pellatispira</i>	

Correlation between paleobiogeographical provinces

The identification of Mediterranean forms in the Oligocene sequence of Kutch is also important because part of them were previously described under SE Asian (or sometimes local) names. Based on a review of published data (see the systematic part for details), only lepidocyclinids appear to belong to different lineages in the Western Tethyan and W Pacific provinces. Species of *Heterostegina* (*H. assilinoidea* = *H. borneensis*), *Spiroclypeus* (*S. margaritatus* = *S. blanckenhorni* = *S. ranjanae*), *Nummulites* and of most miogypsinids from the two provinces display great similarities to each other and they can be described under the priority name.

Based on this, it is possible to establish a correlation between the W Tethyan SBZ zones and the East Indian 'letter stages', as well as between the biostratigraphic events defining their boundaries (see Table 9). The chronostratigraphic calibration of this scheme by SIS is in good agreement, at the stage level, with the chronostratigraphic calibration of the East Indian 'letter classification' proposed by Renema (2007).

Conclusions

- (1) Nummulitids and lepidocyclinids from the Oligocene Maniyara Fort Formation have been investigated with major focus on the morphology of the internal test features. The reticulate *Nummulites* previously reported as *Nummulites fichteli* and *N. clipeus*, present from the Basal Member to Coral Limestone, have been assigned to *N. bormidiensis*. The morphotypes previously identified as *N. cf. fichteli*, present at the base of Basal Member, are here ascribed to *N. aff. bormidiensis*. The nummulitids previously assigned to *Operculina complanata*, occurring throughout the sequence, were

re-arranged under *Nummulites kecskemetii*, *Heterostegina borneensis* (Basal Member) and *Spiroclypeus ranjanae* (Bermoti Member) have been replaced by taxa corresponding to their senior synonyms (*H. assilinoidea* and *Sp. margaritatus*). For lepidocyclinids, we applied Western Tethyan names, such as *Eulepidina ex. interc. formosoides-dilatata* (Coral Limestone) and *Nephrolepidina ex. interc. morgani-praemarginata* (Coral Limestone and Bermoti Member).

- (2) Revised LBF-determinations lead to revised ages. The Basal Member, previously assigned to the early Rupelian SBZ 21 Zone, has been assigned to the early Chattian SBZ 22B Zone, based on the joint occurrence of *Nummulites bormidiensis*, which only occurs in this zone, and *N. kecskemetii* plus *Heterostegina assilinoidea*, which first occur in this zone. The same age is given to the Coral Limestone (formerly assigned to the late Rupelian), where *N. bormidiensis* and *N. kecskemetii* continue with the above mentioned taxa of *Eulepidina* and *Nephrolepidina*, whose range is consistent with an early Chattian age. *Heterostegina* was not found in this member. Consequently, also the Lumpy Clay, lying between the above two units but containing only and sporadically *N. bormidiensis*, is assigned to the SBZ 22B and dated as early Chattian. At least the upper third of the Bermoti Member already belongs to the late Chattian SBZ 23 (in agreement with all former age assignments), based on the well-known occurrence of *Miogypsinoidea complanatus-formosensis* (exclusive for this zone) and also on the appearance of *Spiroclypeus margaritatus*, which seems to have expanded Tethys-wide in this time. The presence of *Nummulites kecskemetii* and of the above listed *Nephrolepidina*-taxon is consistent with a late Chattian age. *N. bormidiensis* and *Eulepidina* are completely missing from this unit, while sporadic occurrence of *Heterostegina assilinoidea* is reported, although it could not be found in our samples.
- (3) Strontium isotope stratigraphy confirms an early Chattian age for the Coral Limestone (26.5–29 Ma) and a latest Chattian age for the uppermost part of the Bermoti Member (22.5–24 Ma), fitting well with the ages supported by LBF biostratigraphy.
- (4) The LBF fauna of the Kutch Oligocene has a strong Mediterranean affinity, since all taxa can also be found in the Western Tethys. It can be considered as a reduced Mediterranean fauna because of two significant differences: (i) the absence of *Operculina complanata* (widespread in both Europe and Turkey) and (ii) the

significantly younger first occurrence of lepidocyclinids in the Coral Limestone of Kutch compared to Europe and Turkey.

- (5) The identification of Western Tethyan forms in the Kutch Oligocene sequence is also important because part of them is traditionally described under W Pacific (or local) names here. Based on a review of relevant literature, only lepidocyclinids are really different between the two provinces. Species of *Heterostegina*, *Spiroclypeus*, *Nummulites* and those of most miogypsinids correspond to each other and can be merged under the priority name. The result of this taxonomic revision is a more straightforward correlation between the W Tethyan SBZ zonation and the East Indian 'letter stages'.

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