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

Chirananda De

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

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 Bhander Groups in ascending order. The unmetamorphozed and nearly undeformed Vindhyans 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 Bhander 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 Bhander and Semri Groups, contain various types of stromatolitic structures. The Bhander 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[1].

The radiometric and biostratigraphic data[2–10] (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 claim[11] of Lower Cambrian age for the Rohtasgarh Limestone Formation (Semri Group) has already been rejected through scientific enquiry[12] and various other fossil findings[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 2 *a*), flat or truncated top (Figure 2 *b*), interference, double-crested (Figure 2 *c*), undulatory (Figure 2 *d*), lunate and linguoid types. These are associated with a variety of wave ripples (Figure 2 *e*–*f*). Similar ripple association is typical of most of the modern and ancient tidalflats[15]. Other associated features with the rain imprints are longitudinal obstacle scour marks (Figure 3 *a*), tool marks, rill marks (Figure 3 *b*, *c*), flute marks (Figure 4 *a*), tidal rhythmic laminations

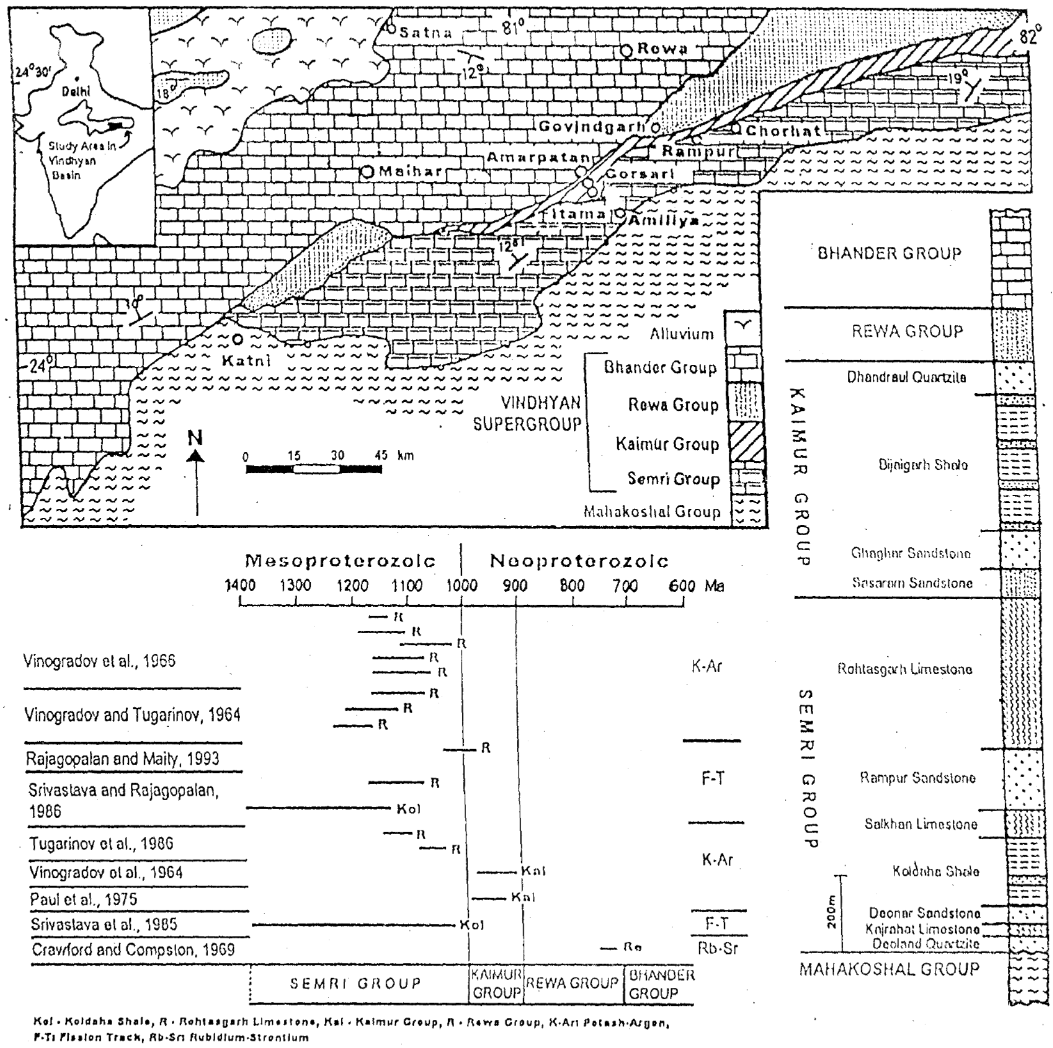

Figure 1. Geological map of part of the Vindhyan Supergroup of the study area.

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 glauconitic sandstones. Recurrent thickness fluctuations provide strong evidence that these deposits must be regarded as tidal rhythmites, 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 Vindhyans of India is to some extent similar to that of the Late Carboniferous tidal rhythmites of Eastern Kansas, USA[16].

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[17]. Tidalflat origin of the Semri glauconitic sandstones is also advocated by a majority of the previous workers[1]. 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

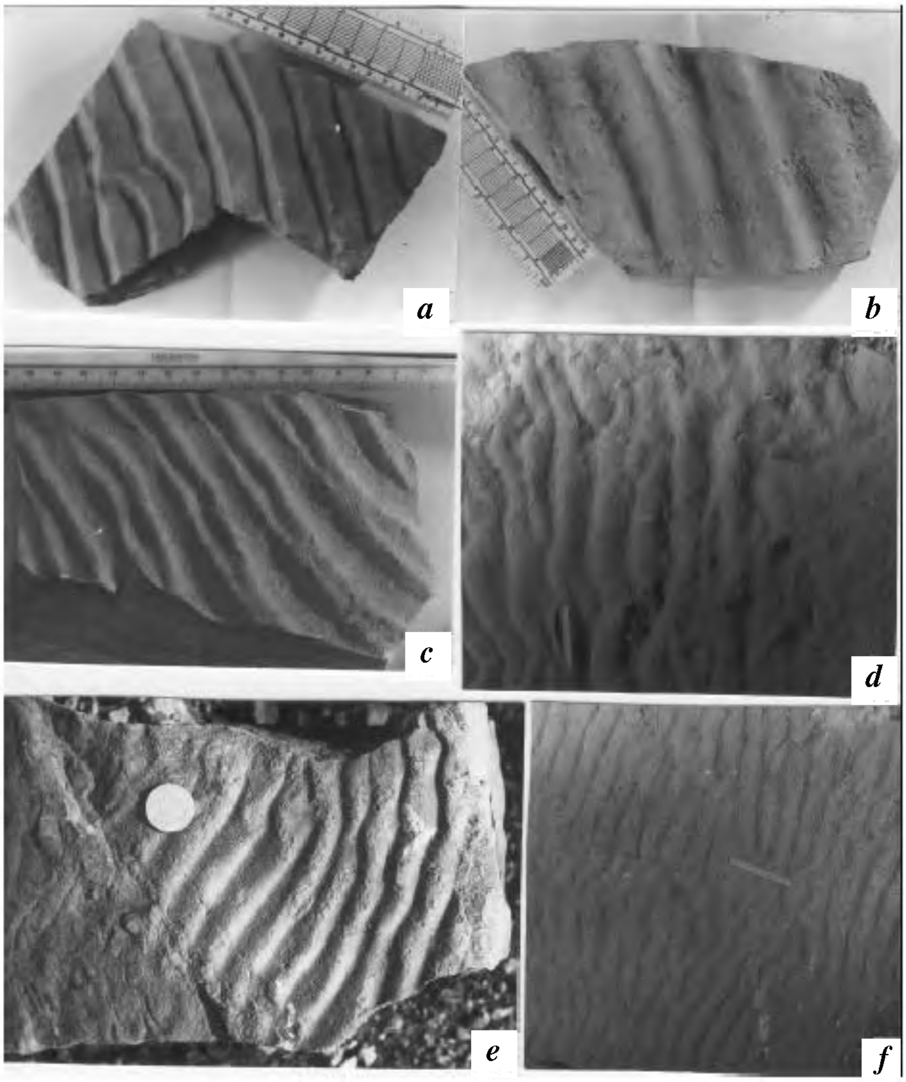

Figure 2. ***a***, Straight linear current ripples; ***b***, Flat to truncated top current ripples; and ***c***, Double-crested linear current ripples, on the glauconitic sandstone beds; ***d***, Ripple train with weakly undulatory small current ripples. The forms are transitional between straight-crested and undulatory ripples and analogous with some forms noticed on the North Sea tidalflats. Scale = 30 cm; ***e***, Symmetrical wave ripples showing slightly curved axes, rounded-off crests and faint impressions of rain craters. Coin diameter = 2 cm; ***f***, Asymmetrical wave ripples forming ripple-mat surface on the sandstone bedding plane. The direction of wave propagation is from left to right. The ripple-mat bears resemblance with the same being formed by wave actions on the North Sea tidalflats. Scale = 30 cm.

oblique paths of the rain drops[18]. 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 rippled surface[18]. 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[18]. Similar features were described[19], 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 7 *b*). 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[20]. Furthermore, the Semri rain craters have low rims and shallow depths (Figure 7 *c*). 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[21]. Preservation of individual rain craters (Figure 7 *c*) 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[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[22]. The Semri craters do not display these shapes.

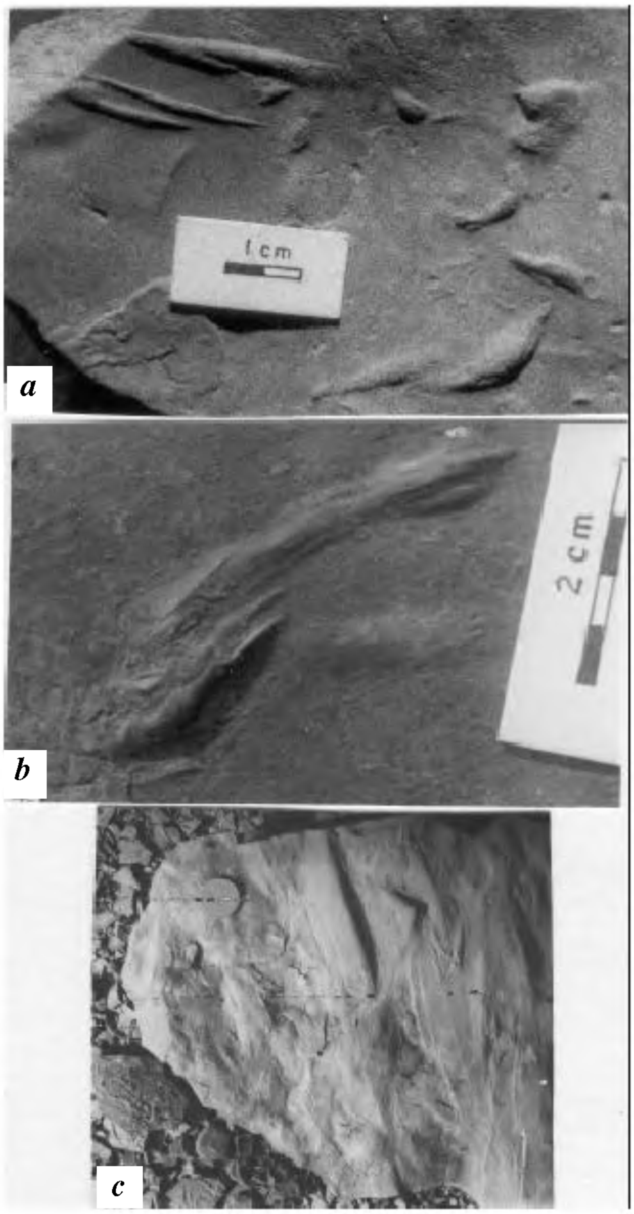

Figure 3. ***a***, Moulds of longitudinal obstacle-scour marks at the sole of bedding surface possibly produced by tools moving down current (left to right). Bar scale = 1 cm; ***b***, Rill marks with terminal accumulation tongues at the sole of beds. Sediments eroded during formation of the rill were deposited at the end of rill system forming a few millimetre thick tongues of sediment. The current flow is from top-right to bottom-left. Bar scale = 2 cm; ***c***, Comb-shaped rill marks on the bedding plane. Current flow pattern is towards the observer. Coin diameter = 2 cm.

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[23,24], 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[25–31], including India[32–36]. It was assumed that during the Hadean period (4.7 Ga–3.8 Ga) there existed a transitory Hadean atmosphere rich in hydrozen, 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_2, N_2 and H_2S by volcanic outgassing probably took place and the atmosphere became highly reducing[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_2 in the prebiotic early atmosphere[38]. Oxygen build-up to significant concentration took perhaps a long time (3.4 Ga–2 Ga), while O_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[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-schiests and meta-conglomerates) do

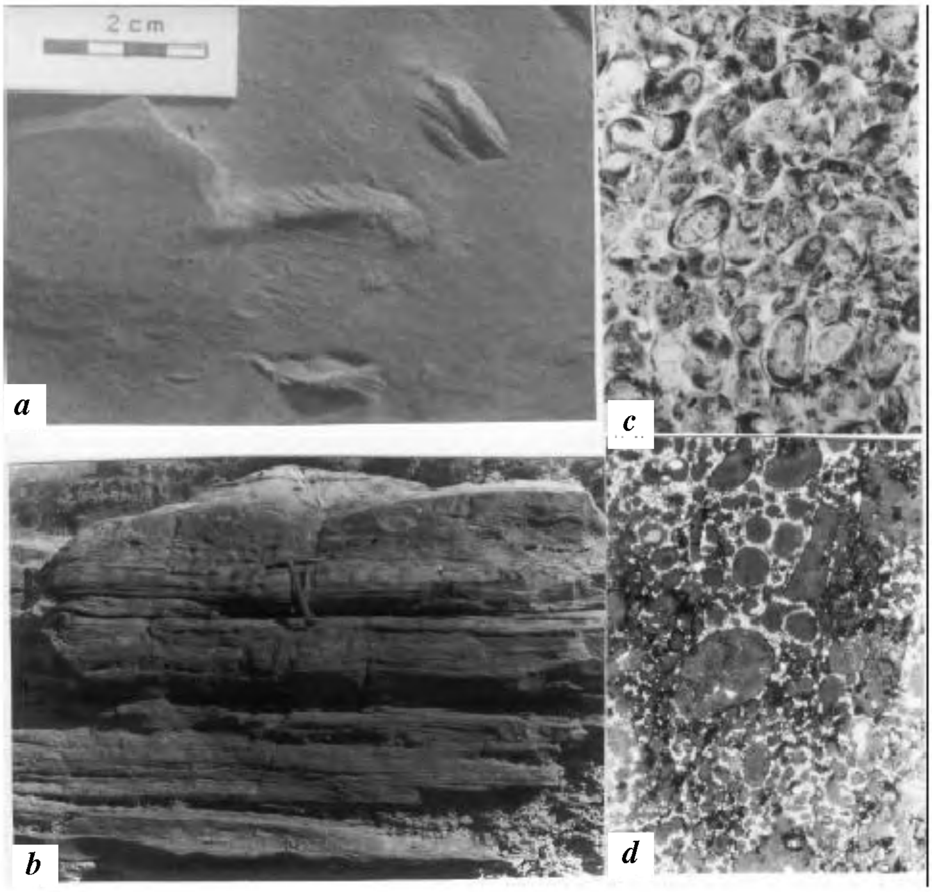

Figure 4. ***a***, Striated flute marks preserved at the sole of bed as flute moulds which are arranged parallel to the current flow (away from the observer for the top-right part, right to left for the middle one and from left to right for the lower-middle one). Bar scale = 2 cm; ***b***, Tidal rhythmic bedding/laminations 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***), × 100.

possess some detrital components derived from thin and fragile anorthositic 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[39]. 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[40,41]. The earth's early atmospheric evolution suggests that the formation of an early atmosphere containing N_2 and CO_2 and an ocean made up of H_2O 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 O_2 levels rose gradually with the decline of CO_2 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 CO_2, surface temperature and weathering rate of the silicates[40].

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)[42] and the Apex cherts (Australia) which contain the oldest (3.46 Ga old) ever known fossil filamentous cyanobacteria[42], 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[39]. 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

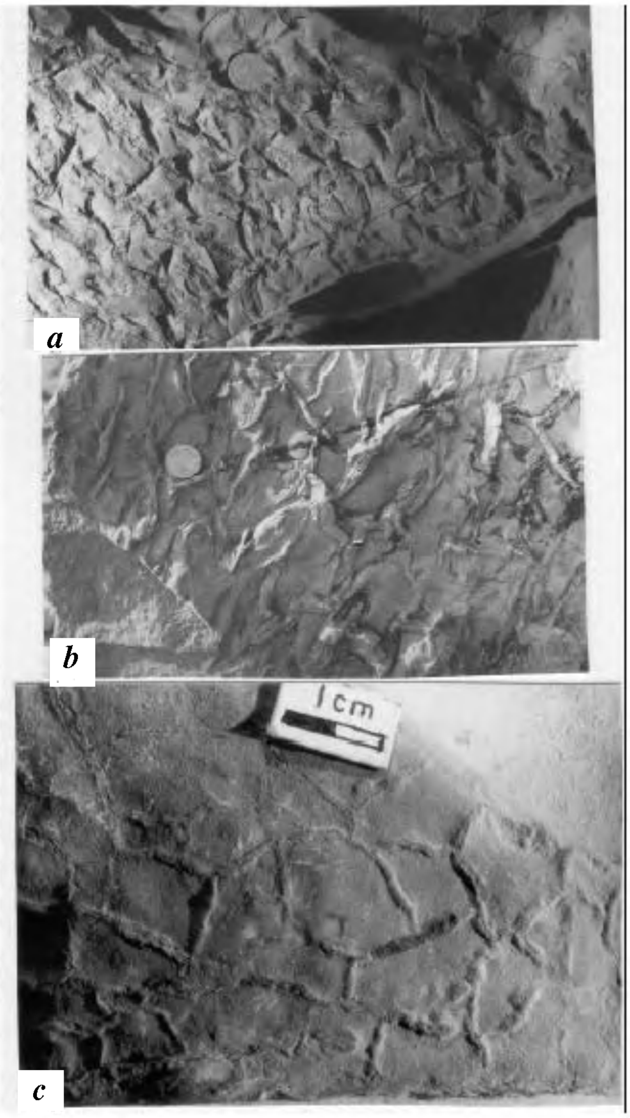

Figure 5. *a*, Desiccation cracks partly developed on fine sandstones. Individual cracks are short and slightly curved with narrow ends. They show bimodal orientation. No distinct polygonal network is formed. Coin diameter = 2 cm; *b*, Sinuous to straight cracks, acute-ended, centrally-bulged and criss-crossed. Triangular bifurcation points (top-right and top-middle) are conspicuous. Polygonal network is not formed here. Coin diameter = 2 cm; *c*, Perfect desiccation crack system in fine sandstones. Note the polygonal network pattern formed by the crack arms emanating from the points of divergence. Bar scale = 1 cm.

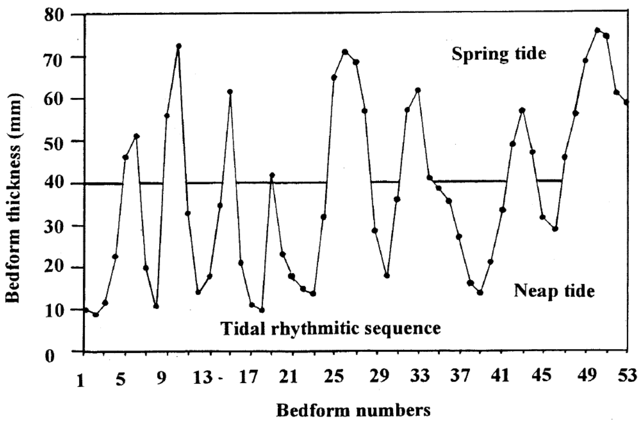

Figure 6. Thickness variation curve of beddings/laminations of the glauconitic sandstone sequence photographically illustrated in Figure 4 *b*. Note rhythmic variation of thickness, typical of tidal rhythmites.

promise to preserve the oldest generation of rain imprints, even though the rain process must have commenced 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 Precambrian tidalflat deposits of Norway[20] and Scotland, Devonian of Germany, Cretaceous Dakota Group of Colorado[43] and Permian dunes of Boulder County (USA)[44]. Rain imprints on the rippled surface are commonly known from the Permian Playa lake complex of western Argentina[45], Late Carboniferous non-marine tidal rhythmites of Kansas[16] and Upper Carboniferous fluvio-estuarine palaeo-valley sandstones of Kansas[46]. They also occur in the younger stratigraphic levels of the Vindhyans. They are known from the Rewa sandstones of Chittorgarh district (Rajasthan)[47], Sirbu shales and Bundi Hill quartzites (Bhander Group) of south-eastern Rajasthan[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 rippled beds of Delhis (Rajasthan) and Gondwanas (Orissa).

A chronicle of atmospheric, hydrospheric, lithospheric 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,

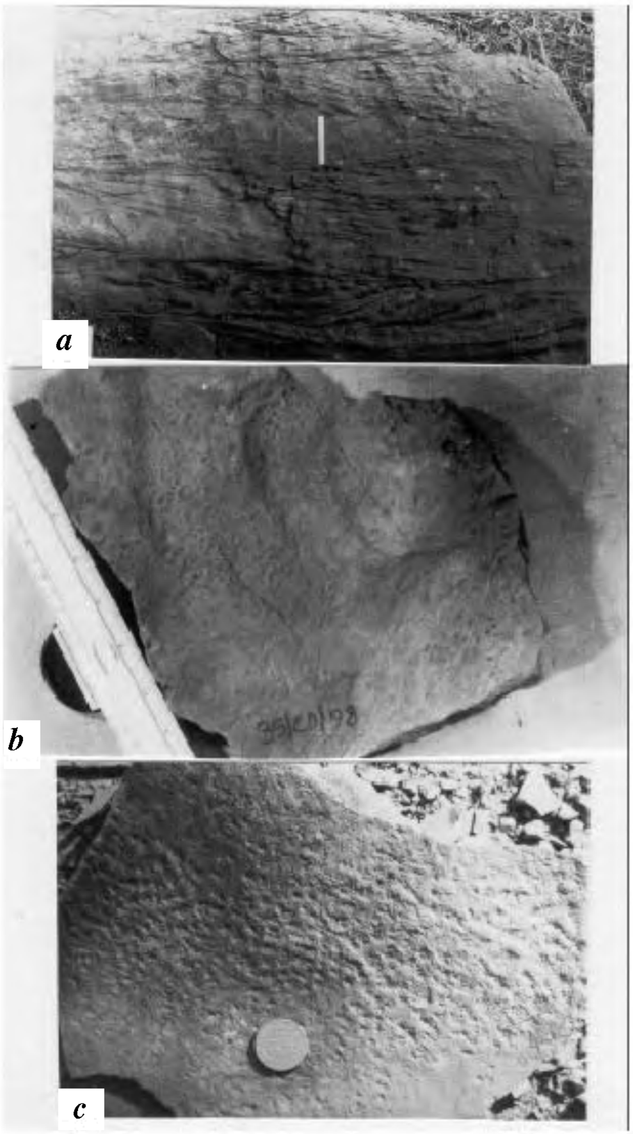

Figure 7. ***a***, Outcrop section showing cosets of cross-stratification. Note the herringbone type of cross-stratification (middle-top) and complete reversal of current flow patterns throughout the section, an excellent criterion for back and forth tidal current flow pattern. Scale = 30 cm; ***b***, Lowly 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

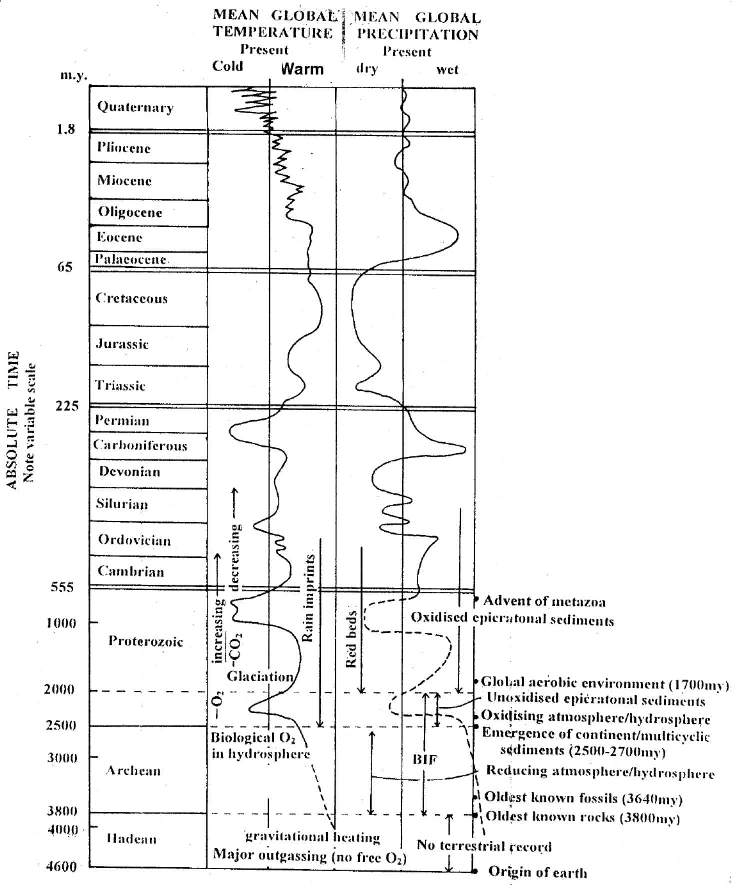

Figure 8. Chronicle of atmospheric, hydrospheric, lithospheric and biospheric events in the earth's geologic history (prepared from different sources referred in the text).

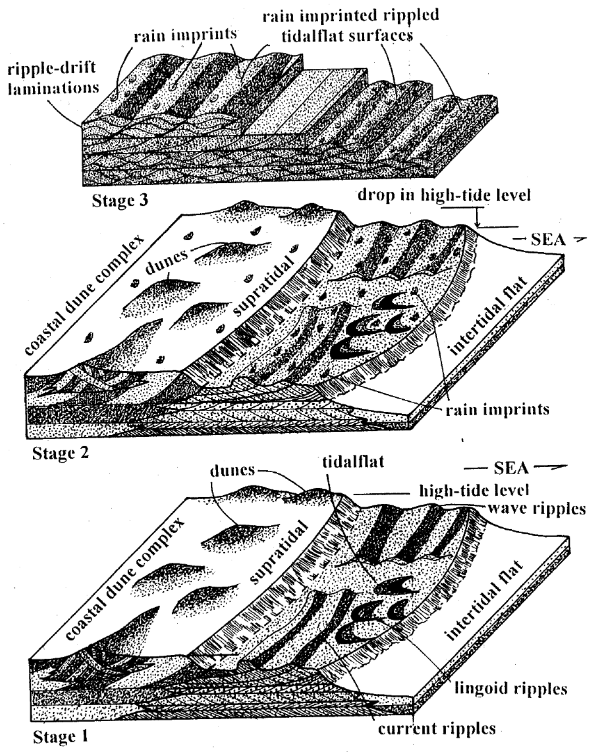

Figure 9. Inferred event sequences of primitive rainfall on Lower Vindhyan tidal sea-coast leading to preservation of rain craters on rippled surfaces.

preservable records of rainfall are expected from the multi-cyclic Proterozoic sediments (e.g. the Vindhyans) laid down in the first generation epeiric 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 imprints on rippled tidalflat surface, besides being oldest in the Vindhyan sequence, undoubtedly belong to the rare class of Proterozoic rain features.

1. Chanda, S. K. and Bhattacharya, A., in *Geology of Vindhyanchal* (eds Valdiya, K. S. and Bhatia, S. B.), Hindustan Publ. Co, Delhi, 1982, pp. 88–101.
2. Rajagopalan, G. and Maity, P. K., Group Discussion on Vindhyan, Jadavpur University, Kolkata, 1993, pp. 35–36.
3. Paul, *et al.*, *Geol. Soc. Am. Bull.*, 1975, **86**, 364–366.
4. Srivastava, A. P. and Rajagopalan, G., in *Nuclear Tracts* (ed. Sharma, K. K.), 1986, pp. 41–42.
5. Vinogradov, A. I., Tugarinov, A. I., Zhikov, C. L., Stupnikova, N. L., Bibinova, E. V., Knorre, K. G. and Mehlrikova, G. L., 22nd Int. Geol. Congress, 1964, vol. 10, pp. 553–567.
6. Vinogradov, A. I., Tugarinov, A. I., Zhikov, C. L., Stupnikova, N. L., Bibinova, E. V., Knorre, K. G. and Mehlrikova, G. L., *Geochronologiya Do Kembriya Indyi*, Moscow Nauka, 1966, pp. 1–327.
7. Vinogradov, A. I. and Tugarinov, A., 22nd Int. Geol. Congress, 1964, vol. 1, p. 12.
8. Tugarinov, A., Shanin, L. L., Kazakov, G. A. and Arakelyants, M. M., *Abstr. Geochem. Int*, 1986, **12**, 504.
9. Srivastava, A. P., Rajagopalan, G. and Nagpaul, K. K., *Indian J. Earth Sci.*, 1985, **12**, 89.
10. Crawford, A. R. and Compston, W., *Q. J. Geol. Soc. London*, 1969, **125**, 351–372.
11. Azmi, R. J., *J. Geol. Soc. India*, 1998, **52**, 381–389.
12. Bhatt, *et al.*, *J. Geol. Soc. India*, 1999, **53**, 717–723.
13. Seilacher, A., Bose, P. K. and Pfluger, F., *Science*, 1998, **282**, 10–13.
14. Sarkar, S., Banerjee, S. and Bose, P., *N. Jb. Geol. Palaeontol. Mn.*, 1996, **H7**, 425–438.
15. Klein, G. D. E. V., *Sed. Geology*, 1977, **18**, 1–12.
16. Buatois, L. A., Gabriela, M. and Maples, C. G., *SEPM, Palaios*, 1997, **12**, 467–481.
17. Raha, P. K. and Sastry, M. V. A., *Precambarian Res.*, **18**, 1982, 293–318.
18. Reineck, H. E. and Singh, I. B., *Depositional Sedimentary Environments*, Springer-Verlag, New York, 1973, pp. 1–439.
19. Reineck, H. E., *N. Jahrb. Geol. Palaeontol. Abh.*, 1955, **101**, 75–90.
20. Singh, I. B., *Nor. Geol. Tidsskr*, 1969, **49**, 1–31.
21. Reineck, H. E., *Senckenbergiana Lethaea*, 1956, **37**, 299–304.
22. Lyell, C., *Geol. Soc. London, Q. J.*, 1851, **7**, 238–247.
23. Bleeker, W. and Stern, R., *J. Earth Sci.,* 1999, **36**, 1083–1109.
24. Sankaran, A. V., *Curr. Sci.*, 2000, **79**, 935–937.
25. Nutman, A. P., Friend, C. R. L., Kinney, P. O. and McGregor, V. R., *Geology*, 1993, **21**, 415–418.
26. Kambler, B. S. and Moorbath, S., *Chem. Geol.*, 1998, **150**, 19–41.
27. Bowring, S. A., Williams, I. S. and Compston, W., *Geology*, 1989, **17**, 971–975.
28. Froude, D. O., Ireland, T. R., Kinny, P. D., Williams, I. S. and Compston, W., *Nature*, 1983, **304**, 616–618.
29. Black, L. P., Williams, I. S. and Compston, W., *Contrib. Mineral. Petrol.*, 1986, **94**, 427–437.
30. Liu, D. Y., Nutman, A. P., Compston, W., Wu, J. S. and Shen, Q. H., *Geology*, 1992, **20**, 339–342.
31. Allaart, J. H., in *The Early History of the Earth* (ed. Windley, B. F.), Wiley, London, 1975, pp. 177–189.
32. Sharma, M., Basu, A. R. and Ray, S. L., *Contrib. Mineral. Petrol.*, 1994, **117**, 45–55.
33. Saha, A. K., *Mem. Geol. Soc. India*, 1994, **27**, 151–176.
34. Beckinsale, R. D., Drury, S. A. and Holt, R. W., *Nature*, 1980, **283**, 469–470.
35. Dhoundial, D. P. and Paul, D. K., *Precambrian Res.*, 1989, **36**, 289–302.
36. McDougal, J. D., Gopalan, K., Lugmeir, G. W. and Ray, A. B., Workshop on Correlation of Archaean Crusts, INSD Tech. Rep., 80–03, pp. 55–56.
37. Cloud, P., *Paleobiology,* 1976, **2**, 351–387.
38. Frakes, L. A., *Climates Throughout Geologic Time*, Elsevier Publ, New York, 1979, pp. 1–310.
39. Monastersky, R., *Nat. Geogr.*, 1998, **193**, 58–81.
40. Kasting, J. F., *Science*, 1993, **259**, 920–926.
41. Nisbet, E. G. and Sleep, N. H., *Nature*, 2001, **409**, 1083–1091.
42. Mojzsis, S. J., Arrhenius, G., McKeegan, K. D., Harrison, T. M., Nutman, A. P. and Friend, C. R. L., *Nature*, 1996, **384**, 55–59.
43. Mckenzie, D. B., *Mt. Geol.*, 1972, **9**, 269–277.
44. Walker, T. R. and Harms, J. C., *Mt. Geol.*, 1972, **9**, 279–288.
45. Zhang, G. *et al.*, *Paleogeor. Paleoclimatol. Palaeoecol.*, 1997, **138**, 221–241.
46. Buatois, L. A., Gabriela, M., Maples, C. G. and Lanier, W. P., *J. Paleontol.*, 1998, **72**, 152–180.
47. Choudhury, A. K., Unpubl. Ph D thesis, Jadavpur Univ., Kolkata, pp. 1–48.
48. Akhtar, K., *Mem. Geol. Soc. India*, 1996, **36**, 127–136.

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