Significance of clastic injectites in the syn-rift Terani Clay Member, Sivaganga Formation, Cauvery Basin, Tamil Nadu, India

Rifting between India, Antarctica and Africa during break-up of the eastern Gondwanaland, led to the generation of many basins along the Eastern Continental Margin of India, with Cauvery Basin, Tamil Nadu being the southernmost of all basins. Sivaganga Formation, directly overlying the Archean basement, represents the first episode of Cretaceous sedimentation in the Cauvery Basin. It has been noted that the sedimentation in the Early Cretaceous Sivaganga Formation commenced with the deposition of fluvial coarse clastics (conglomerates and sandstones) in the early rift stage; and as the rifting progressed, marine influence increased and the deposition of finer clastics (sandy clays and claystones) took place[1]. These syn-rift sediments are overlain by a thick, post-rift, Middle to Late Cretaceous marine mixed siliciclastic–carbonate sequence.

The present communication records, clastic injectites from the onshore Cauvery Basin, exposed along with the fluvial syn-rift sediments of the Terani Clay Member, Sivaganga Formation.

Clastic injectites are remobilized sediment intrusions formed by the injection of sediments into a pre-existing fracture from the rocks below[2]. They may occur in the form of both dykes and sills. These dykes, also known as injection clastic dykes[3], are discordant, tabular bodies of sedimentary origin. Although dominantly made up of sandstone[4], they may also be composed of limestone or calcareous mudstone. According to Levi *et al.*[3], for the formation of such intrusions, there has to be a considerable difference in the pore pressure within the particle–water mixture of the source rock and that in the propagating fracture within the overlying rocks. Because of this sustained difference in pressure, the fracture expands and water-laden sediment propagates along the fracture. Once this difference in pressure starts normalizing, the fracture stops propagating and the injection process ends[3].

In a fire clay quarry about 1.5 km ESE of Karai village (11°7′39.96″N, 78°53′17.88″E) at least four such injected clastic dykes were observed (Figure 1).

At the studied location, a 15 m section is exposed consisting of laminated claystones, followed by sandy claystones with sandstone lenses and sandstones with imbricate clasts[1] (Figure 2). The basal brown-coloured, thinly laminated claystones, commonly containing rhizoliths and devoid of bioturbation indicate overbank floodplain deposition. The overlying buff-coloured sandy claystones are interspersed with sandstone lenses. They show inclined, coarse, lag-rich, interbedded sand with imbricately aligned claystone clasts. Individual beds have sigmoid boundaries shifting laterally to form point bar accretion sets within active channels. These sandy clays contain networks of ichnogenera *Thalassinoides* and *Ophiomorpha* dominated by vertical shafts. Narrow apertural necks were also seen at the top of a few vertical *Ophiomorpha* burrows[1]. Preservation of these apertural necks is rare and indicates rapid deposition associated with little or no erosion[5]. Similarly, the presence and dominance of vertical burrows also indicates high sedimentation rates and high energy conditions, which prevent colonization and thereby development or preservation of horizontal burrows. Based on these observations, the sandy clays and sandstones are interpreted to be multistoried, vertically stacked active channel fill and associated floodplain deposits showing migration of the channel due to meandering. The lensoid sandstones in the section are interpreted as crevasse splay deposits[1]. The clastic injectites have intruded this succession.

Out of the four comparatively well-preserved clastic injectites, two are exposed from the base of the quarry to the top in the form of sub-vertical dykes with a dip of 80°. The third one emerges from below the basal beds and truncates in the overlying beds. The fourth originates as a thin root and expands upwards into a bulbous lensoid body. All the intrusions taper upwards and exhibit varying thickness with a maximum of 0.4 m.

The contact of the dykes with the host sediments, on both sides, is defined by thinly jointed margins on either wall, while the core is massive with fewer joints. The inner portion is more compact and displays horizontal joints, perpendicular to the length (Figure 3 *a*).

The dyke terminating within the sandy clays exhibits pinch and swell along its length (Figure 3 *b*). The terminal part is separated from the main body by a narrow neck and shows slight upwarping of the overlying sediments.

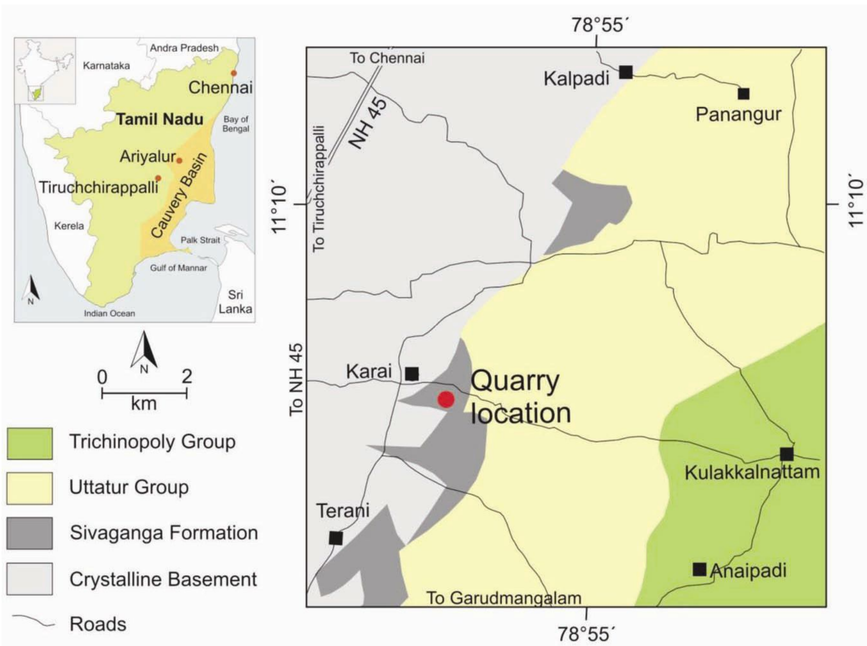

Figure 1. Location and geological map of the study area (modified after Sundaram *et al.*[10]).

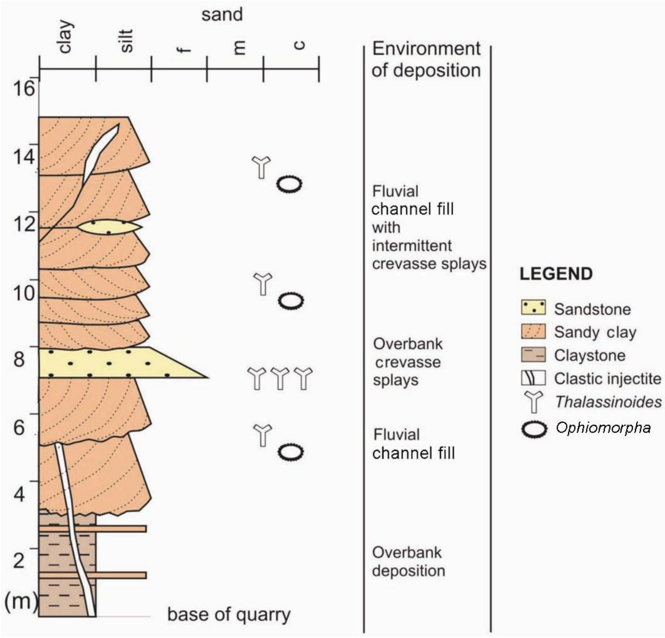

Figure 2. Composite litholog of the sections observed at fire clay quarry representing the syn-rift deposits of the Terani Clay Member.

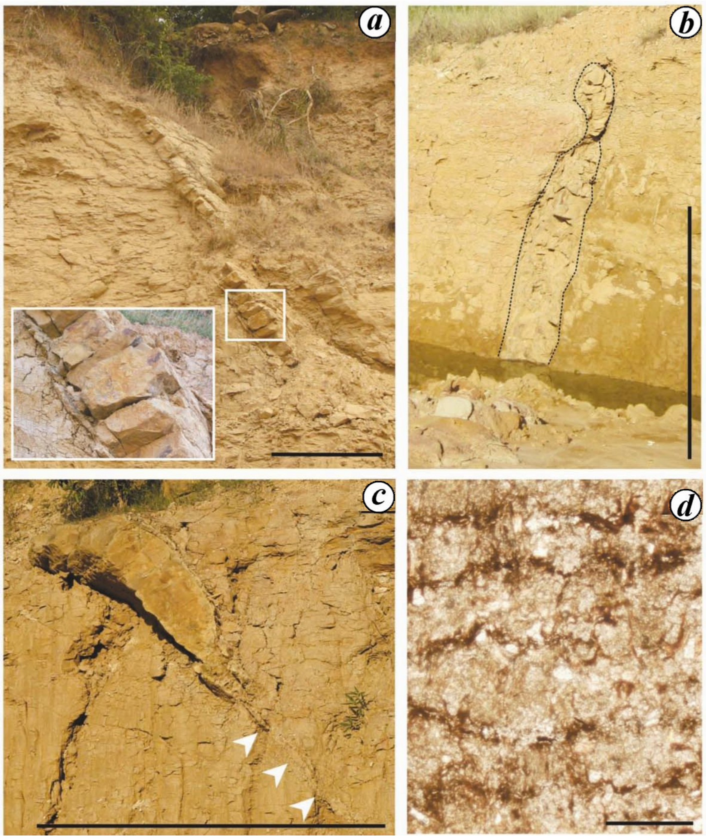

Figure 3. ***a***, Sub-vertical clastic dyke exposed from the base of the quarry to the top. (Inset) Thinly joined margins on either wall of the dyke and inner compact core with horizontal joints. ***b***, Clastic injectite terminating within the sandy clays with the terminal part separated from the main body by a narrow necktop. ***c***, Clastic injectite originating with a thin root (marked by arrows) and expanding upwards into a bulbous lensoid bodytop. ***d***, Photomicrograph of clastic dyke exhibiting the intruded material composed of sandy calcareous mudstone. Sheared surfaces are marked by dark clays, while the sand-size grains are floating in a clayey micritic matrix. (Scale bar = 1 m for (***a***–***c***) and 500 μm for (***d***).)

The fourth clastic injectite shows a bulbous upper end, while it tapers to a thin root which is discerned from the country rock by its colour and sub-vertical disposition (Figure 3 *c*). Moreover, it also exhibits a joint pattern similar to dykes described earlier.

Along parts of contact of the dyke with the host sediments, upward deflection of the bedding is seen.

Petrographically, the dykes are composed of sandy calcareous mudstone. Thin sections exhibit quartz-rich bands parallel to the propagation direction, while oblique to the banding, dark, clay-rich bands represent sheared lamination (Figure 3 *d*). There is coarsening of the grain size from the wall of the dyke to its centre. The percentage of the fine sand to silt-sized quartz grains is seen to increase towards the centre. Most of the quartz grains are angular and floating in a calcareous mudstone matrix.

The most common triggering mechanisms for the injection of sediment are seismicity and overpressure in the lower unit, caused by rapid loading of sediments[6]. In case of the injectites under study, both causes seem likely. As the beds were deposited during syn-rift times, episodic seismicity would be common, whereas the rapid loading of sediments is a consequence of high rates of sedimentation, as interpreted from the ichnofauna present in the host rocks. The high sedimentation rates led to the trapping of fluids in the lower unconsolidated beds, thus building up pore pressure. The rifting and related seismic activities must have generated fractures in the clays and acted as a trigger in creating pathways for the pressurized sediments to mobilize.

Such injectites have been known and reported since the last 200 years, but only in recent years their significance in hydrocarbon exploration and production has been realized[6]. Injectites are known to have both positive and negative effects on the reservoir and trap, i.e. their contact with the reservoir may increase its volume and establish better connectivity, or it may also rupture-off the cap rock, leading to the escape of hydrocarbons[7,8]. The Late Jurassic–Barremian syn-rift sediments in the subsurface of the Ariyalur–Pondicherry sub-basin belonging to the Lower Andimadam Formation are known to be major source rocks[9]. Thus, considering the hydrocarbon potential of these syn-rift rocks, the distribution and understanding of clastic injectites and their effects on migration and entrapment of hydrocarbons within the syn-rift plays are critical. Detailed studies of the same are presently underway.

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Proboscia alata (Brightwell) Sandström bloom in the coastal waters off Bekal, southwest India

The habitual increase in the phenomenon of harmful algal blooms (HABs) in the coastal waters and its consequences on the economy, impact on the environment and human health are particularly being noticed worldwide[1]. The seasonal reversal of monsoon, upwelling and eutrophication make the west coast of India highly productive, leaving the Malabar coast highly vulnerable to HABs[2].

Since 2006, as part of the HAB monitoring programme of the Ministry of Earth Sciences, Government of India, regular monitoring has been carried out in the coastal and estuarine waters along the Kerala coast. A bloom of *Proboscia alata* (Brightwell) Sandström was observed (Figure 1) from 10 to 12 October 2009 in the coastal sea off Bekal (12°38.02′N, 75°04.31′E) with pale brown discolouration of water. The information was provided by the local inhabitants/fishermen of the area, which has been substantiated with satellite imagery of the MODIS 'AQUA' (courtesy: INCOIS, Hyderabad). For this, MODIS AQUA level-2 ocean colour imageries (1 km × 1 km resolution) during the period 10–20 October 2009 were downloaded from OceanColor website (http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am). The images were further processed and analysed using SeaWiFS data analysis system (SeaDAS), ver. 5.4. No classification of the image was done. The exercise was just to find out the spatial extent of the high chlorophyll area in the imagery. The present correspondence discusses the dynamics of the bloom along with the probable role of bacteria associated with the event.

Proboscia is a cosmopolitan centric diatom (order: Biddulphiales) species[3–6]. Diatom–diazotrophic cyanobacterial association and its episodic, monospecific bloom formation, particularly with the diatom genus *Proboscia* is quite frequent. This association thereby contributes to high rate of carbon and nitrogen fixation in the marine ecosystem. Even though *Proboscia* is a dominant genus in highly productive areas, its occurrence as a bloom along the Indian coast is quite uncommon[7].

During the present bloom event, 50 litres of discoloured surface water was filtered through 20 μm bolting silk and transferred into 250 ml clean polyethylene bottles, preserved in 1–3% neutralized formalin and Lugol's iodine solution. For a comparative analysis, sampling was also done from two reference stations, off Thykadapuram (St. 1; 12°22.84′N, 75°10.94′E) and off Puthur (St. 2; 12°55.18′N, 74°95.18′E), one before and one after the bloom station in the same latitude. Quantitative analysis of phytoplankton was done using a Sedgwick–Rafter counting cell and identification of the microalgae was done using standard taxonomic keys[3–6,8–10].

In situ measurements of hydrographic variables like temperature, salinity and pH were done using standard instruments. Inorganic nutrients like nitrate, nitrite, silicate and phosphate, and pigments were also analysed[11] with Hitachi U-3900 spectrophotometer. Dissolved oxygen and primary productivity were measured by Winkler's method[12]. Leica DM 2000 phase contrast microscope with DFC 295 attached digital camera was used for taking photomicrographs. The environmental scanning electron microscopic (ESEM) images were taken using Carl Zeiss EVO-18. In order to understand the probable role of culturable bacteria associated in the bloom dynamics, their isolation, characterization and screening for hydrolytic enzyme production were carried out.

On 10 October 2009, a pale brown discolouration of the surface water, seemingly a monospecific bloom, which extended around 3 nautical miles along the coastal area, was observed. The cell abundance