A first look at the dinoflagellate cysts abundance in the Bay of Bengal: implications on Late Quaternary productivity and climate change

P. Divakar Naidu*, Jagadish S. Patil, Dhiraj D. Narale and A. C. Anil

National Institute of Oceanography (CSIR), Dona Paula, Goa 403 004, India

Abundance and composition of dinoflagellate cysts in a sediment core (SK218/1) from the Bay of Bengal were examined for the last 23 kyr. Cyst abundance at this site varied from 20 to 153 cysts/g dry wt, which is far less than that reported from other oceans. The Holocene harboured higher number of cysts (74–153 cysts/g dry wt) than the last glacial period (up to 67 cysts/g dry wt). Although cyst abundance is low at this site, the cyst composition and its abundance between Holocene and last glacial period reflect the affinity to climate change between these two periods, like other regions. Greater abundance of heterotroph and autotroph cysts and higher species diversity were noticed during Holocene than in the last glacial period, which supports earlier observations depicting higher productivity during the Holocene than in the last glacial period in the southwest monsoon-influenced regions of the Indian Ocean.

Keywords: Climate change, Cyst abundance and composition, dinoflagellates, geological past.

DINOFLAGELLATES are one of the principal groups of marine phytoplankton which has a life cycle that includes a cyst stage in most of the species. Several researchers have shown that the distribution of dinoflagellate cysts corresponds with the physical characteristics of overlying water masses[1]. Hence cysts have been used for reconstruction of paleoenvironmental conditions, such as productivity variations in the Santa Barbara Basin sea level[2], nutrient changes in the South China Sea[3] and palaeoecological and palaeoclimatological conditions in the Mediterranean Sea[4]. The spatial distribution of dinoflagellate cysts has been used to interpret the local environmental conditions and the role of seasonal upwelling intensity on cyst export to the underlying sediments in the Gulf of Alaska[5]. Furthermore, dinoflagellate cyst abundance was also used in quantitative reconstruction of the sea surface temperature (SST) using modern analogue techniques in the Gulf of Alaska[6,7]. Thus, dinoflagellate cysts are a reliable proxy to reconstruct the paleoceanographic changes in the geological past.

Though cyst abundance studies have been carried out in the Arabian Sea using sediment traps[8] and in sediment cores[9–11], so far no study has attempted an analysis of cyst abundance in the sediment traps or in the sediment cores from the Bay of Bengal. This study reports cyst assemblage in a sediment core that depicts Holocene and the last glacial period in the Bay of Bengal.

The northern Indian Ocean has two different surface water masses. A low-salinity water mass is formed in the Bay of Bengal by excess precipitation and abundant river run-off. A high-salinity water mass is formed in the Arabian Sea. Although both the Arabian Sea and the Bay of Bengal are highly influenced by monsoon reversals, the hydrography and biology differ widely. In most oceanic areas variations in temperature are large compared to salinity, but in the Bay of Bengal temperature gradient throughout the year is less compared to salinity[12]. During the SW monsoon high precipitation in the Bay of Bengal and freshwater discharge from the Ganges, Brahmaputra, Irrawadi and Godavari lead to strong stratification preventing the entrainment of nutrients into the surface waters all through the year, resulting in low primary productivity. Biological features such as chlorophyll, primary productivity, phytoplankton abundance and mesozooplankton are lower in the Bay of Bengal compared to the Arabian Sea[13]. The prevalence of stratified and oligotrophic conditions in the Bay of Bengal almost throughout the year is among the causative factors that facilitate the preponderance of diazotrophs[14]. However, information regarding the extent to which the nitrogen fixed by diazotrophs in supporting primary production is not yet available for the Bay of Bengal.

Core SK218/1 was collected at a water depth of 3000 m from the Bay of Bengal (Figure 1). The chronology of the core was established using AMS carbon-14

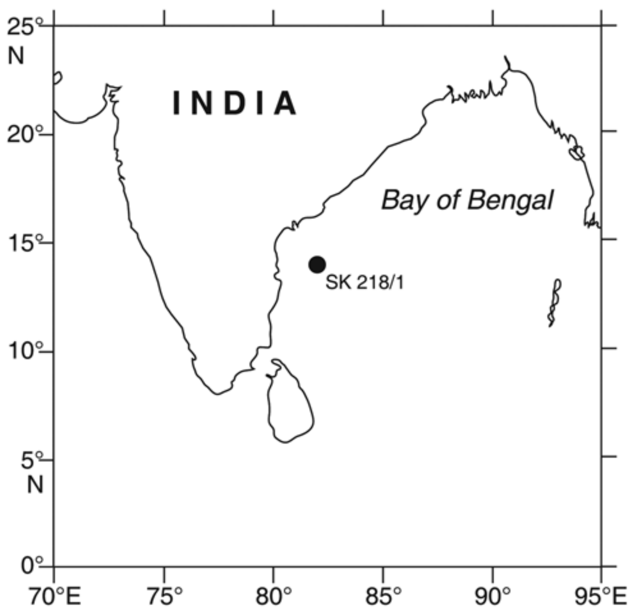

Figure 1. Location of the core in the Bay of Bengal.

*For correspondence. (e-mail: divakar@nio.org)

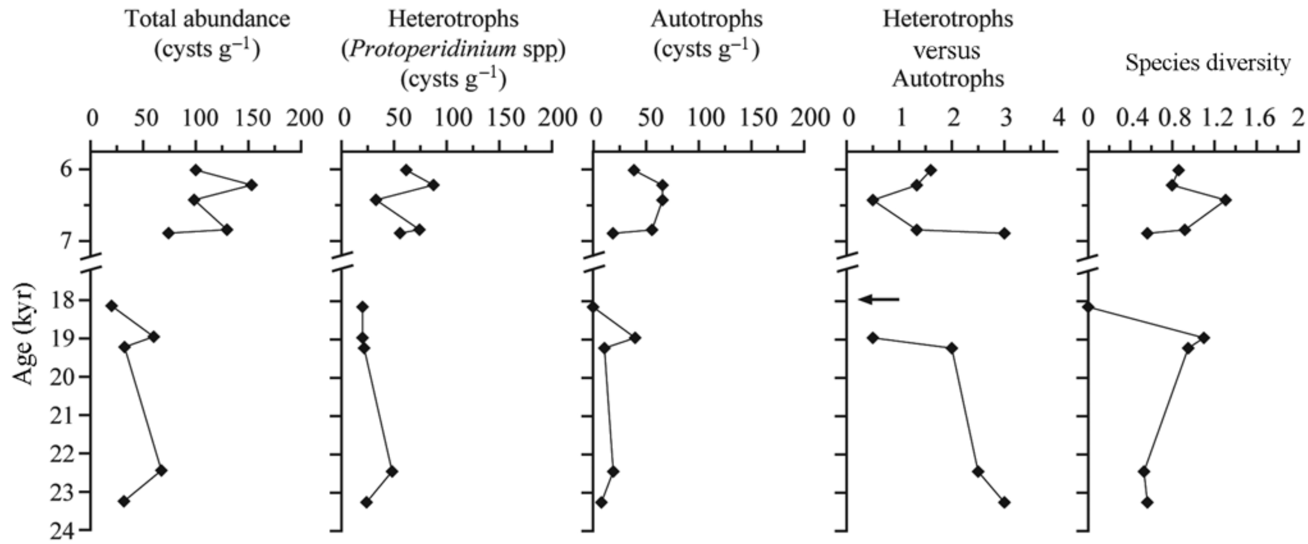

Figure 2. Fluctuations of total dinoflagellates, heterotrophs, autotrophs, ratios of heterotrophs and autotrophs, and species diversity.

dates[15]. Five samples from the Holocene covering a time-span from 6 to 6.89 kyr and five samples from last glacial period from 18 to 23 kyr were processed for the study of dinoflagellate cysts using palynological technique[16,17], with some modification[9]. A known weight of the sediment was repeatedly washed with distilled water to remove salts followed by acid treatment, i.e. HCL (10%) and HF (30%) to dissolve calcareous and silicate materials. Each chemically treated sample was washed with distilled water to remove the acid and then placed in a 10 ml beaker with distilled water to make a slurry. Later, the slurry was sieved through a tier of two different meshes (120 and 20 μm) to remove coarse and fine materials. The residue accumulated on the 20 μm mesh was then suspended in 10 ml distilled water and kept in a vial. For observation, a 0.5–1.0 ml aliquot of the processed sample was used. Observations were carried out under an inverted microscope (Olympus IX 71) at 100 and 400× magnification. Dinoflagellate cysts were identified based on published literature[4,18–21] and cysts abundance was estimated per gram dry weight sediment (cysts/g dry wt). The abundance of dinoflagellate cyst was further used to calculate species diversity (Shannon–Weaver diversity index, i.e. H') using the software PIMER (version 5).

In core SK218/1 autotrophic and heterotrophic forms of dinoflagellate cysts were present during the last glacial period and the Holocene. Heterotrophic forms were dominant during both the periods (Figure 2 and Table 1). High abundance of cysts was observed during the Holocene compared to the last glacial period (Figure 2), and this difference in the distribution of cysts was significant between both the periods (t test: df–20, $P \leq 0.003$, $n = 11$). This is also evident from the t test, which shows a significant difference in the distribution of autotrophic (t test: df–8, $P \leq 0.019$, $n = 5$) and heterotrophic cysts (t test: df–8, $P \leq 0.01$, $n = 5$) between the last glacial period and the Holocene. Species diversity was higher during the Holocene than the last glacial period at this site (Figure 2).

In the present study a total of 19 dinoflagellate cysts belonging to autotrophs (five species) and heterotrophs (14 species) have been reported and presented along with their palynological and modern names (thecate dinoflagellate) in Table 1. Autotrophic cyst assemblages are represented by four Gonyaulacoid (*Spiniferites*, *Polysphaeridium*, *Lingulodinium*, *Operculodinium*) species and *Tuberculodinium vancampoae* (*Pyrophacus steinii*), whereas heterotrophs are represented by the cysts belonging to genera *Protoperidinium* with the following palynological names: *Brigantedinium*, *Selenopemphix*, *Votadinium*, *Stelladinium*, *Quinquecuspis*, *Trinovantedinium* and *Lejeunecysta*. Among the autotrophs, *Spiniferites* cysts were dominant in both the Holocene and the last glacial period. The abundance of *Spiniferites* cysts, however, was high during the Holocene compared to the last glacial period. Cysts of autotrophic dinoflagellates *Polysphaeridium* and *Tuberculodinium* were found only in the Holocene, whereas cysts of *Lingulodinium* were encountered only in the samples representing the last glacial period (Table 1). Ratio of heterotrophs to autotrophs showed a slight decrease in the Holocene (1.3) compared to the last glacial period (1.7; Figure 2).

Abundance of dinoflagellate cysts varied from 20 to 158 cysts/g dry wt sediment (Figure 2). The abundance observed in this site is comparatively lower than that observed in other regions, for example, the Santa Barbara Basin[2], South China Sea[3], Black Sea[22] and Arabian Sea[8,11]. This raises a doubt on whether the cysts represent

Table 1. Dinoflagellate cysts and their abundance (cysts g^{-1} dry wt) documented in core SK218/1 in the Bay of Bengal

		Holocene (kyr)					Glacial (kyr)				
Palaeontologiacl name	Modern name	6.0	6.2	6.4	6.8	6.9	18.2	19.0	19.2	22.4	23.3
Autotrophic											
Spiniferites spp.	*Gonyaulax* spp.	31	60	33	46	0	0	20	5	0	8
Polysphaeridium zoharyi	*Pyrodinium bahamanse*	8	0	0	0	19	0	0	0	0	0
Lingulodinium machaerophorum	*Lingulodinium polyedrum*	0	0	0	0	0	0	20	0	0	0
Operculodinium centrocarpum	*Protoceratium reticulatum*	0	5	16	9	0	0	0	0	19	0
Tuberculodinium vancampoae	*Pyrophacus steinii*	0	0	16	0	0	0	0	0	0	0
Heterotrophic											
Trinovantedinium applanatum	*Peridinium* sp. *cf. P. pentagonum*	0	0	0	0	9	0	0	0	10	0
Stelladinium robustum	*P.* sp. (*Stelladinium robustum*)	8	0	0	0	0	0	0	0	0	0
	Protoperidinium sp. *Type 1*	38	11	8	0	9	10	0	0	19	8
	P. sp. *Type 4*	0	5	0	19	0	0	0	0	0	0
Brigantedinium cariacoensis	*P.* sp. (*P. avellanum*)	0	0	8	28	0	0	0	8	0	0
Stelladinium stellatum	*P. compressum*	0	0	0	0	0	0	10	0	0	0
Quinquecuspis concreta	*P. leonis*	0	22	8	19	9	0	0	8	0	8
	P. thrianum	0	0	8	0	0	0	0	0	10	0
Lejeunecysta concreta	*P.* sp. (*Lejeunecysta concreta*)	8	0	0	0	0	0	0	0	0	0
Selenopemphix nephroides	*P. subinerme*	8	27	0	9	9	10	10	0	10	8
S. quanta	*P. conicum*	0	5	0	0	9	0	0	0	0	0
S. quanta	*P. nudum*	0	5	0	0	0	0	0	0	0	0
Votadinium spinosun	*P. claudicans*	0	0	0	0	9	0	0	8	0	0
V. calvum	*P. oblongum*	0	11	0	0	0	0	0	0	0	0

genuine signals of export productivity or an artifact of poor cyst preservation caused due to well-oxidized conditions in the sediment water interface. However, no visible cyst degradation was noticed in samples from both the Holocene and the last glacial period. Moreover, the maximum cyst density observed in recent sediments along the west coast of India is also low compared to the other regions[9]. Hence we presume that cyst preservation changes might not have contributed to less abundance of cysts at this site. Further, greater abundance of dinoflagellate cysts was reported from the sediment traps and sediment cores in the Arabian Sea from the regions of upwelling[8,11]. Therefore, the most possible reason for the less abundance of cysts at this site in Bay of Bengal could be due to: (i) low salinity and freshwater influx due to river discharge into the Bay of Bengal and the changes brought in by these events (reduced light availability due to cloud cover and increased turbidity); (ii) the present studied core location is not influenced by upwelling, and (iii) the seasonal SST changes are not significant as seen in the temperate regions. Therefore, the less abundance of dinoflagellate cysts is attributable to the lower productivity in the present studied location. Even though abundance was less, the cyst composition and variation in abundance between the Holocene and the last glacial period indicate the similar climatic changes in the past, as observed elsewhere.

The Bay of Bengal was 4°C warmer during the Holocene than in the last glacial period[15], the warmer SST during the Holocene may have been congenial for the thriving of dinoflagellates in this region (corresponds to higher cyst abundance). Similarly, in the Santa Barbara Basin also greater abundance of cysts was noticed during the Holocene than in the last glacial period[2]. In addition, the lower ratio of heterotrophs to autotrophs during the Holocene than in the last glacial period lends support to the distinct SST difference between these two periods. This encourages us to suggest that the ratio of autotroph and heterotroph cysts can be used as a proxy of sea-water temperature in the Bay of Bengal, as lower ratios correspond to warm temperature and vice versa. Cysts of autotrophic dinoflagellates *Polysphaeridium* and *Tuberculodinium* were found only in the Holocene, whereas cysts of *Lingulodinium* were encountered only in the samples representing the last glacial period. This reveals genera preference and/or sensitivity to temperature changes.

Various proxies have been used to determine palaeoproductivity in different regions of the Oceans. For example, the number planktonic foraminiferal species has been identified as an indicator of productivity[23]. Similarly, the fluxes of organic matter, opal, calcium carbonate and benthic foraminifera have been used extensively to study the palaeoproductivity of the ocean basins[24].

Sediment trap experiments have demonstrated that the biological productivity and foraminiferal flux and terrigenous supply in the Arabian Sea are strongly linked to the intensity of the SW monsoon[25]. It is generally understood that the summer monsoon was stronger during the interglacials than in the glacials[23]. Detailed studies have been carried out in the Arabian Sea to understand the influence of monsoon on the biological productivity and terrigeneous supply during the Late Quaternary[26–29]. However, the debate regarding whether productivity in the Arabian Sea was higher during the Holocene or in the last glacial period is ongoing.

Earlier findings from the eastern[30] and western Arabian Sea[26,31] also revealed high productivity during interglacials as a result of strong SW monsoon, and low productivity during glacials due to weak SW monsoon. On the contrary, based on the accumulation rates of organic carbon and alkenones, it was suggested that high productivity during the Last Glacial Maximum than in the Holocene was driven by strong NE monsoons[32]. It is argued here that if the strong NE monsoon had influenced the productivity changes along the eastern Arabian Sea, one would expect high productivity in the Bay of Bengal, because the NE monsoon activity is much stronger in the Bay of Bengal than in the eastern Arabian Sea.

The influence of SW monsoon on the community structure of dinoflagellates has been highlighted based on the recent sediment studies from the west coast of India[9]. Abundance of *Protoperidinium* has been used a proxy in the Arabian Sea[11] and in Santa Barbara Basin[2]. Thus, we use the same proxy to discuss the productivity changes in the Bay of Bengal. In this study higher abundance of *Protoperidium* was documented during the Holocene than in the last glacial period (Figure 2), reflecting higher productivity during the former period. This in turn supports the growing body of evidence that the strong SW monsoon during the Holocene fuelled productivity in the Bay of Bengal and vice versa during the last glacial period. Consequently, weak SW monsoon during last glacial period resulted in less productivity. Though the NE monsoon was stronger during the last glacial period[33], productivity was relatively lower than in the Holocene, which suggests that overall the SW monsoon has a strong bearing on the productivity of the northern Indian Ocean in general and the Arabian Sea and Bay of Bengal in particular.

The study of dinoflagellate cyst abundance in the Bay of Bengal reveals lowest cyst abundance (20–153 cysts/g dry wt) compared to the other regions. The changes in composition of both autotroph and heterotroph cyst assemblages exhibited clear distinction between the Holocene and the last glacial period at this site. Higher abundance of dinoflagellate cysts, their diversity and the dominance of heterotroph and autotroph cysts during the Holocene than in the last glacial period indicate that productivity was higher during the Holocene than in last glacial period in the Bay of Bengal.

1. Rochon, A., de Vernal, A., Turon, J. L., Matthiessen, J. and Head, J., Distribution of recent dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent seas in relation to sea surface parameters. American Association of Stratigraphic Palynologists Ser. 35, 1999, p. 150.
2. Pospelova, V., Pedersen, T. and de Vernal, A., Dinoflagellate cysts as indicators of climatic and oceanographic changes during the past 40 kyr in the Santa Barbara Basin. *Paleoceanography*, 2006, **21**, PA2010 (1–16); doi:10.1029/2005PA001251.
3. Shaozhi, M. and Harland, R., Quaternary organic-walled dinoflagellate cysts from the south China Sea and their paleoclimatic significance. *Palynology*, 1993, **17**, 47–65.
4. Zonneveld, K. A. F. and Brummer, G. A., Paleoclimatic and palaeo-ecological changes during the last deglaciation in the Eastern Mediterranean – implication for dinoflagellate ecology. *Rev. Palaeobot. Palynol*., 1995, **84**, 221–253.
5. Radi, T. and de Vernal, A., Dinocyst distribution in surface sediments from the northeastern Pacific margin (40–60°N) in relation to hydrographic conditions, productivity and upwelling. *Rev. Palaeobot. Palynol*., 2004, **128**, 163–193.
6. de Vernal, A. and Pedersen, T. F., Micropaleontology and palynology of core PAR87A-10: a 23000 year record of paleoenvironmental North Pacific. *Paleoceanography*, 1997, **12**, 821–830.
7. Marret, F., de Vernal, A., McDonald, D. and Pederson, T., Middle Pleistocene to Holocene palynostratigraphy of ODP Site 887 in the Gulf of Alaska, northeast North Pacific. *Can. J. Earth Sci*., 2001, **38**, 373–386.
8. Zonneveld, K. A. F. and Brummer, G. A., Ecological significance, transport and preservation of organic walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. *Deep Sea Res. II*, 2000, **47**, 2229–2256.
9. D'Costa, P. M., Anil, A. C., Patil, J. S., Hegde, S., D'Silva, M. S. and Chourasia, M., Dinoflagellates in a mesotrophic, tropical environment influenced by monsoon. *Estuar. Coastal Shelf Sci*., 2008, **77**, 77–90.
10. Godhe, A., Karunasagar, I., Karunasagar, I. and Karlson, B., Dinoflagellate cysts in recent marine sediments from SW India. *Bot. Mar*., 2000, **43**, 39–48.
11. Reichart, G. J. and Brinkhuis, H., Late Quaternary Protoperidinium cysts as indicators of paleoproductivity in the northern Arabian Sea. *Mar. Micropaleontol*., 2003, **49**, 303–315.
12. Wyrtki, K., Physical oceanography of the Indian Ocean. In *The Biology of the Indian Ocean* (ed. Zeitzschel, B.), Springer, New York, 1973, pp. 18–36.
13. Gauns, M., Madhupratapa, M., Ramaiaha, N., Jyothibabu, R., Fernandes, V., Paul, J. T. and Prasanna Kumar, S., Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and the Bay of Bengal. *Deep-Sea Res. II*, 2005, **52**, 2003–2017.
14. Hegde, S., Anil, A. C., Patil, J. S., Mitbavkar, S., Krishnamurthy, V. and Gopalakrishna, V. V., Influence of environmental settings on the prevalence of *Trichodesmium* spp. in the Bay of Bengal. *Mar. Ecol. Prog. Ser.*, 2008, **356**, 93–101.
15. Naidu, P. D. and Govil, P., New evidence on the sequence of deglacial warming in the tropical Indian Ocean. *J. Quaternary Sci.*, 2010, **25**, 1138–1143.
16. Matsuoka, K., Fukuyo, Y. and Anderson, D. M., Method for modern dinoflagellate cyst studies. In *Red Tides: Biology, Environmental Science, and Toxicology* (eds Okaichi, T., Anderson, D. M. and Nemoto, K.), Elsevier, Now York, 1989, pp. 461–479.
17. Matsuoka, K. and Fukuyo, Y., *Technical Guide for Modern Dinoflagellate Cyst Study*, WESTPAC-HAB/WESTPAC/IOC, Japan Society for the Promotion of Science, Japan, 2000, pp. 1–29.
18. Marret, F., Mudie, P., Aksu, A., Richard, N. and Hiscott, R. N., A Holocene dinocyst record of a two-step transformation of the Neoeuxinian brackish water lake into the Black Sea. *Quaternary Int.*, 2009, **197**, 72–86.
19. Sonneman, J. A. and Hill, D. R. A., A taxonomic survey of cyst-producing dinoflagellates from recent sediments of Victorian coastal waters, Australia. *Bot. Mar*., 1997, **40**, 149–177.
20. Wall, D. and Dale, B., Modern dinoflagellate cysts and evolution of the Peridiniales. *Micropaleontology*, 1968, **14**, 265–304.

21. Harland, R., Nordberg, K. and Filipsson, H. L., A high-resolution dinoflagellate cyst record from latest Holocene sediments in Koljö Fjord, Sweden. *Rev. Palaeobot. Palynol*., 2004, **128**, 119–141.
22. Mudie, P. J., Rochon, A., Aksu, A. E. and Gillespie, H., Dinoflagellate cyst, freshwater algae and faunal spores as salinity indicators in late Quaternary cores from Marmara and Black seas. *Mar. Geol*., 2002, **190**, 203–231.
23. Prell, W. L., Murray, D. W., Clemens, S. C. and Anderson, D. M., Evolution and variability of the Indian Ocean summer monsoon: evidence from western Arabian Sea drilling program. *Geophys. Monogr*., 1992, **70**, 447–469.
24. Herguera, J. C. and Berger, W. H., Paleoproductivity from benthic foraminifera abundance: glacial to post glacial changes in the west-equatorial Pacific. *Geology*, 1991, **19**, 1173–1176.
25. Curry, W. B., Ostermann, D. R., Guptha, M. V. S. and Ittekkot, V., Foraminiferal production and monsoonal upwelling in the Arabian Sea: evidence from sediment traps. In *Upwelling Systems: Evolution Since the Early Miocene* (eds Summerhayes, C. P., Prell, W. L. and Emies, K. C.), Geological Society of Special Publication, Geological Society, London, 1992, pp. 93–106.
26. Murray, D. W. and Prell, W. L., Late Pliocene and Pleistocene oscillations and monsoon upwelling recorded in sediments from the Owen Ridge, northwestern Arabian Sea. In *Upwelling Systems: Evolution Since the Early Miocene* (eds Summerhayes, C. P., Prell, W. L. and Emies, K. C.), Geological Society of Special Publication 64, Geological Society, London, 1992, pp. 301–321.
27. Naidu, P. D., Glacial to interglacial contrasts in the calcium carbonate content and influence of Indus discharge in two eastern Arabian sea cores. *Palaeogeogr*., *Palaeoclimatol*., *Palaeoecol*., 1991, **86**, 255–263.
28. Naidu, P. D., Malmgren, B. A. and Bornmalm, L., Quaternary history of calcium carbonate fluctuations in the western equatorial Indian Ocean (Somali Basin). *Palaeogeogr*., *Palaeoclimatol*., *Palaeoecol*., 1993, **103**, 21–30.
29. Bhusan, R., Dutta, K. and Somayajulu, B. L. K., Concentrations and burial fluxes of organic and inorganic carbon on the eastern margins of the Arabian Sea. *Mar. Geol*., 2001, **178**, 95–113.
30. Pattan, J. N., Masuzawa, T., Naidu, P. D., Parthiban, G. and Yamamoto, M., Productivity fluctuations in the southeastern Arabian Sea during the last 140 ka. *Palaeogeogr*., *Palaeoclimatol*., *Palaeoecol*., 2003, **193**, 575–590.
31. Naidu, P. D. and Malmgren, B. A., A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography*, 1996, **11**, 129–140.
32. Rostek, F., Bard, E., Beaufort, L., Sonzogni, C. and Ganssen, G., Sea surface temperature and productivity records for the past 240 kyr in the Arabian Sea. *Deep Sea Res. II*, 1997, **44**, 1461–1480.
33. Duplessy, J. C., Glacial to interglacial contrast in the northern Indian Ocean. *Nature*, 1982, **295**, 494–498.

ACKNOWLEDGEMENTS. We thank Dr Shetye, Director, National Institute of Oceanography, Goa for providing the necessary facilities and encouragement, and the anonymous reviewer for constructive comments. This work is financially supported by ISRO-GBP and Ministry of Earth Sciences, Government of India. This is National Institute of Oceanography Contribution No. 5107.

Received 6 June 2011; revised accepted 22 December 2011

Correction

Historical and future seismicity near Jaitapur, India

Roger Bilham and Vinod K. Gaur
[*Curr. Sci*., 2011, **101**, 1275–1281]

On page 1275, para 2, line 24, we inadvertently summarize our findings as:

‘Indeed Jaitapur has frequently experienced intensity VII shaking from such earthquakes.’

The sentence should read as:

‘Indeed, Jaitapur has frequently experienced intensity V and occasional intensity VI shaking from such earthquakes.’