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TAPHONOMIC ASPECTS OF THE MIOCENE ICHNOFOSSIL-LAGERSTÄTTE FROM CALCARENITE TURBIDITIC BEDS IN THE VERGHERETO MARLS FORMATION (NORTHERN APENNINES, ITALY)

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Abstract. Five, 3-8 cm-thick calcarenitic turbiditic beds belonging to overbank deposits in the marginal sector of Marnoso-arenacea Basin, close to the intrabasinal high of Verghereto (Romagna, Northern Apennines, Upper Miocene), exhibit a well preserved ichnofossil-*lagerstätte*.

The *lagerstätte* is composed by 43 ichnotaxa: 31 of them are preserved as casts at the sole of turbidites (background hypichnia) (group a), while 12 of them occur at the top (post-turbidite epichnia) and within (endichnia) (group b). The ichnodensity reaches its maximum at the top of the turbiditic beds. Background hypichnia (group a) is represented by graphoglyptids and non-graphoglyptid resting traces (background ichnofauna), with three-dimensional networks and shafts, meander systems, radiate, plug-shaped or stellatae structures forming clusters and unbranched systems of strings. Many taphonomic features suggest a fluting induced by bottom currents; graphoglyptids should have colonised the substrate after the action of these currents being not destroyed or fluted. All hypichnial structures are perfectly preserved by the turbidite casting and in this phase also endichnial burrows could develop. Post-turbidite epichnia (group b) concern vagile feeding burrows that developed horizontal patterns in a post-turbiditic regime, during the suspension phase of fine material; they were probably produced by organisms transported by suspension flows. Here, the very high ichnodensity suggests a competition among burrowers under stable currents with occurrence of vagile opportunistic organisms immediately followed by others that produced radiate spreite structures.

Riassunto. In questo lavoro viene presentato un sito di notevole interesse icnologico (*lagerstätte*) sviluppato su alcuni sottili livelli calcarenitici di origine torbiditica (5 strati spessi 3-8 cm), affioranti nel settore marginale del bacino della Marnoso-Arenacea romagnola in corrispondenza dell'alto strutturale di Verghereto (Formazione delle Marne di Verghereto, Appennino Romagnolo, Miocene superiore). La ricchezza, la diversità e il grado di preservazione delle tracce fossili presenti permette di considerare tali livelli un vero e proprio *lagerstätte*-icnologico in corrispondenza del quale sono stati rinvenuti 43 ichnotaxa, di cui 31 ichnotaxa preservati come riempimenti alla base delle torbiditi

sottili (hypichnia) (gruppo a) e 12 preservati al tetto (epichnia) e internamente (endichnia) (gruppo b). Il primo gruppo (a) è rappresentato da tracce geometriche a sviluppo tridimensionale in genere meandranti (grafogliptidi) e da altre tracce (non-grafogliptidi) che formano gruppi organizzati o isolati di cavità circolari di stazionamento, con pozzi verticali e strutture stellate o radiali. I caratteri dell'orictocenosi indicano processi di fluitazione con deformazione parziale (o completa) di alcune delle cavità per opera di correnti profonde prima del ricoprimento del sedimento sabbioso di origine torbiditica. Il deposito torbiditico veniva rielaborato precocemente già in condizioni sinsedimentarie da organismi trasportati dalla corrente stessa (endichnia). Il secondo gruppo (b) riguarda burrows creati al tetto del deposito di torbida nel materiale fine trasportato dalla corrente durante la fase di decantazione. L'ichnodensità è notevolmente più elevata al tetto rispetto alla base, nonostante l'ichnodiversità risulti essere minore. Queste tracce furono lasciate da organismi vagili ed opportunisti che si alimentavano spostandosi orizzontalmente nel sedimento formando meandri nel sedimento fangoso e variando la propria traccia in funzione delle condizioni ambientali. In seguito, quando le condizioni del fondo marino segnavano una ripresa lenta delle condizioni di sedimentazione normale, altri organismi più specializzati creavano altre strutture complesse (spreite) per lo più radiate che si sovrapponevano alle tracce meandranti precedentemente deposte.

Introduction

Fossil-*lagerstätten*, deposits that contain extraordinary amounts of palaeontological information (Seilacher et al. 1985; Allison 1988), have some counterparts also in the trace fossil realm. Ichnofossil or trace fossil-*lagerstätten* are deposits that contain more palaeobiological and palaeoenvironmental information than normal and exhibit unusually high ichnologic fidelity, very good trace fossil preservation and/or variability (Savrda & Ozalas 1993; Mángano & Buatois 1995; Fornós et al. 2002; Savrda 2007). Ichnologic-*lagerstätten* may pro-

vide very abundant taphonomic data for the exceptional preservation of biogenic activity (e.g. tracks, trails, shallow endogenic and other burrows) and usually biogenic activities are highly concentrated in short time and small space (Monaco et al. 2005; Savrda 2007; Monaco 2008). Two basic categories have been recognized: conservation and concentration *lagerstätten* (Savrda 2007). Conservation *lagerstätten* are those wherein the preservation depends on some processes (e.g. burial, diminished oxygenation, early diagenetic mineralization, bacterial activity) that produce some typical deposits (obruption, stagnation and conservation deposits, respectively). Concentration *lagerstätten* are those wherein trace fossils are unusually abundant reflecting concentration (or condensation) induced by sedimentary or biological processes. According to Savrda (2007) suites of taphonomic factors that influences body fossils and ichnofossil are clearly not identical but slightly different; nonetheless, ichnofossil-*lagerstätten* can be placed in the same genetic categories.

In the turbidite deposits ichnofossil-*lagerstätten* are poorly known, mainly because the very high sedimentation rate of turbidites and sedimentologic conditions of basins generally preclude concentration of trace fossils and ichnofabrics that may occur as *lagerstätten* are rare, although a rapid burial may represents a favourable condition to preserve ichnologic concentrations (Seilacher et al. 1985; Seilacher 2007).

In five fining-upward calcarenitic, middle-late Miocene in age, turbidites (3-8 cm thick) of Romagna Apennines (Ville di Montecoronaro, Verghereto area), an unusual concentration of well preserved trace fossils (ichnofossil-*lagerstätte*) has been recovered. These cm-thick turbidites represent distal fringe (overbank?) sediments deposited in the Marnoso-arenacea Basin at the transition to the Verghereto High (Milighetti et al. 2009; Monaco et al. 2009a). This work is directed to describe the ichnocoenosis that can be subdivided in three sub-ichnocoenoses at the base (hypichnia), within (endichnia) and top (epichnia) of each bed respectively, pointing out ichnodensity and ichnodiversity variability and focusing some taphonomic aspects that allow to define the palaeobiological and palaeoenvironmental setting.

Geological setting and investigated locality

The ichnologic-*lagerstätte* of Poggio Alto corresponds to five calcarenitic beds of a marl unit (Verghereto Marls Fm in the Marnoso-arenacea Basin) that, in the type section of the Verghereto area, are more than 450 m thick (Merla & Bortolotti 1969). This marly unit was deposited during the middle-late Miocene (post-Burdigalian?) after a progressive tectonic uplift that produced intrabasinal highs in the Marnoso-arenacea

Basin. A very complicated topography of sea-floor with highs bounded by narrow, elongated basins and thrusts developed from the Romagna to the Tuscan-Umbria-Marche sectors of Northern Apennines. It may be considered the product of migrating foredeep-thrust belt systems in front of the advancing Apennine accretionary wedge that produced a complex depositional setting with wedge-top, piggyback and foredeep basins (Merla 1952; Ricci Lucchi 1978, 1981, 1986; Boccaletti et al. 1990; Delle Rose et al. 1990; Centamore et al. 2002; Lucente 2004; Conti et al. 2008). In some sectors (e.g. south part of Perugia, Umbria) the intense tectonic activity (uplift) and sea-level fall, promoted accumulation of a prograding fan-delta slope and wedge-top systems replacing the sand-rich lobes that are more typical of northernmost Romagna sector (Conti et al. 2008; Milighetti et al. 2009). The basin configuration and evolution of the foredeep system was strongly controlled by tectonic activity that represents the primary factor producing topographic irregularities in the basin plain setting, in the form of confined troughs separated by intrabasinal structural highs (Lucente 2004). In some north-western sectors of the Marnoso-arenacea Basin (e.g. Mugello area), thrust faults of intrabasinal tectonics promoted the entrapment of gas hydrates derived from methanogenic and thermogenic sources that enclose in pelitic intervals chemoherms with autobrecciated structures (Conti 2001).

The Marnoso-arenacea Basin developed as a narrow basin, approximately over 200 km long, aligned northwest-southeast from Romagna to Umbria-Marchean sectors, separated by the Marecchia allochthonous deposits (Marecchia line) and bounded to the southwest by the Apennine thrust front of Falterona units and Tuscan nappe (Delle Rose et al. 1990; Van Wamel & Zwart 1990; Lucente 2004). A large part of the Marnoso-arenacea is buried beneath overthrust older and inner foredeep deposits to the southwest, the Ligurian Nappe to the northwest, and Messinian to Quaternary deposits to the north and the east. The Marnoso-arenacea Formation is a wedge-shaped body about 3000 m thick of deep-water turbidites that were accumulated from the late Burdigalian (but mainly during the Serravallian age) and represents the last filling stage of the late Oligocene to late Miocene foredeep system (Centamore et al. 2002). The overall stacking pattern of the Marnoso-arenacea records the transition from an older "inner stage" located at southwest to a younger "outer" one disposed at north-east. This shifting corresponds to a basin depocenter shifting through time toward the NE produced by tectonic phases that produced also clay deposits in intrabasinal highs ("clay plugs", such as Marne di Vicchio, Marne di Verghereto; Centamore et al. 2002). The change from inner to outer occurred probably around the Serravallian/Tortonian boundary and was

marked by an increase in the sand/mud ratio and in a decrease in clastic carbonate input (Ricci Lucchi 1981, 1986). The “inner stage” represents a phase of maximum subsidence and wide lateral extent of the basin, with widespread development of mud-rich, basin plain turbidites deposited by high-efficiency, low density flows.

In some marginal sectors (e.g. at the transition of the intrabasinal high of Verghereto) the basin plain turbidites reduce their thickness, progressively becoming very few and thin (but are rhythmically arranged) in distal or marginal parts of basin producing overbank, levee and thin fringe systems of detached lobes very rich in trace fossils (Monaco et al. 2009a). Trace fossils exhibit the maximum of ichnodensity and ichnodiversity such as in the ichnofossil-lagerstätte of Ville di Montecoronaro (Poggio Alto section). Here calcarenites are very thin, no more than 15 cm thick (usually 4 to 8 cm), and consist of rhythmical sharp-based beds, fining-upward disposed and brown to yellowish in colour. Calcarenites alternate with gray hemipelagic mud that in this area is very thick (up to 400 m thick at north of M. Fumaiolo). The basal grain size of calcarenites remains in the range of medium sand while the top is a silt or mud; rippled structures are frequent and disposed internally or at the mud top. Small-scale hummocky cross stratification that may be found in deep water

turbidites has also been recovered (Prave & Duke 1990). Facies analysis indicates a Facies F9b, that are a variation of F9a facies in the model of Mutti (1992), thought to represent an immature expression of deposition from low-density turbidity currents of small-volume flows, in marginal environments (see discussion in Monaco et al. 2009a). The material studied was collected in the Verghereto high (off the E45 road), approximately 800 m from the turning point from Ville di Montecoronaro to Balze-M. Fumaiolo. The outcrop is located at the foot of hills that occur about 1 km at south of Montecoronaro (Poggio Alto, height of 850 m a.s.l.; coordinates in Fig. 1).

Ichnocoenosis of *lagerstätte*

Ichnocoenoses represent very helpful tools to characterize flysch basins (Leszczyński 1993). In the Apennine flysch systems (Oligocene to Miocene) five ichnocoenoses have been distinguished (Monaco et al. 2009a). Their subdivision follows the change of sub-environments and facies from thicker and coarser to thinner and finer, that aspect characterized the Tuscan-Romagna-Umbria foredeep system during the Oligo-Miocene (Uchman 1995a; Monaco et al. 2009a; Milighetti et al. 2009). The stratigraphic position and preser-

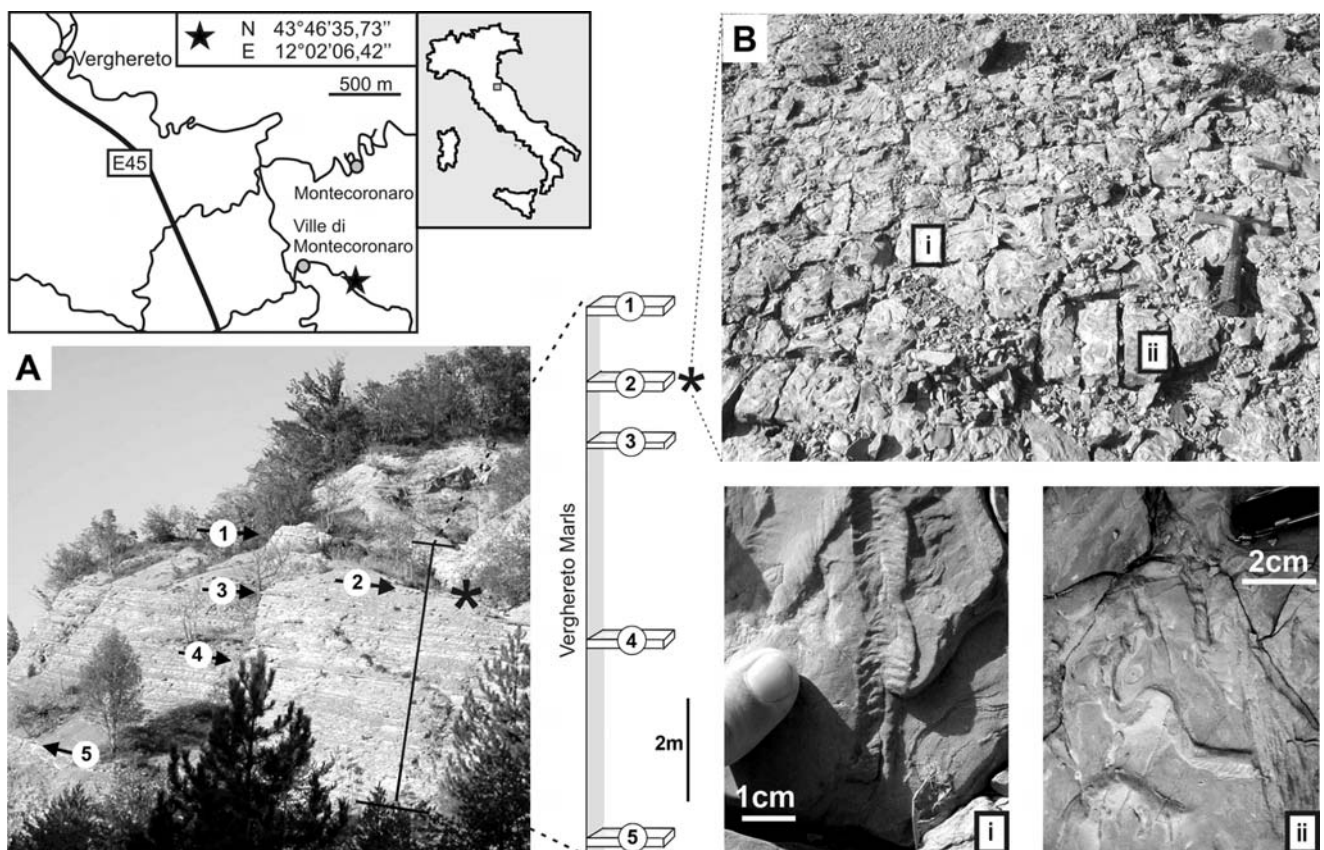


Fig. 1 - Location of the ichnofossil-lagerstätte (Ville di Montecoronaro, Verghereto), with marl and five calcarenitic beds (A) and the top surface (B) with epichnia examples (i and ii).

vation in the sand bed medium of surface or subsurface traces (Seilacher 1964; Martinsson 1970), that depends on different burial conditions in turbidite regimes (Savvada 2007), are fundamental in the study of ichnocoenoses of turbidites. Communities that develop as hypichnia (preserved at the base as casting of surface or shallow structures, Pl. 1) and those that appears at the top (epichnia; Pl. 2) usually are extremely different (Seilacher 2007; Monaco & Checconi 2008; Monaco et al. 2009a). Those that are present inside or outside beds, or vertically cross different lithologies (named endichnia/exichnia, crossichnia, *sensu* Monaco & Caracuel 2007; Monaco et al. 2007, or multilayer colonizers of Uchman 1995b), are on the contrary much less differentiated; they can show high density in some deposits such as channelized lobes (Uchman 2009). This is the case of *Ophiomorpha rudis* that characterizes sandy lobes of the Marnoso-arenacea Fm or *Halopoa* that is concentrated in overbank deposits of Arenarie di M.

Cervarola unit (Milighetti et al. 2009). In such different stratynomic (or toponomic) categories ichnocoenoses occur in pre- and post-depositional communities (Savvada 2007; Seilacher 2007 for preservation variants). They differ substantially with facies variations, sedimentation rate, chemical, physical and biological parameters of basins and their subenvironments (Seilacher 1962, 1974, 1977; Książkiewicz 1977; Uchman 1995a, 2001, 2009; Wetzel & Uchman 1997, 2001; Heard & Pickering 2008; Monaco 2008; Milighetti et al. 2009; Monaco et al. 2009a). Particular interest displays the ichnocoenosis IC4 (described in Monaco et al. 2009a) regarding cm-thick turbidites (mainly F9b Facies) fringing intrabasinal highs (with thick mud deposits) that can be recognized in the Poggio Alto section (Fig. 1). In this locality the ichnocoenosis may be considered as an ichnologic-*lagerstätte* because the exceptional preservation and abundance (Fig. 2).

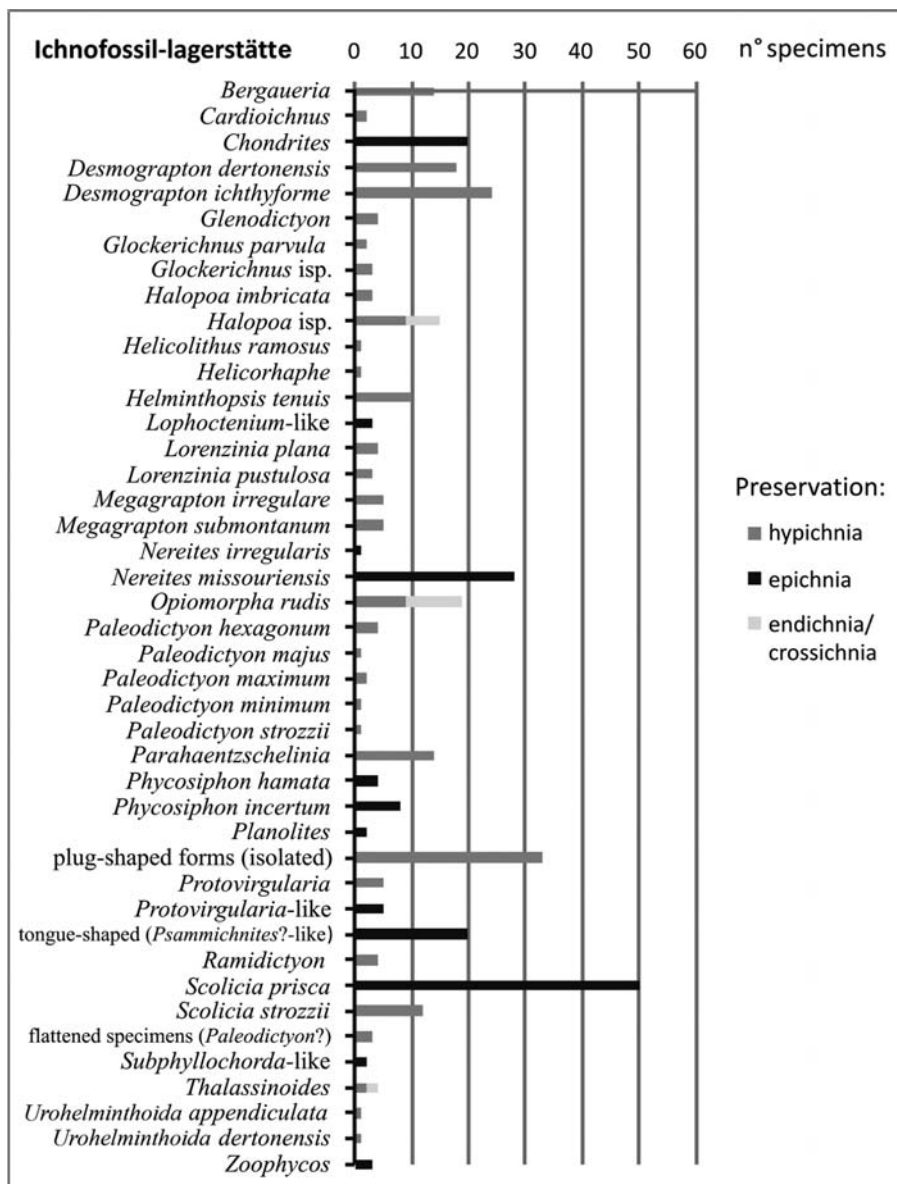


Fig. 2 - Abundance of the recorded ichnotaxa in calcarenitic turbidites in relation to their preservation as hypichnia, epichnia or endichnia/crossichnia.

The preservation in hypichnial, endichnial and epichnial assemblages could be recovered in three parts (sub-ichnocoenoses) from base towards top and their general characteristics are here summarized as follows.

A) *Hypichnial sub-ichnocoenosis with graphoglyptids and plug- or string-shaped forms (hyporeliefs)*. The trace fossil community preserved as hyporeliefs in thin-bedded turbidites is dominated by typical graphoglyptids and plug-shaped forms. String-shaped traces are also present but their abundance is limited to some samples. Total ichnodensity is very high and can reach up to 50 specimens per 0.5 m², which is one of the higher ichnodensity of hypichnia among all studied sections in a foredeep system (Milighetti et al. 2009). Among graphoglyptids, the biramous meander graphoglyptid *Desmograption* (*D. dertonensis*, and *D. ichthyforme*) is the most common hypichnion in the Poggio Alto section (Pl. 1A, E). This ichnogenus represents a system of double rows of string-sized, J- or U-shaped, semi-meanders joined by bars. *Desmograption ichthyforme* (Macsoy) specimens show very narrowly aligned appendages that appear as parallel and very long ridges (Pl. 1A). Moreover, string- and plug-shaped and other trace fossils contribute to form complex burrow systems on the sole face. They exhibit typical unidirectional deformations produced by fluting as smoothing (Monaco 2008).

The graphoglyptid uniramous meander *Urohelminthoidea* (mainly *U. dertonensis* and *U. appendiculata*) consists of hypichnial string-sized, tight meanders, in which turning points are angular, and regularly spaced appendages (up to 60 mm long) protrude outwardly from turning points (Pl. 1C). Another typical graphoglyptid is *Paleodictyon*, which forms regular hexagonal nets or producing irregular nets frequently widened and flattened (Pl. 1B, D). The former is a three-dimensional burrow system (mesh and shafts) that includes several ichnospecies: *P. hexagonum*, *P. majus*, *P. maximum* (Pl. 1D), *P. minimum*, *P. strozzii*. Their string diameter and mesh width varies (see maximum mesh size and string diameter plots, obtained from many specimens of different formations, for determining ichnospecies in Uchman 1995b). The variability of this ichnogenus is much higher here than in the other sites of the foredeep basins of northern Apennines. Morphometric changes of strings and meshes are strictly related to the deep-sea conditions and facies distribution (Monaco 2008; Monaco & Checconi 2008; Milighetti et al. 2009). In the lagerstätte of Poggio Alto *Paleodictyon* reveals the maximum ichnospecies diversity among other environments of the Marnoso-arenacea Formation and the Arenarie di M. Cervarola unit (Monaco 2008; Milighetti et al. 2009). Irregular nets frequently widened and flattened may be probably considered as a deformation feature of *Paleo-*

dictyon cf. *nodosum* illustrated by Crimes & McCall (1995) where strings and mesh change their form for compactional processes. In Poggio Alto ichnofossil-lagerstätte *Paleodictyon* is abundant (>5 specimens per 0.5 m²) and some flattened specimens have a mesh up to 15 cm in width (Pl. 1B), although shafts are not preserved.

Plug-shaped, rosette-shaped and stellatae-shaped forms are also important trace fossils (up to 50 per 0.5 m²) in the Poggio Alto section and dominated by small sized regular plugs (< 1 cm), individuals or arranged in clusters (see Pl. 1A-L). Larger plugs are slightly rare but very interesting (sample MA 171). They, 2.5 cm wide and 3.5 cm long, show a tongue-shaped structure with some internal furrows that can be referred to a *Cardioichnus*-like structure (Pl. 1L). Internal furrows and other structures seem to indicate a biogenic origin (Seilacher 2007, p. 70). Other large plugs are *Bergaueria* isp., that is a typical knob-shaped form, vertically arranged, circular to slightly elliptical in outline, with a rounded base (Pl. 1E, I); the sandy fill is essentially structureless (Prantl 1945). The name plug-shaped has been introduced for peculiar biogenic (endichnial?) structures (Pemberton et al. 1988) that are resting burrows (cubichnia) preserved commonly but not exclusively as undertraces (Savrda 2007; Seilacher 2007); they probably were produced by suspension-feeders such as sea anemones (Pemberton et al. 1988; Uchman 1995a, pl. 2 figs. 4-5). Medium-size plugs are those of the *Parahaentzschelinia* isp. that are the main burrow system at the sole of thin-bedded turbidites at Poggio Alto (Pl. 1H); this endichnial/hypichnial ichnogenus may be preserved as groups of bulges (up to twenty, irregularly disposed), oval to circular in shape (Uchman 1995a). These groups represent vertical shafts (normally up to 12), radiating vertically from one master shaft (usually not preserved) (Chamberlain 1971). *Parahaentzschelinia* plugs are often fluted and bent the action of unidirectional currents on the sea-floor (Monaco 2008). Some plug clusters do not exhibit a typical arrangement or symmetry that can be useful for a classification of this ichnogenus (samples MA 92, 174). These other plugs are probably shafts of large-sized or medium-sized *Paleodictyon* burrow systems (see sample MA 257; Pl. 3F-G) or represent incomplete parts (or shafts) of *Desmograption* (samples MA 88, 168, 256). Other plug-shaped structures may be referred to ending parts of endichnial or crossichnial trace fossils (e.g. *Halopoa* and/or *Ophiomorpha*) that reached the sole of turbidites as illustrated in the sub-ichnocoenosis B. In general, many plugs exhibit taphonomic features, mainly induced by uni-/bi-directional fluting processes, such as smoothing, bending and tapering (Monaco 2008). Other helicoidally twisted and elongated hypichnial plugs are similar to *Helicorhapha* Książkiewicz (Pl. 1F). They show some affinities with *Helicolithus* Azpeitia Moros. Regularly

spaced series of small knobs, 0.3 to 1 mm in diameter, are included in *Helicolithus ramosus* Tunis & Uchman; they probably represent vertical shafts of some thin axial and twisted tunnels.

The rosette-shaped *Lorenzina* (mainly *L. cf. plana* and *L. cf. pustulosa*), shows a typical radial structure, with short, smooth, hypichnial ridges arranged in one or two circular rows, radiating from a central area. Stellatae-shaped forms are also present. They are dominated by *Glockerichnus* (*G. cf. glockeri*), a typical radiate trace fossil formed by linear strings of the same diameter (up to 1 mm), usually radiating from a hollow central area (Pl. 1G). The type species *G. glockeri* (Książkiewicz) is preserved as commonly dichotomous hypichnial branched strings (Uchman 1998, fig. 43). At the soles of thin and fine-grained turbidites of Poggio Alto these specimens (sample MA 89, Pl. 1G) show a depressed central area in the hypichnial hyporeliefs, from which the stellatae strings radiate (Książkiewicz 1977).

String-shaped forms are usually important and can constitute the typical braided pattern of *Megagraption* (irregular net), while unbranched strings characterize *Helminthopsis* and *Protovirgularia*, and bilobate large meanders are typical of *Scolicia strozzii*. *Megagraption* occurs usually as hypichnial irregular nets, sinuous or slightly meandering (Pl. 3B). The string diameter varies for different ichnospecies from 0.3 to 1.5 mm, *Megagraption cf. irregulare* Książkiewicz and *M. cf. submontanum* (Azpeitia Moros), bearing lateral appendages which tend to form irregular tangles. Nets are bordered by distinctly winding strings, and acute angles of branching occur (sample Ma 91). *Helminthopsis* (mainly *H. tenuis*) is a hypichnial horizontal, simple (up to 1.5 mm wide), not branched, internally structureless ridge that shows a sinuous or irregularly winding course which forms serpentine convolutions. *Protovirgularia* is rare but significant. It is a horizontal, cylindrical structure, distinctly or indistinctly bilobate, straight or slightly meandering, formed by successive pads of sediment, seen on the surface as ribs arranged in a chevron-like biserial pattern. Hypichnial *Scolicia strozzii* is rare in the Poggio Alto section, contrarily to nearby areas, e.g. Verghereto-Bagno di Romagna, where it is very abundant. *S. strozzii* is common in many sandy lobes of the northern Apennine flysch and much rarer in thin-bedded facies (Uchman 1995a; Monaco & Caracuel 2007; Milighetti et al. 2009). It is a meandering bilobate or trilobate ridge, up to 25 mm wide with two parallel, locally discontinuous, sediment strings along the lower surface of beds.

B) Endichnial sub-ichnocoenosis with string-shaped forms. Several burrows cross obliquely thin-bedded sandy turbidite producing endichnia while vertical crossichnia that pass through different beds are

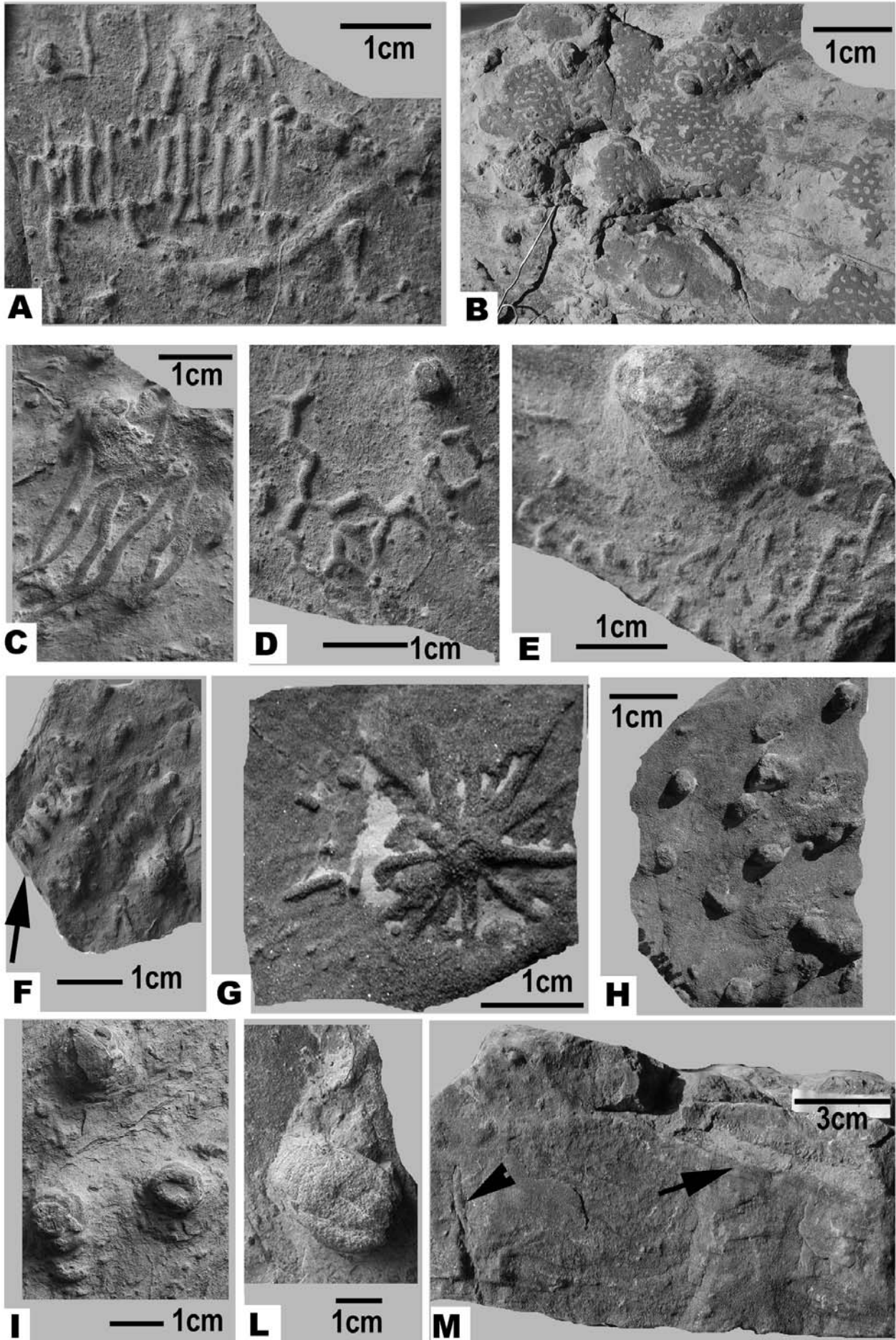
very rare (one specimen of *O. rudis*). The endichnial assemblage includes mainly *Halopoa*, *Ophiomorpha* and *Thalassinoides*. *Halopoa* is an unbranched and generally horizontal structure, 5–10 mm wide, forming longitudinal discontinuous ridges or wrinkles, composed of cylindrical probes which imperfectly overlap the central tube. The main ichnospecies is *H. imbricata* Torell. Locally *Halopoa* shows a tunnel filling that has been pressed radially out or stowed away by the trace-maker, producing elongated fractures and longitudinal cracks that are typical of asterosomids (Seilacher 2007). *Halopoa* in the medium-grained sandstones of the Poggio Alto section is clearly post-depositional (Pl. 3C) because it crosses other ridges. It is rarer here than in the other Apennine sections where it is common in muddy turbidites (Milighetti et al. 2009). Other endichnial galleries, i.e. *Ophiomorpha* (mainly *O. rudis*) and *Thalassinoides* that are preserved as simple oblique tunnels, are probably made by crustaceans. *Ophiomorpha rudis* consists of cylindrical, seldom branched burrows with phantoms imprints of peloids (sample MV 290) mainly arranged perpendicularly to the vertical shaft that connects two different horizontal mesh systems (Uchman 2009); smooth galleries not covered by elongate or irregular pellets are rare. In the Poggio Alto *lagerstätte* branched systems of *Ophiomorpha* and *Thalassinoides* are rarer than in channelized lobes and lobe-fringe deposits of the foredeep system where they are abundant (Monaco et al. 2007; Milighetti et al. 2009). Probably, some *Protovirgularia* may occur as epichnia, but further studies are needed to clarify this view (Monaco 2008).

C) Epichnial sub-ichnocoenosis with meandering and radiate structures with spreite. The epichnia in thin-bedded turbidites of the Poggio Alto section express the most interesting ichnofabric in the ichnologic-lager-

PLATE 1

Trace fossils preserved as hypichnia (sole of calcarenitic turbidites) and endichnia. Scale in cm.

A) *Desmograption ichthyforme*, hypichnion, sample MV 296; B) deformed *Paleodictyon* specimen, hypichnion, sample MA 102; C) *Urohelminthoida dertonensis*, hypichnion, sample MA 278; D) *Paleodictyon maximum*, hypichnion, sample MV 306; E) *Desmograption cf. dertonensis* and fluted plug-shaped form, hypichnia, sample MV 303; note the distribution of strings over fluted structure; F) helicoidally twisted *Helicorbaphe* (arrow), hypichnion, sample MV 293; G) *Glockerichnus cf. parvula*, hypichnion, sample MA 89; H) clusters of plugs (*Parabaentzschelina?*), hypichnion, sample MA 92; I) plug-shaped *Bergaueria* isp., hypichnion, sample MA 213; L) *Cardioichnus*, hypichnion, sample MA 171; M) oblique post-depositional trace fossils (*Ophiomorpha rudis*, arrows), endichnia, sample MA 264.



stätte. In fact, the epichnial community alone may be considered an ichnofossil-*lagerstätte*. It reaches the very higher ichnodensity with approximately > 30 (up to 50 in places) specimens per square metre. Burrowing involves the fine-grained top part of turbidite beds that is composed of 1-2 cm thick rippled grey mud or silt. The topmost surface is fully exposed near Ville di Montecoronaro (approximately 20 m² of exposed surface) and here the ichnofabric of hypichnia and epichnia can be easily analysed (Fig. 1). One of the most important ichnogenus is *Nereites missouriensis* (Pl. 2H-I) and, rarely, *N. irregularis*. *Nereites* is typical of deep-sea turbidites (the *Nereites* ichnofacies), mainly in the distal basin plain (Uchman 2007). It consists of more or less horizontal, winding to regularly meandering ribbon-like burrow that is composed of a median back-filled tunnel (core) enveloped by an even to lobate zone of reworked sediment (mantle) (Pl. 2H). Commonly, only the external part of the mantle is preserved as a densely packed chain of small depressions or pustules (Pl. 2H).

Scolicia prisca de Quatrefages is also typical of this sub-ichnocenosis and it is usually preserved as epichnial trilobate burrow with concave (or convex) bottom and oblique slopes bordering a median furrow and covered with regular, dense transverse ribs, 1 mm-wide, slightly bent externally (Pl. 2E, G). In the Poggio Alto *lagerstätte*, at the top of 5 cm thick sandy turbidite bed, hundreds of *S. prisca* epichnial specimens, from 1.8 to 2.8 cm-wide (mean 2.4 cm), occur. They usually form very narrow meanders, in correspondence of which the trace can twist around the axis or assume a tongue-shaped *Psammichnites*-like structure (Pl. 3I-L). In general they are irregularly disposed and locally crossed by several other similar meandering forms of *Scolicia* (*Subphyllochorda*-like and other *Psammichnites*-like, see Seilacher 2007), simple string-shaped traces (e.g. *Planolites*), *Protovirgularia*, *Phycosiphon incertum* and minute branched burrows white in colour (*Chondrites*). *Scolicia prisca* assemblage represents probably one of the better examples of intensely burrowed sea-floor softground in a submarine high of the Apennine fore-deep system (Monaco & Checconi 2008).

A small *Zoophycos* is a three-dimensional spreite structure of sub-spherical or irregular shape, up to 30 cm in diameter (Pl. 2B-C). The marginal tube is curved and produces a radiate structure; after intense weathering destruction of the spreite only furrows may be observed (Pl. 2B-C). Primary lamellae are visible, while secondary ones are often destroyed. Usually these *Zoophycos* are much smaller than similar specimens of other Upper Miocene marl units of such as the Marne di Vicchio (Badia Prataglia and Valsavignone areas) where they are larger, up to 120 cm in diameter, and helicoidal (Milighetti et al. 2009).

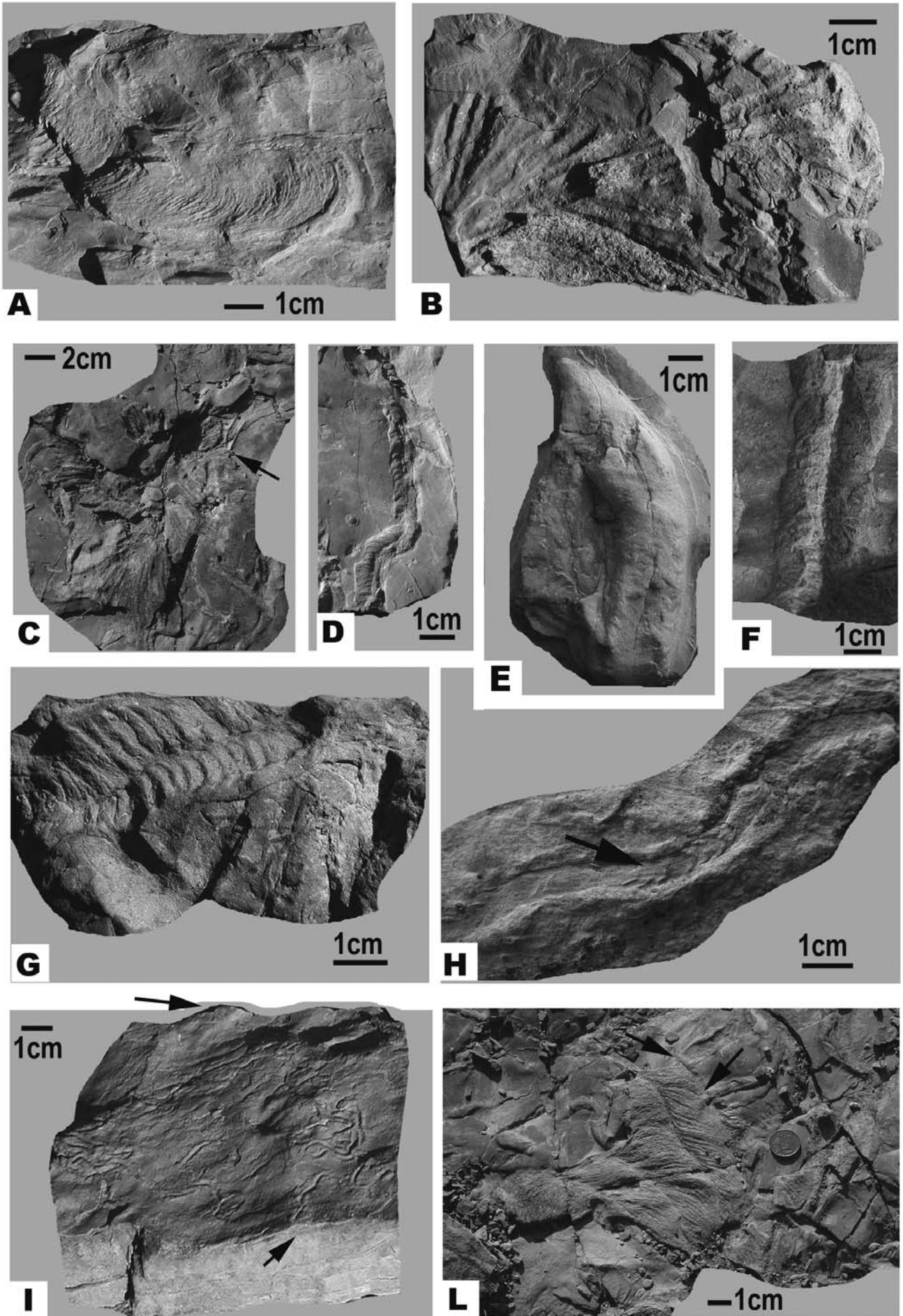
Other epichnia of Poggio Alto are complex spreite *Phycosiphon*-like and *Lophothenium*-like trace fossils; *Phycosiphon* and *Lophothenium* are well known from the Palaeozoic and are grouped in the lophotheniids; they were produced by horizontal strip-mining by probably a bulldozing wormlike animal without an obvious connection to the sediment surface (Seilacher 2007). In the *lagerstätte* these structures exhibit a marginal tunnel (with short and narrow meanders for *Phycosiphon* and longer but irregular for *Lophothenium*) surrounding the strip-mined area (see Seilacher 2007, pl. 40). Tongue-shaped lobes with spreite of *Phycosiphon hamata* Fischer-Ooster develops only in a one level and differ from the lobes of *Zoophycos* that occurs in several adjacent levels (Uchman 1998, fig. 53). *Lophothenium* shows complex spreite lobes with a typical arrangement of the various orders of lamellae that are tangentially disposed (Pl. 2L). *Phycosiphon hamata* (Pl. 2A) occurs in the same horizon where also *Lophothenium* is present (Pl. 2A, L). Spreite structures as *Zoophycos*, *Phycosiphon*-like and *Lophothenium*-like trace fossils were produced in the same mud level but after *Scolicia prisca*, which is undoubtedly crossed by these spreite structures (Pl. 2C, L). Except for the described *lagerstätte*, large *Phycosiphon*-like and *Lophothenium*-like trace fossils are usually poorly preserved in fore-deep basins and request further analyses (Monaco & Checconi, 2008; Milighetti et al. 2009).

Taphonomic remarks

The trace fossil preservation is controlled by several interacting factors that govern the entry of biogenic structures into the stratigraphic record (Savrda 2007). In flysch deposits taphonomy concerns a careful study of

PLATE 2

Trace fossils preserved as epichnia (top of calcarenitic turbidites). A) Horizontal lobate specimen with spreite structures *Phycosiphon hamata*, sample MV 299; B) small-sized *Zoophycos* with radiate pattern, sample MA 96; C) small-sized *Zoophycos* with radiate pattern crossing other *Scolicia prisca* (arrow); D) concave-convex relief of *Scolicia prisca*; E) convex *Scolicia prisca*, sample MV 307; F) unusual concave specimen of *Scolicia* cf. *vertebralis* with a median ridge, sample MV 309; G) convex *Scolicia prisca* with a median furrow and densely-packed transverse ribs bent externally, sample MA 98; H) winding *Nereites missouriensis* with a median back-filled core (arrow) and external convex zone of reworked sediment (mantle), sample MV 291; I) ripple surface (arrows) with looping *Nereites* isp.; L) lophotheniid-like structure (*Lophothenium*?) with several orders of tangentially disposed lamellae; it crosses many other epichnia (arrows).



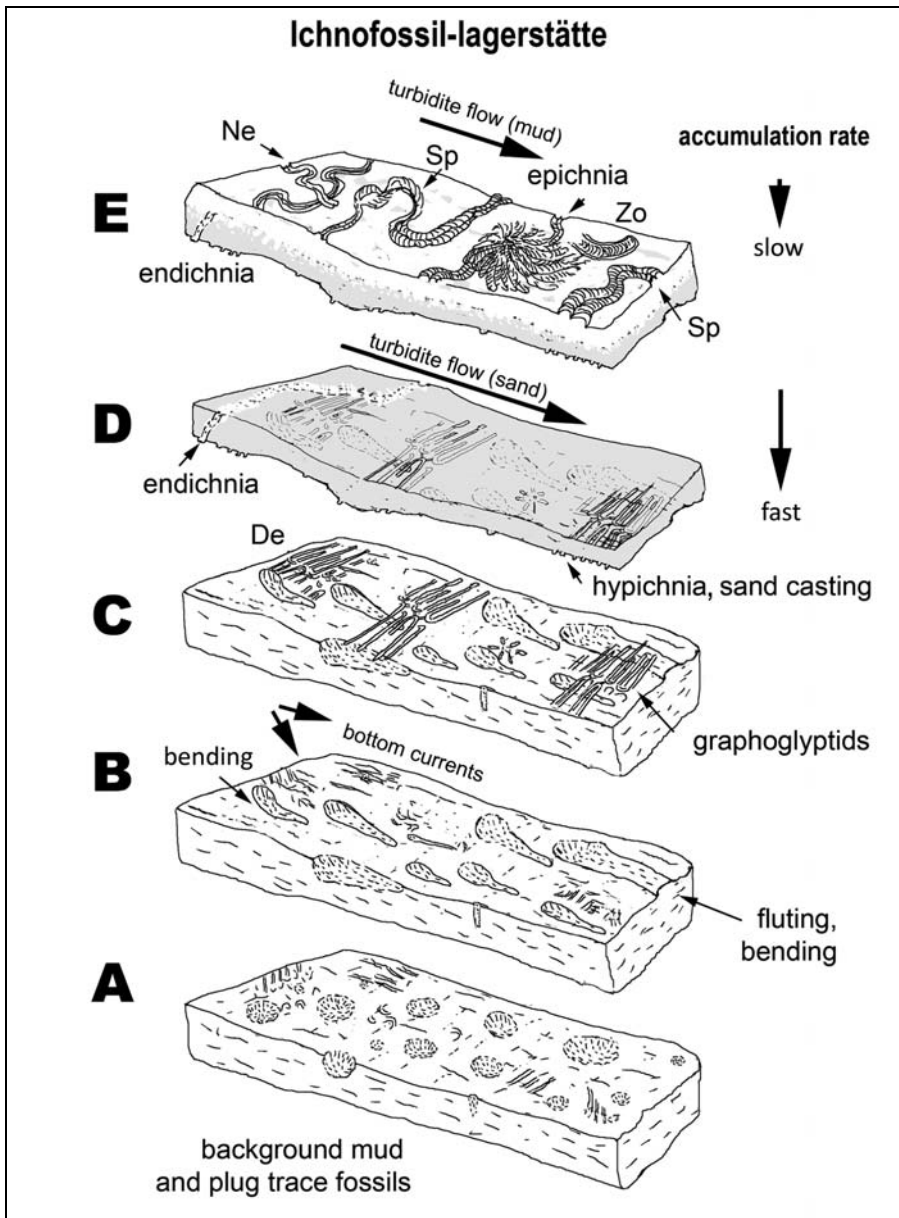


Fig. 3 - Synthetic model that summarise the taphonomic history of the ichnofossil-lagerstätte; see text for explanation (paragraph "Taphonomic remarks"). Ne = *Nereites*, Zo = *Zoophycos*, Sp = *Scolicia prisca*, De = *Desmograption*.

relationships among the delicate structures that are preserved at the base (as casting) and at the top (in hemipelagic mud) of the turbidites, and that show different taphonomic characteristics (Monaco & Caracuel 2007; Savrda 2007). Several of the studied forms exhibit interesting taphonomic features since, after burrowing, deformational agents were active on the sea-floor producing deformations; therefore squeezing and bulldozing are common among biogenic taphonomic categories in epichnia, while fluting tends to prevail in hypichnia (Monaco 2008). Locally, multiphase, intensive burrowing at the top of turbidite result in a mottled ichnofabric (Monaco & Uchman 1999; Wetzel & Uchman 2001). The over 60 samples from Poggio Alto *lagerstätte* exhibit taphonomic features that are here separated in hypichnial and epichnial preservations (panel in Fig. 3). All samples from this locality are gathered in a large

database (see the theca collection layout, Monaco et al. 2009b). They are here analysed separately as follows, and the endichnial structures, being reaching the base and top, are here included in these two categories.

A) *Hypichnial taphonomic structures*. The main preservation factor of hypichnia is physical; in fact a few carbonate-rich sand that is deposited by low-density turbidite flow (poorly erosive) can produce a perfect casting of all surface (or very shallow) structures, with a minute preservation of the pre-turbidite trace of organisms that proliferate in the muddy substrate (background mud structures). They are three-dimensional graphoglyptids (mainly *Desmograption*), plug-shaped and radiate or stellatae forms and many others (Monaco et al. 2009a). The low rate of sedimentation that was typical of thin-bedded rippled sands of overbank depos-

its was enough to preserve the background mud structures that usually are delicate, concave or convex structures created by deep-water organisms. Moreover, the early cementation at the hypichnial face was favoured by the high calcium carbonate content present at the mud/sand interface (background mud-turbidite), producing a resistant film that preserve structures by the weathering destruction. This cemented film acted as a protection also from subsequent compaction and diagenetic processes of burial phases (Monaco 2008). This allows to a very good preservation of very small (<0.3 mm) hypichnial structures that can be observed in the Poggio Alto *lagerstätte*.

In these hypichnial structures the interest may be focused on their genesis; in fact various order of biogenic activities often interact with physical ones producing complex, biogenic-physically induced structures at the sole of turbidites. In the sample MV 302 many elongated plugs occur. They are up to 7 cm long, with thin orthogonal striae probably produced by organisms that form convex resting traces in the background mud as narrow furrows similar to claws (Pl. 3A). They are different from ones of the sample MA 99 where claw-like structures may be referred to *Phycodes*. The structures of MV 302 were fluted by water currents (see upper black arrow in Pl. 3A) in an early phase that affected the background mud of the sea-floor before the casting of turbidite flow, producing unidirectional deformations, such as smoothing or bending (see white arrows in Pl. 3A). Unidirectional deformations of the sample MV 302 do not involve the parallel strings of graphoglyptid *Desmograption* that are on the contrary not deformed (De in Pl. 3A). Not deformed strings have been found in many other samples (see MV 297, 302, 308). This means that three orders of taphonomic processes – forming of plugs, fluting and forming of *Desmograption* meanders, respectively – occurred in the background mud before the casting.

In the sample MV 297 we can observe two main directions that are orthogonally disposed (60–80°, Pl. 3D): the first is a typical fluting clearly produced by physical agents (bottom currents, lower black arrow in Fig. 3B and Pl. 3D), while the other one was probably of biogenic origin (white arrows) and consists of elongated plugs and narrow furrows bent and smoothed (Pl. 3D). Finally, a not deformed graphoglyptid *Desmograption ichthyforme* (De in Pl. 3D) developed cutting the previous structures. In the sample MV 305 the strings of *Desmograption* are unusually curved around a fluted plug indicating that the burrower turned its burrow system around an obstacle that was fluted before the graphoglyptid activity (Pl. 3H arrow). Therefore, *Desmograption* confirms, being the final burrowing expression, that it was produced in the background mud prior to the final casting (Seilacher 1977). This

fact concerns all graphoglyptids that are the latest structures produced in the background mud prior to casting. It has been confirmed by many observations of samples where graphoglyptids cross or are placed undisturbed above fluted structures produced by currents: the MA 91, MA 254, MV 301 samples for *Megagraption*, the MA 88, MA 93, MA 168, MV 283, MV 295, MV 297, MV 302, MV 303, MV 304, MV 305 samples for *Desmograption*, the MA 89 sample for *Glockerichnus*, the MA 278 sample for *Urohelminthoidea appendiculata*, the MV 293 for *Helicorhaphe*, the MV 306 for *Paleodictyon maximum*. In all studied cases graphoglyptids develop preferably in flat or poorly fluted sea floor and places where vertical shafts of their three-dimensional burrow systems are protected from the sediment filling; this is necessary for a good ventilation of the burrow system for bacterial farming (Seilacher 1977).

Another interesting case can be observed in the sample MV 301 (Pl. 3B) that shows three steps in taphonomic history. They reveal a sequence of features that were clearly restricted to the background mud. (i) An unidirectional smoothing produces convex fluting structures in isolated plugs that are all deformed in the same direction (Pl. 3B black arrow). Some circular plugs are vertical shaft terminations on the sea-floor (probably shafts of large *Paleodictyon hexagonum* or *P. cf. nodosum*) and they show convex fluted structures that have short or long tails parallel disposed or bent. (ii) Secondly, a network of a *Megagraption* occurred in the background mud that, on the contrary, is not deformed (Me in Pl. 3B). It consists of a delicate string net that developed mainly orthogonally to the fluting direction but without any deformation by fluting of strings. This testifies that convex *Megagraption* net developed in the background mud after fluting but before the casting. (iii) Thirdly, after casting by turbidite sand post-depositional, endichnial *Halopoa* (Ha in Pl. 3B, C) occurred, producing a concave straight hyporelief that cross many pre-depositional traces, including plugs, of *Megagraption* and ripple laminations.

Many clusters of plugs (*Parahaentzschelinia*, *Ramidictyon* and others) are often rotated or bent by currents (sample MA 92, 99), and in other cases (MA 174, 282, 283, 290, 292, 294, 305, 306) they are tapered or exhibit a sub-quadrangle shape or sub-angular profile (arrows in Pl. 3E). Bending of rows of shafts has also been observed in some samples of the *lagerstätte*, including *Ramidictyon* and shafts of large *Paleodictyon cf. hexagonum*: (samples MA 256, 257, DSCN 6072, 6076, Pl. 3F-G arrow). Here shafts are rotated from their original position, but doubts concern their history; bending was produced during pre- or syn-turbidite phases or by compaction after the casting, though, in samples MA

256 and 257, some subsequent strings (*Megagraption*?) cut, not deformed, the plain of bent shafts.

B) Epichnial taphonomic structures. The epichnia develop at the top of calcarenite beds where fining-upward sand to mud occurs. The main difference from hypichnial regards ichnotaxa: three-dimensional graphoglyptids and plug-shaped trace fossils are lacking, while other new ichnogenera appear with new taphonomic features: *Nereites missouriensis*, *N. irregularis*, *Scolicia prisca*, *Zoophycos*, *Phycosiphon*. They are preserved in concave and convex reliefs with very high ichnodensity (up to 20 burrows of *S. prisca* per m²) and moderate to low ichnodiversity (up to 8 ichnotaxa). Convex epireliefs are dominant (70% in total for *S. prisca*), although in places also concave epireliefs may be abundant (30% in total for *S. prisca* and up to 90% for *Nereites*). In isolated specimens of *Scolicia* (MA 100) the cementation in full convexity can preserve internal structures and the median furrow (Pl. 2E, G). The median ridge can be present in other concave specimens (e.g. *Scolicia* cf. *vertebralis*, Pl. 2F). But in general many variations in shape (and diameter) have been observed following the convex epirelief in mud. This concerns the aspect of *Scolicia prisca* that exhibits wiggling features often twisted axially or disposed in a tongue-shaped expression with internal structures in mud that has been indicated as backfill phantoms (Pls. 2G, 3I). These structures were produced by grazing organisms that bulldozed in echinoid fashion by removing the sediment in front and passing it over the body for terminal backfilling (Seilacher 2007, pl. 28). These structures are *Psammichnites*-like wiggling backfill phantoms (Pl. 3I bottom). Epichnial burrows with convex backfill phantoms may be considered the typical expression of epichnial *lagerstätte* in the Poggio Alto, while they have never been found in other sectors of the foredeep system of northern Apennines. Horizontal crossing between two traces is rare (Pl. 3I top) while vertical motion is common and tends to produce plunging structures into the sediment. In this case a backfill phantom structure of *Scolicia prisca* disappears, evolving sharply in a *Nereites*-like structure with a narrowing of the external diameter and with the development of a central depression and lateral smooth ridges (Pl. 3L arrow). In this case the median furrow of *Scolicia prisca* is not structured, differently from *Nereites missouriensis* which backfill in the median furrows can be easily recognized (sample MV 291, Pl. 2H). These hybrid structures are very common in the *lagerstätte*. *Nereites missouriensis* displays meanders that are irregularly disposed across the ripple crest and along the ripple slope but their diameter remains constant (Pl. 2I).

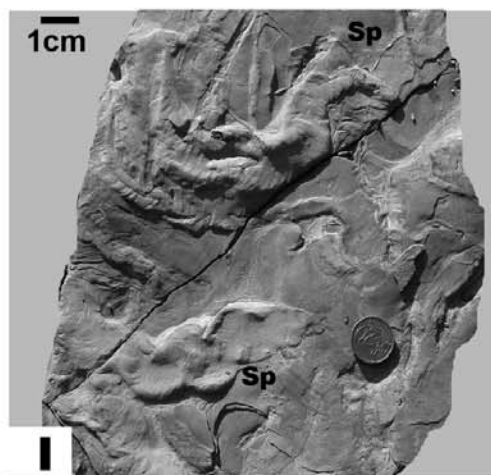
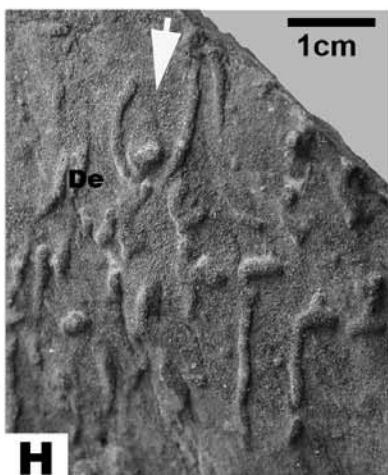
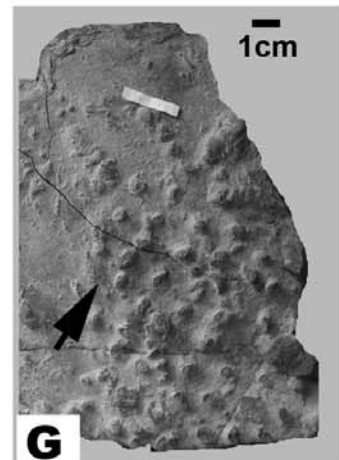
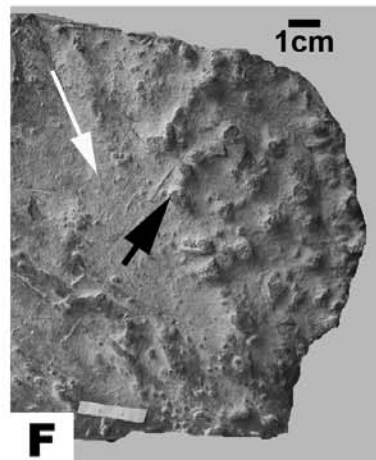
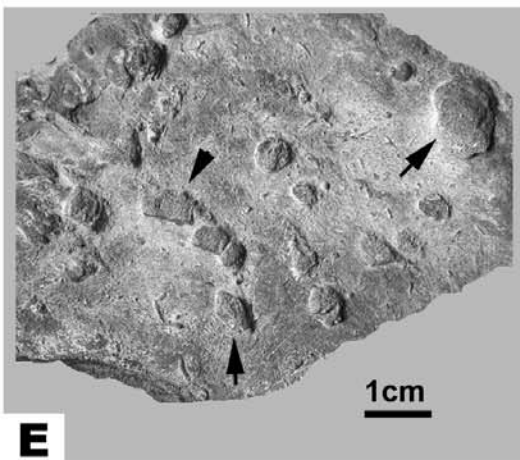
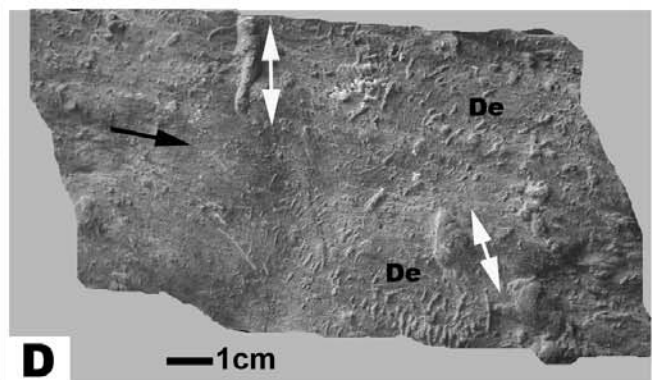
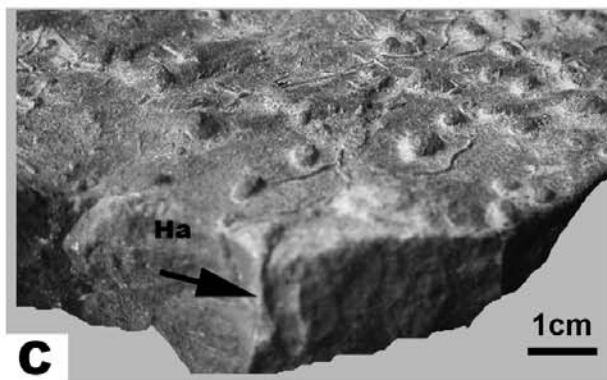
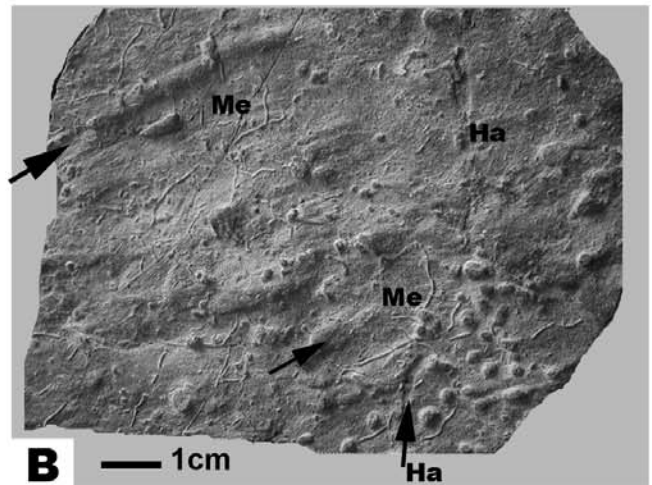
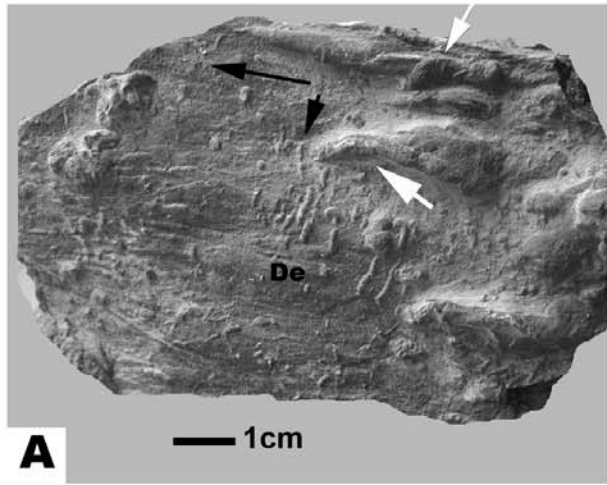
Discussion and conclusions

In the Poggio Alto *lagerstätte* two different sub-ichnocoenosis are fundamental: the background hypichnial sub-ichnocoenosis (A) and the post-turbidite epichnia (and endichnial) sub-ichnocoenosis (B). These two different sub-ichnocoenosis are influenced by preservational processes (Fig. 3). Thanks to the casting at the soles of turbidites, the background ichnofauna can evidences a richness of infauna that populated the hemipelagic marls (Fig. 3A-C). Here the ichnotaxa are preserved in a thin film at the base of a calcarenite beds. The graphoglyptids suggests a wide variability in deep-sea communities that produced many structures: three-dimensional networks and shafts, meander systems, radiate and many plug-shaped or stellatae structures and strings. Some of these structures were deformed by bottom currents while others are subsequent but produced in the same background environment (Fig. 3A-C). This suggests that multi-phase processes acted before turbidity currents. This introduces an important aspect: many of fluted structures are not necessarily the product of a turbid water body in front of turbidite flow as postulated by previous works (the shock wave hypothesis where many phases such as erosion, suction, fluting by shock wave, and sand-cast of suspended sand were invoked, see Seilacher 2007, pl. 52), but they are the evidence of background preceding currents. These currents can produce micro-grooves and mud lineations that survived to the turbidite erosion (Monaco 2008). This aspect is fundamental to explain the preservation of delicate structures in the mud, surviving the erosional phase of a turbidity current. Taking in account the Pog-

PLATE 3

Taphonomic features of the ichnofossil-*lagerstätte*.

A) Not deformed *Desmograption* (De) placed in front of fluted structures (black arrows) smoothed or bent (see white arrows), hypichnion, sample MV 302; B) not deformed *Megagraption* (Me) network on fluted structures (left black arrow) crossed by post-depositional *Halopoa* (Ha, lower arrow), hypichnia, sample MV 301; C) detail of the post-depositional *Halopoa* in side view, hypichnion-endichnion, sample 301; D) fluting (black arrow) and orthogonally disposed biogenic plugs (white arrows) with not deformed *Desmograption* (De), hypichnia, sample MV 297; E) cluster of tapered plugs with a sub-square shape, hypichnia, sample MV 290; F) bended rows of *Ramidictyon* shafts (arrow) in the same direction of the fluted structures (white arrow), hypichnion, sample MA 257; G) bending of some rows (*Ramidictyon*?) of shafts (arrow), hypichnia, sample MA 256; H) strings of *Desmograption* (De) that turn around an obstacle (arrow), hypichnion, sample MV 305; I) narrow meanders, which are twisted or in a tongue-shaped expression of several *Scolicia prisca*, epichnia; L) plunging backfill structures of *Scolicia prisca*, with a narrowing of the external diameter (arrow), epichnia.



gio Alto *lagerstätte*, the taphonomy of the pre-depositional (background) trace fossils is probably more complex than that proposed by Seilacher, and the role of bottom currents was probably underestimated. Probably these (contour?) currents were active on the sides of the intrabasinal high of Verghereto where the agrichnia tracemakers could develop. Vertical shafts in *Paleodictyon*, *Megagraption* and *Desmograption* could also have the function to better ventilate horizontal tunnels for bacterial and microbial proliferations, as postulated by some authors (Crimes & Crossley 1980; Rona et al. 2009). The abnormal distribution of *Desmograption* systems orthogonally disposed and placed between fluted structures suggests that the bacterial farming was fruitful under a stable current regime (Monaco & Checconi, in press). Similar benefits could be obtained also by other organisms that produced an elongated mesh system under stable currents, as observed in many small *Paleodictyon minimum* of thin overbank beds of the Cervarola unit of Alpe di Poti (Monaco et al. 2009a). The controversy about the graphoglyptid preservation is still open but certainly of remarkable interest.

The post-turbidite trace fossils are very different (Fig. 3D-E). Their production is mainly controlled by the large availability of nutrients and organic matter transported by turbiditic flows or settled from suspension clouds. These induced a proliferation of opportunists in totally different conditions respect to those affecting the pre-turbiditic background, including larvae or adults introduced via turbidity currents in deep-sea environment that remain active for long time (Uchman 2009). It is possible that some of these organisms produced also vertically oriented, endichnial traces in the

coarse-grained arenites (*Ophiomorpha rudis*, *Halopoa*) (Fig. 3D). Vagile opportunists fed actively in the new fine-grained sediment at top of ripples and produced a lot of meanders and loops (e.g. *Nereites* and *Scolicia prisca*) (Fig. 3E). In the late post-turbiditic substrate many of earlier burrows were crossed by succeeding spreite structures when the suspension mud deposited slowly (*Zoophycos*, *Phycosiphon* and *Lophoctenium*). They indicate a new stability of the sea-floor with a constant sedimentation of fine-grained material (Fig. 3E). In the studied epichnia *Phycosiphon* is never crossed by *Nereites* and cannot be considered as the first colonizer as observed in other post-turbiditic conditions (Wetzel & Uchman 2001).

The trace fossils examined in cm-thick turbidites do not provide enough data to delineate exactly the current system at the sea floor and where these currents are oriented. It is possible that inorganic nutrients and fine organic material was settled by suspensions and re-distributed by very weak contour currents active along the south-eastern side of the intrabasinal Verghereto High producing the high proliferation of organisms (Trincardi et al. 2005; Stow, pers. comm.). In all cases the taphonomic methodology applied to hypichnial graphoglyptids and epichnial communities in overbank/fringe deposits is extremely helpful and promising for further basin analysis.

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