The ichnocoenosis of the bottom nepheloid layer (BNL) deposits: a case study from the Scaglia Toscana Formation (Paleogene, central Italy)

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ABSTRACT - Some fine-grained sediments from the Eocene in age Scaglia Toscana Formation in the Northern Apennines (Trasimeno area), previously interpreted as mud-silt turbidites, have been reinterpreted herein as bottom nepheloid layers (BNL). They contain a rich ichnocoenosis dominated by endichnial forms, that formed progressively in line with the slow accumulation rate of mud transported by the oceanic thermohaline bottom currents. In a BNL idealized sequence, a slight upward increasing density of trace fossils, suggests some differences with typical muddy turbidites. Together with sedimentary structures, trace fossils form an ichno-sedimentary sequence through the bed, which is explained by a step by step colonization that accompanies deposition of the bottom nepheloid layer by continuous currents. It is possible that these ichnological features are recurrent and helpful in recognition of similar deposits within other geological contexts.

Ichnocoenosis, bottom nepheloid layers: a granulometry fine, presenti nella Formazione della Scaglia Toscana dell’Appennino settentrionale (area del lago Trasimeno), in precedenza reinterpretati come torbiditi fangose, vengono reinterpretate qui come depositi prodotti da correnti di fondo o strati fangosi di fondo (BNL, “bottom nepheloid layers”). Essi contengono una ricca icnocenosi dominata da forme endichiali (endichia), formatesi progressivamente seguendo il lento accumulo di sedimento fangoso trasportato dal movimento di correnti termoaline profonde. In una sequenza BNL ideale si osserva un lento ma progressivo incremento della densità delle forme, manifestando delle differenze con le torbiditi fangose che, diversamente, vengono bioturbate dall’alto verso il basso, essendosi deposite in un brevissimo lasso di tempo. Insieme con le strutture sedimentarie, le tracce fossilis costituiscono un ‘icno-sequenza che è spiegata da una colonizzazione graduale dell’infauna, che segue la deposizione delle correnti nepheloidi continuamente attive sul fondo marino. È possibile che queste caratteristiche icnologiche siano assai più ricorrenti di quanto documentato e quindi utili da riconoscere rispetto alle torbiditi fangose, utilizzabili quindi in altri ambienti geologici.

INTRODUCTION

Fine-grained gravity flow deposits are well studied in recent years with several models and suite of structures (physical and biogenic) through the bed (e.g., Stow & Piper, 1984a, b; Stow & Wetzel, 1990; Monaco, 2000; Wetzel et al., 2008; Monaco et al., 2010; Amendola et al., 2016). In these deposits, also trace fossil suites forming ichnocoenoses, can greatly help to improve the knowledge about infaunal response and biogenic behavior under different silt-mud depositional processes and rates (Stow & Wetzel, 1990; Monaco et al., 2010, 2016a). However, many deep-sea depositional processes of mud are poorly known, including their ichnological features. This concerns the so-called bottom nepheloid layers (BNL: Hunkins et al., 1969; McCave, 1986, 2001; McCave & Hall, 2006; Puig et al., 2013; Dutkiewicz et al., 2016).

The bottom nepheloid layers are deep dense waters, where the sediment is suspended and transported by the density-driven oceanic thermohaline bottom currents. These currents transport suspended clay and silt with organic matter particles from margins to the central part of a basin, with usual suspended sediment concentrations of < 0.1 mg/l above background levels, reaching higher concentrations close to the continental rise and slope with near-bottom peaks >1 mg/l and lesser concentrations ≤ 1 mg/l progressively towards the basin plain (Puig et al., 2013). BNL are very common at recent basin margins, such as on the continental rise of the French Mediterranean Sea, in the North Atlantic and the South Atlantic, or offshore the Namibian coast (e.g., Inthorn, 2005), but their sediments are poorly studied in the geological record with a few exceptions (McCave, 1986, 2001; Thomsen & van Weering, 1998; McCave & Hall, 2006). According to some authors, turbulent flow in BNL could be even more responsible for deposition of mud in flat basin plain settings than fine-grained turbidites (McCave, 1986; Weaver et al., 1992; Peine et al., 2009). Similar observations are recently highlighted from the dedicated workshops in 2010 and 2011 (P. Pilgrim personal communication; Rutgers van der Loeff & Kretschmer, 2011). The thickness of BNL depends on bottom current velocity and the balance between gravitational settling of particles, basin plain morphology and turbulence of the current (McCave, 1986, 2001). Tracemakers intensively exploit organic matter slowly deposited on the sea floor by the BNL; in fact, in the Canadian Atlantic basin plain, some sediment surfaces are extremely bioturbated with hundreds of burrow openings per m² (Hunkins et al., 1969, figs 3-4) and benthic populations are significantly affected by organic matter and phytodetritus within the BNL (Puig et al., 2001).

The aim of this work is to present peculiar sediments from the Scaglia Toscana Formation in the Trasimeno area (central Italy, Figs 1-2), previously considered as muddy turbidites, although some doubts arise for the presence of extremely abundant endichnia such as Averteichmus luisae Uchman & Rattazzi (2011) and other endichnial-epichnial trace fossils (Monaco et al., 2010). In this work they are
better reinterpreted as a typical ichnocoenosis of the BNL (Figs 2-4).

GEOLOGICAL SETTING

The Scaglia Toscana Formation (Merla & Abbate, 1967) in the Trasimeno area (Northern Apennines) consists of rhythmically bedded deposits showing different colours. They are dated to the Late Cretaceous-Early Oligocene. This formation has been called also the Scisti Policromi (Fazzuoli et al., 2002 and references therein) or the Argilloscisti Varicolori in western Umbria (Principi, 1924; Damiani & Pannuzi, 1982; Piccioni & Monaco, 1999). Some members and subdivisions of the Scaglia Toscana Formation have been introduced to explain their very great lithological differences in the Northern Apennines (Fazzuoli et al., 1996, 2002). In the Trasimeno area, lithology of the Scaglia Toscana Formation is highly variable; it includes limestones, marly limestones, variegated marls (yellow, reddish, black to green, often rhythmically arranged), calcarenites (from coarse- to fine-grained), mud beds and mudstone shales (Damiani & Pannuzi, 1982; Damiani et al., 1987; Piccioni & Monaco, 1999; Amendola et al., 2016). In the most complete sections (M. Solare, M. Buono and Montanare, Figs 1-2), thick-bedded limestones dominate in the lower part of the formation (early-middle Eocene) and fine-grained calcarenites and calcilutites in the middle-upper part (middle Eocene, P10-P12 zones), while

Fig. 1 - a) The study area with the geological map and five studied sections (modified from Monaco et al., 2012). b) Synthetic stratigraphic succession of the studied sections with indication of differentiated formations and members.
ICHNOTAXA

The trace fossil suite of the Scaglia Toscana Formation in western Umbria as preliminary stated by Monaco & Uchman (1999), Piccioni & Monaco (1999), and Monaco et al. (2012, 2016a) comprises many ichnotaxa. The trace fossil assemblage includes hypichnial Bergaueria isp. (rare), Cardioichnus isp. (rare, Fig. 4e), Halopoa isp. (common), Helminthopsis isp. (rare), Lorenzoia isp. (rare, Fig. 4b), Megagrapton isp. (rare), Ophiomorpha annulata (Książkiewicz, 1977) (common), Paleodictyon strozzii Meneghini in Savi & Meneghini, 1850 (rare), Scolicia strozzii (Savi & Meneghini, 1850) (common), Spongeliomorpha isp. (rare), Thalassinoides isp. (very common in some levels of the M. Solare section), Ophiomorpha isp. (common) and Urohelmintoidea isp. (rare). Crossichnia (sensu Monaco & Caracuel, 2007) that commonly cross cut beds completely or only parts of them are limited to Ophiomorpha rudis (Książkiewicz, 1977), a system of oblique to vertical straight cylinders, 15 to 30 mm in diameter, which differ in colour from the host rock (Monaco et al., 2016a, fig. 3, pl. 2) (Figs 2 and 4a). This trace fossil, usually found in the Ophiomorpha rudis ichnosubfacies in deep-sea fan deposits (Uchman, 2009), appears in a wide depth range (from outer shelf with storm deposits to the deep sea; Monaco, unpublished). Endichnia are very abundant and characterize BNL; they include Alcyonidioïdipis longobardiae (Massalongo, 1856) (common), Avetoichnus luisae (very common with about 100 specimens measured and studied, Monaco et al., 2012, Fig. 4f, h), Chondrites intricatus (Brongniart, 1823) (abundant), Chondrites targioni (Brongniart, 1828) (abundant), Cladichnus isp. (abundant), Halopoa isp. (common, Fig. 4j), Palaeophycus tubularis Hall, 1847 (rare), Planolites isp. (common), Taenidium isp. (rare), and Thalassinoides isp. (common, Figs 2e and 4i). Endichnia occupy different levels with a characteristic increase in density towards the top of a bed (ICD, Fig. 2); the development can be found typically in the Monte Solare section. Epichnia are poorly visible due to intense mottling (Fig. 4a, white arrows). Some scattered Nereites mossouriensis (Weller, 1899) (rare) are present. Vertically elongated spots are locally abundant (shafts of Ophiomorpha rudis, Chondrites targioni and probably Cladichnus; Fig. 4i, arrows).

THE BNL ELEMENTARY SEQUENCE

The studied hemipelagic or pelagic deposits of the Scaglia Toscana Formation in the study area, show five, usually strongly bioturated intervals named BNL1, BNL2, BNL3, BNL4 and BNL5 (Fig. 2a, e).

BNL1. The basal white interval consists of silt to mud with thin bioclastic horizons, locally forming parallel laminae and very thin rippled laminations; broad scoured base and alternations of erosive surfaces are present (Fig. 2a, e). Grains are represented by minute fragments of undetermined shells, foraminifers and lithic grains (mainly carbonatic). The BNL1 is pervasively bioturated (exhibiting e.g., Thalassinoides, Palaeophycus, Chondrites intricatus, Halopoa, Fig. 2e), and continuous many hypichnia (Fig. 4b-c, e). Graphoglyptids are very few in contrast to non-graphoglyptid forms.

BNL2. The second white interval (Fig. 2e) consists usually of mud, showing (in thin sections) silt laminae often scoured having discrete erosive surfaces. Ripple cross lamination is present. This interval is strongly bioturated too, also with horizontal, scattered, extent cross-section of Zoophycos and Planolites (Fig. 2a, e).

BNL3. This interval is composed of ungraded mud, some centimeters thick, intensely burrowed exhibiting endichnial Alcyonidioïdipis longobardiae, Planolites, Chondrites targioni, C. intricatus, Cladichnus and Taenidium (Fig. 2a, e).

BNL4. This interval is built up by reddish intensely burrowed mud. Chondrites targioni, C. intricatus, Cladichnus, Avetoichnus luisae are the main trace fossils. Ichnodensity may be very high (50-70%, Fig. 2a).

BNL5. The mottled reddish interval at top of the sequence represents a transition to a hemipelagite (He in Fig. 2e) that consists of a laminated red clay. The mottled interval is intensely burrowed (e.g., by Nereites producers) but locally some graphoglyptids are present.

BOTTOM NEPHELOID LAYERS

Nepholoid layer or nepholoid zone is a layer of water in the deep ocean basins, above the ocean floor, that consists of a body of dense water with a high concentration of suspended sediment close to the base of the continental slope. Nepholoid layers are usually several centimeters to meters thick and they carry sediment particles up to 12 μm in size in concentrations of 0.3-0.01 mg/l. The sediment is suspended and transported by the movement of the oceanic thermohaline bottom currents (McCave, 2001). Some authors tend also to include the gravity transport (Inthorn, 2005). The name “nepholoid” comes from the Greek: nephos, meaning “cloud”. The thickness of cloud depends on bottom current velocity and is a result of
### The BNL elementary sequence

<table>
<thead>
<tr>
<th>BNL intervals</th>
<th>Idealized sequence</th>
<th>Ichnodensity (ICD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BNL5</strong> MOTTLED REDDISH MUD</td>
<td>epichnia (e.g. <em>Nereites</em>)</td>
<td>60-90% 6</td>
</tr>
<tr>
<td><strong>BNL4</strong> BURROWED MUD</td>
<td>mottling</td>
<td>50-70% 5</td>
</tr>
<tr>
<td>reddish, intense burrowing</td>
<td><em>Chondrites intricus</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Cladichnus</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>A. luisae</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Avetoichnus luisae</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Alcyonidiopsis</em></td>
<td></td>
</tr>
<tr>
<td><strong>BNL3</strong> UNGRADED MUD</td>
<td><em>Planolites</em></td>
<td>35-60% 4</td>
</tr>
<tr>
<td>burrowing increases upwards</td>
<td><em>Chondrites targioni</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Taenidium</em></td>
<td></td>
</tr>
<tr>
<td><strong>BNL2</strong> BIOCLASTIC SILT-MUD</td>
<td><em>Zoophycos</em></td>
<td>30-40% 3</td>
</tr>
<tr>
<td>intensely burrowed</td>
<td><em>Chondrites</em></td>
<td></td>
</tr>
<tr>
<td>isolated long burrows</td>
<td><em>Planolites</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>abundant endichnia</em></td>
<td></td>
</tr>
<tr>
<td><strong>BNL1</strong> BIOCLASTIC HORIZONS</td>
<td><em>Thalassinoides,</em></td>
<td>15-20% 2</td>
</tr>
<tr>
<td>parallel, rippled lamination</td>
<td><em>Palaeophycus</em></td>
<td></td>
</tr>
<tr>
<td>broad scoured base</td>
<td>hypichnia (locally abundant)</td>
<td></td>
</tr>
</tbody>
</table>

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**b** Image of the BNL elementary sequence.

**c** Image of the field site.

**d** Image of the bioclastic horizons.

**e** Image of the bioclastic silt-mud.
balance between gravitational settling of particles, strength and turbulence of the current. A vertical gradient in the concentration of particles of any given size is observed, with the gradient being steepest for the fastest settling of particles (Fig. 3). In a similar way, a surface nepheloid layer may be created, due to particle flotation, while intermediate and bottom nepheloid layers are different because they may be formed at the slopes and basin plain of the oceans due to the dynamics of internal waves, gravity and downward currents (Dickson & McCave, 1986; McCave, 2001). Differences among hemipelagites, muddy turbidites and muddy contourites and their ichnotaxa suites result from the mode of the sediment accumulation being very rapid in muddy turbidites and very slow and discontinuous in muddy contourites (Wetzel et al., 2008). In any case, bottom nepheloid layers (BNL) are marginally included by Wetzel et al. (2008) in muddy contourites. But BNL are induced also by gravity and not only by bottom currents and, therefore, they may be a mixing phenomenon from muddy gravity flows and muddy contourites (Weaver et al., 1992; McCave, 2001; McCave & Hall, 2006; Peine et al., 2009; Rutgers van der Loeff & Kretschmer, 2011). In fact, the accumulation rate of clay and coarse silt in a typical BNL may be very high and can reach 20 cm/ka with a prevalence of clay + fine silt (C+FS) and sortable silt (SS) (Fig. 3, modified from McCave & Hall, 2006). In any case, pure contourites that exhibit a discontinuous rate of accumulation, show complete bioturbation with many syn- but a few post-depositional trace fossils (Wetzel et al., 2008).

As indicated by McCave (2001) and McCave & Hall (2006), three divisions can be distinguished in BNL, from the base to the top: 1) the basal mud with silt laminae, from 1 up to 5 cm thick, which become finer, thinner and less frequent upwards; 2) the intermediate, graded mud or fine silt; and 3) the top composed by ungraded mud or clay + fine silt, respectively. The upper mud was produced by turbulent flow of suspended mud that was transported by currents and settled very slowly to the sea floor. The consistency of mud was probably very similar to the “cloudground” described by Monaco et al. (2016b) that persists for weeks as an indeterminate layer that moves horizontally, as monitored for weeks in different lakes of Umbria. Thus, the bioturbation rate of BNL cannot be distinguished easily from muddy turbidites because of the similar accumulation rate. In any case, bottom nepheloid layers can be reworked successively by post-depositional bottom currents, as in BNL1 and 2 in the investigated deposits.

FINE-GRAINED TURBIDITES AND HEMITURBIDITES

A lot of literature concerns fine-grained turbidites (O’Brien et al., 1980; Stow & Shanmugam, 1980; Stow & Piper, 1984a; Stow & Wetzel, 1990; Einsele, 1991; Piper & Stow, 1991; Milighetti et al., 2009; Monaco et al., 2010; Amendola et al., 2016). These deposits are not discussed further herein. A large discussion about history and definition of “turbidites”, “debris flow deposits” and “contourites” has been largely reported by Shanmugam (2002, 2017). In his revision of the “ten myths of turbidites”, examining the Grès d’Annot Formation (SE France), Shanmugam evidenced the importance of basical models of Kuenen (1950) and Sanders (1963), which restrict turbidites only to a few types of deposits with simple structures, considering the major other part of deposits to medium- to coarse-grained debris-flow deposits. Mud layers (locally with thin intervals of silts laminae) are genetically attributed by this author to “bottom current reworking” and to pelagic/hemipelagic deposits (Shanmugam, 2002, fig. 17). Nothing was mentioned about BNL deposits, although the thickness and abundance of mud layers are conspicuous.
in sandstones of the Grès d’Annot Formation in France. Fine-grained turbidites were discussed in the Miocene Marnoso-arenacea Formation (Muzzi Magalhaes & Tintneri, 2010; Tintneri et al., 2016) and in the Macigno Formation (Amendola et al., 2016), both in the Northern Apennines, but without any references to BNL. Similar attention has been devoted to transitional deposits between “hemipelagite” sensu stricto and “muddy turbidite”; the “hemiturbidite” concept, which involves a muddy deposit formed by a vanishing turbulent flows on sea floor that became progressively hemipelagic, is burrowed from the top with post-depositional trace fossils (Stow & Wetzel, 1990). Therefore, following these authors, a hemiturbidite could represent a transition between a hemipelagite and a turbidite (Stow & Wetzel, 1990).

**DISCUSSION**

Although some authors have demonstrated the prevalence and importance of modern BNL (McCave, 1986, 2001; Inthorn, 2005; McCave & Hall, 2006; Puig et al., 2013), detailed studies on the subject are absent in the geological record. Therefore, an elementary sequence for the BNL deposits has not been yet proposed (as the Bouma intervals for medium turbidites). The major problem refers to difficulties in identification of structures inside mudstone beds that can be caused by bottom currents similar to some fine-grained turbidite currents. A regional study in the Scaglia Toscana Formation of the Northern Apennines, with application of micro- and macrofacies analyses could help to increase this knowledge. If it will be confirmed, this elementary sequence (see also discussion by Amendola et al., 2016 about provenance of calcilutites in the Macigno Formation), could be refined on the basis of different paleodepositional settings showing different accumulation rates. In any case, distribution of ichnotaxa dominated by endichnia (referred to pre-depositional sediment feeding or suspension feeding), can help to refine the depositional context and paleoecology during a very slow deposition, promoting BNL, although depositional models about deep sea deposition will remain open.

**CONCLUSIONS**

An elementary idealized sequence is herein proposed for nottom nepheloid bottom layers (BNL) interpreted in the Eocene Scaglia Toscana Formation showing in the Trasimeno area. This sequence shows five different intervals, from BNL1 to BNL5. Their lithological, sedimentological and ichnological features are analyzed with special attention to the latest. The elementary sequence could be very useful to analyze accumulation rates and biogenic events in basin environments. A detailed study of such events in a regional context requires further sedimentological and ichnological analyses in order to differentiate between bottom, intermediate and surficial nepheloid layers. In any case, this study represents the first description of these poorly known deposits in the deep sea environments, with respect to their ichnological features.

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