

***Thalassinoides* and *Ophiomorpha* as cross-facies trace fossils of crustaceans from shallow-to-deep-water environments: Mesozoic and Tertiary examples from Italy and Spain**

The morphological expression of trace fossils varies according to whether they are preserved, within/between sandstone or mudstone beds. For this reason a toponomy has been proposed and a series of terms, the so-called Seilacher's and Martinsson's terms, has arisen to describe the preservation potential of trace fossils. They are: hyporelief or hypichnia (base of bed at boundary), full relief or endichnia (inside bed), full relief or exichnia (outside bed) and epirelief or epichnia (top boundary) (Seilacher, 1964; Martinsson, 1970). Both of these classifications involve structures which are strictly related to the casting medium of an event bed or transition with underlying or overlying beds (Bromley, 1990). Typical expression of hyporelief are graphoglyptids (Fuchs, 1895), a large supergroup of geometrical trace fossils usually preserved at soles of deep-water turbidite deposits of basin plains, which includes a very high diversity of ichnogenera and species (Seilacher, 1977).

Thalassinoides-type branched fossil burrow systems in the geological record, known mainly as *Thalassinoides* and *Ophiomorpha* (chiefly but not exclusively produced by decapod crustaceans), usually are preserved in beds as hypichnia, endichnia and exichnia but their preservation potential and toponomy strictly depend upon the environment and type of event sedimentation. Moreover, the large distribution of these ichnogenera differ from graphoglyptids which are strictly confined to deep water conditions and affecting inter-turbidite muddy deposits (Monaco, in press). *Thalassinoides* and *Ophiomorpha*, therefore, are typical cross-facies trace fossils (Frey *et al.*, 1978), which usually spread in every environments during the Phanerozoic and occur from shallow facies (beach, near-shore and shelf), mainly in the Paleozoic and Mesozoic, to very deep environments (slope to distal basin plains) in the Tertiary (Książkiewicz, 1970; Frey *et al.*, 1978; Palmer, 1978; Archer & Maples, 1984; Sheehan & Schiefelbein, 1984; Bromley, 1990; Fürsich, 1998; Uchman, 1998; Monaco, 2000b; Monaco & Garassino, 2001; Tchoumatchenco & Uchman, 2001; Giannetti & Monaco, 2004). The ichnogenus *Thalassinoides* Ehrenberg (1844) is applied to smooth-walled, essentially cylindrical Y- to T-shaped branched trace fossils. In the Early Jurassic time *Thalassinoides suevicus* (Rieth 1932) characterizes shallow-marine environments as three-dimensional systems of branched, Y-shaped tunnels of variable diameter enlarged at the bifurcation points (Fürsich & Oschmann, 1993; Giannetti & Monaco, 2004). This form is predominantly horizontal, more-or-less regularly branched, essentially cylindrical, and dichotomous bifurcations are

more common than T-shaped branches (Howard & Frey, 1984). The origin and palaeoenvironmental significance of *Thalassinoides* has been recently summarised (Howard & Frey, 1984; Ekdale, 1992). Instead, the ichnogenus *Ophiomorpha* Lundgren (1891) commonly occurs as vertical to horizontal or sub-horizontal cylindrical tunnel systems, seldom branched and covered by elongate or irregular pellets arranged perpendicular to the long axis. Branching points are usually preserved in both ichnotaxa but these features are more typical of some ichnospecies (e.g. *T. suevicus*) and reveal sharp angles, locally with characteristic enlargements (Monaco & Giannetti, 2002; Giannetti & Monaco, 2004). Some horizontal segments of *Ophiomorpha*, lacking knobby appearance, resemble typical *Thalassinoides*, but vertical portions are generally lined (Frey *et al.*, 1978; Uchman, 1995; Monaco, 2000). These trace fossils have been generally attributed to the activity of crustaceans, but not only decapods (Frey *et al.*, 1978; Monaco & Garassino, 2001), and their toponomic preservation is here investigated in four cases of event sedimentation from Mesozoic and Cenozoic deposits.

The four case-studied are the follow: A) Lower Jurassic (Pliensbachian) lagoonal limestones and marly beds of the northeastern Prealps (Calcarei Grigi); B) Lower Cretaceous inner shelf with unidirectional tractive contour currents, from eastern Spain (Serra Gelada); C) Lower Jurassic outer shelf to basinal nodular deposits with storm/turbidite calcarenites, central Italy (Rosso Ammonitico); D) Miocene slope to basin plain systems with deep water turbidite deposits, northern Apennines (Macigno and Marnoso Arenacea flysch deposits).

A) In lagoonal nodular limestones of the Early Jurassic (Pliensbachian) in northeastern Prealps (Calcarei Grigi formation), trace fossils of crustaceans (*Thalassinoides* and *Ophiomorpha*) are very abundant. They are found in limestones forming hexagonal mazes distributed horizontally, and they are particularly well developed at the base of the recorded parasequences: endichnia and hypichnia. In the well-exposed endichnia and hypichnia the maze is regular in shape, branching points exhibit enlargements and the diameter of tunnels decreases progressively from the branched points (diameter varies from 16 to 4 cm). Meshes are horizontal, forming irregular cells up to 30 cm wide, and locally tunnels are randomly distributed in the marls and at the limestone/marl transition at the base of the parasequences. In this case, bioturbation can reach down the marly levels producing nodules suggesting that the trace maker was active to maximize the capture of organic material when the substratum has a low nutri-

tional value (see Giannetti *et al.*, 2007). When tunnels are in the clay or marly levels they are particularly flattened (rare case). Crustacean trace fossils develop at the base of parasequences during rising sea level, indicating that oxygenated and nutrient-rich open marine conditions were induced progressively and are well exploited by crustaceans. In these open marine conditions the high rate of sedimentation, oxygenation, and nutrients are ideal conditions for crustacean burrowing. This new opportunistic fauna populates the lagoon, replacing the oligotrophic fauna (only infaunal bivalves) of restricted and poorly oxygenated conditions typical of the low sea level stand. The arrangement of skeletal grains and peloids in wall structures of thalassinoids commonly reflects an ichnofabrics of decapod crustacean activity (Giannetti & Monaco, 2004). Structure of the burrow linings and lithified calcareous walls (see type IV) display concentric layering due to crustacean and biogenic stria (see type III and type B of authors), probably related to activity of decapods (Frey *et al.*, 1978; Hasiotis & Mitchell, 1993; Anderson & Droser, 1998; Monaco & Garassino, 2001). In some cases the shape of some non-branched burrows (*Thalassinoides* ? *isp.*) resembles those of modern stomatopods (Monaco & Giannetti, 2002).

B) In the Lower Cretaceous (Albian) of the Sácaras Formation in the Serra Gelada succession (Prebetic of Alicante, Spain) carbonate-rich, upward thickening inner shelf parasequences were deposited. They are dominated by deposits and features indicating strong currents (maybe contour currents), and many types of trace fossils have been identified (Monaco *et al.*, 2005). Shell-covered, structured trace fossils (*Ereipichnus geladensis*) and unstructured, non-imbricated ones such as *Scolicia* and *Cardioichnus* (produced probably by irregular or heart-shaped spatangoid sea-urchins) and various types of *Thalassinoides* and *Ophiomorpha* have been recorded (Monaco *et al.*, 2005). In this section *Thalassinoides* consists of branched, Y-shaped hypichnia or endichnia, similar to those recovered in Calcari Grigi (mainly type II, III, and IV giant type up to 30 cm in diameter, and type D similar to *Thalassinoides* ? *isp.*, see Giannetti *et al.*, 2007). In some levels a close relationship exists between shell-armoured *Ereipichnus* and large *Thalassinoides* types. Horizontal mazes of this branched endichnia are always distributed deeper (often reaching the hypichnia position) than *Ereipichnus* which tend to occupy shallower tiers to better utilize strong unidirectional currents at the seabottom (Monaco *et al.*, 2005). *Thalassinoides*, therefore, develops in deeper tiers when currents at sea-floor are active, and these traces were produced by crustaceans mainly when high sea level conditions occurred (as in the case A). The vertical or oblique *Ophiomorpha*, conversely, develop as endichnia (more properly crossichnia, a new category here introduced to describe trace fossils which cross obliquely two or three beds) exclusively in calcarenites during the lowstand intervals at the top of parasequences. The Serra Gelada section, therefore, is important from the ichnological point of view because a very close relationship exists among current sensitive trace fossils, active bottom currents and sea-level variations in a shallow water environment.

C) The Toarcian Rosso Ammonitico facies in the central Apennines (Italy), was deposited in a relatively shallow (100-150m deep) middle-outer shelf to inner basin,

periodically submitted to seaward-oriented tempestites/turbidites (with hummocky cross-stratification). This facies is very rich in small and medium size *Thalassinoides* of types I and II (Monaco *et al.*, 1994; Caracuel *et al.*, 2000). The medium-size Type II has been found as hypichnia at the soles of distal tempestite/turbidite events and develops when calcarenitic material eroded and then deposited on the autochthonous mud (casting). The small Type I, conversely, is more commonly found as endichnia (but also epichnia) mainly close the top of a calcarenite beds (calclutite) and was subjected to tiering, which represents a vertical partitioning of burrow distribution within the calcarenitic sediment (Caracuel *et al.*, 2000). The shallowest, more oxygenated tier of a typical Rosso Ammonitico tempestite bed, the nodular calclutite interval, is dominated by small *Thalassinoides* type I, while other minute trace fossils (e.g. *Planolites*, *Helminthopsis* and *Chondrites*) are distributed at depth in the less oxygenated calcarenite material (Caracuel *et al.*, 2000). A colonisation depth of tiers therefore reflects the new substrate characteristics induced by the event sedimentation. Tiering from reduced (base of bed) to more oxygenated conditions (top of bed) was controlled by the substrate characteristics and by the organic content. The organic matter may be superficially exploited by small crustaceans (one ammonite mould exhibits *Thalassinoides* type I burrow, F. Venturi pers. com.) only when sedimentation rate of unidirectional/oscillatory flow regime decreases to normal conditions. When normal condition re-established (e.g. re-oxygenation) in non-redeposited marls of Rosso Ammonitico facies, then small *Thalassinoides* type I are leaders among other trace fossils and burrowing of shallower tiers (endichnia/epichnia) was very abundant inducing nodularity in the substrate and producing a "gradational" tiering in marls (Caracuel *et al.*, 2000).

D) In Oligo-Miocene siliciclastic deep-water turbidite units of the northern Apennines (central Italy), known as Macigno, Cervarola and Marnoso Arenacea flysch deposits, trace fossils are very abundant and are represented by hypichnia, endichnia, exichnia, epichnia, and crossichnia (if they cross obliquely two or three beds). In thin-bedded, low-density turbidites graphoglyptids (*Paleodictyon* and many others, see Monaco, in press) are exclusively hypichnia, while epichnia groups are formed by totally different traces (e.g. *Scolicia prisca*). Conversely, in medium to thick-bedded ones (mainly high-density turbidity flow deposits) *Thalassinoides* and *Ophiomorpha* occur as hypichnia, endichnia exichnia (never epichnia), and crossichnia when they cross obliquely the massive sand reaching the underlying marly beds. As indicated by Uchman (1998), the *Ophiomorpha* found in flysch deposits differ from those recovered from shallow water deposits because they commonly occur as small hypichnial specimens which are smooth and straight at the bottom of turbidites (e.g. *O. annulata* and *O. rectus*, see Książkiewicz (1977). Large *Ophiomorpha rudis* (Tunis & Uchman, 2003), is most common in the medium to thick bedded turbidites of Marnoso Arenacea flysch. This very large trace (up to 12 cm in diameter) appears as subhorizontal hypichnia-endichnia in the lower half of the turbidite beds and is characterized by irregular thick ridges, up to 3-4 cm thick, commonly developed as large knobby bulges, with irregular thickening of tunnel diameter. Locally, branches are

very short and represent dead ends. Other forms of high-density turbidites are unbranched and straight, exhibiting a regular thickening of the burrow diameters (twice normal diameter) and producing a typical shape like a car silencer (car silencer-shaped trace fossils). These forms are distributed very commonly (30 specimens preserved at the BIOSEDLAB of Perugia University) as endichnia close to the bottom of meter-thick, sandy turbidites, where they cut giant groove casts at angles up to 60-90°, suggesting adaptative burrowing strategies to high energy and tractive current flows. Other *Ophiomorpha*-like trace fossils are preserved as vertical or oblique, cylindrical, knobby structures, cutting many calcarenite and calcisiltite beds (crossichnia). They are unwallled, sand- or silt-filled, 18-33 mm in diameter reaching up 30 cm in length, and some exichnia/crossichnia specimens show typical ring-shaped, transverse segments (Uchman & Demircan, 1999). Others crossichnia are subquadrate in cross section, revealing regular knobby surfaces, up to 55 mm in diameter and 50 cm in length. These structures were probably not produced by crustaceans. According to (Föllmi &

Grimm, 1990), the crustaceans producing *Thalassinoides* and *Ophiomorpha* in deep turbiditic environments may survive transport by turbiditic currents and can produce burrows under anoxic conditions for a limited numbers of days.

The four examples here reported are indicative of cross-facies thalassinoidian trace fossils which are produced by opportunistic organisms. A close relationship probably exists among infaunal activity of crustaceans, event sedimentation, rising of sea level, increasing in the oxygen content and characteristics of the substrate from shallow to deep water conditions where high-density flow or peculiar sedimentary processes occur. Further quantitative analyses are welcome in order to try to define all relationships between these traces and different cases of event sedimentation. The fundamental aim is not only to characterize the toponomy of these important traces, but also to define the palaeoenvironmental features, morphologic expressions (Giannetti *et al.*, 2007) and distribution of crustacean activity in marine substrates.

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