Billion-year-old rain-imprinted tidal sea-coast in eastern Madhya Pradesh, India

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The Lower Vindhyan glauconitic sandstone beds (Semri Group) represent a glossary of tidalflat ripples overprinted by rain craters which expound deep-time rainfall over dynamic tidal sea-coast, about a billion-years ago in eastern Madhya Pradesh, India. The rain imprints, being exceptionally preserved, together with background sedimentary structures reveal periodic subaerial exposures of the tidalflats and spasmodic non-torrential rainfall. Their antiquity provides insight into the physiographic, climatic and atmospheric conditions of the primitive earth. Proterozoic rain imprints possibly constitute one of the oldest sets of preservable geological documents of rainfall in the earliest multicyclic sediments piled up within first generation epeiric seas, which presumably developed soon after the emergence of true continental land masses above the oceanic wave base sometime between 2.5 Ga and 2.7 Ga ago. The Semri rain imprints record the lowest level of stratigraphic evidence of a billion-year-old rainfall in the Vindhyan sequence. Rain imprints over shallow marine tidalflats of such antiquity are rare and thus, the Semri fossil rain craters belong to that rare category which provides much needed information on our earth’s primitive atmospheric conditions.

Rain-imprinted rippled palaeo-tidalflat surfaces are discovered in the glauconitic sandstone unit of the lower Vindhyan Semri Group exposed in parts of Satna and Rewa districts of eastern Madhya Pradesh. Fossil rain imprints, especially geologically older ones, preserved in the sedimentary rock layers usually receive least importance in most of the published literature in comparison to sedimentary structures of younger ages. Rain imprints received on intermittently exposed depositional surface marked by currents and wave ripples by receding tides, provide a clear insight into some environmental aspects of sedimentation. Rain craters preserved in deep-time rocks such as those in the billion-year-old rippled tidalflat sediments of the Semri Group, are of special significance. This paper describes the Semri rain imprints against the background of depositional environment, nature of rainfall and atmospheric conditions one billion years ago.

The Proterozoic Vindhyan Supergroup forms a huge synclinorium trending east-west in central and western India (Figure 1) and contains the Semri, Kaimur, Rewa and Bhandar Groups in ascending order. The unmeta-morphized and nearly undeformed Vindhyan s form about 4000 m thick pile of sedimentary rock sequence. The Semri Group, resting unconformably over the Mahakoshal Group, is predominantly composed of alternate sequences of shales and limestones within which there lies a conspicuous ridge-forming arenaceous horizon known as the Rampur Formation, overlain and underlain respectively by the Rohtasgarh Limestone and Salkhan Limestone (= Fawn Limestone) Formations. The concerned glauconitic sandstones are part of the Rampur Formation and are very well exposed in the Chorhat–Rampur–Gorsari areas of eastern Madhya Pradesh (Figure 1). The Semri Group forms the outer rim of the Vindhyan synclinorium. The Kaimur Group, on the contrary, is dominantly composed of siliciclastics. The Rewa Group is composed mainly of sandstones and shales. The topmost Bhandar Group being exposed in the central part of the synclinorium is composed mainly of limestones and shales with minor amount of sandstone–shale intercalations in the upper part. The arenaceous and argillaceous facies are the storehouse of various types of sedimentary structures. The calcareous facies, particularly those belonging to the Bhandar and Semri Groups, contain various types of stromatolitic structures. The Bhandar nonstromatolitic limestones, in particular, are of cement-grade. Various types of shallow marine depositional models such as barrier island–lagoon, tidalflat–lagoon–sand waves and shoal bar–lagoon, have been proposed for different segments of the Vindhyan sequence.

The radiometric and biostratigraphic data2–10 (Figure 1) suggest 1.4 Ga to 0.6 Ga age for the Vindhyan Supergroup, 1.4 Ga to 1 Ga for the Semri Group and preferably about 1 Ga for the upper Semri glauconitic sandstones. In this context it is relevant to note that the claim1 of Lower Cambrian age for the Rohtasgarh Limestone Formation (Semri Group) has already been rejected through scientific enquiry11 and various other fossil findings12,13,14.

The glauconitic sandstones of the upper Semri Group exposed in and around Chorhat–Gorsari areas (Figure 1) are characterized by the presence of variable quantities of green to yellowish-green glauconite grains (7.1–15.7% of the total detritals), varied ripple forms and well-preserved rain imprints. The current ripples are of straight linear (Figure 2a), flat or truncated top (Figure 2b), interference, double-crested (Figure 2c), undulatory (Figure 2d), lunate and linguoid types. These are associated with a variety of wave ripples (Figure 2e–f). Similar ripple association is typical of most of the modern and ancient tidalflats15. Other associated features with the rain imprints are longitudinal obstacle scour marks (Figure 3a), tool marks, rill marks (Figure 3b, c), flute marks (Figure 4a), tidal rhythmic laminations.
or beddings (Figure 4 b), ripple-drift laminations, thin layers of oolites (Figure 4 c, d) and desiccation cracks (Figure 5 a–c), all of which collectively indicate sweeping tidal current action, periodic inundation and subaerial exposure of the sediment surface and shifting bottom-sediment conditions typical of shallow coastal tidalflat-beach environments. The thin layers of oolites (simple and composite) specifically suggest back and forth rolling action of the tidal processes over a flat surface of deposition.

Analysis of the variations in the bed thickness (Figure 6) also demonstrates strong influence of tidal processes on deposition of the glauconite sandstones. Recurrent thickness fluctuations provide strong evidence that these deposits must be regarded as tidal rhythms, with thicker strata representing the spring tides and the thinner ones recording neap tides (Figures 4 b and 6). The resulting sequence is, thus, interpreted as having been deposited in a neap-dominated diurnal tidal system with brief to long periods of subaerial exposures, when rain drop impressions, rill marks and desiccation cracks were developed. This mode of deposition of the glauconitic sandstones of the Lower Vindhyan of India is to some extent similar to that of the Late Carboniferous tidal rhythms of Eastern Kansas, USA.

The cosets of the cross-beds in single exposure (Figure 7 a) show repeated reversal of current flow directions. The resultant structures, thus, formed were herringbone cross-beds, typically indicative of tidal actions.

Rain-induced rippled sediment mats of the glauconitic sandstones are overlain by stromatolitic Rohtasgarh limestones of subtidal to intertidal origin. Tidalflat origin of the Semri glauconitic sandstones is also advocated by a majority of the previous workers. They have also noted sedimentary structures similar to those described in this paper.

The Semri rain imprints are represented by small (3 to 5 mm diameter on average)-impact craters of circular to elliptical shapes, suggesting respectively, vertical to...
oblique paths of the rain drops. The craters have partial to complete rims of sediments that rise slightly above the sediment surface. In this respect they differ from the foam bubble pits. It is known that only one side of the ripple shows rain imprints when rain falls obliquely on a ripple surface. Rain craters formed on all the sides of a ripple, as in the present case, may be due to cumulative effects of high-angle rainfall on broad – or flat – crested ripples and low-angle rainfall under varied wind directions on sharp – crested ripples. At places, the back sides of the rims around elliptical craters are found broken. This could be due to oblique-falling of the raindrops on the plain surface. Similar features were described, both from the modern and ancient sediments (Rotliegendes of Germany). The Semri rain craters are equally well-developed on crests, flanks and troughs of the ripples (Figure 7b). This is suggestive of good subaerial exposures of the rippled surfaces before rainfall. If it rains over just-exposed rippled bed, the impacts are seen better developed on relatively drier crests than in the wet troughs. Furthermore, the Semri rain craters have low rims and shallow depths (Figure 7c). These properties reject their origin in the same way as deeper craters encircled by high rims, produced by large water drops falling from low heights on muddy surface due to melting of ice blocks. Preservation of individual rain craters (Figure 7c) on plane beds of the Semri sediments signifies non-
torrential and occasional nature of the ancient rainfall. Perhaps, it was drizzling, as otherwise a torrential rain on the soft and rippled sediment surfaces would have polished them off into small irregularities, devoid of any identifiable rain crater. Rain imprints usually have the best chance of preservation in the arid and semi-arid continental deposits\textsuperscript{18}, such as wadi (desert stream) deposits. Their chance of preservation on tidalflats, as in the present case, is least due to repeated tidal action and hence, the Semri craters are exceptional and very rare. Craters caused by hailstones are usually much larger, deeper and more irregular than the rain craters\textsuperscript{72}. The Semri craters do not display these shapes.

It is, thus, generalized that the Semri rain imprints are exceptionally preserved and rare documents of occasional and non-torrential rainfall on long exposed and uniformly dried rippled tidalflat surfaces developed a billion-years ago along the Lower Vindhyan sea-coast.

The antiquity of the above discussed rain imprints can possibly be more significantly analysed in terms of primitive atmospheric, climatic and physiographic scenarios with the help of existing models, assumptions and presumptions related to the origin and evolution of our planet. When did the atmospheric process of rainfall begin on earth? An answer to this question is a prerequisite for the understanding of the development of rain imprints in the geologic past.

Virtually, there is very little geologic record of the first one billion years (Hadean period) of the earth’s history. The oldest preserved rocks now known on earth belong to the Acasta Gneissic Complex of Slave Province of North-west Canada\textsuperscript{25,24}, which exposes tonalites 4.0 Ga to 4.055 Ga old. Rocks of high antiquity (3.0 Ga to 3.8 Ga) occur in a number of other countries like Greenland, Australia, USA, China\textsuperscript{25–31}, including India\textsuperscript{32–36}. It was assumed that during the Hadean period (4.7 Ga–3.8 Ga) there existed a transitory Hadean atmosphere rich in hydrogen, helium, neon, argon and other light inert gases derived directly from cosmic clouds and volcanic outgassing. None of these gases is abundant in the present atmosphere. On sufficient cooling of the earth, liberation of abundant water along with CO\textsubscript{2}, N\textsubscript{2} and H\textsubscript{2}S by volcanic outgassing probably took place and the atmosphere became highly reducing\textsuperscript{37}. The water vapour was probably dissociated in the upper atmosphere by ultraviolet light to yield free oxygen and hydrogen. This process might have constituted the sole source for free O\textsubscript{2} in the prebiotic early atmosphere\textsuperscript{38}. Oxygen build-up to significant concentration took perhaps a long time (3.4 Ga–2 Ga), while O\textsubscript{2} in the high atmosphere was photochemically converted to ozone in layer as at present to screen ultraviolet light. Accumulation of water molecules in the atmosphere caused extensive rainfall for the first time to initiate oceans of condensed volatiles, sometimes prior to 3.76 Ga ago\textsuperscript{38}. Thus, initiation of rain process, appearance of primordial ocean and formation of the first chemical precipitates in the form of Isua meta-cherts seem to be interdependent and sequential events of the prebiotic late Hadean period.

The grand-old Isua rocks (amphibolites, ultramafics, meta-cherts, mica-schists and meta-conglomerates) do
Figure 4. *a*. Striated flute marks preserved at the sole of bed as flute moulds which are arranged parallel to the current flow (away from the observer for the top-right part, right to left for the middle one and from left to right for the lower-middle one). Bar scale = 2 cm; *b*. Tidal rhythmic bedding/deflections in glauconitic sandstone (sectional view). Note recurrent thickness fluctuations (see Figure 6) suggestive of tidal rhythmic deposition (thicker layers in spring tides vs thinner layers in neap tides). Hammer length = 36 cm; *c*, *d*. Thin sectional view under microscope of the oolites found in glauconitic sandstones. Note the reworked (composite) nature of the oolites in (*d*) and non-composite nature in (*c*), x 100.

possess some detrital components derived from thin and fragile anorhotic continental crust. None of these sedimentary rocks (now metamorphosed) contain rain imprints, even though rain used to erode away almost every scrap of rock older than 3.5 Ga. All the above cited Archean terrains contain predominantly ultramafics, mafics and felsic igneous rocks besides subordinate amount of first-cycle sedimentary rocks rich in pyroclastics and inter-layered silicious precipitates. Shallow-water features like cross-beddings and ripples from these sediments are known. So far, no rain imprint is recorded from them.

The nature of early atmosphere and life are well-debated subjects. The earth’s early atmospheric evolution suggests that the formation of an early atmosphere containing N₂ and CO₂ and an ocean made up of H₂O appears to be a natural consequence of planetary accretion in the terrestrial planet region. A weakly-reducing primitive atmosphere provided an environmental condition conducive to the origin of life, regardless of whether the essential biological precursor compounds were synthesized on the earth or elsewhere. As a consequence of organic carbon burial and photosynthesis, atmospheric O₂ levels rose gradually with the decline of CO₂ and other greenhouse gases in such a way as to compensate for the brightening sun. The earth’s relatively stable climate was probably the result of negative feedback between atmospheric CO₂, surface temperature and weathering rate of the silicates.

The nonavailability of rain imprints at Palaeoarchean time level is very much related to the nature of the post-Hadean Archean earth. During the deposition of Isua Banded Iron Formation which bears the oldest evidence of life (3.8-Ga-old unicellular organic body) and the Apex cherts (Australia) which contain the oldest (3.46 Ga old) ever known fossil filamentous cyanobacteria, the earth was spinning so fast that each day lasted for less than 18 h and there were no continents, but only volcanic archipelagoes jutting above the oceanic waves. True continental land mass emerged
above the wave base around 2.5 Ga to 2.7 Ga ago (i.e., start of Proterozoic) resulting in the formation of first
generation epeiric seas, wherein chemically matured
first multicyclic sediments were deposited in bulk. One
can, thus, expect oldest rain imprints preserved in such
sediments. In other words, the unmetamorphosed and
least deformed Proterozoic sedimentary rock sequences
promise to preserve the oldest generation of rain im-
prints, even though the rain process must have com-
enced roughly around the late Hadean period (3.8 Ga).
The Semri rain craters are, thus, rare examples of those
first generation (Proterozoic) rain imprints.

The ancient examples of undoubted and well-
preserved rain craters are too many, spanning from the
Lower Proterozoic to Quaternary periods. Some of the
best developed rain imprints are known from the Pre-
cambrian tidal-flat deposits of Norway and Scotland,
Devonian of Germany, Cretaceous Dakota Group of
Colorado and Permian dunes of Boulder County
(U.S.A)\textsuperscript{14}. Rain imprints on the rippled surface are com-
monly known from the Permian Playa lake complex of
western Argentina\textsuperscript{15}, Late Carboniferous non-marine
tidal rhythms of Kansas\textsuperscript{16} and Upper Carboniferous
fluvio-estuarine palaeo-valley sandstones of Kansas\textsuperscript{46}.
They also occur in the younger stratigraphic levels of the
Vindhyan. They are known from the Rewa sand-
stones of Chittorgarh district (Rajasthan)\textsuperscript{17}, Sirbu
shales and Bundi Hill quartzites (Bhandar Group) of south-
eastern Rajasthan\textsuperscript{48}. Thus, the present Semri structures
constitute the oldest (~ 1 Ga) ever known evidence of
palaeo-rainfall in the Proterozoic Vindhyan sequence.
Other Proterozoic basins of India also bear rain craters,
but reports of rain imprints on palaeo-tidalflat surfaces
are rare. The author had also noticed rain craters on rip-
pled beds of Delhi (Rajasthan) and Gondwana
(Orissa).

A chronicle of atmospheric, hydrospheric, litho-
spheric and biospheric events in the earth's geologic
history prepared from different sources referred in the
text is presented in Figure 8 and the event sequences in
three steps leading to rain imprint preservation in the
Semri rocks in Figure 9.

The billion-year-old rain imprinted tidalflat surfaces
of glauconitic sandstones of the Semri Group enable
interpretation about palaeo-environment of deposition,
Figure 7. *a.* Outcrop section showing cosets of cross-stratification. Note the herringbone type of cross-stratification (middle-top) and complete reversal of current flow patterns throughout the section, an excellent criterion for back and forth tidal current flow pattern. Scale = 30 cm; *b.* Lowlv rippled surface of the glauconitic sandstone bed with rain craters developed on the crest, flanks and troughs; *c.* Rain craters with low rims (complete to incomplete) and shallow depths on the rippled glauconitic sandstone surface.

Palaeo-geomorphology and palaeo-atmospheric conditions. The rain imprints and their background sedimentary structures suggest the existence of shallow coastal tidalflats with various aqueous ripple forms, mainly of tidal current origin. Those flats used to be subaerially exposed and received non-torrential and spasmodic rainfall. The rain craters constitute the oldest exceptionally preserved record of rainfall in the Vindhyan sequence. The present-day geomorphic set-up of eastern Madhya Pradesh comprising subdued Vindhyan hill ranges separated by wide and flat valleys contrasts sharply with what had prevailed about a billion years ago – just an epeiric sea with coastal tidalflats.

The billion-year-old Vindhyan rain craters endorse our general perceptions on atmospheric evolution of primitive earth and provide an insight into the palaeoclimatic and palaeo-physiographic scenarios of the Proterozoic earth. Possibly the geological records of the Hadean rainfall, if any, were lost forever in the volcano-tectonic phases of the evolving earth. The oldest ever
Figure 8. Chronicle of atmospheric, hydropheric, lithospheric and biospheric events in the earth's geologic history (prepared from different sources referred in the text).

Figure 9. Inferred event sequences of primitive rainfall on Lower Vindhyian tidal sea-coast leading to preservation of rain craters on rippled surfaces.
preservable records of rainfall are expected from the multi-cyclic Proterozoic sediments (e.g. the Vindhyanas) laid down in the first generation epicene seas (e.g. the Vindhyan sea) developed subsequent to the emergence of thick and true continental landmasses above the wave base, around 2.5 Ga to 2.7 Ga ago. The Semri rain craters and others of similar antiquity testify our belief that the process of atmospheric condensation of water vapour into rain drops, as in the present-day oxidizing atmosphere, was in operation at least a billion years ago. The Semri rain impressions on rippled tidallflats surface, besides being oldest in the Vindhyan sequence, undoubtedly belong to the rare class of Proterozoic rain features.

2. Rajagopalan, G. and Maity, P. K., Group Discussion on Vindhyan, Jadavpur University, Kolkata, 1993, pp. 35–36.

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