Parallel succession of ichnologic and diagenetic events from Baisakhi Formation (Kimmeridgian), Rajasthan

The ethological responses of organisms to their substrate are governed by attributes of the sediment such as its consistency, availability of food, energy conditions at the depositional interface, depth, etc. As a corollary, the trace fossil community reflects various parameters of the environmental niche[1]. It has also been appreciated that complex ichnofabrics result from the juxtaposition of trace fossil assemblages in a progressively lithifying substrate. This phenomenon is aptly described as a 'parallel succession of diagenetic and ichnologic events'[2].

Near village Khabhiya (26°48′18″: 70°41′33″), Jaisalmer district, Rajasthan, a palimpsest ichnofabric was recently discovered in a limestone of the Baisakhi Formation, about 20.0 m above its contact with the underlying Jajiya Member of the Jaisalmer Formation (Figure 1). The rock, following Folk[3], is a packed biomicrite with equant sparry calcite in a micritic cement, suggesting neomorphism. The ichnoassemblage provides an ideal example of a palaeontological record with high potential of revealing early diagenetic history of a sediment layer. Similar cases have been reported earlier from the Cretaceous chalky sediments[2,4,5].

The Baisakhi Formation belongs to the marine Mesozoic sequence of the Jaisalmer basin[6], one of the four basins constituting the tectonic province designated as western Rajasthan shelf[7]. This sequence rests unconformably over the Lower Jurassic (Liassic) Lathi Formation and is succeeded by the Tertiary rock formations. Lithostratigraphy of the marine Jurassic rock formations of Jaisalmer basin bears a close similarity to that of Kachchh[6].

The ichnoassemblage comprises burrows including *Planolites*, *Zoophycos*, *Ophiomorpha*, *Thalassinoides* and *Rhizocorallium* and the bivalve lithic-boring *Gastrochaenolites*. It is a composite set of ichnogenera, characteristic of a hardground episode. The trace fossils constituting such an ichnoassemblage can be grouped into pre-omission, omission and post-omission suites[2,8] depending upon the respective time slots during which they were emplaced. The limestone bed under consideration exhibits the first two, viz. the pre-omission and omission suites. The omission suite consists of two phases: (i) burrows emplaced prior to lithification and (ii) borings drilled after lithification. They are conveniently termed pre-lithification subsuite and post-lithification subsuite[2].

The bioturbation that took place during the soupground stage was not visible on the bedding plane in the outcrop. A limestone slab, cut along a vertical plane in the laboratory, on polishing and staining with Safranin-red revealed the traces of this initial stage (Figure 2 *a*). The ichnoassemblage of the soupground stage consists of *Thalassinoides* and *Planolites* and is characterized by ill-defined burrow outlines and mottling produced (shown by arrows in Figure 2 *a*) due to churning of the sediment by causative organisms.

The softground ichnofauna dominantly consists of *Zoophycos* (Figure 2 *b* and *c*) and *Planolites* with well-defined outline. Occurrence of *Thalassinoides* and *Ophiomorpha* (Figure 2 *e*) is subordinate. *Zoophycos* characterizes burrowing at depths in a softground under dysaerobic and nutrient-deficient conditions[9]. Association of well-formed *Thalassinoides* and *Ophiomorpha* with *Zoophycos* and *Planolites*, a ubiquitous form, speaks for a substrate with softground consistency. This pre-omission suite stands testimony to the change in substrate from soupground to firmground through softground.

During the firmground stage, *Thalassinoides* and *Rhizocorallium* were emplaced. Well-defined burrow form, perfect development of spreite of *Rhizocorallium*, as also the typical branching and network of *Thalassinoides* (Figure 2 *d*) are indications of their emplacement in a firmground, when sedimentation had ceased and the sediment has become firm. The conspicuous nature of burrows evinces that they represent pre-lithification subsuite of the omission suite[8]. Irregular network of the *Thalassinoides* system (Figure 2 *f*) with vertical components being better preserved, distinctly visible on outcrop, is proof of further progress in lithification[2]. This assemblage represents the pre-lithification subsuite.

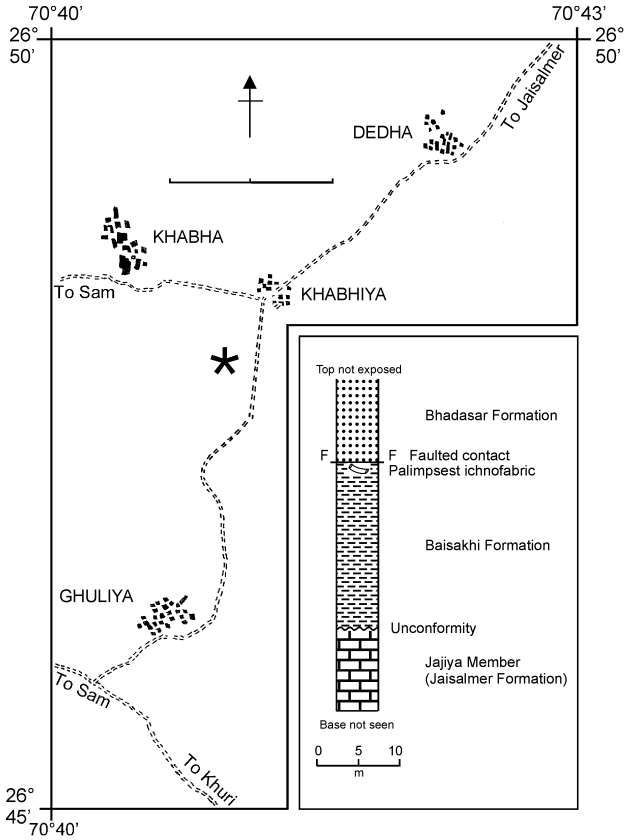

Figure 1. Locality map. Fossiliferous horizon marked by asterisk. (Inset) Lithosection.

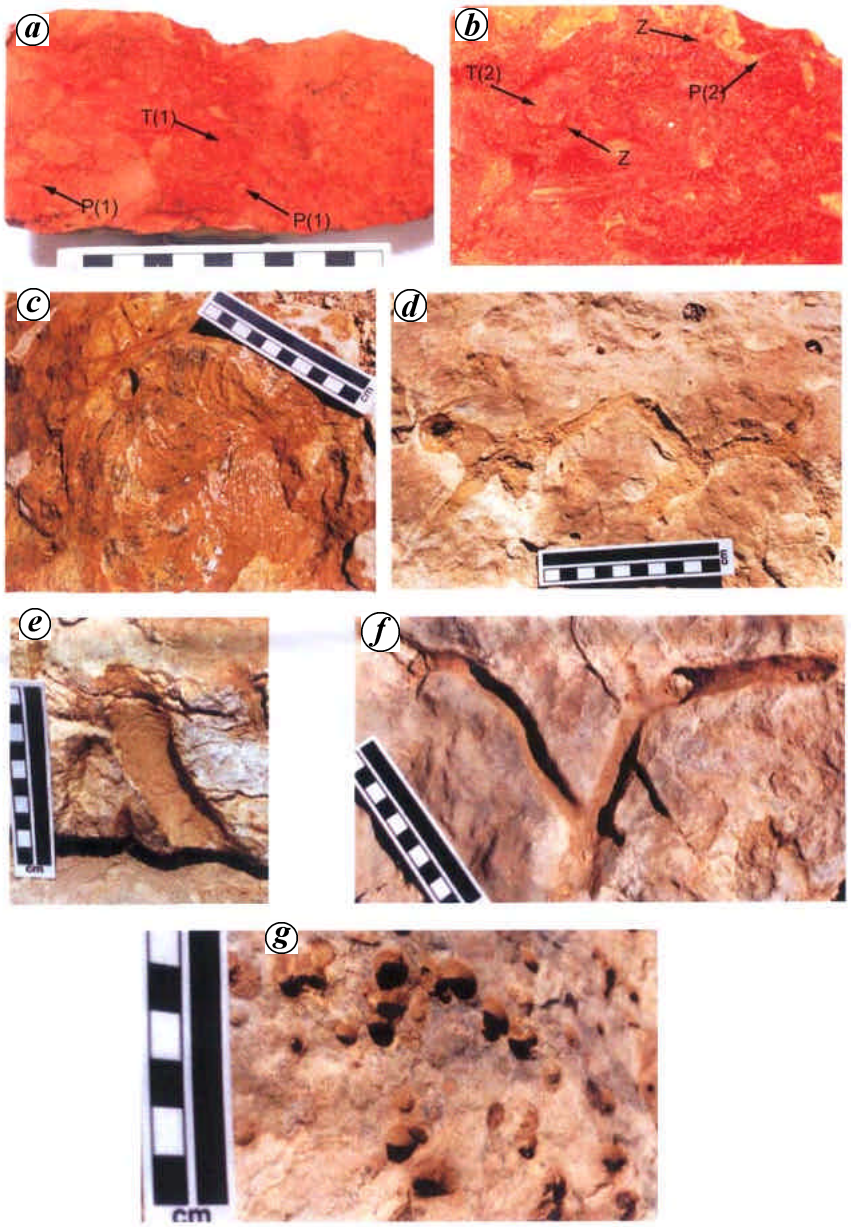

Figure 2. ***a***, Polished and stained vertical section of limestone slab. Note mottling produced due to bioturbation during the soupground stage. Arrows indicate *Thalassinoides* T(1) and *Planolites* P(1). ***b***, Close-up of a portion of (***a***) crescentic lamellae of *Zoophycos* (Z). Also seen are softground *Thalassinoides* (T_2) and *Planolites* (P_2). ***c***, Bedding plane expression of *Zoophycos* (lobe). Note boring in top left quadrant. ***d***, *Thalassinoides* network penetrated by boring (left half of picture). ***e***, Vertical component of *Ophiomorpha* showing pitted appearance. ***f***, Irregular branching in *Thalassinoides* reflecting firmground consistency of the substrate. ***g***, Bivalve rock-boring *Gastrochaenolites*; evidence for hardground conditions.

The final stage of ichnoactivity witnessed by this limestone bed is represented by the bivalve-boring *Gastrochaenolites* (Figure 2 *g*). The borings are short, club-shaped and penetrate all traces of earlier suites. This constitutes the post-lithification subsuite. The dense population of *Gastrochaenolites* records a period of non-deposition, formation of hardground and exposure of this surface to marine waters. This ichnogenus is known to characterize shallow-water hardgrounds[10]. This limestone bed is capped by a thin veneer of iron mineralization, about 25 mm thick. Iron oxides usually are results of late diagenetic phenomenon[2].

Ichnofabric trends reflect changes in ecological and taphonomic parameters (e.g. substrate stability and consistency), many of which are governed by variations in sedimentation rate[11]. The sequence of ichnologic events is recorded in the composite ichnofabric[12]. From the sequence of biologic events that occurred in the sediment at Khabhiya, one can infer the tiered nature of the infaunal communities that inhabited the sediment (Figure 3). With

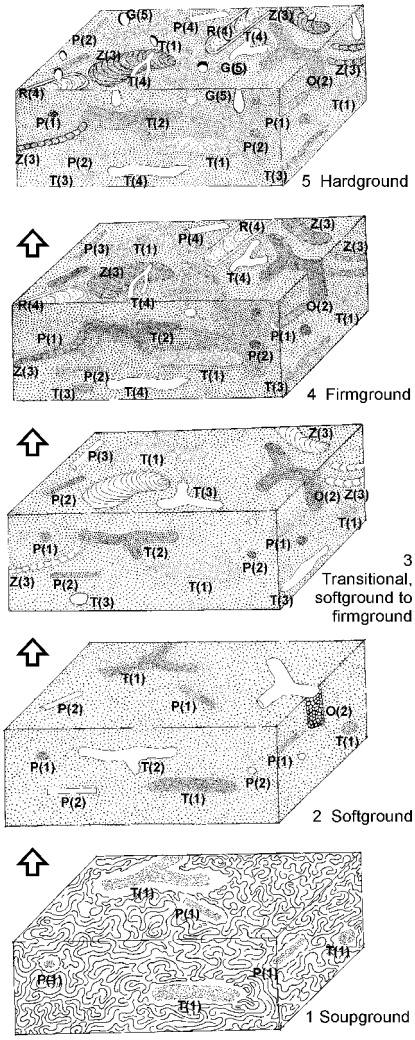

Figure 3. Tiered nature of infaunal communities controlled by texture and consistency of substrate. G, *Gastrochaenolites*; O, *Ophiomorpha*; P, *Planolites*; R, *Rhizocorallium*; T, *Thalassinoides*; Z, *Zoophycos.* Numbers within parentheses indicate tiers.

burial, compaction alters the texture and consistency of the substrate, making it firm. Minor breaks in a sedimentary sequence correspond to changes in depositional environment, which are, many a time better registered in the ichnological record than by any other sedimentary feature. A hardground is a type of discontinuity surface connoting a minor depositional hiatus, usually typified by a palimpsest ichnofabric.

The ichnofabric observed in the carbonate horizon of the Baisakhi Formation at Khabhiya is represented by four distinct tiers, each assignable to Seilacherian ichnofacies (Table 1). The shallowest tier is recognized by compressed, smeared *Planolites* with poorly defined burrow outline and is assigned to *Cruziana* ichnofacies. It constitutes the background fabric, over which the deeper tiers are imprinted. Slightly compressed *Thalassinoides*, *Ophiomorpha* and well-defined *Planolites* constitute the second tier and are also assigned to the *Cruziana* ichnofacies. *Zoophycos* and *Planolites*, which constitute the third tier are assigned to the *Zoophycos* ichnofacies. Well-defined *Thalassinoides* with prominent vertical components and *Rhizocorallium* which symbolize the last tier also point to firm substrate and represent the *Glossifungites* ichnofacies. The hardground *Trypanites* ichnofacies is characterized by *Gastrochaenolites*.

Such an ichnofabric, thus, is an indicator of both progression of lithification (change in substrate consistency) as well as increase in the depth of bioturbation. As stated earlier, hardgrounds symbolize breaks in sedimentation, marking minor discontinuity surfaces.

Table 1. Traces emplaced, ichnofacies and substrate consistency

Stage	Traces emplaced	Facies	Substrate consistency
5	*Gastrochaenolites*	*Trypanites*	Hardground
4	*Thalassinoides* *Rhizocorallium*	*Glossifungites*	Firmground
3	*Planolites* *Thalassinoides*	*Zoophycos*	Transitional from softground to firmground
2	*Thalassinoides* *Ophiomorpha* *Planolites*	*Cruziana*	Softground
1	*Thalassinoides* *Planolites*	*Cruziana*	Soupground

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