sectorial waves of semi-daily period (N₂, M₂) 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.

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

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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 ichnocenooses (trace fossil assemblages)¹, 58 ichnocenooses of palaeosol insect origin with 29 as recurring examples of *Coprinisphaera* ichnofacies² and a large number of ichnocenooses of lacustrine³⁻⁶ and freshwater inner estuarine⁷⁻¹⁰ 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 ichnocenooses¹¹ reported from Argentina, Australia, Ecuador, Egypt, France, Ethiopia,Kenya, Namibia, South Africa, UAE, Uruguay and USA¹². 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 Himalayas¹².

The present study focuses on the Holocene relict-gounds 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 Quaternary
evolutionary history and represents coalesced multi-
geneneration deltas that prograded in phases during positive
interglacial eustatic sea-level changes towards the Bay of
Bengal, leaving behind distinctive multilevel deltaic sur-
faces, terraces and palaeoshorelines13. The oldest Worgram
Formation14 (Upper Pleistocene, 120 to 35 m amsl and
hard crust lateritic) is exposed in the north. The Late
Pleistocene Kusumgram (semi-lithified calcareous con-
cretionary clay-silt), Holocene Kalna (0.5 to 7 m amsl,
firm brown-to-black mottled and firm clay soil) and
Recent Nabdwip (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
Nabdwip 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 Nabdwip 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 foreshore15. 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 relics
of ancient mangrove forest-ground (Figure 2 a) in the
middle to lower inter-tidal zone in the Bakkhali Beach
have been observed. Relicts of the Kalna surface occur in
the inter-tidal Nabdwip surface in down-drift coastal
tract of the Bakkhali area (Figure 2 b).

The ichniform is found in the Holocene Kalna relict
surfaces (firm clays). In lithological section, the bur-
rrowed 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 hori-
zontally along the bedding planes. In vertical section,
individual burrows possess paired circular openings (0.2–
0.3 cm diameter) almost touching each other. In longitudi-
nal 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,
Texas11. The Bryan burrows closely resemble the present
structures in all geometric aspects. The present structures
are distinctly different from the known bee-trace fossils,
Uruguay2, containing circular tubes arranged around a
central mass of sediment and Palmirarchmus, 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 dwell-
ing tubes and is considered as the Holocene analogue of
the Tertiary Bryan burrows.

As a part of life habits, mayflies habitually and selec-
tively 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 level16.

Bathymetric zones of common riverbank trace makers, as
noticed along the Brazos River and in Houston, Texas11,
have revealed the same ecological niches for mayflies.
Thus, modern as well as ancient mayfly ichnofaunas are
suggestive of continental (ephemeral) stream-bank (satu-
rated edges just below water level) environments. Besides
dwelling burrows, mayflies also produce sprawling, rest-
ning 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. Scoye-
nia in river floodplain17, Merminia in subaqueous lacsus-
trine1, Coprinisphaera in palaeosol2 and Termiichnus in

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Figure 1. a, Regional Quaternary geological map of a part of
Gangetic Delta Complex (modified after Niyogi11); b, Details of Bak-
khali 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.

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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\textsuperscript{18} settings) described so far. However, from the ecological point of view, as discussed, they are expected in the \textit{Scygenis} 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\textsuperscript{19}. There are several other evidences of Holocene rise of sea level from the eastern Indian coast\textsuperscript{20–25}. Lastly, glacio-eustacy-related Holocene rise in sea level and consequent transgression is a globally observed phenomenon\textsuperscript{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 1c). 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.

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