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Ichnocoenoses in the Oligocene to Miocene foredeep basins (Northern Apennines, central Italy) and their relation to turbidite deposition

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ABSTRACT :

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Analysis of trace fossil abundance and diversity in the Oligocene to Miocene foredeep and piggyback basins of the Tuscan–Romagna–Umbrian Apennines allows us to recognize five ichnocoenoses. The deposits reflect sedimentary environments from slope to basin plain, whose sedimentation was directly controlled by synsedimentary tectonics: attached fan lobes and channels, lobe- and channel-fringes, overbank-fringes of intrabasinal highs, distal detached lobes of basin plain and slope-proximal interfans. The graphoglyptid:non-graphoglyptid ratio has been considered as the chief factor in the study of ichnologic material from Falterona–Cervarola–Trasimeno, Marnoso-arenacea and Marne di Vicchio-Verghereto stratigraphic units. The study shows that there is an increase in ichnodiversity and ichnodensity of graphoglyptids, which are typical mainly in detached lobes of basin plain and overbank-levee deposits whose background ichnofauna also shows better preservation.

Key words: Ichnocoenoses; Trace fossils; Burrows; Turbidites; Foredeep basins; Northern Apennines; Italy.

INTRODUCTION

Despite abundant research on taxonomy of flysch trace fossils, few investigators have attempted to integrate sedimentology with ichnology in deep-sea environments in the geological record (Crimes 1973, 1976, 1977; Uchman 2007; Heard and Pickering 2008). Some studies have indicated that in deep-sea deposits diverse environmental parameters and sea-floor conditions also produced a great diversification in the behaviour of different groups of animals (Seilacher 1967, 1974, 1977; Crimes 1974; Uchman 2007). According to some authors, the richness and diversity of deep-sea tracemakers are conditioned by facies distribution, basin morphology and bathymetry, as indicated by the ichnofacies variation (Seilacher 1967; Frey *et al.* 1990; Bromley and Asgaard 1991). Trace fossil diversity is less marked in fine-grained and uniform deep-sea deposits of slope facies (*Zoophycos* ichnofacies) and increases progressively in sandy lobe to distal turbidite deposits of the *Nereites* ichnofacies.

Higher lithological diversity leads often to high diversity in typical groups such as graphoglyptids that are dominant compared to other non-graphoglyptid forms (Seilacher 1977; Uchman 2001; Heard and Pickering 2008). Pre-depositional graphoglyptids, while normally preserved on turbidite soles, typically include trace fossils forming geometric patterns such as meanders, spirals and geometrical nets of various shapes and size (Fuchs 1895); post-depositional non-graphoglyptids, while normally penetrating turbidite beds, comprise all other trace fossils that span the range from simple strings (more or less structured and branched) to plug-shaped forms (Frey and Pemberton 1984; Bromley 1990; Uchman 1995a). Usually graphoglyptids and non-graphoglyptids (considering only pre-depositional forms) are common in the same environment and the preservation of delicate spirals and nets depends not only by physical processes (currents) but also by the intensity of burrowing and bulldozing (Monaco 2008). In fact, an ichnofacies can be a taphofacies and the resultant assemblage can depend on preservational processes before and after casting (Bromley and Asgaard 1991). This is particularly true for the *Nereites* ichnofacies, where graphoglyptids require delicate scouring and casting and very poor destructive burrowing to be preserved at soles of turbidites (Seilacher 1977; Bromley and Asgaard 1991; Monaco 2008).

Another aspect of the *Nereites* ichnofacies is the variation of ichnoassemblages that follows characteristics of sub-environments of the same basin; for this reason some ichnosubfacies have been proposed (Seilacher 1974; Uchman 2001, 2007). The *Ophiomorpha rudis* ichnosubfacies is characterized by post-depositional trace fossils in thick-bedded sandstones of channels and proximal lobes (Uchman 2001), while patterned forms of the *Paleodictyon* and *Nereites* ichnosubfacies occur in sand-dominated and mud-dominated distal flysch deposits, respectively (Seilacher 1974). The typical succession of ichnosubfacies from *Ophiomorpha rudis* to *Paleodictyon* and *Nereites* can reflect a bathymetric trend from shallower to deeper parts of the deep-sea fan systems (Uchman 2007).

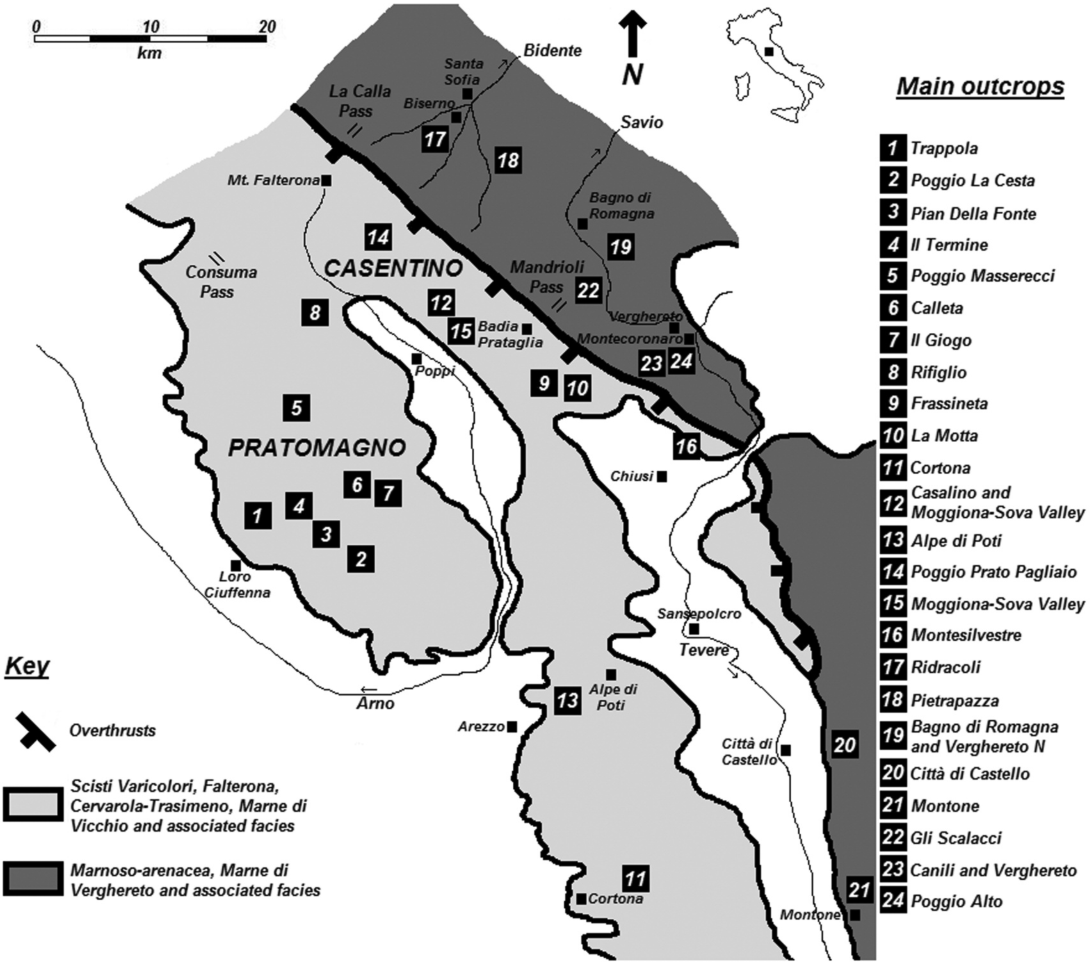
The aim of this paper is to investigate how the proportion of graphoglyptids and non-graphoglyptid burrows has developed in foredeep basins of northern Apennines that were narrow and indented due to tectonics in the Oligocene and Miocene and to analyze how facies variations and lithologic diversity influenced the main ichnocoenoses and ichnosubfacies.

METHODS

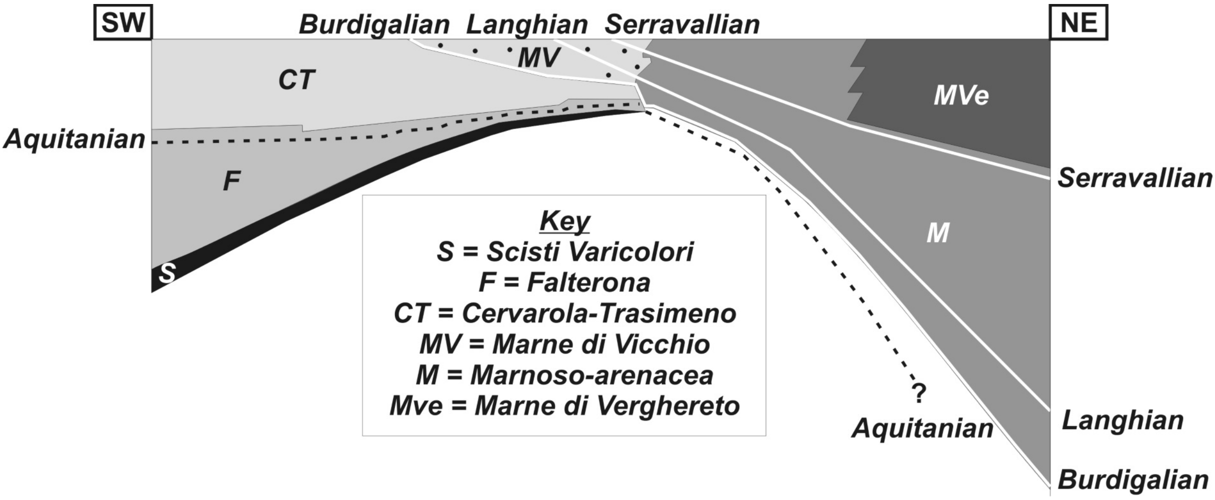
Representative outcrops and stratigraphic sections of deep-marine siliciclastic units of the Northern Apennines were logged (Text-fig. 1) with respect to trace fossil diversity (for taxonomy, see Monaco and Checconi 2008). Trace fossils were studied analyzing their stratinomic position relative to bedding (hypichnia, epichnia and endichnia/exichnia); in particular, trace fossils crossing different lithologies (crossichnia *sensu* Monaco and Caracuel 2007; Monaco *et al.* 2007) or multilayer colonizers (Uchman 1995b), which have very interesting sedimentologic implications, were noted. Individual trace fossils were identified and the percentage of biogenic activity was estimated following semi-quantitative or quantitative methods (Miller and Smail 1997; Heard and Pickering 2008). In the case of very large trace fossils such as *Ophiomorpha, Thalassinoides, Spongeliomorpha, Scolicia* and *Halopoa,* the average of their density on the bed surface was measured semi-quantitatively following the method of Miller and Smail (1997). In other cases, where abundant, minute trace fossils tended to prevail on bedding planes, for instance, delicate plug-shaped graphoglyptids, *Arthrophycus, Parahaentzschelinia* and many other radiate forms, a pure quantitative analysis consisting of placing a 10 × 10 cm grid randomly on the bedding plane and measuring the percentage of trace fossils as the number of 100-cm squares containing significant trace fossils (Heard and Pickering 2008). In the case of post-depositional trace fossils such as *Halopoa, Ophiomorpha* and *Thalassinoides,* the lateral variability and patchiness was also observed (McIlroy 2007). Ichnological observations focused on the type (ichnodiversity) and abundance (ichnodensity) in the different siliciclastic formations from Oligocene to Miocene: Falterona–Cervarola–Trasimeno, Marnoso-arenacea and Marne di Vicchio–Marne di Verghereto units. The stratigraphical and areal distributions of sedimentary facies with diagnostic groups of deep-marine trace fossils, both pre- and post-depositional, were evaluated as the main tool for the characterization of ichnocoenoses in the *Nereites* and *Zoophycos* ichnofacies (Seilacher 2007; Uchman 2007, Heard and Pickering 2008). Trace fossils were studied not only in place but also in samples collected from talus. Over 900 beds were analyzed in total. All ichnotaxa here considered (35 ichnogenera and many ichnospecies, see taxonomic description in Monaco and Checconi, 2008) are reposited in the ICHNOTHECA of the Biosedimentary Laboratory of the Earth Science Department, Perugia University (BSED-IDTB 3.01 database, Monaco and Checconi in press).

GEOLOGICAL SETTING

Flysch deposits of the northern Apennines were formed in a compressional tectonic setting during the Apennine tectogenesis (Merla 1951), which produced the thrust-belt to foredeep system in the late Eocene to Miocene, corresponding to the Africa-Europe collisional phase. The thrust-belt to foredeep system induced by the compressional deformation first involved the African Promontory, and then migrated from west to east with a shifting of foredeep turbiditic basins, from the "Coastal Macigno Basin" to the Chianti Basin to the Cervarola–Falterona–Trasimeno Basin (representing the innermost, intermediate, and outer turbiditic areas of the Tuscan domain, respectively) to the Marnoso-arenacea Basin (Umbrian–Marchean Domain) and to other external basins (intra-Apenninic basins, Laga and Cellino basins, Periadriatic Domain) (Centamore *et al.* 2002, and cited papers; Milighetti *et al.* 2009). From the Oligocene to early Pliocene, the thrust-belt system shifted eastward and incorporated increasingly external sectors of the foreland; in this phase, synsedimentary tectonics were intense in the Tuscan and in the Umbrian–Marchean domains and some ridges evolved to become intrabasinal highs, some with neritic sedimentation and locally also volcanic deposits (Centamore *et al.* 2002). The foredeep basins are characterized by wide, NNW-SSE oriented longitudinal depressions in which a poorly extensive basin plain developed due to the presence of many tectonically induced intrabasinal ridges. Within these depressions, slope to submarine fan-plain basin depositional systems (*sensu* Mutti and Ricci-Lucchi 1972) developed; siliciclastic materials are represented by thinning-upward (mainly medium- to fine-grained) sequences of gravity flow deposits and mixed (siliciclastic and carbonate) turbidite sequences (Ricci-Lucchi and Valmori 1980; Ricci-Lucchi 1981; Abbate and Bruni 1987; Amorosi 1987; Delle-Rose *et al.* 1990; Landuzzi 1991; Centamore *et al.* 2002; Plesi *et al.* 2002; Lucente 2004). The main arrangement of these deposits consists of lenticular sandy bodies that are indicated as inactive and active lobes (*sensu* Einsele 1991). These siliciclastic deposits, in Cervarola–Falterona–Trasimeno Basin and in Burdigalian Marnosoarenacea Basin of the inner Romagna–Umbrian area, are mixed with calcareous turbidites with neritic bioclasts (Boccaletti *et al.* 1986; Centamore *et al.* 2002). Siliciclastic sediments derived primarily from Alpine sources (NNW), whereas clastic carbonates derived mainly from southern areas (SSE). Regional sources are intrabasinal highs and Apenninic



Text-fig. 1. The study area and location of the 24 studied sections



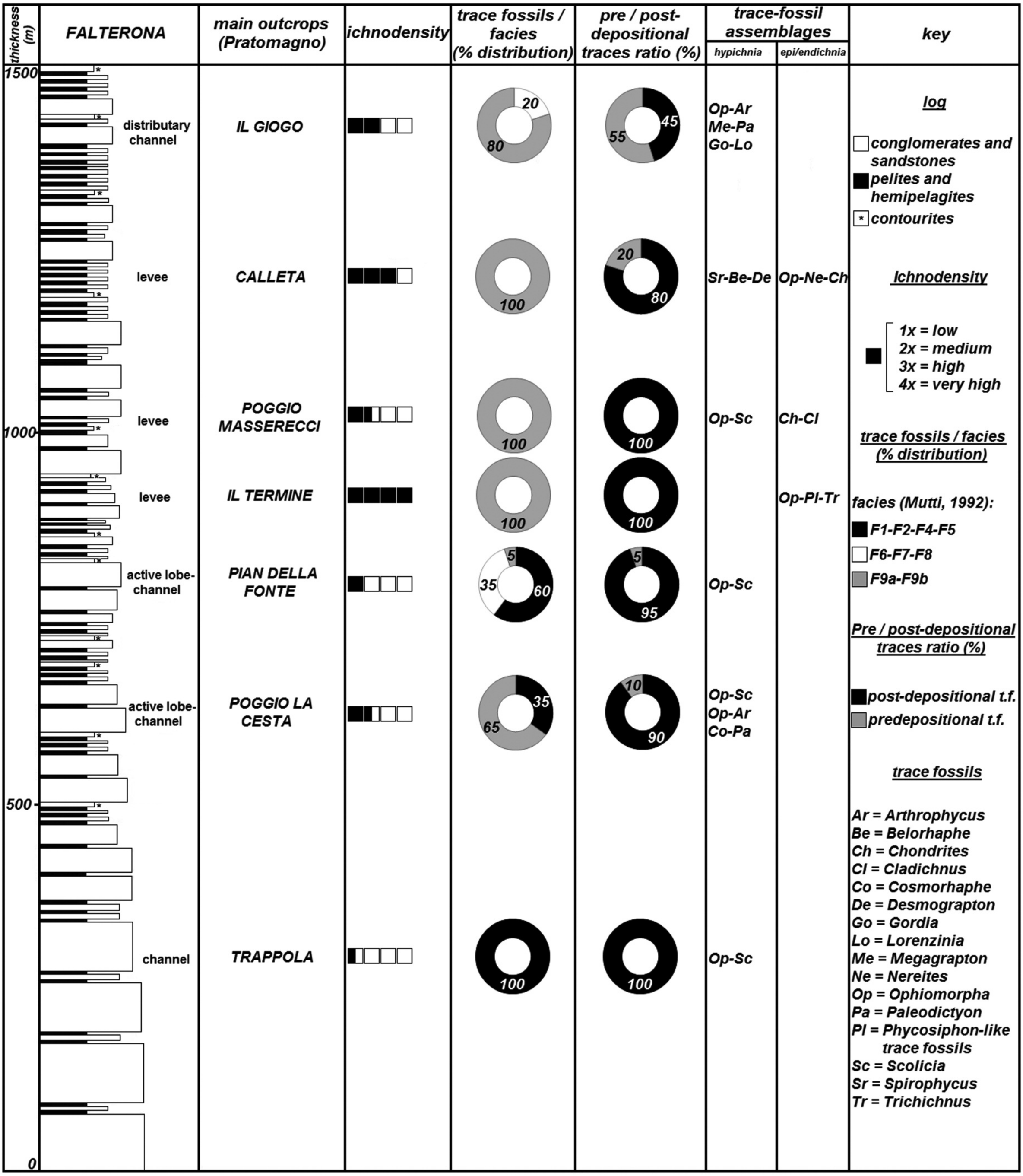
Text-fig. 2. Stratigraphic relationships of the Oligocene–Miocene turbiditic units in northern Apennines

Platform areas (Bruni and Pandeli 1980; Valloni and Zuffa 1984; Costa *et al.* 1997). During the late and post-orogenic phase, in response to the migration of thrust to belt-foredeep system, some orogenic domains were isolated and received only fine-grained and pelagic material ("clay plugs" such as Marne di Vicchio, Marne di Verghereto and others, see Centamore *et al.* 2002); these domains were directly controlled by the thrust activity and rise forming piggyback basins (Ori and Friend 1984) and wedge-top basins (Conti *et al.* 2008).

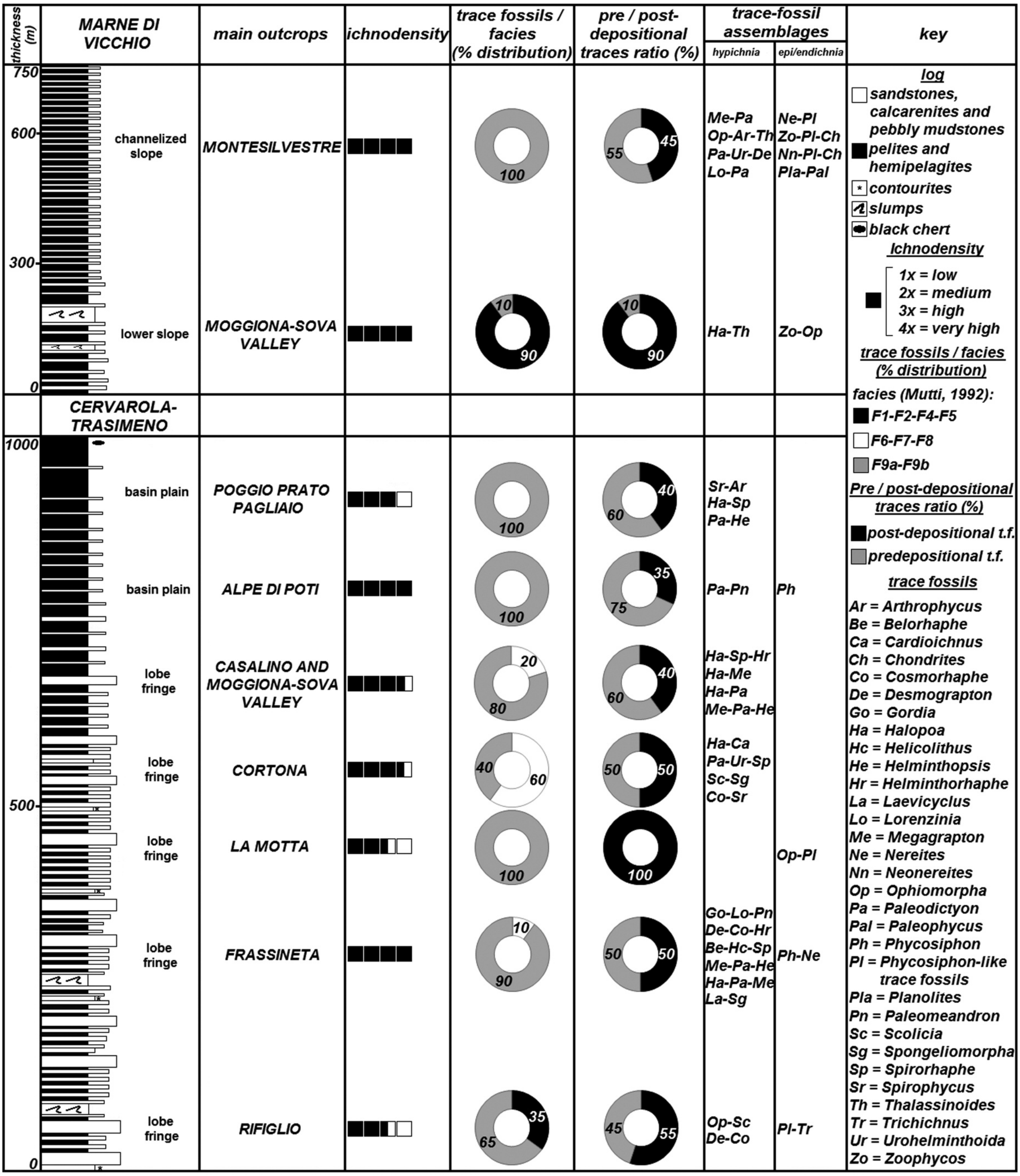
In the study area, from Pratomagno ridge to the Casentino area (Text-fig. 1), the western Falterona–Cervarola–Trasimeno structural unit of the Tuscan Domain (mainly Aquitanian–Langhian) is succeeded by a southwest-dipping thrusts displaying a leading imbricate geometry, up to the Monte Nero and Poggio Castellaccio structural sub-units of inner Marnoso-arenacea (mainly Langhian–Serravallian), that are autochthonous deposits of the Romagna–Umbrian Domain (Text-fig. 2). Marne di Vicchio and Marne di Verghereto units (probably post-Serravallian) are disposed on the top (Text-fig. 2). The Scisti Varicolori unit (Villore Member), composed primarily of incompetent varicoloured shales (S in Text-fig. 2), represents the décollement level of this important tectonic feature (Guenther and Reutter 1985; Bally *et al.* 1986; De-Feyter *et al.* 1986; Boccaletti *et al.* 1990; Abbate *et al.* 1991; Cipriani *et al.* 1993; Pandeli *et al.* 1997).

SEDIMENTARY FACIES

Twenty-four stratigraphic sections were studied in detail (Text-fig. 1), the deposits being late Oligocene to middle–late Miocene in age. They exhibit siliciclastic deposits of Falterona–Cervarola–Trasimeno units, marly beds of the Marne di Vicchio unit (about 3250 m thick) and turbiditic or hemipelagitic material of the Marnoso-arenacea and Marne di Verghereto units (about 2650 m thick) (Text-figs 3–5). Idealized stratigraphic sections (Text-figs 3–5) show a gradual decrease upwards of the sand:mud ratio and a slight increase of the carbonate supply into the Tuscan successions from lower part of the Falterona to upper part of the Cervarola–Trasimeno, and from Marnoso-arenacea to Marne di Vicchio or Marne di Verghereto units (Milighetti *et al.* 2009). The carbonate content shows no appreciable variation in the lower part of the Marnoso-arenacea unit, but typical carbonate turbidites occur as important marker levels (Ricci-Lucchi 1981) in the middle to upper part of the formation (Contessa and Colombine beds; Text-fig. 5). The Falterona unit, mainly found in the westernmost sector of Tuscany (Trappola section in the Pratomagno ridge), consists for the most part of very thick-bedded, medium-grained turbidites of channelized lobes (attached fan, *sensu* Einsele 1991), that are generally high-efficient flow deposits with traction carpets that are organized in thinning- to thickening-upward sequences. Deposits of channels, levee and active fan lobes have been recognized (Text-fig. 3). The thinning-upward trend can be observed in the upper part of the Falterona unit (Calleta, Il Giogo sections). The Cervarola–Trasimeno units are represented by irregularly bedded turbidites of channelized and non-channelized lobes (detached lobes, *sensu* Einsele 1991), lobe-fringe deposits (bundles of thick and thin beds in the same outcrop, e.g. Cortona, Rifiglio, Frassineta sections) and basin plain deposits (Poggio Prato Pagliaio section) (Text-fig. 3). Thick marlstone intervals (up to 250 m) with sporadic thin-bedded turbidites (lobe-fringe) of the lower slope or proximal interfan were observed in the Marne di Vicchio unit (Montesilvestre section; Text-fig. 4). The overall stacking pattern of the Marnoso-arenacea formation records a gradual transition from typical channelized and non-channelized fan lobes with inter-lobes and overbank deposits of active fans (Ridracoli–Pietrapazza, Mandrioli NW-Bagno di Romagna), to lobe-fringe (Montone–Città di Castello) and distal detached lobes that evolved gradually to typical basin plain deposits (Gli Scalacci of Mandrioli Pass, Verghereto N) (Text-fig. 5). Basinal slump deposits found in the upper part of the sequence (Gli Scalacci) are probably tectonically induced products of the remobilization of intra-

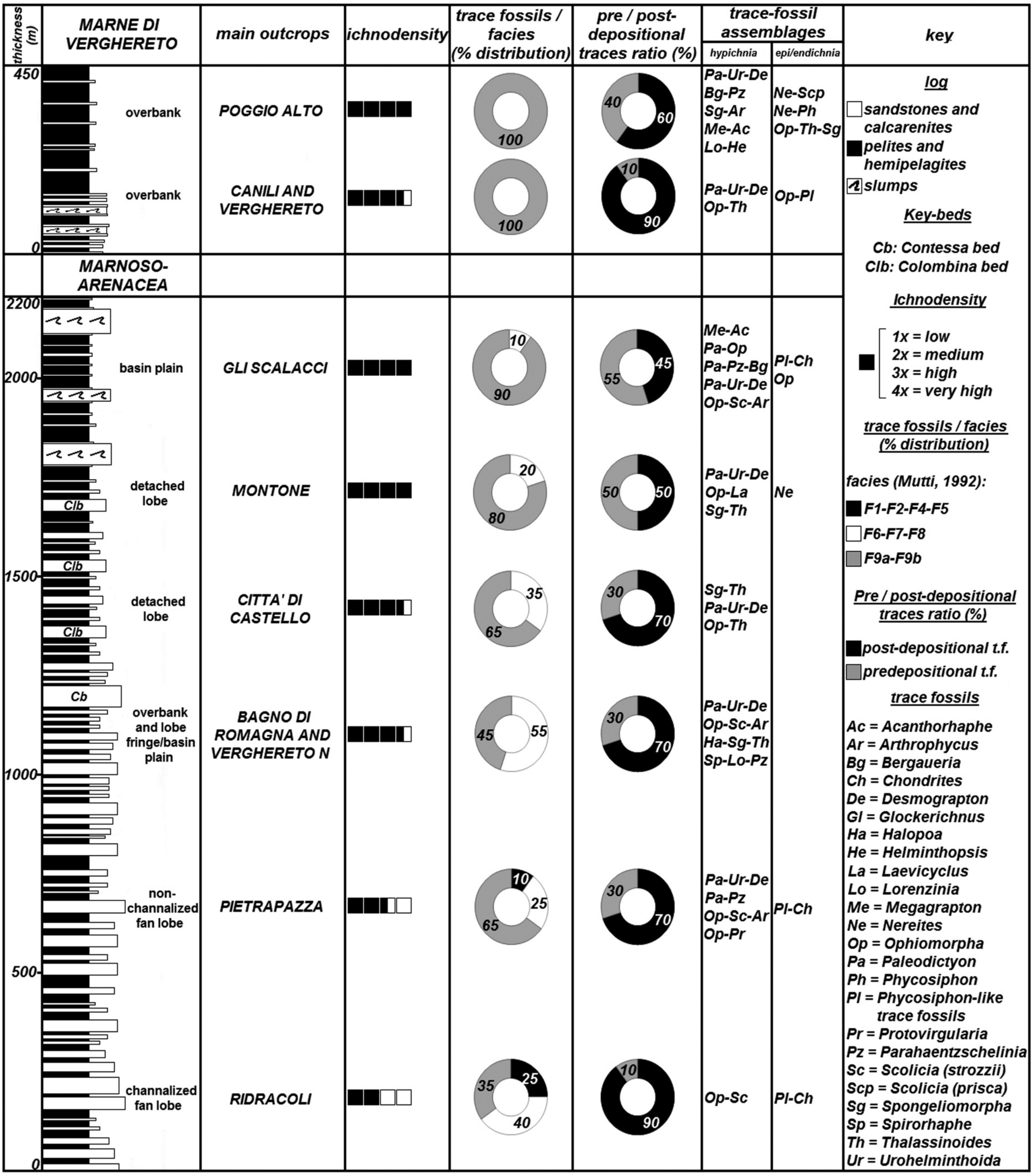


Text-fig. 3. The trace fossil characteristics of the Falterona unit: ichnodensity, semi-quantitative estimation of pre- and post-depositional ichnoassemblages and relationships with facies and stratinomy basinal muds (Text-fig. 5) or produced by other processes (see Lucente 2004). Very interesting is the gradual transition from non-channelized detached lobes, where turbidity currents were not affected by submarine channels with their levee deposits, to distal basin plain deposits (Einsele 1991, fig. 8). While observable for more than 20 km along the Tiberina road (upper Savio valley, from Bagni di Romagna to Verghereto village), turbidite beds show a progressive reduction in thickness, and facies change progressively in terms of proximal-distal trend (Monaco 2008) (Text-fig. 6). The overbank deposits of Poggio Alto section (Marne di Verghereto unit) probably were produced by a lateral dispersion of sand of (distal detached?) lobes,

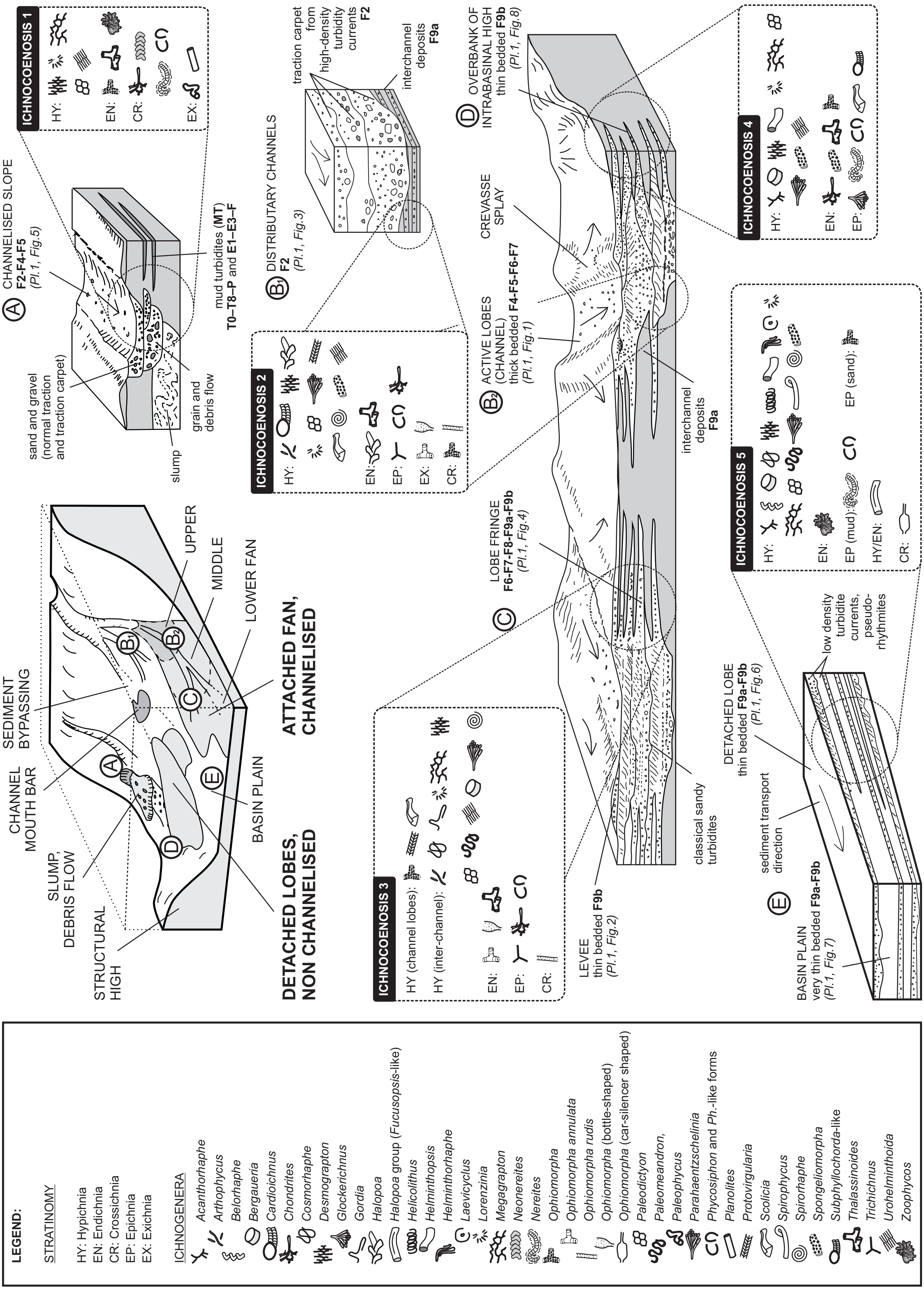


Text-fig. 4. The trace fossil characteristics of the Cervarola–Trasimeno and Marne di Vicchio units: ichnodensity, semiquantitative estimation of pre- and post-depositional ichnoassemblages and relationships with facies and stratinomy in the marly complex of the Verghereto High (over 450 m thick marls), that are no longer preserved. These cm-thick sandy turbidites are notable for their content of epichnia that were formed by organisms utilizing the abundant benthic food transported by currents beside an intrabasinal high (Verghereto), as some taphonomic features probably indicate (Monaco 2008).

Turbidites and turbidite facies were classified by using the model of Mutti (1992), who defined different deposits of a hypothetical tract-system facies arrangement produced by a specific parent flow. Flow transformations in a down-current direction (proximal-distal trend) lead to the deposition of facies assemblages that are characterized by different grain size, textural organization, fabric, specific internal sedimentary structures and scour marks (Mutti and Ricci-Lucchi 1972;



Text-fig. 5. The trace fossil characteristics of the Marnoso-arenacea and Marne di Verghereto units: ichnodensity, semiquantitative estimation of pre- and post-depositional ichnoassemblages and relationships with facies and stratinomy



Text-fig. 6. Ichnocoenoses distribution along a hypothetical deep-sea channelized fan system, northern Apennines

Shanmugam and Moiola 1985; Einsele 1991; Mutti 1992). Mainly on the basis of grain size and textures, different facies were found in the study area (Text-fig. 6A–E) and were subdivided into four groups:

Very coarse-grained facies (VCGF: F1-F2): F1 are cohesive debris flow deposits (such as olistostromes) characterized by large clasts (boulders, cobbles or pebbles) floating in a muddy matrix. F2 consist of mud-supported conglomerates and coarse-grained sandstones with various levels of internal organization (e.g. traction carpets) and deep basal scours. They are typical of the channelized, proximal slope but occur also in intermediate slope settings (Text-fig. 6A–B1). Large rip-up mudstone clasts may be common at the base of the beds. F2 is interpreted as produced by hyperconcentrated flows (sand or mud), producing sandy or muddy megabeds.

Coarse to medium-grained facies (CMGF: F4-F5-F6): F4 and F5 are high-density turbidity current deposits, mainly on channelized, proximal slopes, but also occur in active lobes and channels (Text-fig. 6A–B2). The former are characterized by thick traction carpets; the latter are lacking in internal structures (with the exception of fluid escape structures at the top of the bed). F6 are medium to coarse-grained and well-sorted facies. Internal sedimentary structures such as thin traction carpets and ripples (or large megaripple bedforms) at the top of the bed, are very common. These irregularly bedded facies are very common in active lobes with channels (Text-fig. 6B2).

Medium to fine-grained facies (MFGF: F7, F8, F9a, F9b): F7 and F8 sediments are represented by medium- to fine-grained deposits produced by sandy, high-density turbidity currents. The difference between F7 and F4 deposits (as well as F8 and F5) is the smaller grain size of the former, whereas internal sedimentary structures are the same. F8 deposits correspond to the *a* division of the Bouma sequence. F7 and F8 are typical of lobe fringe areas (e.g. Cortona) (Text-fig. 6C).

F9 deposits are produced by low-density turbidity currents, mainly through traction-plus-fallout processes. F9 is subdivided in two types, F9a and F9b, following Mutti (1992). F9a comprises fine-grained deposits that correspond to base-missing Bouma sequences (Tb-c, Tc-e, Td-e and Te). F9b deposits differ from F9a because of their internal organization and grain size (structureless intervals, composed of coarse to fine sand with superimposed ripple bedforms). F9b is thought to represent an immature expression of deposition from low-density turbidity currents (small-volume flows, proximal and marginal environments), whereas F9a beds are produced by large-volume flows rich in suspended fine sediments (distal and open environments, such as fan-fringe, distal detached fan lobes and basin plain deposits). These facies are typical of distal and marginal environments, such as overbank of lobe fringes (Text-fig. 6C), intrabasinal highs (Text-fig. 6D) and detached lobes-basin plain (Text-fig. 6E).

Very fine grained facies (VFGF): Very fine grained (mud) turbidites (MT in Pl. 1, Fig. 5; Text-fig. 6A) are silty to muddy deposits that exhibit the typical mud sequence T0–T8–P and E1–E3–F (Stow and Piper, 1984a, b; Walker, 1984). The transition from fine sand, 1–3 cm thick, or silt-mud is sharp, as observed typically in some dark rhythmic deposits in the channelized intermediate slope of the Montesilvestre Member of Marne di Vicchio unit. They represent extremely diluted deposits produced by deposition of suspended, very fine sediment that reached hemipelagic, marginal environments, e.g. levees or overbank deposits in slope (Text-fig. 6A) and other distal environments (e.g. basin plain).

ICHNOCOENOSES

In the study area five ichnocoenoses (IC in Text-fig. 6) have been distinguished.

Ichnocenosis IC 1

General characteristics: Slope and proximal interfan deposits with gravity-induced slumps and turbidites (Facies F2–F5 and mud turbidites MT): *Zoophycos-Nereites* ichnocoenosis with rare graphoglyptids (Text-fig. 6A).

Sedimentology: The slope and proximal interfan areas are represented by thick marly deposits (hemipelagic muds), up 300 m thick, that show gravity-induced chaotic intervals (slumps), and coarse-grained turbidites of F2 and F5 facies (Text-fig. 6A). Typical debris and grain flow deposits are present in channel axes (Lowe 1982, Einsele 1991, Mutti 1992). Thin-bedded mud turbidites may occur typically as overbanks of sand and gravel channelized deposits in proximal interfans of slope areas (Montesilvestre, Text-fig. 6A). They form rhythmic levels, 3–5 cm thick, of graded silt to mud from base to top. All these sediments can be found mainly in the lower part of the Marne di Vicchio unit at Moggiona (Lama Member) and Montesilvestre sections (Montesilvestre Member).

Ichnology: In the Marne di Vicchio unit a low-diversity and low-density trace fossil assemblage occurs that consists of large endichnial forms, up to 130 cm wide, of the *Zoophycos* group (Olivero and Gaillard 2007). Occasionally *Thalassinoides suevicus* and

Ophiomorpha annulata are present (Moggiona and Montesilvestre sections) (Text-figs 4, 6A). In the Moggiona marls large *Zoophycos* exhibits a slightly oblique marginal tube (last gallery inhabited by the worm-like tracemaker); here menisci, which correspond to the sections of primary lamellae, are seldom preserved and the concavity trend indicates the shifting direction of the lamina (Olivero and Gaillard 2007). The marginal tube is darker than the host sediment and occurs with a very high density of specimens (3–5 m^{-2} at Moggiona section; Pl. 2, Fig. 7). The upper surface of marl beds of the Montesilvestre Member exhibits *Zoophycos* all having a subcircular marginal tube that forms the outer border of the whole spreite of primary lamellae. Laminae are spirally coiled around a vertical central axis forming a conical trace with an apex that points upwards. Large *Zoophycos* are very abundant also in similar muddy deposits of the eastern Umbrian system such as the lower Miocene Bisciaro Formation, where volcaniclastic deposits have been found (Amorosi *et al.* 1994). As hypichnia in turbidites of Marne di Vicchio unit, some graphoglyptid specimens are present (locally abundant), only in the Montesilvestre section but none at Moggiona: *Desmograpton dertonensis, Lorenzinia* cf. *plana* (and other plug-shaped forms), *Megagrapton submontanum, Urohelminthoida* (*U. dertonensis* and *Urohelminthoida* isp.), and medium- to large-sized *Paleodictyon* (mainly *P. hexagonum* and *P. majus*) (Text-fig. 6A). Other exichnial forms are rare: *Planolites* (*P.* cf. *beverleyensis*) and *Palaeophycus* isp. Epichnial preservation of the *Nereites* group (*Nereites missouriensis* and *Neonereites* preservation, Uchman 1995a) characterizes many calcarenitic beds. Meandering and bulging forms very similar to "*Neonereites*" figured by Uchman (1995a, fig. 8) and Chamberlain and Clark (1973, fig. 5, pl. 1, fig. 4) are locally very well preserved in sandy beds and their ichnodensity may be high (3–5 specimens up to 40 cm long m^{-2}) (Pl. 3, Fig. 10). Other epichnia of mud overbank turbidites are *Chondrites* (*C. intricatus* and *C. targionii*) and *Phycosiphon*-like trace fossils. In other cases mud turbidites are so intensely bioturbated that they appear mottled (Monaco and Uchman 1999; Uchman 2007).

Ichnocenosis IC 2

General characteristics: Fan lobes and channels, thick-bedded high-density turbidite flow deposits (Facies F2–F7): *Ophiomorpha rudis*-*Scolicia strozzii* ichnocoenosis with sporadic large graphoglyptids (interchannel) (Text-fig. 6B1–2).

Sedimentology: Depositional lobes represent the most common type of thick-bedded sand fill of the foredeep basins in the northern Apennines and correspond to the maximum extent to which the NW-SE oriented sand was transported into the basin (Ricci-Lucchi 1981, Mutti and Normark 1987, Mutti 1992). Beds, 150-450 cm thick, were produced by high-density turbidite current flows, and can be ascribed mainly to F4–F7 facies assemblages of Mutti (1992) (Text-fig. 6B2). Lobes are the main sand bodies (up to 80%) of the siliciclastic sediments in the investigated foredeep basins (the sand:mud ratio up to 8:1), which are organized in thinning- to thickening-upward sequences (e.g. Pian della Fonte and Poggio Masserecci sections, Pratomagno Ridge) (Pl. 1, Fig. 1). Sediments consist of immature arenites, calcarenites and micro-conglomerates with heterogeneous intraclasts, igneous, metamorphic and sedimentary rock fragments and locally abundant plant remains. Debris flow deposits (F2 facies) have been found as channel axis fills in intermediate slope (Il Giogo section; Pl. 1, Fig. 3; Text-fig. 6B1). Lobe deposits usually are massive, irregularly bedded and structureless (rarely graded), but some thick beds, up to 150 cm in thickness, show tractional laminae due to the reworking action of contour currents (Mutti 1992), as observed in the Pratomagno area. Dark gray hemipelagic mud of interlobe, 30–350 cm thick, is locally intercalated with F9b sandy turbidites (e.g. Poggio Masserecci and Pian della Fonte sections, Pl. 1, Fig. 1). Thick-bedded channelized lobes are typical of inner allochthonous units that crop out in Tuscany (e.g. Falterona unit of ENE of Pratomagno Ridge) involved in eastward thrusting over the Marnoso-arenacea and associated facies (Costa *et al.* 1997).

Ichnology: Pre-depositional ichnotaxa are poorly preserved due to erosion by highly efficient flow processes and very rapid sedimentation. In all truth, the traction carpets, large groove casts and high sand:mud ratio of facies F2–F7 are not ideal factors for the preservation of pre-depositional ichnoassemblages (Monaco 2008). At the channel-lobe transition, between relatively high-gradient channelized flow and the gentler gradient at the beginning of the depositional lobe, turbidity currents may suddenly change from rapid to tranquil flow, creating a hydraulic jump accompanied by increased turbulence and expansion and dilution of the flow; the sea bed is marked by large-scale scour features and rapid deposition of sand (Einsele 1991). All these processes reduce the record of graphoglyptids, which are common but delicate structures made by pre-depositional mud dwellers (Seilacher 1977; Kern 1980; Uchman 2007). Only rarely in interchannel deposits of proximal lobes (Text-fig. 6B1; Pl. 1, Fig. 2) are some large graphoglyptid specimens preserved as hypichnial semirelief in F9a turbidites: *Cosmorhaphe* (mainly *C. sinuosa*), *Urohelminthoida* (mainly *U. appendiculata* and *U. derto-*

nensis), *Paleomeandron* (mainly *P. elegans*) and *Megagrapton* (mainly *M. submontanum*) (Text-fig. 6B1). When multidirectional scours and large grooves (up to 60 cm wide) are present in channel-lobe deposits of Miocene turbidites, trace-makers adapted to rework turbiditic sand (post-depositional) are active scavengers, producing bulging and meandering burrows. In general, the burrowing organisms were probably crustaceans, spatangoid echinids and locally also bivalves (Seilacher 2007; Uchman 2007), as represented here respectively by the most important trace fossils: *Ophiomorpha* (mainly *O. rudis*), *Scolicia* (mainly *S. strozzii* and *S. magna*) and *Protovirgularia* (mainly *P. vagans* and *P. obliterata*) (Pl. 2, Figs 2, 4, 5, Text-fig. 6B2). *Scolicia* is common in very thick beds (3–5 m of Poggio La Cesta, Poggio Masserecci, Pian della Fonte of Pratomagno Ridge, Falterona unit) (Pl. 2, Fig. 4). Hypichnial *Ophiomorpha* (formerly *Granularia* and *Sabularia*) cross grooves, flute casts and frondescent marks in the Bagno di Romagna section. Knobby bulges produce irregular thickening of burrow diameters, and locally branches are very short and end where they cross groove casts (Pl. 2, Fig. 2). Epichnial trace fossils are rare; in muddy deposits some *Trichichnus, Chondrites* and *Phycosiphon*-like forms have been found, while in sandy bed-top settings only *Ophiomorpha* specimens are present (Il Termine and Calleta sections, Pl. 2, Fig. 3). In interlobe muddy deposits endichnia and crossichnia (Monaco and Caracuel 2007; Monaco *et al.* 2007) are preserved: bottle-shaped with knobby surface (*Macanopsis* isp.) (Canili section, Pl. 2, Fig. 8), *Ophiomorpha rudis* (Montone), *O. annulata* (Bagno di Romagna). In cross-section the horizontal tunnels of exichnial *Ophiomorpha* are circular, indicating cementation before burial (Caracuel *et al.* 2000), and subquadrate forms of undetermined trace fossils (crossichnia, Monaco *et al.* 2007) are present as well. In inter-channel deposits of the Il Giogo section (Falterona unit), the trace fossil assemblage consists of *Arthrophycus strictus, Lorenzinia pustulosa* and *Gordia marina* and shows a very reduced amount of graphoglyptids, sporadic *Megagrapton submontanum* and minute *Paleodictyon* (*P. majus*) have been found (Text-fig. 6B1).

Ichnocenosis IC 3

General characteristics: Lobe-fringe and channel-fringe deposits, medium-bedded, high- to low-density turbidites (Facies F6–F9a-b): *Scolicia–Spongeliomorpha–Arthrophycus–Paleodictyon* ichnocoenosis, other graphoglyptids rare (Text-fig. 6C).

Sedimentology: Lobe-fringe deposits (usually poorly channelized) can be found in some sections and the variety of trace fossils depends on the erosive power of turbidity currents and the activity of mud dwellers. The main characteristic of lobe-fringe and channel-fringe deposits is the minor thickness of sand bodies respect to IC2, with strong irregularity in the bedding and sharp facies variation: bundles of thick-bedded F6–F7 sandy beds and thick marls are randomly intercalated in the same outcrop with sets of thin-bedded F8–F9a and F9b beds (Text-fig. 6C). Typical lobe-fringe deposits are those of Cortona (Trasimeno-Cervarola units; Pl. 1, Fig. 4), Mandrioli, Bagno di Romagna, Montone-Città di Castello sections (Marnoso-arenacea unit), where channel-and lobe-fringe deposits show peculiar ichnocoenoses (Text-figs 3–5, 6C).

Ichnology: Typical forms at soles of well cemented, mainly thick-bedded but also medium-bedded calciturbidites are hypichnial *Scolicia* (mainly *S. strozzii* and *S. magna*), which appear as long or meandering semi-reliefs having a bulge at the end that can be very similar to *Cardioichnus* isp. (Monaco *et al.* 2005); other cylindrical string-shaped forms are *Spongeliomorpha sublumbricoides, Protovirgularia obliterata* (Pietrapazza, Pl. 2, Fig. 5) and *Arthrophycus* (mainly *A. strictus*). Usually the concentration of *Arthrophycus* does not correspond with other ichnogenera; the maximum density of *Spongeliomorpha* (with 8–10 specimens in the same bed) occurs in the High-Savio valley (north of Verghereto), while the highest density of *Arthrophycus* (up to 70 traces m^{-2}) occurs in the southern Bagno di Romagna in medium-thick beds. *Desmograpton* (mainly *D. dertonensis, D. ichthyforme*)*, Urohelminthoida* (*U. dertonensis* and *U. appendiculata*), *Spirorhaphe* (mainly *S. involuta*), and other rosette or plug-shaped trace fossils (*Bergaueria, Lorenzinia, Parahaentzschelinia*) are also common (Text-fig. 6C). A typical graphoglyptid assemblage is the net-shaped group of large *Paleodictyon hexagonum* (and *P. majus*), which is very abundant in the Marnoso-arenacea of the Savio and Tiber valleys (e.g. Canili of Verghereto, Montone, Città di Castello). On the soles of medium-bedded turbidites *P. hexagonum* can be very wide (a single specimen can reach 130 × 100 cm) and shows shafts and mesh (with different mesh levels) that are stretched and deformed (Monaco 2008). Frequently many endichnia occur, including branched *Thalassinoides suevicus* and crossichnia (Monaco *et al.* 2007) such as *Ophiomorpha rudis* in lobe-fringe deposits (Città di Castello, Montone, Verghereto).

Ichnocenosis IC 4

General characteristics: Overbank cm-thick turbidites (mainly F9b Facies) fringing intrabasinal highs (with thick mud deposits): *Scolicia prisca-Glockerichnus* (epichnia), hypichnial uniramous-biramous and rosette to plug-shaped graphoglyptid ichnocoenosis (Text-fig. 6D).

Sedimentology: Overbank deposits are thin-bedded sandy turbidites that probably represent marginal (often lateral and distal) products of main sand bodies wedging out intrabasinal highs (e.g. Verghereto, Text-fig. 6D). These deposits exhibit a high trace fossil diversity, but the ichnofabric is poorly known though many ichnogenera and ichnospecies can be identified (Wetzel and Uchman 1997). Overbank deposits consist of very thin beds that were deposited laterally from the main sandy input of channelized areas and active depositional fan systems (Einsele 1991). Overbank beds were formed usually by low-density sandy turbidity currents, typically cm-thick bedded yellow calcarenites of F9b facies (very rare F9a, Tb-c intervals). They are sporadically interbedded with thick hemipelagic muds which consist of gray marls, up to 450 cm thick in the Verghereto High (Pl. 1, Fig. 8), and probably up to 300 cm in the Biserno area. Thin-bedded mud turbidites, which may occur typically in overbank deposits (Einsele 1991), are very rare, while occurring in other portions of the lower slope of Verghereto structural high (not considered here) with gravity-induced mass flow deposits (slumps and mud flows). Overbank beds are ichnologically interesting because rippled sands up to 6 cm thick, and that gradually pass into a very thin muddy interval (1–2 cm thick), are strongly deformed by intense biogenic activity (Poggio Alto section, Montecoronaro; Monaco 2008, fig. 6).

Ichnology: Beds show hypichnial, endichnial and epichnial guilds with the highest ichnodensities encountered in all studied facies (>50 specimens m^{-1}) (Text-fig. 6D). Hypichnial communities are dominated by the biramous graphoglyptid *Desmograpton* (*D. dertonensis* and *D. ichthyforme*), which is very common throughout the Montecoronaro–Poggio Alto area. Other forms are the uniramous meander *Urohelminthoida* (mainly *U. dertonensis*), rosette and plug-shaped *Bergaueria, Lorenzinia, Parahaentzschelinia,* and net-shaped *Paleodictyon* (*P. hexagonum, P. majus, P. minimum, P. strozzii*). In overbank deposits *Paleodictyon* has the maximal ichnospecies diversity. Other forms are uncommon: *Acanthorhaphe, Megagrapton,* and some string-shaped *Helminthopsis* and *Spongeliomorpha*. The exceptional preservation of a large, readily accessible upper surface (exposed for ~40 m^2) exhibits a great epichnial ichnodensity. The epichnial community is formed by meandering hyporeliefs of *Nereites missouriensis, Scolicia prisca, S.* cf. *vertebralis*, *Psammichnites* – like trace fossils and radiate or irregular forms that can be ascribed to *Glockerichnus* isp. A (large and radiate) and *Phycosiphon hamata*. Many other undescribed trace fossils (e.g. *Phycosiphon*-like) are present but require further analysis (Monaco and Checconi 2008). The density of *Scolicia prisca* is very high (approximately > 10 specimens m^{-2}). Many of these forms can be analysed by observing taphonomic features of the sea-floor: crossing and deformation (squeezing and bulldozing, Monaco 2008). Burrowing at the top of turbidite was locally so intense that many burrows were destroyed, and the ichnodensity is so high that a mottled fabric resulted (Monaco and Uchman 1999; Wetzel and Uchman 2001). Endichnial forms are both string-shaped and branched forms such as *Halopoa, Spongeliomorpha, Thalassinoides* and *Ophiomorpha*.

Ichnocenosis IC 5

General characteristics: Distal detached lobe of basin plain, pseudo-rhythmites with thin-bedded, fine-grained turbidites (Facies F9a–F9b): *Nereites–Phycosiphon–Halopoa* ichnocoenosis with abundant graphoglyptids (Text-fig. 6E).

Sedimentology: Distal detached lobes of basin plain consist of regularly thin-bedded, sandy to muddy deposits (hemipelagic muds) and calcarenites (Text-fig. 6E). The most important feature of such studied deposits is the rhythmic arrangement between marl and sand beds that can be called pseudo-rhythmites (Ricci-Lucchi and Valmori 1980; Ricci-Lucchi 1981). Such typical pseudo-rhythmic deposits include thin-bedded marls and regularly spaced, laminated thin sands (usually 10–20 cm thick) that show usually the final Bouma intervals (Tc-e) (Pl. 1, Fig. 7; Text-fig. 6E) of F9a turbidites (Ricci-Lucchi 1981; Mutti 1992). The pseudo-rhythmic arrangement of marls and sands in the basin plain probably was controlled primarily by orbital precessional events that influenced facies distribution (and ichnologic preservation) in deep-water environments. The fluctuation of lithologic composition is complicated by interactions of water motions on the sea-floor (turbiditic flows and bottom currents) that influenced turbiditic preservation in distal environments; in order to clarify the depositional setting of these pseudo-rhythmites a detailed study of flysch rhythms is fundamental and further study is needed (e.g. redox oscillations in the substrate; Grippo *et al.* 2004). Commonly, sands reworked by bottom currents are present in the Verghereto area and thin beds (F9b facies), with a higher sand:mud ratio and ripples (bottom-top, unbioturbated), replacing convolute laminae of Tc interval (bioturbated). This is significant for ichnologic variability.

Ichnology: In the Calleta section (Falterona unit), hypichnial graphoglyptids are rare. *Desmograpton* (*D. dertonensis*) is the dominant trace fossil; other trace fossils are *Spirophycus bicornis* and *Belorhaphe zickzack* that are typical of distal detached lobe beds. Epichnial specimens are meandering forms of the *Nereites* group: *Nereites irregularis* and *N. missouriensis* are very common in silty-muddy gray level at the top (Te Bouma interval?) (Frassineta and Calleta sections, Pl. 3, Fig. 9). When the top of F9a turbidites is sandy (Tc Bouma interval or ripples of F9b), epichnial *Ophiomorpha* (horizontal and regularly branched) replace *Nereites* and become ubiquitous in sand, crossing horizontally the sand ridges of ripples (Calleta and La Motta sections) (Text-fig. 6E; Pl. 2, Fig. 3). In the Frassineta section of the Cervarola unit and in the Gli Scalacci section of Marnoso-arenacea, which are rich in ichnofauna, the detached lobe of basin plain environment shows a very rich hypichnial, endichnial and epichnial assemblage (Text-fig. 6). The hypichnia are dominated by *Acanthorhaphe* isp., *Belorhaphe zickzack, Cosmorhaphe sinuosa, Desmograpton dertonensis, Helicolithus* isp., *Helminthopsis tenuis, Helminthorhaphe japonica, Laevicyclus mongraensis, Lorenzinia pustulosa, Megagrapton submontanum, Paleomeandron transversum, Spirorhaphe involuta, Spongeliomorpha sublumbricoides;* other plug-shaped and pit-shaped trace fossils (*Bergaueria, Parahaentzschelinia*) are rare. Medium- and small-sized *Paleodictyon* are very abundant (*P. majus* and *P. minimum*) and in some beds meshes show typical features of very distal turbidites (Monaco 2008). In some thin intervals of the Cervarola unit (Alpe di Poti, Arezzo area), a very high concentration of *Paleodictyon minimum* (15–20 specimens m^{-2}) has been found with peculiar taphonomic features of the mesh (mainly unidirectional elongation) produced by the tracemaker under current action (Monaco 2008, Monaco and Checconi 2008). Another typical trace fossil community of detached lobes is the variations in the aspect of *Ophiomorpha* that sharply changes its shape and diameter of tunnels crossing obliquely many beds (Gli Scalacci section of Mandrioli Pass, Marnoso-arenacea; Pl. 2, Fig. 1). In the Cervarola unit the hypichnial-endichnial assemblage is dominated by post-depositional sand dwellers that produced the *Halopoa* group (formerly *Fucusopsis*) that is very abundant in some intervals (8–10 specimens dm^{-2} at Frassineta; Pl. 2, Fig. 6). *Halopoa* shows a typical burrowing technique (like that of asterosomids) of radial backfill in which the material of the tunnel walls is pressed radially outward or stowed away by the animal, producing elongate longitudinal fractures (Seilacher 2007). These features of *Halopoa* (*H. imbricata*) are very common in the detached lobes of basin plain in the Cervarola unit (Frassineta, Casalino and Moggiona-Sova valley, Poggio Prato Pagliaio sections), but are slightly less common in other environments of the same unit (e.g. lobe-fringe deposits, Cortona section) (Text-figs 6C–E). Other endichnia include sporadic and small *Zoophycos* (up 30 cm in diameter) that has been observed in some marly beds. Epichnial assemblages in basin plain deposits are dominated by *Nereites* (*N. irregularis* in silt and mud and *N. missouriensis* in sands); therefore in many cases this group can be replaced by *Phycosiphon;* in fact, in those beds that exhibit *Halopoa* as hypichnia/endichnia, the epichnial assemblage is dominated by *Phycosiphon incertum* and *P. hamata* (Frassineta section).

THE VALUE OF ICHNOCOENOSES IN THE APENNINE TURBIDITE SETTING

In ichnofabric analysis of depositional events some authors use the term ichnocoenosis to indicate ecological synchrony and timing for burrower activity (e.g. McIlroy 2004, 2008; Giannetti and Monaco 2004); where synchrony and timing cannot be easily recognized, the more general term ichnoassemblage is preferred (e.g. Monaco and Uchman 1999). In the investigated flysch deposits of the Apennines, the time sequence of burrowing can be detected before, during and after the flood event, and the term ichnocoenosis may be used. A typical turbidite ichnocoenosis can start with burrows that were inherited by the background sedimentation (Leszczyński 1993) and may be preserved by casting processes (e.g. hypichnial agrichnia; Seilacher 1977). The timing of pre-depositional burrows can be delineated by careful examination of single processes that were produced on mud (Gaillard 1991); the exact timing of other, post-depositional burrows is difficult to quantify and usually it is limited to the length of the turbidity event, although their preservation may depend by a lot on sedimentological conditions (Uchman 2007). In turbidity events, where endichnial burrows dominate and produce fodinichnia and domichnia (e.g. some crustaceans or spatangoid echinids), the time sequence of burrowing and related taphonomic processes may be detected (Giannetti and Monaco 2004; Monaco *et al.* 2005); this depends on the potential of the burrower in thick sandy medium to adapt their burrowing activity to burial conditions, to sedimentary variations and penecontemporaneous diagenetic surfaces that protect the burrower during its activity. In these cases the co-presence of post-depositional trace fossils within a bed may not necessarily indicate a contemporaneity of burrower activity (e.g. multilayer colonizers; Uchman 1995b; Wetzel and Uchman 2001; Carloni and Monaco 2004). In this paper we choose to use the term ichnocoenosis also when the synchrony of burrower activity cannot be certainly defined, while ichnofacies and ichnosubfacies are maintained without deviation from the literature.

In flysch systems (Leszczyński 1993; Heard and Pickering 2008), the analysis of graphoglyptid and non-graphoglyptid content in ichnocoenoses is the most helpful tool to characterize bed-by-bed deep-sea subenvironments in foredeep basins (Monaco and Checconi 2008; Milighetti *et al.* 2009). Ichnocoenoses are more precise than ichnoassemblages because they can recur unchanged in different environments, while ichnoassemblages can change casually and rapidly (Monaco 1995; Carloni and Monaco 2004); moreover, ichnocoenoses are more flexible than ichnofacies in tectonically controlled depositional systems, especially where narrow longitudinal depressions with intrabasinal highs and short basin plain typical of the Apennine foredeep occur; they can be considered a refinement also in terms of ichnosubfacies (Seilacher 1974; Uchman 2001). Ichnocoenoses can be studied in thinning-, stationary or thickening-upward sequences more easily than ichnosubfacies, specifically when a tectonically influenced system rapidly changes their depositional characteristics at the same water depth and in the same or in different stratigraphic units (e.g. from channelized, attached fan-lobe complex to non-channelized, detached lobe systems). In foredeep and piggyback systems, which represent complex dynamic deposition produced during multiphase tectonics, ichnocoenoses can be used easily than ichnofacies because they are controlled by synsedimentary inputs and single flow processes; features may be observed mainly when post-depositional forms occur in different beds of the same ichnocoenosis (e.g. *Ophiomorpha*, *Thalassinoides*, *Scolicia*, *Arthrophycus*, *Halopoa*). Another interesting aspect concerns the variation of the background ichnofauna in subenvironments that are confined in marginal areas of tectonically induced systems, e.g. well aerated, short terraces contiguous with narrow, poorly ventilated troughs; in these very common situations the environmental setting may range from oligotrophic (well oxygenated) to eutrophic (poorly oxygenated) conditions and with dramatic changes in the characteristics of the substrate (consistency, food availability, etc.); the latter also represents boundary conditions for the burrowing technique and an ichnocoenosis can be influenced by the number of specialized trace-makers (e.g. asterosomids, as indicated by the very high density of *Halopoa* in some intervals of the Cervarola unit).

The five ichnocoenoses of Falterona–Cervarola–Trasimeno, Marnoso-arenacea and Marne di Vicchio-Verghereto units seem to recur strictly depending on facies: they correspond to the *Zoophycos–Ophiomorpha–Paleodictyon–Nereites* ichno(sub)facies of the typical *Zoophycos–Nereites* ichnofacies, which expresses a bathymetric trend from shallower to deeper parts of slope to deep-sea fan systems (Seilacher 1967; Uchman 2007). The five ichnocoenoses essentially reflect also the spatial accumulation pattern of submarine mass-flow deposits: slope-proximal interfans, attached fan lobes and channels, lobe- and channel-fringes, overbank-fringe of intrabasinal highs and distal detached lobes of basin plain. The maximum ichnodiversity of graphoglyptids, that locally corresponds to the highest ichnodensity, has been recorded in overbank deposits fringing submarine highs and in distal detached lobes on basin plain (*Paleodictyon-Nereites* ichnosubfacies); here pre-depositional graphoglyptids exhibit a great variety of forms and species (more than 10 ichnogenera and more than 15 ichnospecies), with meanders (winding, coiled, uniramous and biramous), spirals, rosette, plugs, nets (small to large) and others (Monaco and Checconi 2008; Milighetti *et al.* 2009). If *Nereites*, however, are rare or poorly preserved (e.g. *N.* cf. *irregularis*), as commonly found in many studied situations, it is difficult to attribute the corresponding ichnosubfacies. In lobe- and channel-fringe and distal detached lobe deposits, *Paleodictyon* exhibits its maximum diversity; 5–8 species of all sizes may occur on the same thin and fine-grained bed. This is typical of the Falterona–Cervarola–Trasimeno units but it has been observed also in the Marnoso-arenacea formation, and in these facies scoured specimens are rare (cf. Uchman 1995a). The taphonomic preservation of mesh and shafts strictly depends on casting processes of poorly efficient suspension flows (Seilacher 1977); casting processes in overbank and distal lobes by low-density turbidity-current sand led to a perfect preservation of delicate structures of the background ichnofauna (e.g. elongation of the mesh of *Paleodictyon minimum*, Monaco 2008); other large features of three-dimensional deformation were produced by the water mass at the front of turbidity and pre-turbidity currents, and may be detected perfectly in *Paleodictyon hexagonum* specimens of slope areas or external lobes (e.g. stretching, Monaco 2008). Moreover, the richness of the background ichnofauna that has been observed as hypichnia and epichnia in the ichnocoenosis of overbank deposits fringing the submarine high of Verghereto might be explained by the increase of benthic food; this increase cannot be explained by food availability at the tail of turbiditic flow deposits because a rise has never found in other similar beds; it is possible that benthic food was transported as suspension material by contour currents that were active along sides of the intrabasinal high (Trincardi *et al.* 2005; Stow, pers. communic.). To the contrary, in highly efficient deposits such as attached lobes of active fans and channelized zones, graphoglyptids show a minimum of ichnodiversity, and they are poorly preserved because of scouring, even though in marginal overbank and levee complex such forms can occur abundantly (e.g. wide *Cosmorhaphe*, *Spirorhaphe*, *Megagrapton* and *Paleomeandron* among others). In many of these deposits, non-graphoglyptid ichnofauna express the advantage of opportunistic burrowers in the presence of high food availability and many typical and strange forms show a wide diversity of form: a shape that reminds a catalytic converter of a car (indicated as “car-silencer” shaped, Monaco 2008) or bottle-shaped exichnia (full relief, *Ophiomorpha* ispp. A, B and *Macanopsis*-like trace fossil), very long (up to 1 m) and branched tunnels at top of sandy beds (semi-relief, *Ophiomorpha annulata*), complex and structured strings (e.g. *Neonereites* preservation, *Spongeliomorpha* or *Protovirgularia*, *Halopoa*, *Spirophycus*) while vertical crossichnia are rare. This diversity of form suggests diversification of fodinichnial and domichnial behaviours (Ekdale 1985; Giannetti and Monaco 2004); morphological diversification requires further analysis – considering density and diversity bed by bed – to explain why broad variation in shapes of the same ichnogenus can occur in contiguous subenvironments of the same depositional system. Ichnotaxa that show a maximum diversification are *Ophiomorpha* isp., *O. rudis*, *O. annulata*, *Spongeliomorpha sublumbricoides*, *Protovirgularia*, *Halopoa* (*Fucusopsis* preservation) and *Thalassinoides suevicus*. In the Montone section *Ophiomorpha* (similar to *O. rudis* shown by Uchman 2007, fig. 15.5) penetrated at least six mud turbidites (multilayer colonizer of Uchman, 1995b; crossichnia of Monaco *et al.* 2007), but at Montone usually is concentrated (6 specimens m^{-2}) in lobe-fringe deposits. In this case, the correspondence with the *Ophiomorpha rudis* ichnosubfacies proposed by Uchman (2001) and Heard and Pickering (2008) for distributary channels is not so evident and indicates that other low-energy environments such as marginal areas (interchannels) may contain these trace fossils, perhaps indicating colonization of older, buried sediment. Moreover, other forms must be considered as the elite trace fossils of ichnocoenoses and lateral expressions in future analyses such as *Scolicia*, *Protovirgularia* and *Arthrophycus*; they in many cases are more abundant than *Ophiomorpha* and easily observed in the attached and channelized fan lobe (e.g. *Scolicia*) or in middle part of lobes (e.g. *Arthrophycus strictus*), and therefore they may be useful in facies distribution and basinal studies. Also, in future work the morphological diversity of *Ophiomorpha* specimens and other ichnotaxa should be helpful in ichnocoenosis analysis and ichnosubfacies characterization, which again require further detailed study.

CONCLUSIONS

Sedimentologic/ichnologic study of the siliciclastic units from the foredeep system of the northern Apennines evidences the following aspects:

- The five ichnocoenoses in tectonic-controlled, narrow foredeep/piggy-back basins are strictly associated with rapid facies differentiation and turbidite characteristics that occurred in a narrow space and at very different sedimentation rates, and they are more helpful than the ichnosubfacies of the literature: a) slope-proximal interfans display a scoured background ichnofauna and selected post-depositional forms; b) attached fan lobes and channels have a typical opportunistic ichnotaxa; c) lobe- and channel-fringes contain pseudo-rhythmic deposits with a diversified ichnofauna; and d) overbank-fringe of intrabasinal highs and e) distal detached lobes of basin plain exhibit the most abundant and diversified ichnofauna.
- The most important and easily detectable ichnotaxa that are characteristic of turbidite facies form ichnocoenoses that should be analysed carefully in all gravitative facies (from coarse-grained, thick-bedded to fine-grained and thin-bedded) that are developed in a tectonically controlled system, because the *Ophiomorpha–Nereites–Paleodictyon* ichnosubfacies do not express adequately all the variations of the ichnofauna that can be found in these environments.
- The morphologic variability involves the shape of many important ichnotaxa that occurs in some facies, e.g. *Ophiomorpha, Halopoa* and many others, requiring much more attention than in the past time; this is possible when behaviours of burrowers are strictly conditioned by environmental variations in foredeep systems (e.g. very rapid changes in sedimentary input in unpredictable environments, or pseudo-rhythmic sedimentation in predictable and stable environments).
- Further analysis is needed to investigate the food and nutrient availability in foredeep systems, not only transported by gravity flows but also redistributed by deep-water currents (e.g. contour currents); the study of deep-water currents represents an interesting opportunity to understand the diversity (and density) of the background hypofauna as contrasted with the epifauna that colonized the top of overbank deposits fringing intrabasinal highs.

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PLATES 1–3

PLATE 1

Examples of turbidite deposits and related facies found in the study area

1 – Thickening upward sequence (active lobe-channel, F4-F6). Falterona unit, Pian della Fonte (Pratomagno)

2 – Thin-bedded turbidites of levee (grey marls and fine-grained sandstones with ripples in the upper part). Falterona unit, Calleta (Pratomagno). Bar is 50 cm long

3 – Distributary channel deposit (F2) superimposed on thin-bedded turbidites of proximal environment (F9b). Falterona unit, Il Giogo (Pratomagno)

4 – Bundles of thick (F6) and thin-bedded turbidites (F9a-F9b) of lobe fringe deposits. Cervarola–Trasimeno units, Cortona

5 – Hemipelagites, calcarenites and pebbly mudstones of channelized slope. Marne di Vicchio unit, Montesilvestre

6 – Detached lobe deposits (thin-bedded and fine-grained F9a). Marnoso-arenacea unit, Montone. Bar is 50 cm long

7 – Rhythmic thin-bedded turbidites (F9 facies) of basin plain. Marnoso-arenacea unit, Verghereto N

8 – Thick hemipelagites with sporadic thin-bedded overbank F9b turbidites. Marne di Verghereto unit, Poggio Alto. Bar is 50 cm long

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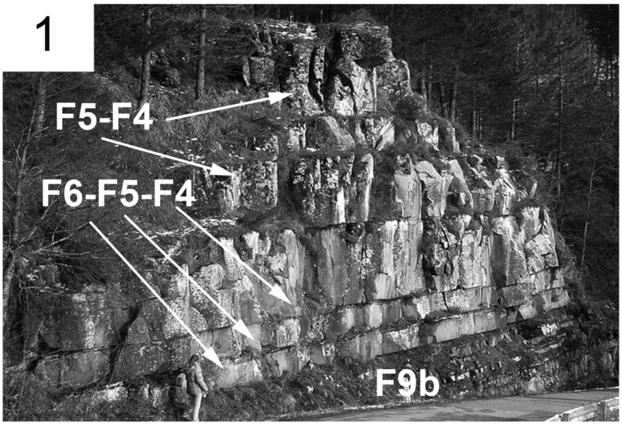

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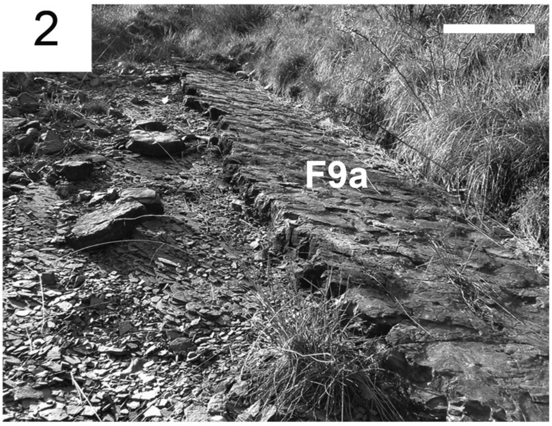

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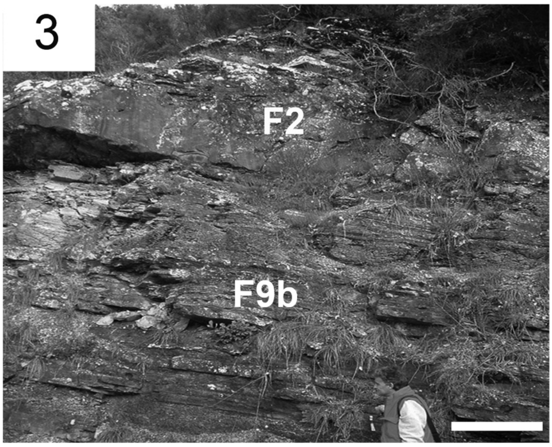

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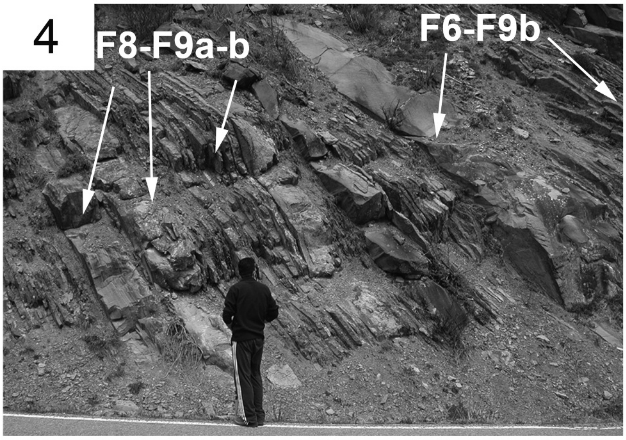

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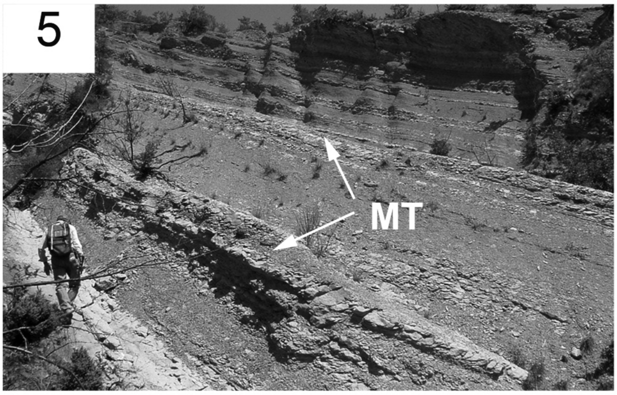

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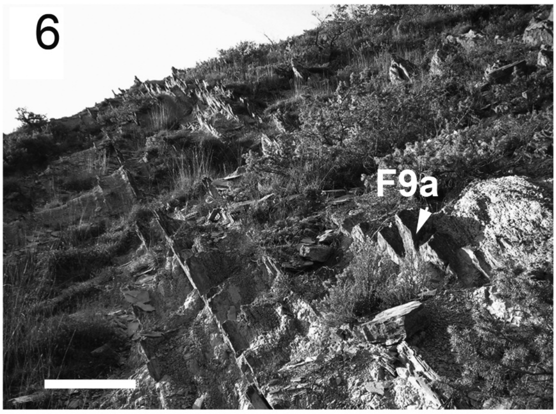

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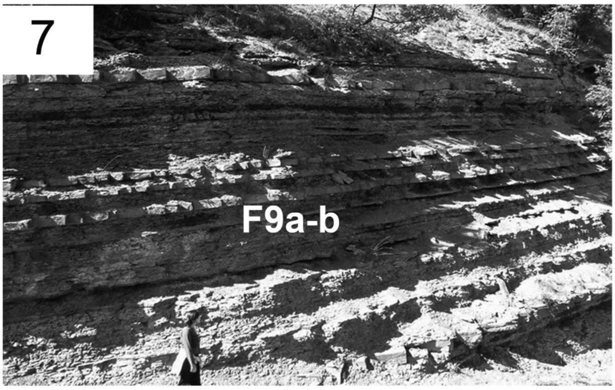

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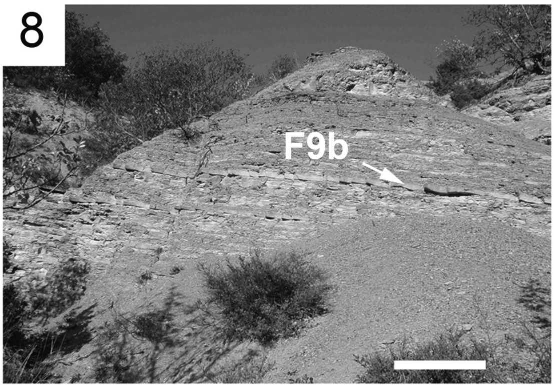

PLATE 2

Hypichnial, exichnial and epichnial non-graphoglyptid trace fossils

1 – Car silencer-shaped *Ophiomorpha* (hypichnion). Marnoso-arenacea unit, Gli Scalacci. Bar is 5 cm long. Arrow indicates a change in diameter.
2 – Bulging *Ophiomorpha rudis* (hypichnion). Marnoso-arenacea unit, Ridracoli. Bar is 5 cm long. Arrow indicate changes in diameter.
3 – *Ophiomorpha* isp. (epichnia) at the top of a fine-grained thin sandstone level. Falterona unit, Calleta (Pratomagno). Hammer (handle) for scale.
4 – *Scolicia strozzii* (hypichnia). Falterona unit, Pian della Fonte (Pratomagno). Bar is 10 cm long.
5 – *Protovirgularia* isp. (maybe *P.* cf. *obliterata* , hypichnion). Marnoso-arenacea unit, Pietrapazza. Coin is 2 cm wide.
6 – *Halopoa* (hypichnion). Cervarola unit, Casalino. Bar is 3 cm long.
7 – *Zoophycos* (epichnion). Marne di Vicchio unit, Montesilvestre. Hammer for scale.
8 – Bottle-shaped *Macanopsis*-like trace fossil (exichnion). Marnoso-arenacea, Canili di Verghereto. Knife is 2.5 cm wide
9 – *Helminthopsis tenuis* (hypichnion). Cervarola unit, Poggio Prato Pagliaio. Bar is 5 cm long

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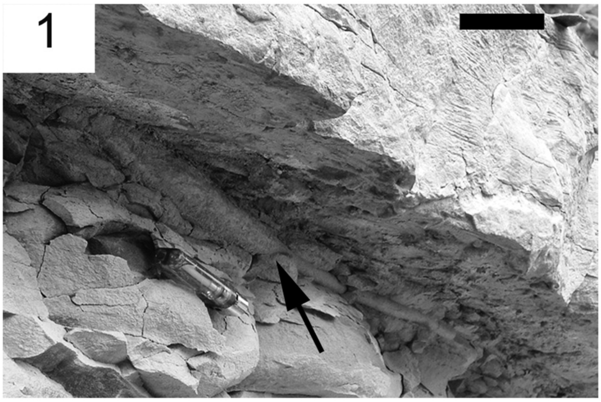

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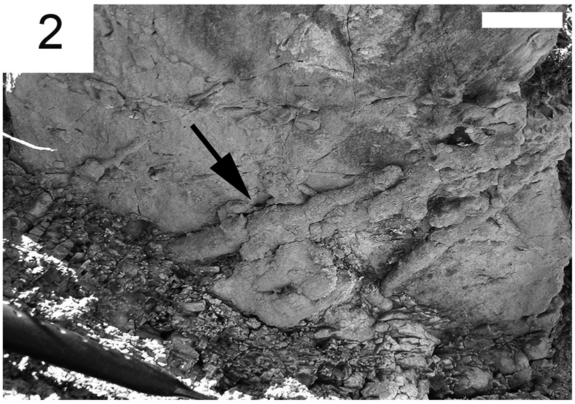

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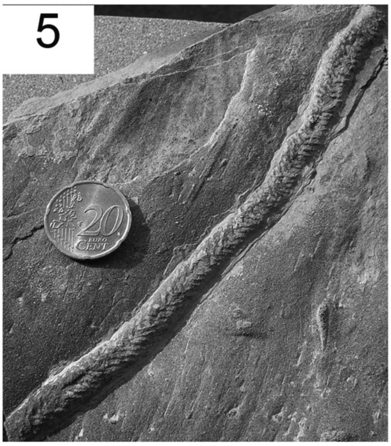

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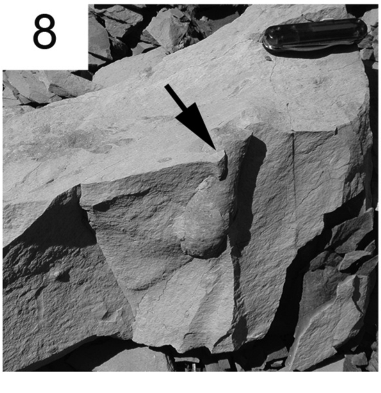

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PLATE 3

Hypichnial and epichnial graphoglyptids

1 – *Cosmorhaphe lobata* (hypichnion). Falterona unit, Poggio La Cesta (Pratomagno). Bar is 5 cm long
2 – *Paleodictyon hexagonum* (hypichnion). Marnoso-arenacea unit, Pietrapazza. Bar is 5 cm long
3 – *Spirorhaphe* cf. *involuta* and *Paleodictyon minimum* (arrow) (hypichnia). Cervarola–Trasimeno units, Cortona. Bar is 3 cm wide
4 – *Megagrapton* cf. *irregulare* (hypichnion). Marne di Vicchio unit, Montesilvestre. Coin is 2 cm wide
5 – *Helminthorhaphe* cf. *japonica* (hypichnion). Cervarola unit, Moggiona-Sova Valley. Bar is 3 cm long
6 – *Paleomeandron* cf. *elegans* (hypichnion). Cervarola unit, Alpe di Poti. Bar is 2 cm long
7 – *Desmograpton* cf. *dertonensis* (hypichnion). Marne di Vicchio unit, Montesilvestre. Coin is 2 cm wide
8 – *Urohelminthoida dertonensis* (hypichnion). Marnoso-arenacea unit, Pietrapazza. Bar is 3 cm long
9 – *Nereites* isp. (maybe a variant of *N.* cf. *irregularis*, epichnion). Falterona unit, Calleta (Pratomagno). Bar is 3 cm long
10 – "*Neonereites*" (epichnia). Marne di Vicchio unit, Montesilvestre. Knife is 2.5 cm wide.

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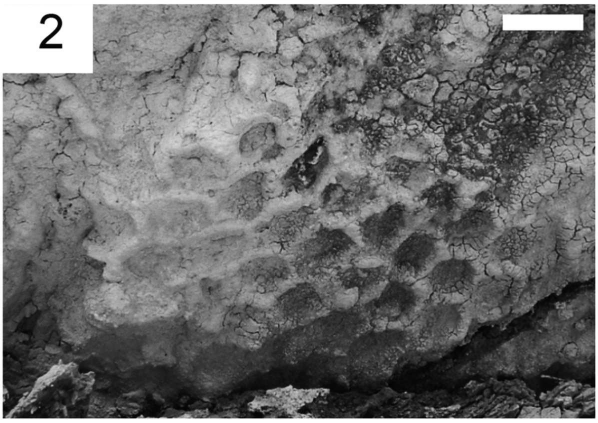

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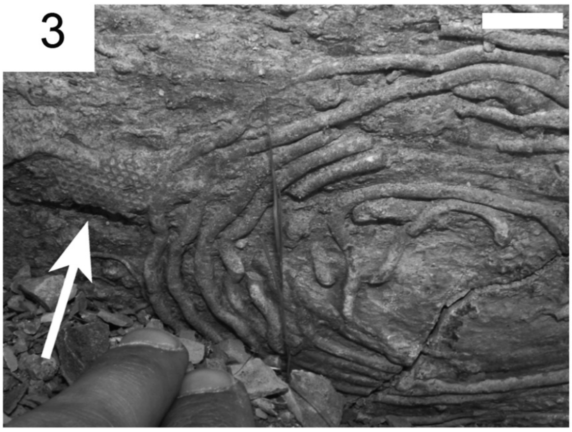

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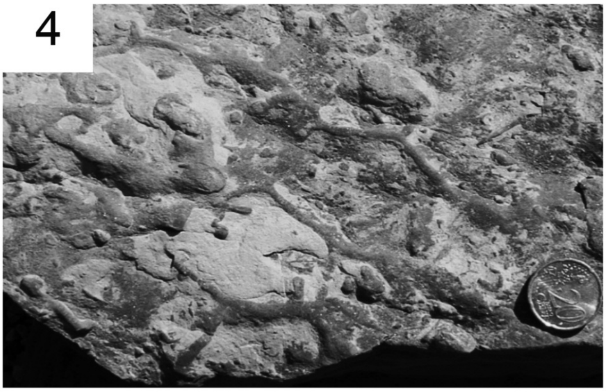

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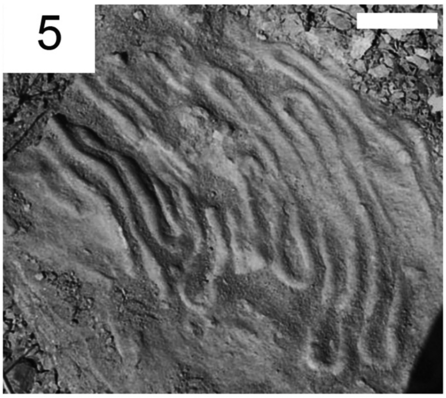

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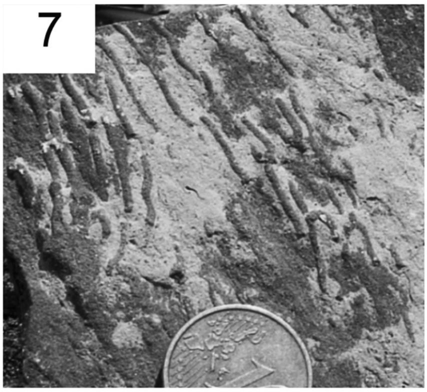

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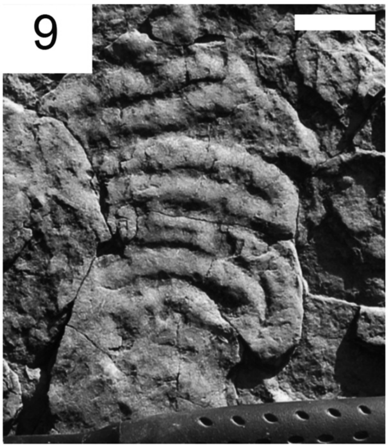

10