

Stilostomella: extinction or local disappearance of elongated species?

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Benthic foraminiferal analysis of 15 core top samples from the Indian Ocean, revealed the presence of eight pristine elongated benthic foraminiferal species and one group of species. Six have been already reported as extinct group, whereas three have been categorized as survival group. Documentation of these species from recent sediments of the Indian Ocean allowed us to use the term ‘local disappearance’ rather than ‘extinction’ for the Mid-Pleistocene Transition. The present study also documents their shallow infaunal habitat in high organic carbon and low temperature environments. However, these species are also able to tolerate high temperature and well-oxygenated condition.

Keywords: Benthic foraminifera, elongated species, extinction, local disappearance.

THE study of benthic foraminifera provides important tools in understanding palaeoceanographic and palaeoclimatic changes. On the other hand, benthic foraminifera are rarely used as biostratigraphic markers owing to their endemism and extended stratigraphic range. *Stilostomellidae*, *Pleurostomellidae* and *Nodosariidae* are elongated benthic foraminifera and common components of all marine benthics prior to the Mid-Pleistocene Transition (MPT)^{1–9}. These species sharply declined in their abundance during MPT throughout the globe. This event is commonly referred to as the ‘*Stilostomella* extinction’², during which climate experienced a shift to a 100 kyr cycle from a 41 kyr cycle^{10–12}. In this time interval, the oceans were flushed with well-oxygenated bottom currents with a contemporaneous decrease in marine surface productivity^{6–9}. The term ‘*Stilostomella* extinction’ was first coined by Weinholz and Lutze², but the extinction of the genera *Stilostomella* along with *Orthomorphina*, *Plectofrondicularia* and *Ellipsoglandulina* was first reported in DSDP Site 397, off northwest Africa in the Atlantic Ocean by Lutze¹. In the Indian Ocean, this extinction was first documented by Gupta³. However, a recent study shows that the extinction of this group of species was not

abrupt, but gradual, which occurred during the late Pliocene (~2.6 Ma) to the middle Pleistocene (~0.6 Ma)⁸. As the species of these genera reveal strong declination in their abundance during MPT, it is difficult to understand their ecological preferences. However, several previous studies inferred that they were infaunal in habit and preferred to live in organic carbon-rich and low oxygen environments.

We analysed recent core top sediments of different Ocean Drilling Program (ODP) holes from the Indian Ocean, to document abundances of elongated species. We have also established their ecological preferences with the help of published hydrographic data along with stable isotope records of *Stilostomella* ex gr. *S. lepidula*.

Several studies have been carried out on marine sediments of the Indian, Atlantic and Pacific Oceans to understand time and causes of extinction of elongated species during MPT. The ‘*Stilostomella* extinction’ event recorded from different previous studies^{13–26} is summarized in Table 1.

Initially Weinholz and Lutze² suggested that these elongated species were sensitive to ecological factors and progressively reduced their geographical distribution from the deep ocean to the shallow ocean. However, these elongated species, including *Stilostomella* and *Pleurostomella*, were considered as moderately deep infaunal benthic and good indicators of low bottom water oxygenation and high organic input to the sea floor^{3,5,18,21,25,27,28}. Enhanced relative abundance of these groups of species during the early to middle Eocene indicates that they were able to tolerate strong warm climates and low oxygen conditions, probably owing to their moderately deep infaunal habitat⁹. They disappeared during MPT, probably owing to the presence of increased cold, better-ventilated water masses and highly fluctuating seasonal surface water productivity^{5–7}. Probably the colder bottom waters affected the metabolic rates of these foraminifera⁵. Hayward *et al.*²⁹ showed that they were tolerant to an extremely wide ranges of bottom temperature and dissolved oxygen levels. On the other hand, Kaiho³⁰ inferred that such taxa could live beneath low-productivity areas.

However, studies from the Andaman Sea³¹, Indian Ocean³², tropical Indo-Pacific^{33,34} and Eastern Indian Ocean³⁵ revealed that the *Stilostomella* group of species was recovered from the Recent sediments. Douglas and Woodruff³⁶ also recorded live specimens of *Stilostomella antillea* (Cushman) from the Peru–Chile trench.

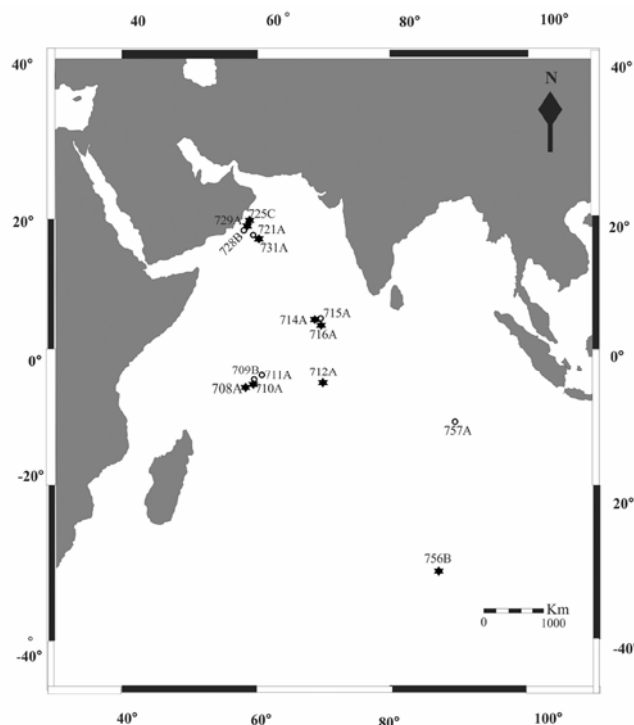
Fifteen ODP core top (top 0–2 cm) sediment samples from the Indian Ocean were considered to pursue the present study. The location of each site with present-day water depth is described in Table 2 and Figure 1.

In general, the Indian Ocean is dominantly flooded by three types of water masses. Shallower depth (up to ~1200 m) is dominated by the North Atlantic Intermediate Water³⁷. Depths between 1200 and 3800 m are mostly dominated by a mixture of the North Atlantic Deep Water

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Table 1. Previous works that documented '*Stilostomella* extinction' from different ocean basins during the Mid-Pleistocene Transition with DSDP/ODP site numbers and present-day water depth

Ocean/sea	Sites at which ' <i>Stilostomella</i> extinction' was documented	The respective present-day water depths (m)	Reference
Indian Ocean	ODP 738, 744	2252, 2307	13
	DSDP 214, 216, 217, 219, 223	1665, 2247, 3020, 1764, 3633	3
	ODP 758	2925	14
	ODP 722, 758	2045, 2925	7
	ODP 722, 758, 763, 738, 744	2045, 2925, 1367, 2253, 2308	8
	DSDP 214, 219, ODP 752, 757, 758	1665, 1764, 1086, 1652, 2925	15
Atlantic Ocean	DSDP 548, 549	1256, 2535	16
	DSDP 397, ODP 658, 659, M 13519	2900, 2263, 3081, 2862	2, 17
	ODP 980, 982	2168, 1145	6
	ODP 1000	916	18
	ODP 980A, 981A	2171, 2173	19
	ODP 991A, 994C, 995A, 997A	2800	15
	DSDP 548, 608, ODP 980, 982, 1055	1250, 3534, 1145, 2168, 1798	9
Pacific Ocean	DSDP 438A	1558	20
	ODP 790, 791	2300	21
	Piston-Core 34KL	2612	22
	ODP 861	800	23
	DSDP 593, 594, ODP 1119, 1120, 1123, 1125	1050, 1204, 395, 545, 3290, 1365	4, 5
	DSDP 317, ODP 865, 1012, KR 9912	2598, 1518, 1772, 2326	9
South China Sea	Gravity core 17957-2	2195	24
	ODP 1143	2772	25
	ODP 1143, 1146	2772, 2092	26

**Figure 1.** Location map of the studied Ocean Drilling Program sites. Sites with elongated benthic foraminifera are marked by solid stars and other sites are marked by open circles.

and the nutrient-rich oxygen-poor North Indian Deep Water³⁷⁻⁴¹. The deeper part (> 3800 m) is mainly flooded by well-oxygenated, cold Antarctic Bottom Water³⁷.

Unconsolidated sediment samples of 10 cm³ volume were used for this study (Table 2). The sediments were

washed to obtain foraminifera following the procedure described by Gupta and Thomas⁴². Sediment samples were soaked with water in pre-cleaned beakers and kept overnight for the disaggregation of the sediments. Sediments within the beaker were then washed over a 63 µm

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Table 2. Details of the studied sites along with their geographic positions

ODP leg and site	Sample ID	Latitude	Longitude	Water depth (m)	Area
115-708A	1H-1, 0-2	5°27.35'S	59°56.63'E	4120.80	Western Indian Equatorial Ocean, Near Seychelles Bank
115-709B	1H-1, 0-2	3°54.90'S	60°33.10'E	3051.30	
115-710B	1H-1, 0-2	4°18.70'S	60°58.80'E	3834.80	
115-711B	1H-1, 0-2	2°44.56'S	61°09.78'E	4440.30	
115-712A	1R-1, 0-2	4°12.99'S	73°24.38'E	2914.80	Chagos Bank, East of Central Indian Ridge Maldives Ridge, Northern Equatorial Indian Ocean
115-714A	1H-1, 0-2	5°03.60'N	73°47.20'E	2048.80	
115-715A	1R-1, 0-2	5°04.89'N	73°49.88'E	2276.80	
115-716A	1H-1, 0-2	4°56'N	73°17'E	554.80	
117-721A	1H-1, 0-2	16°40.636'N	59°51.879'E	1955.30	Oman margin, Arabian Sea
117-725C	1H-1, 0-2	18°29.2'N	57°42.030'E	322.00	
117-728B	1H-1, 0-2	17°40.790'N	57°49.553'E	1438.30	
117-729A	1R-1, 0-2	17°38.715'N	57°57.221'E	1409.00	
117-731A	1H-1, 0-2	16°28.229'N	59°42.149'E	2376.30	
121-756B	1H-1, 0-2	27°21.33'S	87°35.805'E	1518.10	
121-757A	1H-1, 0-2	17°01.458'S	88°10.90'E	1650.20	

Table 3. Census data (relative abundance) of elongated benthic foraminifera, and carbon and oxygen isotope values of *Stilostomella* ex gr. *S. lepidula* and *Cibicides wuellerstorfi* (unpublished). Hydrographic data in terms of salinity, temperature and oxygen have been adapted from GEOSECS³⁹ at the same water depth against respective ODP holes

Sample number	117-725C, 1H-1, 0-2	115-716A, 1H-1, 0-2	117-729A, 1R-1, 0-2	121-756B, 1H-1, 0-2	115-714A, 1H-1, 0-2	117-731A, 1H-1, 0-2	115, 712A, 1R-1, 0-2	115-710A, 1H-1, 0-2	115-708A, 1H-1, 0-2
Water depth (m)	322	555	1409	1518	2049	2376	2915	3835	4121
<i>Amphicoryna hirsuta</i>		0.42							
<i>Amphicoryna proxima</i>	0.14	1.25	0.34						0.20
<i>Nodosaria calomorpha</i>						0.47			
<i>Orthomorphina challengiriana</i>	0.28								
<i>Orthomorphina koina</i>									0.20
<i>Pleurostomella acuminata</i>				2.98					
<i>Pleurostomella alternans</i>							0.65	1.05	
<i>Stilostomella affistuca</i>									1.00
<i>Stilostomella</i> ex gr. <i>lepidula</i>	0.14			5.95	4.00		11.11		11.20
Oxygen (µm)	177	47	146	110	134	92	162	173	186
Salinity (‰)	35.4	35.1	34.7	34.7	34.8	34.8	34.7	34.7	34.7
Temperature (°C)	16.50	10.12	3.357	3.69	2.5	2.91	1.79	1.55	1.36
$\delta^{13}\text{C}$ of <i>Stilostomella</i> ex gr. <i>S. lepidula</i> (‰)				-0.30			-0.7		-0.57
$\delta^{18}\text{O}$ of <i>Stilostomella</i> ex gr. <i>S. lepidula</i> (‰)				3.45			3.24		2.06
$\delta^{13}\text{C}$ of <i>C. wuellerstorfi</i> (‰)				0.33			-0.04		0.10
$\delta^{18}\text{O}$ of <i>C. wuellerstorfi</i> (‰)				3.29			2.77		3.19
GEOSECS station number	425	447	425	439	447	416	449	421	421

size sieve under a shower of water. After washing, the residue lying over the sieve was collected in a beaker and placed in a hot-air oven for drying, with a temperature of ~60°C. Washing of samples was done in the sample preparation unit at the Indian Institute of Technology (IIT), Kharagpur. Greater than 150 µm fractions were used for the faunal study.

Carbon and oxygen isotope analysis were performed on pre-cleaned 10–13 specimens of *Stilostomella* ex gr. *S. lepidula* having size > 150 µm. Samples were run at

Brown University, USA in batches of ~40 on a Finnigan MAT 252 equipped with a carbonate (Kiel) III autosampler that reacts samples in individual reaction vessels at 70°C using H₃PO₄. Reproducibility based on repeated analysis of Carrara marble (*N* = 12) and Brown Yule marble (BYM; *N* = 10) was ± 0.02‰ and ± 0.06‰ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ respectively (1 σ). The Carrara and BYM in-house standards were calibrated to NBS-19 for conversion to the Vienna Pee Dee Belemnite (VPDB) scale. All data have been reported in ‰ units relative to VPDB.

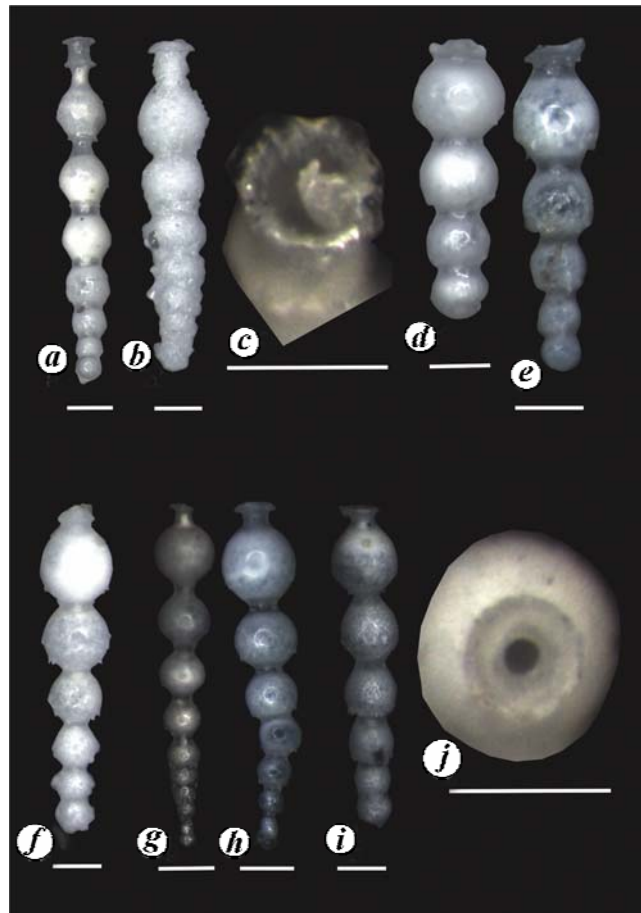


Figure 2. Photomicrograph (scale bar = 100 μm) of the individuals of the *Stilostomella* ex gr. *S. lepidula* obtained from the core top samples. *a-c* are from Hole 708A, *d-f* from Hole 712A and *g-j* from Hole 756B.

Photomicrographs of *Stilostomella* ex gr. *S. lepidula* were taken under Leica MZ 16 microscope in the Micropaleontology Laboratory at IIT. Individuals of this group have been given a common name based on the study of Boltovskoy³² (Figure 2).

We adopted published bottom water hydrographic data (temperature, salinity and oxygen) from several stations close to the studied ODP holes for comparison³⁹ (Figure 3).

De and Gupta⁴¹, in a study from adjacent Hole 723A, calculated an age of 522 ± 25 yrs BP for a near core top sample (1H-1, 4-6). They also suggested that sediments from a few centimetres below the sea floor can be treated as Recent materials, though the age can vary depending upon the sedimentation rate and bioturbation. Hence, we suggest that all the core top sediments from the studied holes/sites without turbidity can be treated as Recent or Holocene in age.

Elongated benthic foraminifera have been recognized from nine core top samples. The identified species are *Amphicoryna hirsuta* (d'Orbigny) (0.42%), *Amphicoryna proxima* (Silvestri) (up to 1.25%), *Nodosaria calomorpha* (Reuss) (0.47%), *Orthomorphina challengeriana* (Thal-

mann) (0.28%), *Orthomorphina koina* (Schwager) (0.2%), *Pleurostomella acuminata* (Cushman) (2.98%), *Pleurostomella alternans* (Schwager) (up to 1.05%), *Stilostomella fistuca* (Schwager) (1%) and *Stilostomella* ex gr. *S. lepidula* (Schwager) (up to 11.2%). Most of them are rare in abundance; only *Stilostomella* ex gr. *S. lepidula* (Figure 2) and *P. acuminata* show significant abundances in three and one sample respectively (Table 3). Maximum four species were recorded from the deepest ODP Hole 708A (water depth 4121 m).

A. proxima, *A. hirsuta* and *N. calomorpha* have been already reported as the 'survivor group' during the so called '*Stilostomella* extinction' event⁷. Some species of *Orthomorphina* (e.g. *O. laevis*, *O. perversa*, etc.) have been already reported as extinct^{2,9}. Yet *O. koina* and *O. challengeriana* are documented in this study from the Recent or Holocene sediments. Other documented species, *P. alternans*, *P. acuminata*, *Stilostomella* ex gr. *S. lepidula* and *S. fistuca* have been also previously considered as having become extinct during MPT^{2-9,26}. Yet all of these species are extant in the studied sites. This observation also corroborates a few earlier studies³¹⁻³⁶. Hence, perhaps this group shows a local disappearance during MPT

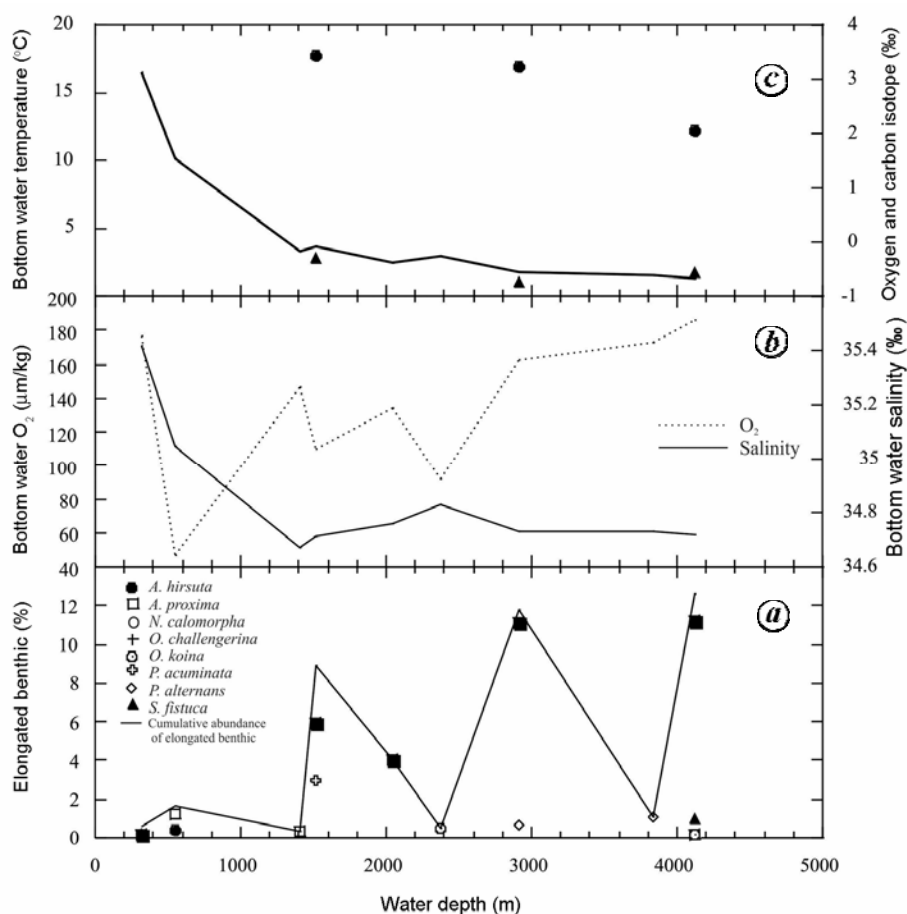


Figure 3. Comparison of faunal abundances with isotopic and hydrographic data with respect to depth. *a*, Individual plots with different symbols indicate relative abundance of different elongated species and continuous line represents their cumulative relative abundance. *b*, Hydrographic data: dotted line represents bottom water dissolved oxygen concentration and continuous line represents bottom water salinity³⁹. *c*, Solid line indicates bottom water temperature³⁹. Solid circles and solid triangles represent oxygen and carbon isotopic values of *Stilostomella* ex gr. *S. lepidula* respectively.

instead of extinction. So, 'local disappearance' would be the more appropriate terminology in lieu of 'extinction' during MPT. Rai and Singh³⁵ also opined that the use of the terminology '*Stilostomella* extinction' is not an appropriate one and requires scrutiny.

Reworking of older sediments could be responsible for the presence of these reportedly extinct elongated benthic foraminifera in Holocene sediments as described by Hayward and Kawagata⁴³. Microscopic observation reveals that these specimens neither contain any earthy colour nor are they highly polished or badly abraded, and thus do not bear any signature of reworking. On the other hand, a review of the ODP Initial Reports of all these sites (except Site 708) reveals that there is no such evidence of reworking of sediments or turbidity flow within the topmost sediment column. However, turbidity was recorded in section 1H-1 and 1H-2 at Hole 708A, but the presence of *Pseudoemiliania lacunosa* at the top and *Emiliana huxleyi* at the bottom of the two sections strongly indicates that they were deposited in the latest

Pleistocene to Holocene⁴⁴. On the basis of the abundance of *E. huxleyi* within all the studied samples, this event can be placed in the nannoplankton zone CN15 or latest Pleistocene to Holocene⁴⁵. Also, no evidence of mixing of older sediment within the topmost sequence at the time of coring was recorded⁴⁴.

Stable carbon and oxygen isotopic analyses of benthic foraminifera are widely used for palaeoenvironmental reconstruction. It has been already established that pore water chemistry significantly differs from the overlying sea water owing to the decomposition of organic matter within the sediments, which results in the depletion of $\delta^{13}\text{C}$. Enhanced organic input to the sea floor, owing to high surface productivity, and subsequent degradation within the sediments can be responsible for depletion of $\delta^{13}\text{C}$. Hence infaunal taxa (e.g. *Bulimina* spp., *Uvigerina* spp.) reflect lower $\delta^{13}\text{C}$ values of the pore water, whereas epibenthic forms (e.g. *Cibicides*) show enriched $\delta^{13}\text{C}$ values reflecting carbon isotopic composition of the sea water⁴⁶.

Carbon and oxygen isotopic values of *Stilostomella* ex gr. *S. lepidula* measured on three samples ranged between -0.3‰ and -0.74‰ , and 2.06‰ and 3.45‰ respectively. However, carbon isotope values showed limited depletion (0.63‰ to 0.7‰) with respect to the unpublished carbon isotope data of *Cibicides wuellerstorfi* from the same samples, whereas oxygen isotope values showed a wide range of depletion (1.13‰) and enrichment (0.47‰) with respect to the oxygen isotope values of *C. wuellerstorfi* (Table 3).

Depletion in carbon isotopic values of *Stilostomella* ex gr. *S. lepidula* with respect to the epifaunal *C. wuellerstorfi* in the range 0.63‰ – 0.7‰ indicates their infaunal habitat in the organic carbon-rich environment and corroborates the observations of Gupta³ and Hayward *et al.*^{8,9,18}. As all the elongated species were recorded from the core top samples (0–2 cm), we can infer that these species have a shallow infaunal habitat.

Several previous records (Table 1) and the present study show that distribution of elongated benthic foraminifera covers a wide range of bathymetry, ranging from 800 to 4120 m. Increased cumulative abundance within the deeper sites indicates they are more abundant within low salinity and low bottom water temperature environments (Figure 3). However, Hayward *et al.*^{8,9} showed that they were able to survive within extreme climatic warm intervals during the Palaeocene–Eocene Thermal Maximum. Particularly, the higher abundance of *Stilostomella* ex gr. *S. lepidula* within the zone of high bottom water oxygenation indicates that they can also survive within the high oxygenated environments (Figure 3), as suggested by Kaiho³⁰.

The present study of benthic foraminifera in core top samples reveals that some of the elongated species, which were considered as extinct groups in the previous studies are still present in the Holocene sediments of the Indian Ocean. Hence, we suggest that these species did not go extinct during MPT, but declined sharply during this time and disappeared from the previously examined sites. We also suggest the use of the term ‘local disappearance of *Stilostomella*’ instead of ‘*Stilostomella* extinction’.

This elongated benthic group indicates a shallow infaunal habitat. They prefer to live in high organic carbon environment and can tolerate very low temperature conditions. However, they are also capable of surviving in well-oxygenated environments.

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Mapping onland river channels up to the seafloor along the west coast of India

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A river channel terminates at the sea in the form of a delta. Recent research has reported the existence of marine channels and depositional environments. This has been further corroborated by the significant discoveries of oil and gas in deepwater. Such studies have raised several questions like: How do these channels originate deep in the ocean floor? Are these channels extensions of present-day onland river systems? The present communication presents a GIS-based analytical study of bathymetry and elevation to establish the relation between present-day onland river systems and marine channel systems in the offshore west coast of India.

Keywords: River channels, mapping, seafloor, oil and gas.

A RIVER originates from the hills, flows through the plains and terminates at the sea. Significant channel sand

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