Hazard assessment is another important issue in earthquake-prone areas. The meizoseismal and isoseismal maps are prepared after the earthquake has occurred and the damages are assessed. However, it is observed in Latur region that zones of low resistivity are more prone to damages. Keeping this aspect in view, it is possible to prepare the resistivity contour maps and update them from time to time in order to identify the zones likely to be damaged.

The network of lineaments and their density contours, as observed in the Latur region, may act as a forerunner for hazards. The NE-SW trending lineament density map shows strong correspondence with the isoseismal contours. In the light of this, if the lineaments from the satellite imageries are interpreted annually and the changes in lineament density are monitored, one can succeed in identifying the zones of possible hazards.

To conclude, the temporal resistiviy variations are of use in earthquake-prone areas for possible prediction and hazard assessment.

1. Geller, R. J., *Geophys. J. Int.*, 1997, **131**, 425–450.
2. Martin Ian, Debate on Earthquake Prediction, *Nature – Online*, http://helix.nature.com/debates/earthquake, 1999.
3. Asolkar, M. R., Report, Directorate of Geology and Mining, Govt. of Maharashtra, Aurangabad, 1983, pp. 1–37.
4. Kaila, K. L. and Sarkar, D., *Geophys. Res. Bull.*, 1978, **16**, 233–267.
5. Kaila, K. L. and Madhava Rao, N., *Geophys. Res. Bull.*, 1979, **17**, 293–301.
6. Kaila, K. L. and Prasad Rao, P., Proceedings of the Fourth International Conference on Seismic Zonation, 26–29 August, Stanford University, California, USA, 1991.
7. *Geol. Surv. India, Spec. Publ.*, No. 27, 1995.
8. Appa Rao, M., Sastry, C. B. K., Ananda Reddy, R., Somayajulu, P. S. and Srinivas, S., *Geol. Surv. India, Spec. Publ.*, No. 27, 1995.
9. Bolt, Bruce, A., *Earthquakes*, W. H. Freeman, New York, 1993, vol. XIII, p. 331.
10. Zongjin, M., Zhengxiang, F., Yingzhen, Z., Chengmin, W., Guomin, Z. and Defu, L., *Earthquake Prediction (Nine Major Earthquakes in China)*, Springer Verlag, 1990, p. 332.
11. Jiadong Qian, Xai Gui, Huaizhou Ma, Xikang Ma, Huapina Guang and Qingming Zhao, Proc. of Int. Symp. on Earthquake Prediction, Terra Scientific Publishing, UNESCO, Paris, 1984, pp. 145–155.
12. Rao, V. K. and Prasad, S. N., *Earth Planet. Sci. Lett.*, 2001, **190**, 79–91.
13. Gupta, H. K., Rao, R. U. M., Sreenivasan, R., Rao, G. V. and Reddy, G. K., *Geophys. Res. Lett.*, 1999, **26**, 1985–1988.
14. Gupta, H. K. and Dwivedy, K. K., *J. Geol. Soc. India*, 1996, **47**, 129–131.
15. Sarma, S. V. S. *et al.*, *Mem. Geol. Soc. India*, 1994, 35, 101–118.
16. Jain, S. K., Marwaha, S., Agashe, R. M. and Mehta, M., *Geol. Surv. India, Spec. Publ.*, 1995, 27, 243–250.
17. Singh, R. P., Report, Central Groundwater Board, 1987.
18. Karve, A. K., *Geol. Surv. India, Spec. Publ.*, 1995, 27, 235–242.
19. Mogi, K., in *Earthquake Prediction*, Academic Press, New York, 1995, p. 355.
20. Gowd, T. N., Sri Rama Rao, S. V., Chary, K. B. and Rummel, F., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1986, **95**, 311–319.
21. Chetty, T. R. K. and Rao, M. N., *Mem. Geol. Soc. India*, 1994, **35**, 65–73.
22. Gupta, H. K., *Curr. Sci.*, 1992, **62**, 257–263.
23. Barsukov, O. M. and Sorokin, O. N., *Acad. Sci. USSR, Phys. Solid Earth* (Engl. Trans.), 1973, **8**, 685–687.
24. Sadovsky, M. A., (ed.) *Inst. Zemli. Akad. Nauk. USSR* (Japanese edn).

ACKNOWLEDGEMENTS. We thank Dr H. K. Gupta, former Director, NGRI and presently Secretary, Department of Ocean Development, Govt. of India, for his keen interest and Dr S. M. Naqvi, Acting Director for his permission to publish the paper. We thank Mr G. Ramakrishna Rao for help in preparing the manuscript and Mr Sham Vaidya in drafting the figures. We also thank the reviewer for very constructive comments to improve the paper.

Received 5 February 2001; revised accepted 19 June 2001

---

18 Ka BP records of climatic changes, Bay of Bengal: Isotopic and sedimentological evidences

Onkar S. Chauhan* and J. Suneethi

National Institute of Oceanography, Dona Paula, Goa 403 004, India

Based upon the oxygen isotopic records of *Globigerinoide sacculifer*, the clay mineral assemblages and aridity indicator chlorite/illite (C/I) ratio, the palaeoclimatic changes during the past 18 Ka BP have been archived. The results show intense arid climate between 18 and 15 ^{14}C Ka BP, a variable climate between 15 and 13 Ka BP, and again an arid climate at 12.5 Ka BP. The negative δ^{18}O, reduced C/I and higher smectite document a humid phase culminating at 12 Ka BP. Arid climate phases are also identified at 10.3 and 11.5 Ka BP. The later event matches well with that of the 'Younger Dryas' event of world climate models. The beginning of the Holocene is marked by lighter δ^{18}O values (at around 9.5 Ka BP), which has been interpreted as onset of a humid phase and high freshwater influx into the bay, correlating with the world climatic event 'mwp IB'. We also identify two more arid events at ~ 4800 and 2300–2200 yr, hitherto unreported from the Bay of Bengal.

Monsoon variability in the Indian subcontinent is regulated by coupled heating–cooling between the Himalayas and the southern Indian Ocean[1–3]. There are two monsoon seasons, i.e. the NE and the SW prevalent during boreal winter and summer respectively. The SW monsoon accounts for over 80% of rainfall in the Indian subcontinent.

---

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

The Bay of Bengal is a unique site, which receives the largest freshwater influx and sediment (2000 m tonnes annually) from the Himalayan and the Indian peninsular rivers during the NE and the SW monsoons. The higher influx of freshwater reduces the salinity of the bay water by 7‰ in the northern bay[4]. Due to these inputs, the bay is the ideal site for deciphering the signature of the palaeoclimatic changes in the Indian subcontinent.

Available palaeoclimatic studies from the bay are scanty and have very coarse resolution[5–7]. In the present work, the results of stable isotope and sedimentological proxies are integrated in a ^{14}C-dated, high-resolution, turbidity-free core to determine the climatic variability in the last 18 Ka BP from the central Bay of Bengal region.

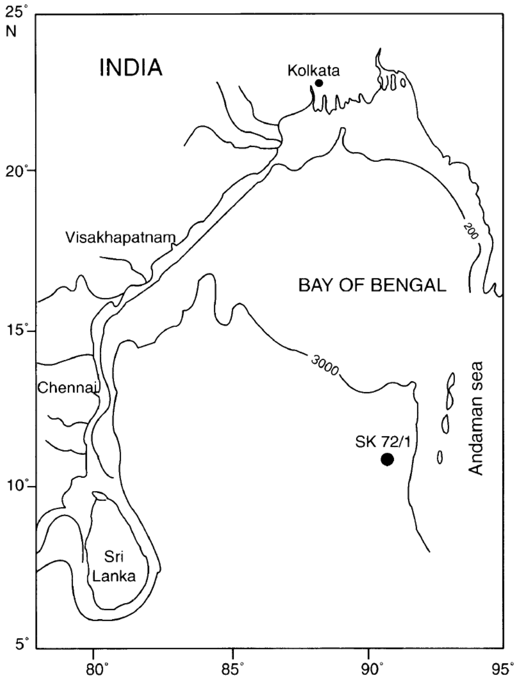

Figure 1. Location of the core in the Bay of Bengal.

From among 13 cores, a turbidity-free core (SK 72/1) was selected from the central region of the Bay of Bengal (position 10°N lat. and 91°E long.; water depth 3200 m; Figure 1). The core was sub-sampled at 2 cm intervals and the sediments were washed salt-free, and oven-dried at 40°C. The clay mineral analysis was performed on $CaCO_3$- and organic carbon-free, oriented samples of < 2 μm on a Philips X-ray diffractometer (model 1840) using Ni-filtered CuKα radiation ($\lambda = 1.541$ Å). Clay minerals have been identified and quantified using the methods elaborated by Biscaye[8] and Carrol[9]. The analysis of 20% replicate samples showed that the results have ± 8% accuracy for smectite and ± 5% for other clay. $\delta^{18}O$ $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1]10^3$, } were determined in 25–30 shells (size 315–400 μm) of *Globigerinoides sacculifers* (without sac) against PDB standard on a VG Micromass Analyser in the Isotope Laboratory of the University of Kiel. The standard deviation of the results was 0.04–0.07‰. Thirteen levels were ^{14}C-dated to determine the chronology for the core (Figure 2). In the absence of availability of precise estimation of ocean-mixing in the region, ^{14}C ages have been corrected for standard 400 years to nullify the reservoir effects[10], but these are not corrected for secular changes in atmospheric ^{14}C level[11].

The temporal variations in the clay mineral assemblage are presented in Figure 3. Illite is the most dominant mineral (range 38–61%) followed by smectite (5–27%), chlorite (9–36%) and kaolinite (8–26%). The content of smectite is found to be low in the Pleistocene section

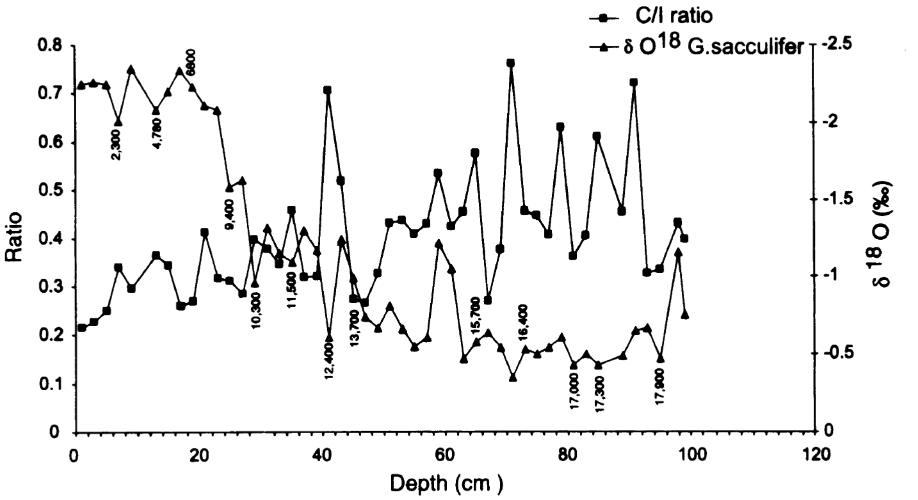

Figure 2. Variations in $\delta^{18}O$ in *G. sacculifer* in the core against aridity indicator C/I ratio. Note a good correlation between heavier incursion of $\delta^{18}O$ and higher C/I ratio. Corrected ^{14}C ages of the levels are shown.

(below 20 cm), whereas chlorite is reduced in the Holocene section (in upper 18 cm).

The $\delta^{18}O$ of *G. sacculifer* together with the ^{14}C ages are presented in Figure 2. In general, the heavier values of $\delta^{18}O$ in the Late Pleistocene, become progressively lighter in the Holocene. Heavier incursions of $\delta^{18}O$ values have been observed at 12.5 Ka (– 0.61‰), 11.5 Ka (– 0.1.09‰) and 10.3 Ka (– 0.96‰) in the Late Pleistocene, and 4800 and ~ 2200 years in the Holocene. The heavier incursion of $\delta^{18}O$ (– 2.08 and – 2.01‰, respectively for 4.8 and 2.3–2.2 Ka BP) is much reduced in the Holocene.

Studies have used chlorite/illite (C/I) ratio as aridity indicator[12]. In Figure 2, the $\delta^{18}O$ value of *G. sacculifer* is plotted against C/I ratio to re-examine the utility of this proxy in identifying the arid events *vis-à-vis* stable isotopes. A positive spurt in C/I ratio correlates well with heavier incursion of $\delta^{18}O$ (Figure 2). Therefore, in the present study, these two proxies are used to identify the aridity and to estimate the palaeoclimatic variability.

A heavier $\delta^{18}O$, a higher chlorite (clay mineral produced under arid climate) and C/I ratio, and a reduced kaolinite (clay mineral produced under humid climate) indicate an arid climate and weak monsoon between 100 and 60 cm level (age 18.0 and 15.0 Ka BP). A dominant arid climate was also reported in the Greenland and North Arabian Sea at these times[13,14], and this event corresponds to the Last Glacial Maxima (LGM) event of the world climate models[15–18].

There is a decrease in C/I ratio together with lighter oscillating $\delta^{18}O$ between 15 and 13.0 Ka BP (60–45 cm level). Humidity indicators, kaolinite and smectite, have enhanced content at these levels, but the produce of arid climate chlorite is reduced. It is, therefore, interpreted that the climate turns humid during these times, with variable intensity. At 12.5 Ka BP, an increase in C/I ratio, heavier incursion of $\delta^{18}O$ and higher chlorite is observed. This

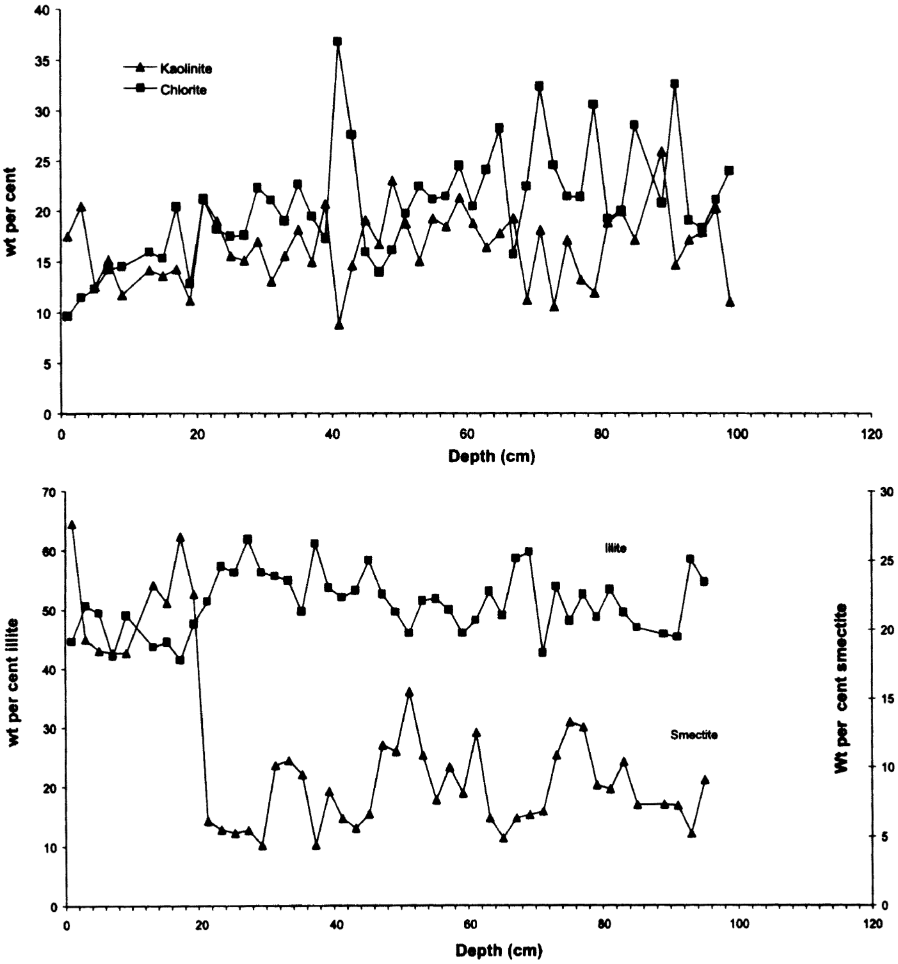

Figure 3. Downcore variations in the abundance of clay. Note a higher illite and chlorite in LGM (100–60 cm levels), suggesting an enhanced contribution from the Himalayas. Also significant is higher smectite in upper 20-cm levels depicting a change in the dispersal of the Himalayan clay during Holocene.

arid event is followed by a humid phase at ~ 12 Ka BP, in which the $\delta^{18}O$ values become lighter from – 0.6 to – 1.3‰. In the northern Indian Ocean, 0.3‰ change in $\delta^{18}O$ corresponds to 1 p.s.u. change in sea surface salinity (SSS). Also, 0.6‰ change in $\delta^{18}O$ may be tied to 2° change in sea surface temperature (SST)[19]. These $\delta^{18}O$ changes, therefore, correspond to either 2 p.s.u. changes in SSS or 2–3° changes in SST. In the world climate model, there was a rapid rise of 24 m in sea level in ~ 1000 years, at 12 Ka BP (ref. 15), and this event has been termed as melt water pulses 'mwp 1A'. Considering the global trend, it is therefore interpreted that the lighter $\delta^{18}O$ values observed in the present study at 12 Ka BP are manifestation of enhanced freshwater flux due to increased precipitation in the Indian subcontinent and in the Himalayas.

At 11.5 and 10.5–9.5 Ka BP, an enhanced C/I ratio, and heavier $\delta^{18}O$ value (– 1.09 and 0.96‰, respectively) indicate a weak monsoon, i.e. a reversal in the climate with reduced freshwater influx. The later event corresponds to the Younger Dryas event[15,17] in which production and supply of freshwater to the world ocean was minimal. After 9.5 Ka BP, $\delta^{18}O$ values compared to LGM (– 0.35‰) are reduced to about – 2.35‰, and remain constantly lighter, except at 4.8 and 2.3 Ka BP. A change of 1.2 ‰ in $\delta^{18}O$ has been attributed to the global ice changes from LGM to Holocene[20]. Our results show a change of 2.0‰, which is higher than these global estimates, and cannot be fully accounted for by them. In the world climate models[15–17], the event at 9.5 Ka BP is identified as 'mwp IB', in which, global sea level rose to around 28 m (ref. 15). The excess lighter $\delta^{18}O$ at the beginning of the Holocene is, therefore, a manifestation of an intense monsoon (precipitation), which contributed higher fluvial flux into the Bay of Bengal. The observed lighter $\delta^{18}O$ in the core, therefore, archives the onset of Holocene sea level transgression after 9.5 Ka BP in the Bay of Bengal. From the uniformly lighter $\delta^{18}O$ values during 9.5–5 Ka BP, it may also be deduced that the monsoon had remained active and intense during the entire mid-Holocene. There is high C/I ratio, accompanied by two heavier incursions of $\delta^{18}O$ of about – 0.3‰ at 4.8 and 2.3–2.2 Ka BP. Chlorite, the clay mineral produced during arid climate has higher content accompanied by a reduced content of kaolinite (clay of humid climate) during these events (Figure 3). From these results, two short arid events have been deduced during these times. In the northern Arabian Sea, the arid event at 4.8 Ka BP has been documented in the cores off the western continental margin of India and from the Laccadive Ridge[12,21]. Similarly, off Pakistan, Von Rad *et al.*[13] have documented an arid event and reduced fluvial supply from the Indus corresponding to the event centred at 2.2–2.3 Ka BP.

To conclude, the short-term climatic fluctuations in the Bay of Bengal correspond well with global climatic changes. The influx of freshwater associated with mwp IB (9.5 Ka BP) marks the onset of the Holocene sea level transgression in the bay.

1. Hasternath, S., *Climate and the Circulation of the Tropics*, D. Reidel, Boston, 1985, p. 220.
2. Anderson, D. M. and Prell, W. L., *J. Geophys. Res.*, 1992, **15**, 481–487.
3. Webster, P. J., in *Monsoons* (eds Fein, J. S. and Stephens, P. L.), Wiley, New York, 1987, pp. 3–32.
4. Wyrtki, K., Bennett, E. B. and Rochford, D. J., *Oceanographic Atlas of the International Indian Ocean Expedition*, National Science Foundation, Washington DC, 1971, p. 531.
5. Fontugne, M. R. and Duplessy, J. C., *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1986, **56**, 69–88.
6. Chauhan, O. S., Borole, D. V., Gujar, A. R., Antonio, M., Mislanker, P. G. and Rao, C. H. M., *Curr. Sci.*, 1993, **65**, 558–562.
7. Duplessy, J. C., *Nature*, 1982, **295**, 494–498.
8. Biscay, P. E., *Geol. Soc. Am. Bull.*, 1965, **76**, 803–832.
9. Carrol, D., *Geol. Soc. Am., Spec. Pap.*, 1970, 80.
10. Sirocko, F. and Lange, H., *Mar. Geol.*, 1991, **97**, 105–119.
11. Stuiver, M. and Braziunas, T. F., *Radiocarbon*, 1993, **35**, 137–189.
12. Chauhan, O. S., *Indian J. Mar. Sci.*, 1999, **28,** 99–101.
13. Von Rad, U., Schaaf, M., Michels, K. H., Schulz, H., Berger, W. H. and Sirocoko, F., *Quat. Res.*, 1999, **51**, 39–53.
14. Dansgard, W. *et al.*, *Nature*, 1993, **364**, 218–220
15. Fairbanks, R. G., *Nature*, 1989, **342**, 637–642.
16. Broecker, W. S., Peteet, D. M. and Rind, R., *Nature*, 1985, **315**, 21–26.
17. Boyle, E. A. and Keigwin, L., *Nature*, 1987, **330**, 35–40.
18. Prell, W. L, Hutson, W. H., Williams, D. F., Be, A. W. H., Geitzenauer, K. and Molfino, B., *Quat. Res.*, 1980, **14,** 309–336.
19. Sarkar, A., Ramesh, R., Bhattacharya, S. K. and Rajagopalan, G., *Nature*, 1990, **343**, 549–551.
20. Sirocko, F., Sarnthein, M., Erlenkeuser, E., Lange, H., Arnold, M., and Dupplessy, J. C., *Nature*, 1993, **364,** 322–324.
21. Chauhan, O. S., Sukhija, B. S., Gujar, A. R., Nagabhushanam, N., and Paropkari, A. L., *Geo. Mar. Lett.*, 2000, **20**, 118–122.

ACKNOWLEDGEMENTS. We thank the Director, National Institute of Oceanography, Goa. Thanks are also due to M. Saranthein, E. Vogelsang, and G. Prabhu for help with oxygen and carbon isotopic and clay mineral analysis. Financial assistance from the Indian National Science Academy, New Delhi, for the visit of O.S.C. to the University of Kiel is gratefully acknowledged.

Received 19 June 2001; revised accepted 4 September 2001