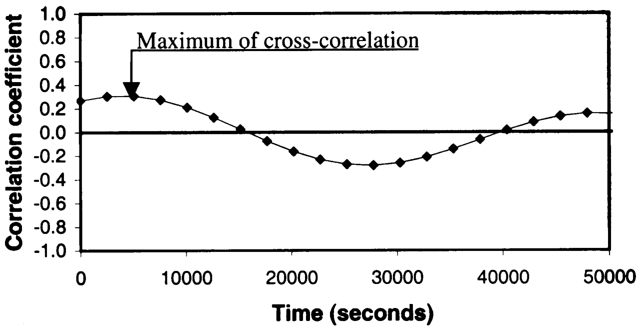

Figure 8. Cross-correlation function between gravity fluctuations due to synthetic earth tides and water levels.

sectorial waves of semi-daily period (N_2, M_2) are identified as the origin of the water-level fluctuations. Spectral analysis has shown that there is a direct linear relation between earth tides and water-level fluctuations in the studied well. The observation of such fluctuations in this hard-rock aquifer, apparently unconfined, implies that the aquifer is characterized by a low porosity.

1. Bredehoeft, J. D., *J. Geophys Res.*, 1967, **72**, 3075–3087.
2. Bovardson, G., *ibid*, 1970, **75**, 2711–2718.
3. Melchior, P., *The Tides of the Planet Earth*, Pergamon, Paris, 1978, p. 609.
4. Rojstaczer, S. and Agnew, D. C., *J. Geophys. Res.*, 1989, **94**, 12403–12411.
5. Marsaud, B., Mangin, A. and Bel, F., *J. Hydrol.*, 1993, **144**, 85–100.
6. Box, G. E. P. and Jenkins, G., *Time Series Analysis: Forecasting and Control*, Holden Day, San Francisco, 1976, p. 575.
7. Hsieh, P. A., Bredehoeft, J. D. and Farr, J. M., *Eos, Trans. Am. Geophys. Union*, 1985, **66**, 891.
8. Mehnert, E., Valocchi, A. J., Heidari, M., Kapoor, S. G. and Kumar, P., *Groundwater*, 1999, **37**, 855–860.
9. Ritzi, R. W., Sorooshian, S. and Hsieh, P. A., *Water Resour. Res.*, 1991, **27**, 883–893.

ACKNOWLEDGEMENTS. We thank Dr J. L. Pinault from BRGM, French Geological Survey who developed the software TEMPO used for the processing of signals. We also thank Mr T. R. M. Prasad for his advice on computation of synthetic tides.

Received 16 October 2001; revised accepted 16 April 2002.

Continental mayfly burrows within relict-ground in inter-tidal beach profile of Bay of Bengal coast: A new ichnological evidence of Holocene marine transgression

Chirananda De

Geological Survey of India, 15 Kyd Street, Kolkata 700 016, India

The present study documents the first record of preserved mayfly burrows and an important record of continental ichnofauna in India. Ecologically, mayfly burrows suggest continental ephemeral stream bank (saturated edges just under water level) settings. Their presence in the Holocene relicts of the Kalna surface exposed in the modern inter-tidal beach profile (Nabadwip surface) at Bakkhali (West Bengal coast) provides a new ichnological evidence of the Holocene rise in sea level and consequent marine transgression of the Bay of Bengal Sea, a fact otherwise well supported globally as well as regionally by many geological features. The specific orientation of mayfly burrows with respect to river bank may be useful in interpreting palaeochannel courses (or aquifers) in rock records. The present application of mayfly burrows for interpretation of environment, sea level and aquifers remains unmatched in published literature.

MARINE ichnology is now an advanced scientific discipline within palaeontology. Continental ichnology, on the contrary, is a relatively new field and has begun to be incorporated into the theoretical framework of ichnology. The main credit goes to some very significant recent studies that have revealed 166 examples of continental ichnocoenoses (trace fossil assemblages)[1], 58 ichnocoenoses of palaeosol insect origin with 29 as recurring examples of *Coprinisphaera* ichnofacies[2] and a large number of ichnocoenoses of lacustrine[3–6] and freshwater inner estuarine[7–10] palaeoecosystems. These studies have also revealed that a large community of non-marine organisms is capable of making environment-sensitive and distinct traces, the most delicate of which can also be preserved in the rock records. Insects, in particular, are prolific trace-makers. Among them, stoneflies (Plecoptera), mayflies (Ephemeroptera), dragonflies (Odonata), Alder and Dobson flies (Megaloptera), bugs (Hemiptera), caddisflies (Trichoptera), beetles (Coleoptera), flies (Diptera), ants (Hymenoptera) and crickets (Orthoptera) are very well represented in continental ichnocoenoses[11] reported from Argentina, Australia, Ecuador, Egypt, France, Ethiopia, Kenya, Namibia, South Africa, UAE, Uruguay and USA[2]. From India there is only one record of continental ichnofaunas (*Termitichnus* and meniscus burrows) from Plio-Pleistocene Upper Siwalik sub-Group (previously Boulder Formation) of Punjab Himalayas[12].

The present study focuses on the Holocene relict-grounds of Bakkhali inter-tidal beach (the Bay of Bengal) from where documentation of mayfly burrows is made, and discusses their significance relative to Holocene sea-level changes and depositional environment.

The coastal plains of the Bay of Bengal incorporate a part of the Ganges Delta Complex that exposes from north to south successively younger deltaic surfaces (Figure 1 *a*). The complex has a very dynamic Quarternary evolutionary history and represents coalesced multi-generation deltas that prograded in phases during positive interglacial eustatic sea-level changes towards the Bay of Bengal, leaving behind distinctive multilevel deltaic surfaces, terraces and palaeoshorelines[13]. The oldest Worgram Formation[14] (Upper Pleistocene, 120 to 35 m amsl and hard crust lateritic) is exposed in the north. The Late Pleistocene Kusumgram (semi-lithified calcareous concretionary clay-silt), Holocene Kalna (0.5 to 7 m amsl, firm brown-to-black mottled and firm clay soil) and Recent Nabadwip (0.5 to 7 m amsl, unconsolidated and mangrove forested sand–silt–clay) formations crop out successively towards the southern sea (Figure 1 *a*). The Nabadwip surface (2 to 18 km wide zone along the present strand-line) is being subjected to shallow marine tidal processes, while others experience estuarine to inland fluvial deltaic processes. The Nabadwip and Kalna surfaces are the main concerns of this paper. In the Bakkhali beach (West Bengal) the exposed geomorphic profile (Figure 1 *b*) includes from land to sea mangrove forested back-swamps–floodplains–salt marshes, beach-dune ridges, supra-tidal backshore, inter-tidal foreshore and sub-tidal foreshore[15]. Grain-size measurements show a predominance of clay-silt in the swamps, marshes and lower foreshore, while sand-silt in varied proportions comprise the supra-tidal and inter-tidal beaches (MZ 2.75 phi to 1.4 phi). Oyster shell concentration in the lower inter-tidal beach around low water level and relicts of ancient mangrove forest-ground (Figure 2 *a*) in the middle to lower inter-tidal zone in the Bakkhali Beach

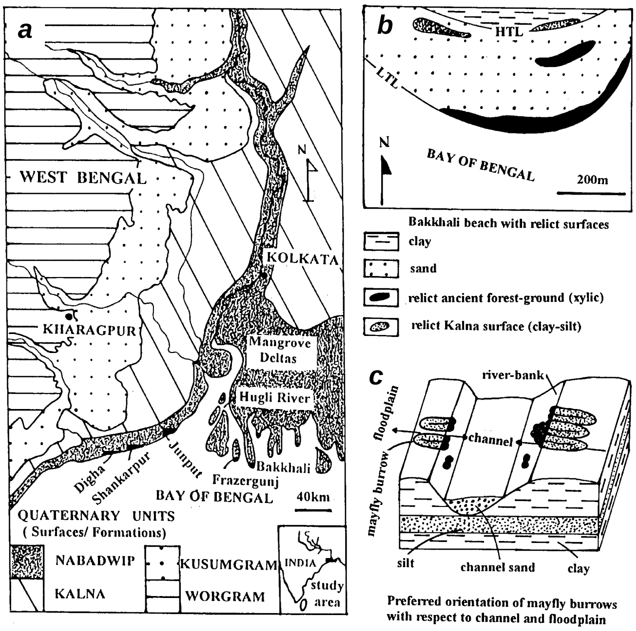

Figure 1. ***a***, Regional Quaternary geological map of a part of Gangetic Delta Complex (modified after Niyogi[13]); ***b***, Details of Bakkhali beach profile showing the positions of Kalna relict-ground and ancient forest-ground; ***c***, Preferred orientation of mayfly burrows with respect to floodplain and channel.

have been observed. Relicts of the Kalna surface occur in the inter-tidal Nabadwip surface in down-drift coastal tract of the Bakkhali area (Figure 2 *b*).

The ichnoform is found in the Holocene Kalna relict surfaces (firm clays). In lithological section, the burrowed zones (5–10 cm thick) occur alternately with parallel-laminated silt beds (Figure 2 *c*). The structures occur en masse as filled-in, looped U-tubes dug horizontally along the bedding planes. In vertical section, individual burrows possess paired circular openings (0.2–0.3 cm diameter) almost touching each other. In longitudinal section, the U-tunnels show very consistent geometry and bilateral symmetry. The U-turns are very much alike, smooth and broad. The tunnel width (0.3–0.4 cm) is constant throughout. The total U-length (8–10 cm) is also near constant. The parallel U-arms are joined sidewise against a thin vertical wall of clayey sediment (Figure 2 *e, f*). The burrows, while occurring en masse, look like honeycomb structures (Figure 2 *d–f*).

There is no published document of mayfly burrows in older rock records for easy comparison with the present structures. However, U-burrows of mayfly nymph *Pentagenia* are known from the Tertiary Shales near Bryan, Texas[11]. The Bryan burrows closely resemble the present structures in all geometric aspects. The present structures are distinctly different from the known bee-trace fossils, *Uruguay*[2], containing circular tubes arranged around a central mass of sediment and *Palmiraichnus*, having open-ended oval tubes with juxtaposed openings. The Bakkhali form morphologically contrasts also with dung beetle trace fossil, *Coprinisphaera* having a spherical form with single opening, and vertical U-burrow, *Arenicolites*. The Bakkhali ichnofauna has been attributed to mayfly dwelling tubes and is considered as the Holocene analogue of the Tertiary Bryan burrows.

As a part of life habits, mayflies habitually and selectively construct dwelling burrows in the saturated edges of ephemeral streams within pliable fine sand, silt and firm mud just below water level, in association with crayfish, beetles, crickets, ants and worms that dwell in dry and damp higher river banks above water level[16]. Bathymetric zones of common riverbank trace makers, as noticed along the Brazos River and in Houston, Texas[11], have revealed the same ecological niches for mayflies. Thus, modern as well as ancient mayfly ichnofaunas are suggestive of continental (ephemeral) stream-bank (saturated edges just below water level) environments. Besides dwelling burrows, mayflies also produce sprawling, resting and creeping traces, but traces other than their burrows have not been found in the study area.

Because of the paucity of mayfly burrows in the rock records, excepting in the Tertiary and Holocene deposits, their dwelling burrows cannot be attributed to any of the four established continental ichnofacies (e.g. *Scoyenia* in river floodplain[17], *Mermia* in subaqueous lacustrine[3], *Coprinisphaera* in palaeosol[2] and *Termitichnus* in

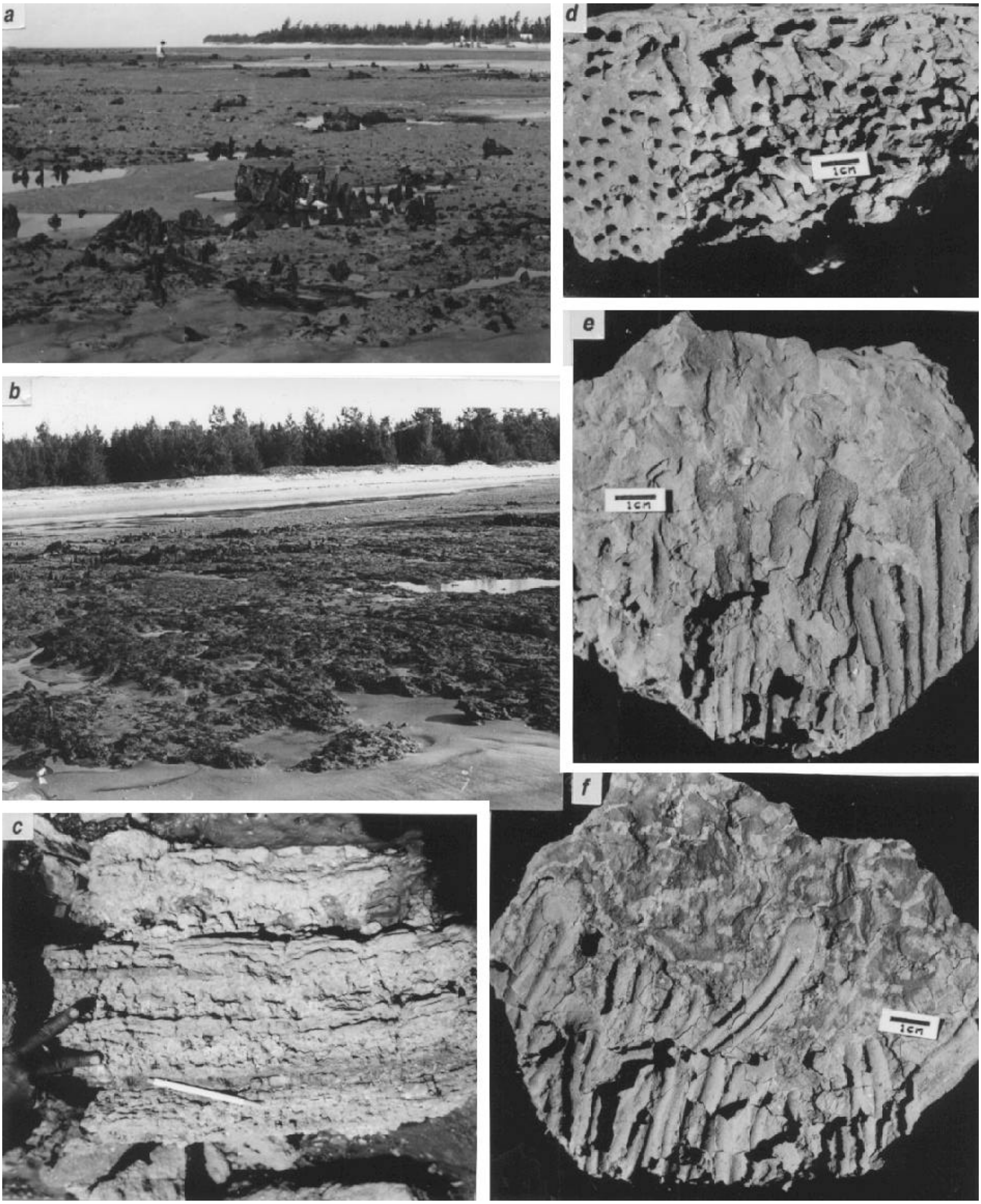

Figure 2. ***a***, Relict outcrop of ancient forest-ground; and ***b***, Firm clay-ground of Kalna surface containing mayfly burrows. ***c***, Lithological section of the Kalna relict ground showing (pointed by fingers) alternate burrowed and non-burrowed beds; ***d***, Mayfly burrow in three dimensions; ***e, f***, Detailed view of horizontal U-looped mayfly burrows. Note the geometric consistency and paired openings.

low-energy terrestrial[18] settings) described so far. However, from the ecological point of view, as discussed, they are expected in the *Scoyenis* ichnofacies in rock records.

Mayfly traces in the Holocene relict-ground now located in the inter-tidal modern beach profile of Bakkhali indicate Holocene rise of sea level, inundation of coastal tracts, regradation of coastline and transgression of sea. This ichnological evidence is also corroborated by the presence of relict ancient forest-ground in the middle to lower inter-tidal Bakkhali beach. Normally, the modern swarf-zone in the upper inter-tidal flat in a coastal profile, as observed in the Bay of Bengal coast, shows concentration of dead shells of marine invertebrates. An impersistent, oyster shell-concentrated zone is observed along the low-tide level in the Bakkhali beach. This feature also suggests sub-Recent rise in sea level. Moreover, the Holocene transgression of the Bay of Bengal is evidenced by algal microboring structures made on ooliths sampled from 60 to 110 m isobaths off Chennai coast[19]. There are several other evidences of Holocene rise of sea level from the eastern Indian coast[20–25]. Lastly, glacio-eustacy-related Holocene rise in sea level and consequent transgression is a globally observed phenomenon[26]. Thus, the present ichnological evidence from the Bay of Bengal coast is conformable with other evidences, local as well as global.

Moreover, the orientation of the mayfly burrows is important (Figure 1 *c*). The paired openings always lie towards the channel side, while the U-loop points away from the channel. This preferred orientation makes the mayfly burrows significant in the interpretation of channel courses in rock records. Ancient channel courses are often filled with aquifers. Thus, if preserved suitably in rock records, mayfly burrow orientation may provide valuable clues in locating ancient aquifers and channel courses.

Published documents of continental ichnofaunas in India are absent, except for one (Plio-Pleistocene Boulder Formation, Punjab Himalayas). Continental mayfly fossil burrows are extremely rare in rocks older than Upper Tertiary and Quaternary. The present study documents first record of mayfly burrows and second record of continental ichnofauna in India. Ecologically they indicate saturated edges (firm clay substrate) of ephemeral riverbank settings. Their presence in Holocene relict-ground exposed in modern, inter-tidal beach profile suggests sub-Recent rise in sea level and marine transgression, the facts otherwise well evidenced by other geological features documented locally as well as globally. Mayfly burrows, in a similar situation in rock records provide a new ichnological tool for palaeoecological interpretations and identification of glacio-eustacy-related transgression–regression events, the crucial aspects of sedimentary basin analysis.

1. Buatois, L. A., Mángano, M. G., Genise, J. F. and Taylor, T. N., *Palaios*, 1998, **13**, 217–240.
2. Genise, F. G. *et al*., *ibid*, 2000, **15**, 49–64.
3. Buatois, L. A. and Mángano, M. G., *Ichnos*, 1995, **4**, 151–161.
4. Buatois, L. A. and Mángano, M. G., *Palaeoecology*, 1998, **140**, 367–382.
5. Buatois, L. A., Mángano, M. G., Wu, X. and Zhang, G., *Ichnos*, 1996, **4**, 283–303.
6. Zhang, G., Buatois, L. A., Mángano, M. G. and Aceñolaza, F. G., *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1998, **138**, 221–243.
7. Buatois, L. A., Mángano, M. G., Maples, C. G. and Lanier, W. P., *Palaios*, 1997, **12**, 467–481.
8. Buatois, L. A., Mángano, M. G., Maples, C. G. and Lanier, W. P., *Bull. Kansas Geol. Surv.*, 1998, **241**, 1–27.
9. Buatois, L. A., Mángano, M. G., Maples, C. G. and Lanier, W. P., *J. Paleontol.*, 1998, **72**, 152–180.
10. Buatois, L. A., Mángano, M. G. and Carr, T. R., *Curr. Res. Earth Sci.*, 1999, **241**, 1–27.
11. Frey, R. W., *The Study of Trace Fossils*, Springer-Verlag, New York, 1975, pp. 1–562.
12. Tandon, S. K. and Naug, B., *Paleogeogr. Paleoclimatol. Paleoecol.*, 1984, **47**, 277–299.
13. Niyogi, D., Proceedings of the Seminar on Geomorphology, Geohydrology and Geotectonics of the Lower Ganga Basin, IIT, Kharagpur, 1972, pp. 71–90.
14. Mallick, S., Bhattacharya, A. and Niyogi, D., *ibid*, 1972, pp. 91–104.
15. De, C., *Ichnos*, 2000, **7**, 89–113.
16. Needham, J. G. *et al*., *The Biology of Mayflies*, Comstock Publ Co, 1935, pp. 1–759.
17. Frey, R. W., Curran, H. A. and Pemberton, S. G., *Palaeontology*, 1984, **58**, 333–350.
18. Smith, R. M. H., Mason, T. R. and Ward, J. D., *Geology*, 1993, **85**, 579–599.
19. Bandyopadhyay, A. and De, C., *Indian J. Mar. Sci.*, 2000, **29**, 181–184.
20. Naidu, A. S., *Bull. Natl. Inst. Sci. India*, 1988, **38**, 467–471.
21. Sreenivasa Rao, P., Krishna Rao, G., Durgaprasada Rao, N. V. N. and Swamy, A. S. R., *Indian J. Mar. Sci*., 1990, **19**, 261–264.
22. Mahapatra, G. P., Rao, B. R. and Biswas, N. R., *Geol. Surv. India, Spec. Publ.*, 1990, **29**, 229–243.
23. Banerjee, A. and Sengupta, R., *ibid*, 1990, **29**, 163–170.
24. Rao, K. M. and Rao, T. C. S., *J. Geol. Soc. India*, 1994, **44**, 585–589.
25. Vaz, G. G., *Curr. Sci.*, 1996, **71**, 240–241.
26. Fairbanks, R. G. A., *Nature*, 1989, **342**, 637–642.

ACKNOWLEDGEMENTS. I thank Mr T. C. Lahiri, Director, GSI for his guidance in preparing the draft manuscript.

Received 18 December 2001; revised accepted 13 April 2002