3. Duda, R. O. and Hart, P. E., *Pattern Classification and Scene Analysis*, Wiley, New York, 1973.
4. Devijver, P. and Kittler, J., *Pattern Recognition: A Statistical Approach*, Prentice Hall, London, 1982.
5. Vapnick, V. N., *Statistical Learning Theory*, Wiley, New York, 1998.
6. Bishop, C., *Neural Networks for Pattern Recognition*, Oxford University Press, Oxford, 1995.
7. Breiman, L., Friedman, J., Olshen, R. and Stone, C., *Classification and Regression Trees*, Wadsworth, Belmont, CA, 1984.
8. Geman, S. and Geman, D., Stochastic relaxation, Gibbs distribution, and the Bayesian restoration of images. *IEEE Trans. Pattern Anal. Mach. Intelligence*, 1984, **6**, 721–741.
9. Besag, J., On the statistical analysis of dirty pictures. *J. R. Stat. Soc. B*, 1986, **48**, 259–302.
10. Chellappa, R. and Jain, A. K. (eds), *Markov Random Fields: Theory and Applications*, Academic Press, Boston, 1993.
11. Van Deusen, P., Modified highest confidence first classification. *Photogramm. Eng. Remote Sensing*, 1995, **61**, 419–425.
12. Schroder, M., Rehrauer, H., Siedel, K. and Datcu, M., Spatial information retrieval from remote-sensing – Part-II: Gibbs–Markhov random fields. *IEEE Trans. Geosci. Remote Sensing*, 1998, **36**, 1446–1455.
13. Lillesand, T. M. and Kiefer, R. W., *Remote Sensing and Image Interpretation*, John Wiley, NY, 1979, pp. 469–470.
14. Swain, P. H. and Davis, S. M. (eds), *Remote Sensing: The Quantitative Approach*, McGraw-Hill, New York, 1978.
15. Congalton, R., Oderwald, R. and Mead, R., A quantitative method to test for consistency and correctness in photo interpretation. *Photogramm. Eng. Remote Sensing*, 1983, **49**, 69–74.
16. Congalton, R. G., A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing Environ.*, 1991, **37**, 35–46.
17. Cohen, J., A coefficient of agreement of nominal scales. *Psychol. Meas.*, 1960, **20**, 37–46.
18. Bishop, Y., Fienberg, S. and Holland, P., *Discrete Multivariate Analysis Theory and Practices*, MIT Press, Cambridge, Massachusetts, 1975, p. 575.
19. Fung, T. and Ledrew, E., The determination of optimal threshold levels for change detection using various accuracy indices. *Photogramm. Eng. Remote Sensing*, 1988, **54**, 1449–1454.
20. Gong, P. and Howarth, P. J., An assessment of some factors influencing multispectral land-cover classification. *Photogramm. Eng. Remote Sensing*, 1990, **56**, 597–603.
21. Frizelle, B. G. and Moody, A., Mapping continuous distribution of land-cover: A comparison of maximum-likelihood estimation and artificial neural networks. *Photogramm. Eng. Remote Sensing*, 2001, **67**, 693–705.
22. Michelson, D. B., Liljeberg, B. M. and Pilesjo, P., Comparison of algorithms for classifying Swedish land-cover using Landsat TM and ERS-1SAR data. *Remote Sensing Environ.*, 2000, **71**, 1–15.
23. Hixson, M., Scholz, D., Fuhs, N. and Akiyama, T., Evaluation of several schemes for classification of remotely sensed data. *Photogramm. Eng. Remote Sensing*, 1980, **46**, 1547–1553.

ACKNOWLEDGEMENTS. We thank to Dr R. R. Navalgund, Director, Dr D. P. Rao, Ex-Director and Dr A. Bhattacharya, Deputy Director, RS and GIS, National Remote Sensing Agency (NRSA), Hyderabad for providing the necessary facilities. We also thank Mac Ramachandran, WFP, UN, Rome and his team for providing ground-truth information. We are grateful to A. S. Manjunath, Group Director, Special Products and Quality Evaluation, NRSA for valuable suggestions.

Received 29 May 2003; revised accepted 2 September 2003

Mangrove associated lignite beds of Malvan, Konkan: Evidence for higher sea-level during the Late Tertiary (Neogene) along the west coast of India

K. P. N. Kumaran*, Mahesh Shindikar and Ruta B. Limaye

Geology and Palaeontology Group, Agharkar Research Institute, Pune 411 004, India

Fossil pneumatophores (breathing roots) of *Avicennia* are recovered and reported from the lignite beds exposed in Kolamb well-section near Malvan, Konkan area of western Maharashtra. The accrued palynoflora is dominated by mangroves (*Avicennia*, *Aegialitis*, *Excoecaria*, *Rhizophora* and *Sonneratia*). The spores of mangrove fern (*Acrostichum aureum*) an estuarine fungus *Cirrenalia* indicate that these lignites are autochthonous and deposited in a near-shore environment. Presence of foraminiferal linings (= microforaminifera), dinoflagellate cysts, a few calcareous nannofossils and scolecodonts is an irrefutable proof of marine and brackish water influence during the deposition of lignites under intertidal/tidal swampy condition (mangrove influenced) with fair input from freshwater swamps and hinterland. Freshwater-related forms, viz. *Ceratopteris thalictroides*, Nymphaeaceae, Ctenolophonaceae and hinterland taxa (*Cullenia/Durio*) of Bombacaceae along with abundance of microthyriaceous fungi in the palynoflora imply a warm humid tropical climate with high precipitation during the depositional period. The presence of *Ctenolophon englerianus* (= *Ctenolophonidites costatus*) in Kolamb lignites suggests the Late Neogene (Late Miocene–Early Pliocene) age. The occurrence of pneumatophores and associated lignite deposits ~ 37 m above the present mean sea-level, and much inland, clearly indicates the higher sea-level strand during Late Neogene along the west coast of India.

THE Konkan or coastal tract of Maharashtra and Goa is one of the major geographic divisions of western India. The geomorphology of Konkan is characterized by a coastal plain of variable altitude and width, backed by the escarpment of the Western Ghats on the east and the Arabian Sea with or without a cliff on the west. It stretches between lat 14°49′ and 20°05′N covering a distance of about 720 km, with an average width of 60 km[1]. The pneumatophore-bearing lignites excavated from a well in Kolamb (73°28′78″E and 16°05′67″N) located near the Ozar–Kandalgaon phata along Malvan–Achra Road (Figure 1), is the subject matter of the present communication.

Konkan, for a greater part, is developed on a basement of basalt flows of the Deccan Volcanic province. The

*For correspondence. (e-mail: kpnkumaran@hotmail.com)

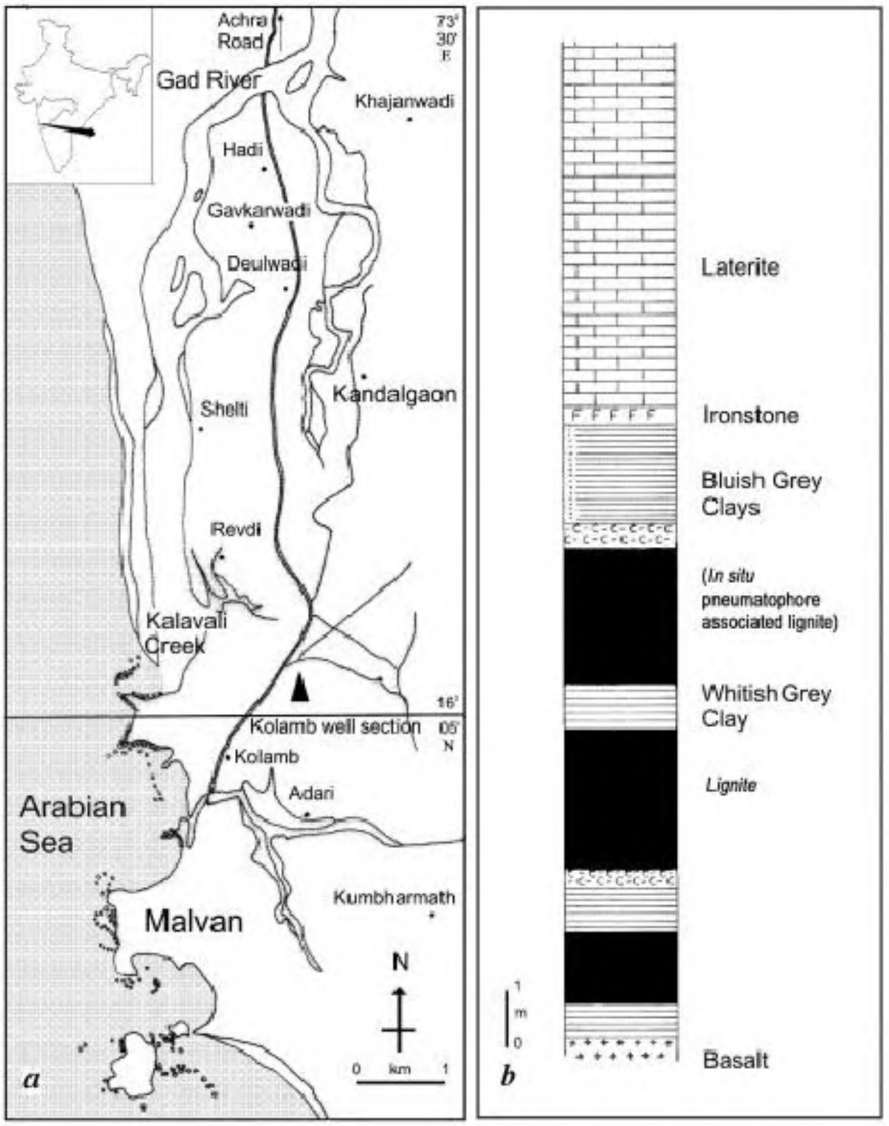

Figure 1. ***a***, Location map of the Kolamb well near Malvan; ***b***, its lithological details.

overlying Tertiary formations comprise laterites and submarine fossiliferous sediments, while the Quaternary formations include soils, alluvia, laterite and littoral deposits. The laterites are underlain by clays, sandstones and lignites, and carbonaceous/grey-bluish clays occur sporadically along the Konkan coast. Some of these deposits, particularly the carbonaceous clays and lignites are highly fossiliferous and yield both micro and mega fossils of different ecological complexes ranging from terrestrial to aquatic environments. Of these, fossils attributed to mangrove are important and significant as they are reliable indicators of ancient sea-level[2]. Although there are many reports of fossils referable to mangroves known from various lignite deposits of Konkan[3–5], *in situ* pneumatophore-associated lignite is not known in the literature and as such the present communication is of considerable palaeobotanical interest in general and fossil mangrove in particular.

During a recent field trip to Malvan, the authors had come across a huge pile of lignite, carbonaceous clays and grey clays excavated from a well in Kolamb (73°28′78″E and 16°05′67″N) located near the Ozar–Kandalgaon phata along Malvan–Achra Road. In fact, deposits of such carbonaceous and grey clays are known from a large number of wells along the Konkan coast[3–5] ever since Wilkinson[6] reported about them from Ratnagiri. The location of the well and details of the well-section from where the pneumatophores are being recorded are given in Figure 1 *a* and *b*. Although the stratigraphical, palaeoecological and sedimentological information of these deposits is little known, the distinct lithological units of the well-section match well with the generalized lithology of the Sindhudurg Formation[7]. In Kolamb well-section, however, the lignite/carbonaceous clays/grey-bluish clays occur at relatively deeper levels and at other places even up to 18 m deep, as revealed by villagers on the basis of bore-holes drilled for water re-

Figure 2. ***a***, Pneumatophores of *Avicennia* presently growing at Kolamb creek. ***b***, *In situ* pneumatophore-bearing lignite. ***c***, Comparison of fossil and modern analogue of pneumatophore of *Avicennia*.

Table 1. Lithosection of Kolamb well, Malvan

Lithology	Thickness (m)
Laterite	6.60
Ironstone	0.30
Bluish-grey clay	1.80
Lignite/carbonaceous clay	0.40
Lignite	2.50
Grey clay	0.80
Lignite/carbonaceous/grey clay	Continues till approx. at 18 m depth
Unconformity	
Basalt (Deccan Traps)	–

sources. In some places towards the coast, the lignite/grey clay/carbonaceous clay sequences rest on the Deccan Traps at 18–20 m depth (Pendulkar's well, Devulwadi, Achra – 73°27′93 E and 16°13′19″N), whereas the reverse trend was observed towards inland regions in some of the wells drilled in Kolamb and Kandalgaon villages.

The material used in the present study is in the form of pneumatophores associated with lignites. These fossil pneumatophores occur *in situ*, as if they were found in the modern mangrove swamps. The specimens (Figure 2 *b*, *c*) have been curated and deposited in the collection of Geology and Paleontology Group, Agharkar Research Institute, Pune for future reference. The generalized lithology of Kolamb well-section is shown in Table 1, taking also into account the details of an adjacent well (16°05′73″N and 73°28′81″E) of J. G. Jadhav. Similar lignite deposits have also been reported much inland of the Konkan area at altitudes 43–50 m[8] and also at 168 m above the present sea-level[9]. These lignite deposits were considered as a northward extension of the Miocene Warkalli Formation of Kerala. While discussing the geomorphological aspects and neotectonic activity in coastal Maharashtra, however, the Pliocene age has also been suggested for these beds[10,11].

The megafossils recovered from the lignites are pneumatophores, the breathing roots of mangroves, specially adapted to swamp environment and a few mummified leaves. Most of the fossil leaves are damaged during excavation and only three could be eventually retrieved. The overall size of lamina, leaf base, apical part and venation pattern match well with that of extant *Avicennia* type. However, the pneumatophores are intact with the lignites (Figure 2 *c*) and appear as if they were found *in situ* in the modern mangrove swamps dominated by *Avicennia* community (Figure 2 *a*). Further, these pneumatophores are oriented perpendicular to lignite beds (Figure 2 *b*) and as such indicate another evidence of their *in situ* nature. The size of the fossil pneumatophores varies from 2.67 to 7.5 cm (average: 4.75 cm), while that of a recent *Avicennia* pneumatophore reaches up to 30 cm height. The diameter of the fossil specimens ranges from

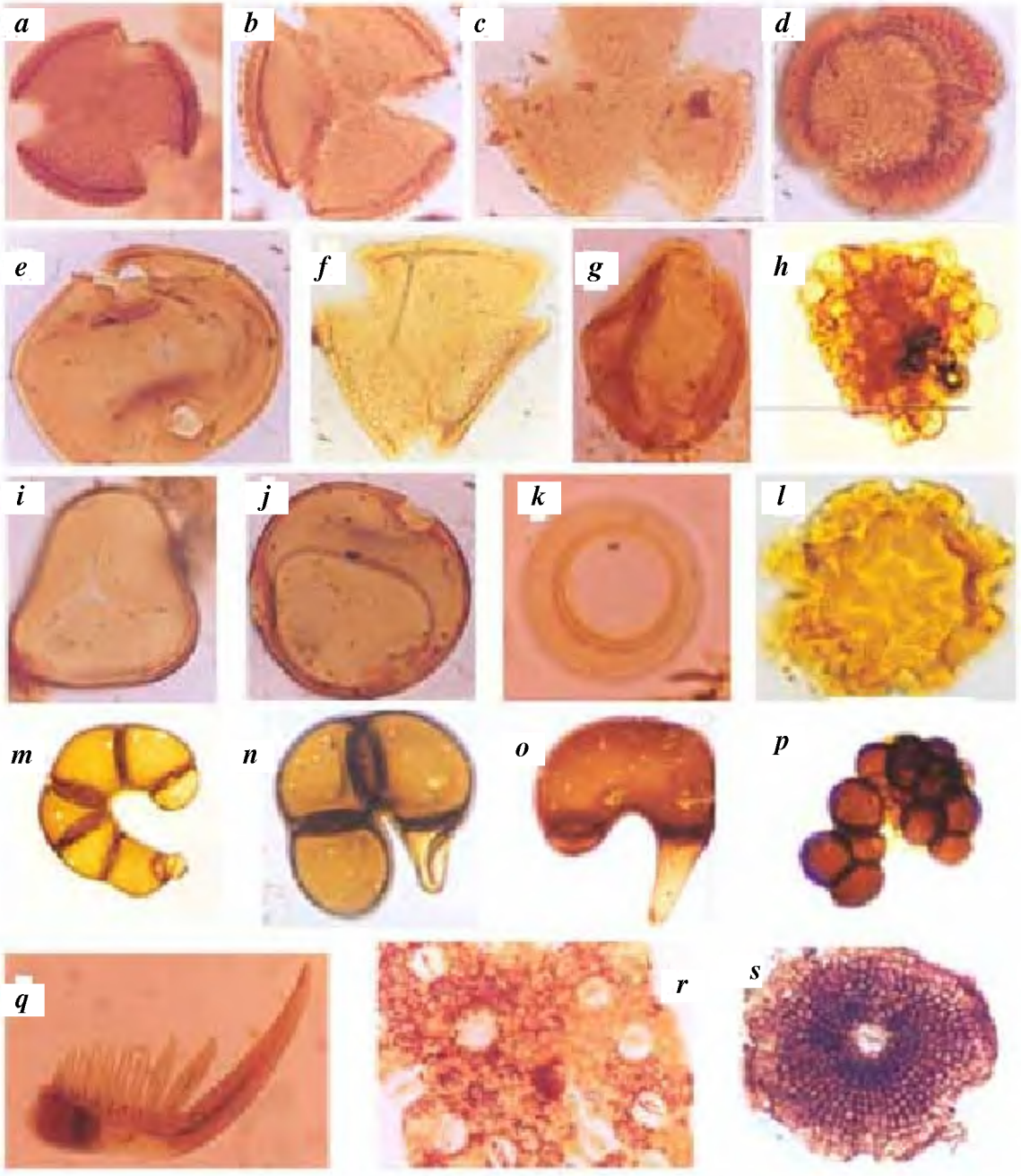

Figure 3. ***a***, ***b***, ***d***, Pollen of *Avicennia*; ***c***, ***f***, *Warkallipollenites erdtmanii* (= *Aegialitis rotundifolia*); ***e***, *Sonneratia apetala*; ***g***, *Excoecaria agallocha*; ***h***, group of Rhizophoraceae pollen; ***i***, spore of *Acrostichum aureum*; ***j***, pollen of Bombacaeaeae [*Lakiapollis* (*Durio*/*Cullenia*)]; ***k***, pollen of *Nymphaea*; ***l***, *Ctenolophonidites costatus* (*Ctenolophon englerianus*); ***m–p***, conidia of *Cirrenalia tropicalis*, *C. pseudomacrocephala*, *C. pygmea* and *C. macrocephala*; ***q***, Scolecodont; ***r***, leaf cuticle of *Rhizophora*; ***s***, microthyriaceous fruiting body.

0.35 to 0.95 cm (average: 0.56 cm), while that of recent one measures up to 1.00 cm. Since the fossils have been retrieved from the broken blocks of lignite, the actual length of the specimen is difficult to be ascertained. However, the overall morphological features and size are comparable to the pneumatophores of extant *Avicennia* (Figure 2 *c*). The pneumatophores of modern *Avicennia* are pencil-like erect structures that tend to taper to bluntly pointed tips and have a corky texture, while those of *Sonneratia* have characteristic flaky bark in younger roots and the older ones are robust and stout. The other associated mangrove species, viz. *Bruguiera* and *Ceriops* have distinct knobby aerial roots forming 'knees'-type growth[12].

The pneumatophore-bearing lignites have yielded a fairly rich palynoflora consisting of a diverse ecological complex, but the mangroves are well represented and

dominating. The palynological assemblage is dominated by pollen of *Avicennia*, *Aegialitis* and Rhizophoraceae followed by that of *Sonneratia* and *Excoecaria* (Figure 3 *a–h*). Nevertheless, spores of *Acrostichum aureum* (mangrove fern) (Figure 3 *i*) and estuarine fungus *Cirrenalia* are also equally well-represented. In fact, all the four species of *Cirrenalia*, (viz. *C. macrocephala*, *C. pseudomacrocephala*, *C. pygmea* and *C. tropicalis*) known from the mangrove swamps of the tropics[13] are present in this palynological assemblage (Figure 3 *m–p*). *C. tropicalis* has yet to be recorded from the modern mangrove swamps of India.

Other mangrove fungi associated with the palynoflora of Kolamb lignite are *Cladosporium* sp., *Didmyospheria* sp., *Trichocladium achrasporum*, *Monodictys pelagicus*, *Periconia prolifica* and *Zalerion varium*. Incidentally, *Palaeocirrenalia* is the only fossil mangrove fungus so far known from the Tertiary lignites of India[5,14,15]. Besides, dinoflagellate cysts, foraminiferal linings, scolecodonts (Figure 3 *q*) and a few calcareous marine nannofossils have also been recognized in the palynological preparations. A variety of leaf cuticles were observed in the assemblage. Many of them show good resemblance with modern leaves of *Rhizophora* (Figure 3 *r*). Their abundance also compliments the palynoflora contributed by the mangrove swamp vegetation. The diversity of mangrove pollen and marine fungi and their relevance to palaeoclimate and palaeobiogeography will be dealt with elsewhere.

Although the palynoflora is dominated by the mangrove taxa and their associates, freshwater aquatics, freshwater edge and hinterland elements flora are also fairly represented in the palynological assemblage. The spores of freshwater marsh fern, *Ceratopteris thalictroides*, pollen of Potamogetonaceae and Nymphaeaceae (Figure 3 *k*) are a few of such kinds of plants represented in the lignite assemblage. The pollen of Ctenolophonaceae (*Ctenolophon englerianus*) and Bombacaceae (*Durio*/*Cullenia*) are other important constituents of the palynoflora (Figure 3 *j*, *l*). They constitute significant environment markers and also have palaeobiogeographic implications as these taxa have a disjunct distribution at present. Both *Ctenolophon* and *Durio* require excessive humid conditions, with annual rainfall over 3500 mm. Though the fossil pollen of these taxa are known from various Tertiary deposits, they are extinct in the modern floristic complexes of India and are endemic to West Africa and Southeast Asia. Their conspicuous absence in the Indian subcontinent is attributed to climatic shift as a result of northward drift of the Indian plate from its equatorial position in the Miocene, and the decline in rainfall. Such climatic shift is more pronounced from Karwar to further north and relatively less towards south (Kerala coast) where wet evergreen forests are still surviving, probably due to unchanged tropical climate right from the Neogene period[16].

The other important constituents of the palynological assemblage of Kolamb lignite are microthyriaceous fungal fruiting bodies (Figure 3 *s*). At least five morphological types of such forms have been recognized. It is beyond the scope of the present communication to consider them in detail. Nevertheless, their importance in palaeoecological context is relevant to the lignite deposit. Though these fungal fruiting bodies are of epiphyllous origin, their association with mangroves is yet to be known despite the fact that cuticles of Rhizophoracae are well represented in the palynological assemblage. It is likely that terrestrial contribution to the site of deposition would have been considerably fair, which might account for the presence of microthyriaceous fungi.

On the whole, the youngest pneumatophore bearing lignite bed of Kolamb is dominated by the pollen of important mangrove taxa and about seven species of a dozen known hyphomycetes of the marine habitat. In fact, the palaeopalynological data certainly suggest that these lignites are autochthonous and deposited under inter-tidal/tidal swampy conditions (mangrove-influenced) with a fair input from the freshwater swamps and evergreen taxa of hinterland. The abundance of particulate organic matter (palynodebris) derived from mangrove/coastal/terrestrial habitats along with epiphyllous fungal fructifications collectively account for a warm, humid tropical climate with heavy rainfall.

Megafossil evidence from the contemporaneous lignites of other localities along the Konkan coast also compliment the above observations[17]. Such climatic conditions and heavy rainfall must have enabled the terrestrial elements to get themselves transported through the streams and rivers draining in the mangrove swamps. In this regard a gross analogy of ancient mangrove swamps, leaving aside specific details, can be made with the modern estuaries/creeks existing all along the western coast of India. These observations amount to the fact that the lignite beds were deposited in the mangrove-influenced environment despite the fact that they now occur at a considerably higher altitude (47 m) above the present mean sea-level, and much inland from the present coast. Accordingly, their occurrence with respect to the present coast reflects the relationship between the land and the sea of the past (ancient sea-level and palaeostrandline). Thus, the pneumatophore-associated lignites serve as an evidence for a higher sea-level strand along the west coast of India during Late Neogene (Mio-Pliocene), which is in agreement with that of the global scenario[18,19].

1. Guzder, S., Quaternary environment and Stone age cultures of the Konkan, coastal Maharashtra, India, Deccan College, Pune, 1980, p. 100.
2. Ellison, J. C., Pollen analysis of mangrove sediments as sea-level indicator: Assessment from Tongatapu, Tonga. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1989, **74**, 327–341.
3. Kulkarni, A. R. and Phadtare, N. R., Leaf epidermis of *Nypa* from lignite beds of Ratnagiri district, Maharashtra. *Geophytology*, 1980, **10**, 125–128.

4. Phadtare, N. R. and Kulkarni, A. R., Palynological investigations of Ratnagiri lignite, Maharashtra. *Geophytology*, 1980, **10**, 158–170.
5. Phadtare, N. R. and Kulkarni, A. R., Palynological assemblages of lignite exposure of Ratnagiri district. Proceedings of X Indian Colloquium Micropaleontology and Stratigraphy, Pune, 1984, pp. 515–532.
6. Wilkinson, C. J., Sketch of the geological structure of the southern Konkan. *Rec. Geol. Surv. India*, 1871, **4**, 44–47.
7. Saxena, R. K., Sindhudurg Formation – A new lithostratigraphic unit in Konkan area of Maharashtra. *Geophytology*, 1995, **24**, 229–232.
8. Rajaguru, S. N. and Marathe, A. R., Neotectonic activity around Ratnagiri, Western India. Proceedings of the Symposium in Quaternary Episodes, Department of Geology, M.S. University, Baroda, 1984, pp. 1–6.
9. Bruckner, H., New data on evolution of Konkan (western India). *Exploration in Tropics* (eds Datye, V. S. *et al.*), Kalpana Pvt Ltd, Pune, 1987, pp. 173–184.
10. Powar, K. B., Neogene uplift and geomorphic rejuvenation of the Indian peninsula. *Curr. Sci.*, 1993, **64**, 793–796.
11. Rajshekhar, C. and Kumaran, K. P. N., Micropalaeontological evidence for tectonic uplift of near-shore deposition around Bankot–Velas, Ratnagiri district, Maharashtra. *Curr. Sci.*, 1998, **74**, 705–708.
12. Tomlinson, P. B., *The Botany of Mangroves*, Cambridge University Press, New York, 1994, p. 419.
13. Kohlmeyer, J. and Kohlmeyer, E., *Marine Mycology: The Higher Fungi*, Academic Press, New York, 1979, p. 690.
14. Ramanujam, C. G. K. and Srisailam, K., Fossil fungal spores from the Neogene beds around Cannanore in Kerala State. *Botanique*, 1980, **9**, 119–133.
15. Rao, M. G., Reddy, P. R. and Ramanujam, C. G. K., Palynoassamblage of the subsurface Tertiary sediments at Kulasckharamangalam in Kottayam district, Kerala. *Birbal Sahni Centenary Volume*, 1995, pp. 371–374.
16. Ramanujam, C. G. K., Tertiary floristic complexes of southern India – a critical appraisal. *Geophytology*, 1996, **25**, 1–14.
17. Guleria, J. S., Neogene vegetation of peninsular India. *Paleobotanist*, 1992, **40**, 285–311.
18. Haq, B. U., Hardenbol, J. and Vail, P. R., Chronology of fluctuating sea-levels since the Triassic. *Science*, 1987, **235**, 1156–1167.
19. Michelsen, O., Thomsen, E., Danilsen, M., Heilmann-Clausen, C., Jordt, H. and Laursen, G. V., Cenozoic sequence stratigraphy in the eastern North Sea. *Soc. Econ. Paleontol. Mineral. Spec. Publ.*, 1998, **60**, 91–118.

ACKNOWLEDGEMENTS. We thank Dr V. S. Rao, Director, Agharkar Research Institute (ARI), Pune for providing facilities and encouragement. Discussion with Dr Aniruddha S. Khadkikar is gratefully acknowledged. The suggestions and the critical review by two anonymous referees are appreciated. M.S. and R.B.L. acknowledge the financial assistance provided by ARI and CSIR respectively.

Received 20 June 2003; revised accepted 3 October 2003