

# Facies analysis, palaeoenvironmental reconstruction, and biostratigraphy of the “Pesciara di Bolca” (Verona, northern Italy): An early Eocene *Fossil-Lagerstätte*

Cesare Andrea Papazzoni <sup>a,\*</sup>, Enrico Trevisani <sup>b,1</sup>

<sup>a</sup> Dipartimento del Museo di Paleobiologia e dell’Orto Botanico, via Università, 4, I-41100 Modena, Italy

<sup>b</sup> Museo di Storia Naturale di Ferrara–Via De Pisis 24, I-44100 Ferrara, Italy

Received 2 September 2005; received in revised form 12 May 2006; accepted 17 May 2006

---

## Abstract

The world-famous “Pesciara di Bolca” *Fossil-Lagerstätte* has been examined in its palaeontological and sedimentological aspects. A re-examination of the co-occurring age-diagnostic larger foraminifers (*Alveolina* and *Nummulites*) indicates a SBZ 11 (late Ypresian) age. Sedimentological characters allowed us to distinguish between autochthonous micritic limestones and allochthonous biocalcarenes–biocalcirudites; the latter are the product of penecontemporaneous transport from nearby areas. The depositional model here proposed involves a basin with restricted circulation and a prevailing micrite sedimentation. This basin was affected by relative sea-level oscillations and coarser grained storm-induced deposition. The palaeoenvironmental reconstruction suggests neighbouring emerged land and very shallow sea bottoms inhabited by large foraminifers such as *Alveolina* and *Nummulites*. As yet, it is unclear whether a true coral reef was present nearby. The bottom on which the Pesciara deposits accumulated is interpreted as poorly oxygenated, possibly with stromatolite-like bacterial mats, thus allowing the exceptional preservation of the fish and plants.

© 2006 Elsevier B.V. All rights reserved.

**Keywords:** Biostratigraphy; Palaeoenvironment; Sedimentology; *Alveolina*; Early Eocene; Italy

---

## 1. Introduction

The world-famous locality of Bolca is located about 25 km north-east of Verona (northern Italy), in the Alpone River Valley (eastern Lessini Mts.). In the surroundings of Bolca, there are several fossil localities

with exceptional fossil content, including Monte Postale (with molluscs, fish, corals, foraminifers), Monte Vegroni (with palms and other plant remains, turtles, etc.), the Pesciara (with fish, molluscs, foraminifers), Monte Purga di Bolca (with crocodilians, palms, and other plant remains), and Spilecco hill (with foraminifers, crinoids, shark teeth).

At present, Bolca is the only Italian fossil site proposed as a candidate for entering the World Heritage List (Wells, 1996), the UNESCO list of localities of extraordinary interest for humankind.

The object of the present study is the “Pesciara di Bolca” (from now on simply Pesciara), which crops out

---

\* Corresponding author. Tel.: +39 059 2056538; fax: +39 059 2056535.

E-mail addresses: [papazzoni@unimore.it](mailto:papazzoni@unimore.it) (C. Andrea Papazzoni), [consgeol@comune.fe.it](mailto:consgeol@comune.fe.it) (E. Trevisani).

<sup>1</sup> Tel.: +39 0532 203381; fax: +39 0532 210508.

on the right side of Val del Fiume, about 2 km north-east of Bolca (Fig. 1).

The Pesciara *Fossil-Lagerstätte*, known for its exceptionally preserved fossil fish since the 16th century, was exploited at first as an open-cast mine, then some tunnels were opened to follow the more productive beds. Quarrying activity from these tunnels has stopped since 1988. After borehole tests in 1999 and 2000, on the nearby Monte Postale quarrying has restarted at the end of 2003. The Pesciara outcrop underwent a substantial “make-up” in 1998, including building of a stone staircase and an amphitheatre for educational activities. Only one of the tunnels remains open to the public.

The scientific debate over the Bolca fossils (mainly focussing on the Pesciara fishes) provides a unique opportunity for investigating the historical development of geo-palaeontological thinking over more than four centuries. From the pioneering works of the 17th and 18th century, where observations were mixed with religious preconceived ideas, we arrive to the 19th century gaining a modern scientific view of the Pesciara *Lagerstätte*. Solinas (1971) and

Sorbini (1972) provide valuable summaries on this long-lasting scientific debate and the history of the Pesciara.

Over the last four centuries, only a few aspects of the Pesciara *Fossil-Lagerstätte* were studied in detail. Since the beginning of the scientific studies, the attention has been focussed mainly on the spectacular vertebrate fauna (the complete history of the so-called “ittioliti” of Bolca has been reported by Sorbini, 1972). This resulted in significant advances in the knowledge of the fossil vertebrate content, whereas palaeoenvironmental interpretation, larger foraminiferal biostratigraphy, and the relationship between volcanic activity and sedimentation were largely neglected.

The aim of this paper is to bring new data regarding the larger foraminifer assemblages and the sedimentological features leading to a new palaeoenvironmental interpretation of the Pesciara *Lagerstätte*.

The stratigraphical correlation between the Monte Postale succession and the Pesciara is at present unknown, because the first one was never studied after Fabiani (1915). This correlation is currently underway, and the results will be soon published.

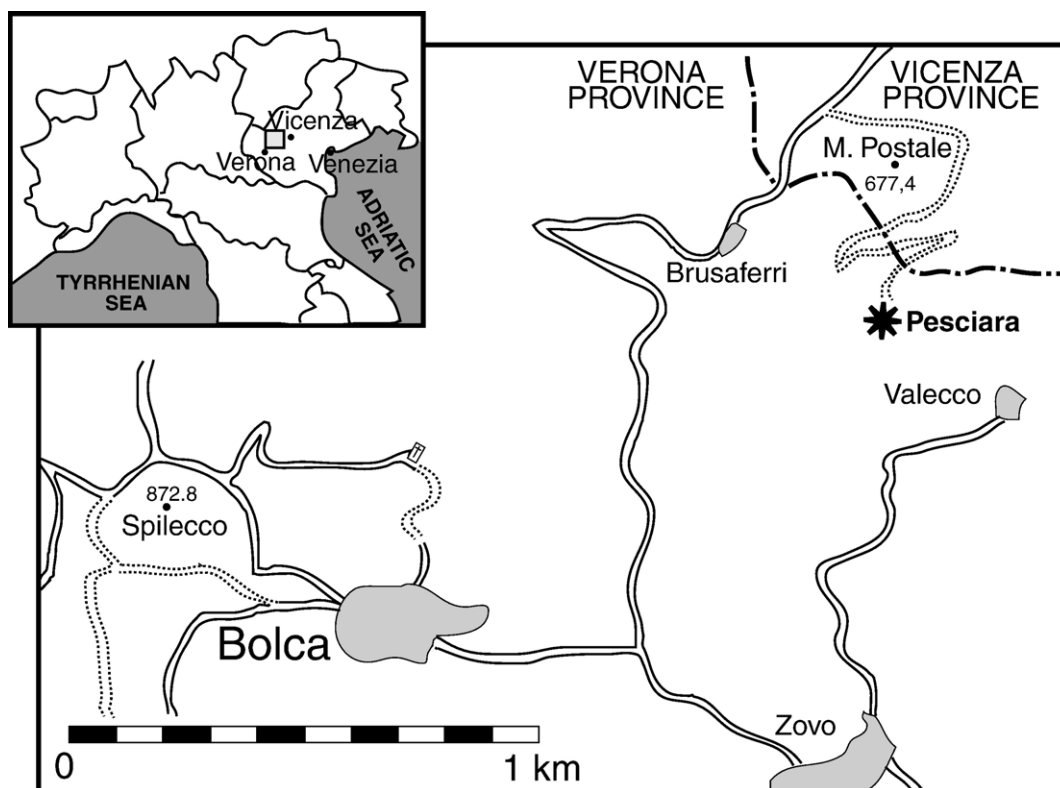


Fig. 1. Location map of the Pesciara outcrop.

## 2. Geological setting

The Pesciara outcrop appears as a white “patch” of limestones surrounded by dark volcanoclastic rocks. It is a block of calcareous beds plunging approximately south-east with highly variable inclination (about 30–70°), less than 20 m thick, and covering an area of few hundred square metres.

The Pesciara beds belong to a lower–middle Eocene informal unit named “*Calcari nummulitici*” (nummulitic limestone), widespread in the western part of Veneto. This lithostratigraphical unit is not well-constrained, including limestones with nummulites of different ages and depositional settings. A comprehensive revision on a regional scale of these rocks is needed, because there are various distinct Paleogene carbonate platforms which were formed after the deposition of the pelagic sediments of the underlying Upper Cretaceous–Eocene Scaglia Rossa Fm.

The stratigraphical reconstruction in the Bolca area is hampered by vegetation cover and the widespread volcanic rocks. The sedimentary rocks are few, often dislocated and dismembered by tectonics. Nevertheless, since the 19th century, several authors attempted to explain the geology of this area (Suess, 1868; Bayan, 1870; Munier-Chalmas, 1891).

The first modern study of the whole area date back to Fabiani (1912). He proposed the “Spileccian” stage and gave a very detailed description of the geology and palaeontology of the surroundings of Bolca (Fabiani, 1914, 1915) including a famous stratigraphical sketch of the Monte Postale section.

After Fabiani’s (1915) monograph, only Barbieri and Medizza (1969) published a modern re-examination of the geology and biostratigraphy in the Bolca area. However, they did not examine the Monte Postale–Pesciara area for which the most recent geological and stratigraphical study remains Fabiani (1915).

Sorbini (1967) and Massari and Sorbini (1975) examined the sedimentology of the Pesciara *Lagerstätte*.

The relationships between the volcanic activity and sedimentation in the eastern Lessini (including the Bolca area) were summarised by Barbieri et al. (1982, 1991).

During the late Paleocene–middle Eocene, intense volcanic activity took place in the central-eastern Lessini area. The basic volcanic products were ejected at irregular intervals, with long periods of stasis during which the normal marine sedimentation took place (Barbieri et al., 1982, 1991; De Vecchi and Sedeà, 1995).

Bolca is close to the eastern side of the Castelveto Fault, running NNW to SSE, on the right side of the Alpone Valley. This fault was crucial for the structural and palaeoenvironmental evolution of the central-eastern Lessini in late Paleocene–middle Eocene times. In this time interval, the Castelveto Fault interrupted the extent of the volcanics westward. It was an effective threshold separating the western area, with thin and discontinuous volcanic deposits, from the eastern one, where the volcanic rocks prevail. The Castelveto Fault determined an increase in subsidence in the eastern area and the onset of the Alpone-Agno graben (or semi-graben) (Barbieri et al., 1982, 1991). Here were deposited mainly volcanic rocks, intercalated to marine carbonates (Barbieri, 1972; De Zanche and Conterno, 1972), as in the Pesciara.

Close to the Castelveto Fault, tectonics acted intermittently and contemporary to the main volcanic stages recognized by Barbieri et al. (1991). They distinguished six volcanic stages in the late Paleocene–middle Eocene time span. Barbieri et al. (1991) dated the Pesciara limestone to the time-interval between the third and the fourth volcanic stage. Accordingly, the basaltic veins crossing the limestone are possibly referred to their fourth volcanic stage.

## 3. The stratigraphical section

We sampled the Pesciara stratigraphical section both on the surface and into the tunnels opened to extract the fossil fishes. As yet, the only detailed stratigraphical column of the Pesciara limestones has been published by Massari and Sorbini (1975). We provide here a new column (Fig. 2).

The stratigraphical succession mainly consists of

1. grey fine-grained limestone, organised into metric strata sets, with decimetric beds, which are evenly laminated and separated by thin clayey levels (“*strati a pesci e piante*”=“fish and plants-bearing beds”);
2. coarse-grained biocalcarene-biocalcirudite with molluscs and foraminifers (“*strati sterili*”=“barren beds”, obviously in regard to fish and plants).

The vast majority of the fish and plants dugged out from the Pesciara comes from five about 1 m thick levels, described in the scientific literature, together with some thinner and discontinuous levels never described nor systematically mined. These five levels are

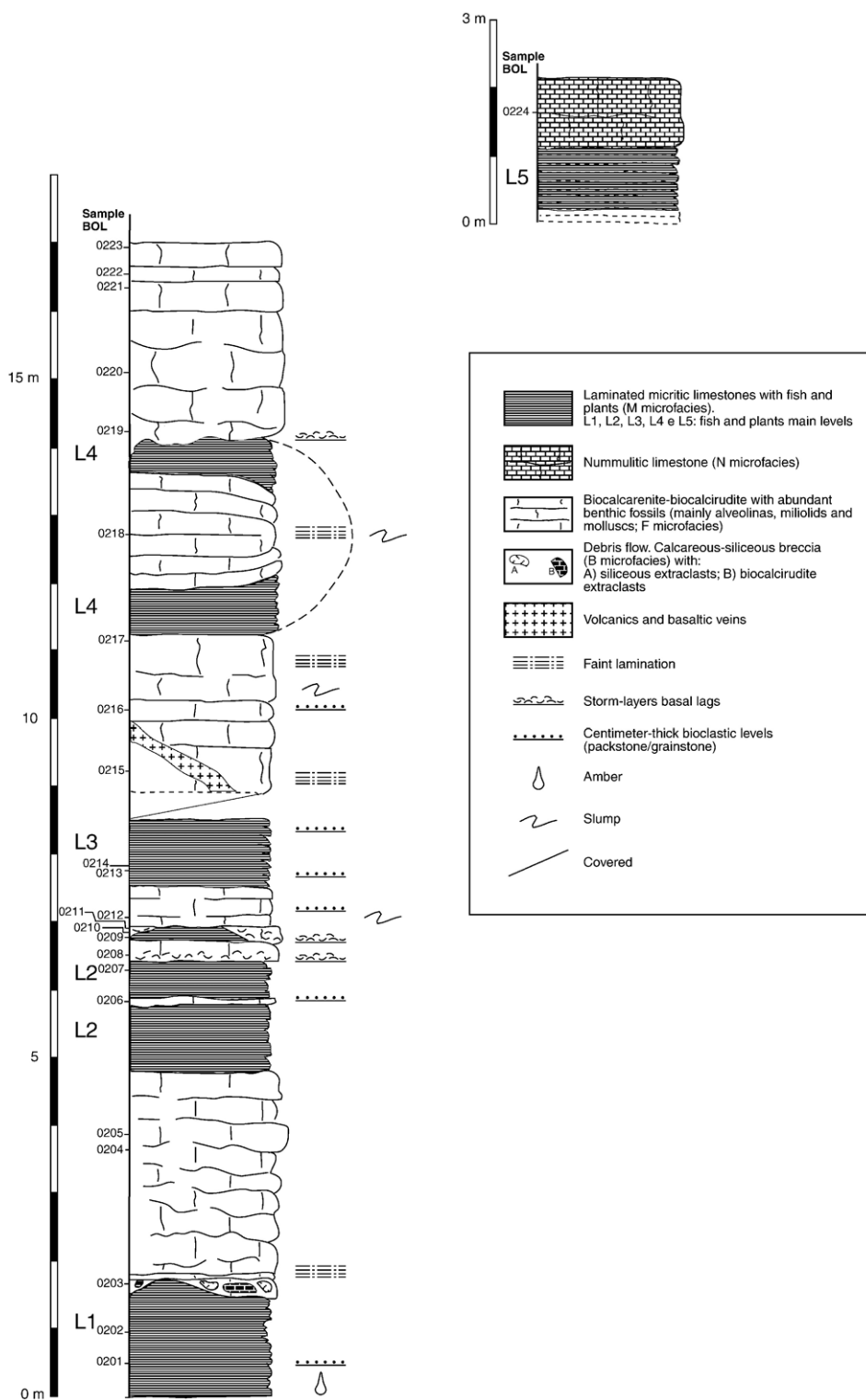


Fig. 2. Stratigraphic section of the Pesciara succession. The fifth fish-bearing level (L5) has been inferred (see text for details).



Fig. 3. Slump straining the fourth fish-bearing level (L4) close to the opening of the uppermost tunnel.

intercalated with limestones containing molluscs and foraminifers, but no fishes. They are referred to here as “fish-bearing levels”, L1 to L5, from the lowest (L1) to the highest (L5).

The L5 is no longer exposed, because it was completely destroyed by the mining activity of the last four centuries. Conversely, the L4 and L3 were not very much digged out, because they yield aesthetically unattractive fishes, being strained and deformed by the gravity-driven slumping events affecting the levels themselves (Fig. 3). Therefore, the greater part of the Pesciara fishes come from the L1 and L2, together with the now-exhausted L5.

The observation of the thin sections, including lithological features and palaeontological content, allowed us to distinguish four main microfacies and three minor subdivisions (Fig. 4):

- M microfacies. Micritic limestones, often bearing fish and plants, further subdivided into:
  - M1 microfacies. Micritic, evenly laminated limestone with black laminae.
  - M2 microfacies. Micritic, irregularly laminated limestone with white (sparitic) laminae.
  - M3 microfacies. Micritic, non-laminated limestone.
- F microfacies. Biocalcarenite–biocalcirudite with abundant benthic fossils (mainly foraminifers and molluscs).
- B microfacies. Calcareous–siliceous breccia with extraclasts.
- N microfacies. Biocalcarenite–biocalcirudite with abundant nummulites and assilinas.

### 3.1. M microfacies

This microfacies includes somewhat different types of limestone, characterized by abundant micritic matrix. In all cases, there are few recognizable bioclasts, mainly of very small size. The M microfacies often alternates with levels bearing larger bioclasts, especially miliolids and alveolinids, assigned to the F microfacies.

The sedimentological and palaeontological features of this microfacies agree with that of several well-known *Fossil-Lagerstätten*, such as Solnhofen (e.g., Barthel et al., 1990).

### 3.2. M1 microfacies

The main feature of this microfacies is the regular, thin lamination with alternating levels of light and dark colour (Fig. 4A, upper part). This varve-like alternation is indicative of nearly complete absence of bioturbation. In fact, this microfacies is characteristic of the fish-bearing levels. The dark laminae contain also some opaque minerals, probably pyrite. In some places there are brownish “droplets”, probably vegetal remains. The fossil content is very scarce, including calcispheres, ostracod valves and very small foraminifers. Among the latter are possible Verneulinidae, with a characteristic profile, rare Valvulinidae, miliolids, and possible rotaliids. It is worth noting that, among the very scarce foraminifers recognized from the Solnhofen faûle there is *Gaudryina bukowiensis* Cushman and Glazewski, a Verneulinidae (Groiss, 1967, cited in Barthel et al., 1990). Exceptionally, some tracks of benthic organisms



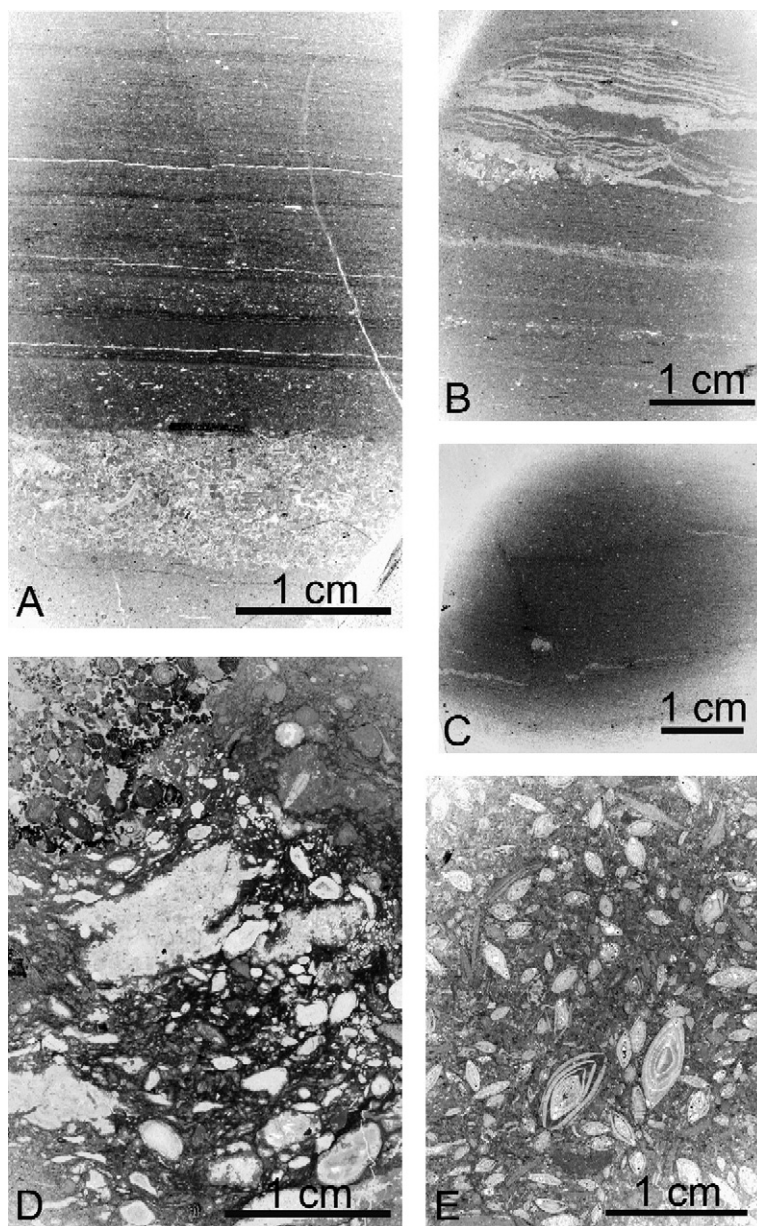


Fig. 4. (A) Thin section showing the F microfacies (in the lower part) and the M1 microfacies (in the upper part); (B) M2 microfacies; (C) M3 microfacies; (D) B microfacies; (E) N microfacies.

have been observed over the surface of these levels (Fig. 5).

### 3.3. M2 microfacies

This microfacies is similar to M1, but the lamination is in places uneven, often wavy, with thicker, light-coloured laminae (Fig. 4B). There is a striking similarity between this microfacies and some laminations of probable bacterial origin recorded from the “flinz” of

the Solnhofen limestone (see Barthel et al., 1990, Fig. 3.10b). The fossil content is very scarce, as in M1. This microfacies has been observed especially within L3 and L4, alternating with the M1 one.

### 3.4. M3 microfacies

This microfacies is usually not associated with the fish-bearing levels. It contains again very scarce fossils, among which are miliolids, textulariids, rare

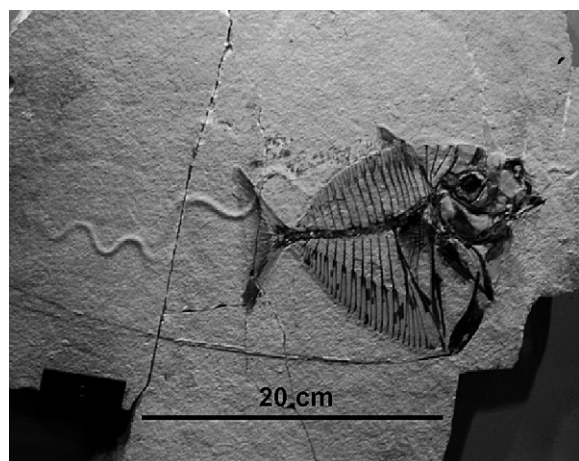


Fig. 5. An exceptional track of a benthic organism (a worm?) over the surface of a micritic fish-bearing bed (M1 microfacies).

Valvulinidae, and possibly ostracods (Fig. 4C). The absence of lamination and fish remains points to different water chemistry and/or oxygen content, affecting the preservation potential.

### 3.5. *F* microfacies

This microfacies is represented by more or less thick biocalcarentic levels intercalated with the M microfacies (Fig. 4A, lower part). They are easily distinguished because of their bioclastic nature: usually they contain well-preserved foraminifers, both large (especially alveolinas) and small (often miliolids). Previously, they have been interpreted as reworked, devoid of palaeoenvironmental or stratigraphical usefulness (e.g., Sorbini, 1972). Our observations do not support this interpretation; whereas the foraminifers are certainly transported (resedimented), they are not reworked. So, they give both stratigraphical and palaeoenvironmental information. The assemblages, even if allochthonous, are coherent with provenance from very shallow palaeoenvironments, in which communities dominated by *Alveolina* or miliolids thrived.

The bioclasts, especially the larger ones, show some diagenetic alteration due to silicification; starting from the normal intrabioclastic porosity, autigenic silica has gradually substituted both portions of the matrix and part of the calcitic tests. The silica is now represented by microcrystalline quartz or, less frequently, by chalcedony. The origin of the silica could be volcanic, but we cannot definitely exclude some biogenic source.

Summarizing, this microfacies represents the abundant detrital limestones produced presumably at the edge of the Pesciara “basin”, coming from areas very close to the latter.

### 3.6. *B* microfacies

In the lower part of the section, we found some levels with brecciated appearance. In thin section they revealed to contain extraclasts. These extraclasts are distinctly silicified, they could be confused with the F microfacies, due to the abundant alveolinas. Nevertheless, all the alveolinas are completely silicified and, more importantly, the assemblages indicate an older biozone (SBZ 10, i.e., early Cuisian according to Serra-Kiel et al., 1998; the Cuisian corresponds roughly to the late Ypresian) when compared with the F assemblages. Instead, the matrix and possibly some clasts attest a middle Cuisian (SBZ 11) age (Fig. 4D).

This microfacies is of particular interest because it testifies to the existence of an older carbonate platform below the Pesciara limestone. This breccia could be linked to a relative uplift of the area. Some bioclasts and lithoclasts are black, probably because of impregnation by iron sulphide (pyrite), or manganese oxides and hydroxides (pyrolusite and/or wad).

### 3.7. *N* microfacies

This microfacies is limited to one sample from a disjointed block coming from the limestones covering L5 (Fig. 4E). The block sampled is a nummulitic limestone containing a very rich and apparently autochthonous assemblage with several species of the genera *Nummulites*, *Assilina*, *Discocyclus*, and very few *Alveolina*. This assemblage, indicating a “normal” platform (probably more distal with respect to the F microfacies), points again to a middle Cuisian age.

### 3.8. The succession

The first fish-bearing level (L1; sampled inside the tunnel) is known as “Cava Bassa” (lower quarry; Sorbini, 1967). It is 1.6 m thick, made up of laminated micrite in decimetric layers interbedded with centimetre-thick silty clays. From the basal portion of L1 rare centimetre-sized amber nodules (Fig. 6) were collected (Trevisani et al., 2005).

The beds are evenly laminated wackestone yielding plant remains, fishes, ostracods, and calcispheres; the lamination is even, parallel and slightly undulated, 1 mm thick or less, rarely reaching 1 cm. There is a direct

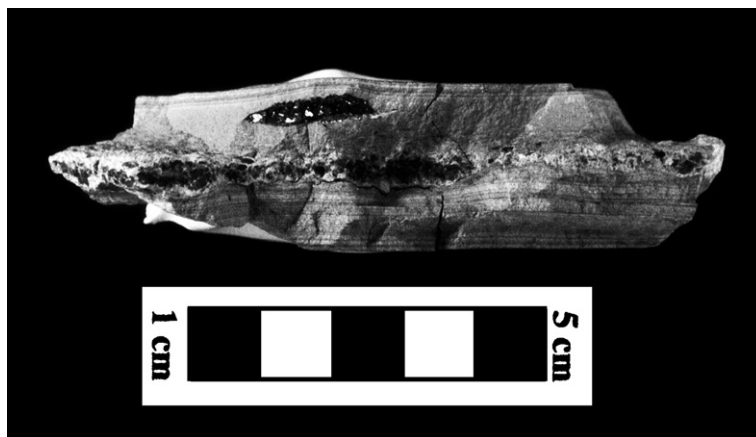


Fig. 6. Transversal section of a portion of the L1 fish-bearing level. Near the top an amber nodule is visible. The typical laminae of the fish-bearing levels (M1 microfacies) are evident, interrupted by a biocalcarenic level with silicified alveolinas in the middle part.

gradation of the laminae, the top of which is capped by a clay film, sometimes oxidized. Some laminae have a “massive” appearance, being separated each other only by a thin clay film. There are grainstone interbeds with erosional base, a few millimetres to 1 cm thick, containing alveolinas, miliolids, and other small benthic foraminifers, along with molluscs, bryozoans, corals, and algae.

Between the levels L1 and L2 (the second fish-bearing level) there are 3.1–3.4 m of ruditic biocalcarenites with nodular (or “mamellonar” *sensu* Trevisani, 1994) texture, clearly bounded by silty clays with interbedded laminated micrites. The base of this layer is erosional over L1, with an undulated paraconglomerate bed (0–30 cm thick) containing calcareous lithoclasts, roughly graded, often silicified and nearly always oxidized (Fig. 7). These lithoclasts contain the reworked alveolinas indicating the SBZ 10 Biozone. The micritic layers are often strongly folded (Fig. 7D). The level as a whole is here interpreted as a consistent debris flow in a plastically deformed matrix (micrites of the microfacies M3 at the top of L1).

The ruditic biocalcarenites contain calcareous lithoclasts, with rounded to sharp edges. The ruditic fraction is coarser (reaching over 10 cm in diameter) and more abundant in the lowermost part of the layer. Inside the lithoclasts we have found:

- a. peloidal grainstone with small benthic foraminifers (especially miliolids);
- b. wackestone–packstone with alveolinids and peloids, also containing corals, algae, bryozoans and plant remains; the bioclasts often show broken, abraded and red- or black-stained tests probably due to oxidization and/or pyritization; some bioclasts show

vadose cements; silicification is pervasive, as microcrystalline quartz which replaces calcite starting from the intrabioclastic porosity; the relict texture is often evident; some lithoclasts and bioclasts are black, probably because of impregnation by manganese sulphides and/or oxides and hydroxides.

The second fish-bearing level (L2; sampled inside the tunnel) is made up of decimetric beds of laminated micrites, intercalated with millimetric to centimetric silty clay, with an overall thickness of 1.6 m; the L2 level is also known as “Cava Alta” (higher quarry; Sorbini, 1967). This level is strikingly similar to L1 with regard to the texture, organization and nature of the laminae. All over the Pesciara outcrop, 1 m above the base of L2, we can follow a packstone horizon 3–5 cm thick, “barren” with respect to fish and plants but containing abundant peloids and miliolids, together with alveolinids and molluscs; the bioclasts of this level are often silicified.

The top of L2 has been eroded by two undulated and gradated beds, with a lumachelle basal lag and overall thickness variable between 30 and 50 cm. These beds are packstones–wackestones with miliolids, molluscs, alveolinids (sometimes oxidized), corals, green algae, echinoids and intraclasts; the bioclasts are sometimes partially silicified. There are centimetre-thick laminated micrites with ostracods intercalated to these levels.

Over the lumachelle layers the laminated micrites reappear with two beds whose thickness varies between 25 cm and 0 cm, due to an erosional contact with the overlying 20 cm-thick bed with a lumachelle basal lag.

Upsection, a 60 cm-thick layer follows, a wackestone with peloids, miliolids, and alveolinids. Within this level we recognised millimetric laminations indicating



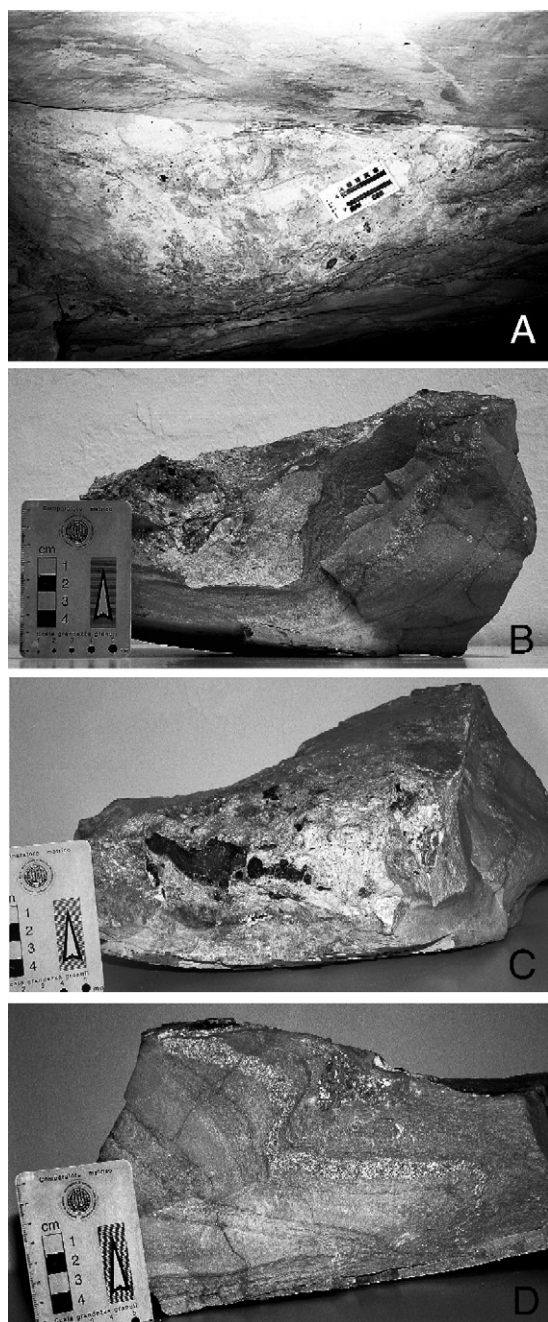


Fig. 7. (A) Mud-supported, polymictic breccia sampled near the top of the first fish-bearing level (L1). It contains silicified lithoclasts and biocalcarentic lithoclasts impregnated by manganese oxides and hydroxides (dark “spots”). The level as a whole is here interpreted as a consistent debris flow in a plastically deformed matrix (micrites of the microfacies M3 at the top of L1); (B) detail of (A) with some lithoclasts (to the left) and bioclastic levels with silicified alveolinids (to the right); (C) detail of (A) with dark lithoclasts impregnated by manganese oxides and hydroxides; (D) detail of (A) showing the marked plastic deformation of the bioclastic levels with alveolinids intercalated with the micrites.

tractive currents with miliolids; the coarse bioclastic fraction is almost completely silicified.

The third fish-bearing level (L3; sampled inside the tunnel) is about 1 m thick. It is made up of 9 laminated micrite beds, intercalated by several coarser layers (significantly more common than in L1 and L2) less than 1 cm thick. The laminated micrites are mudstones–wackestones with graded laminae capped by clay films, less apparent than those of L1 and L2. This subtle lamination is made up of pure micritic limestone intercalated with fine-grained bioclastic levels. In fact, other than ostracods, fish and plant remains, the micrites contain a tiny bioclastic fraction made up of small benthic foraminifers (especially miliolids), which often break the laminae surfaces. Moreover, there are light-coloured, undulated sparitic laminae distinct from that of L1 and L2. The biocalcarentic centimetre-thick interbeds with erosional base are packstones with peloids, miliolids, alveolinids and molluscs; the coarser tests are often silicified.

Upsection, there are 0.5 m covered, near the tunnel entrance, then 2.35 m of non-laminated (or weakly laminated) mudstones–wackestones with ostracods, interbedded with centimetric bioclastic levels (packstones with alveolinids, molluscs, nummulites, and oxidized extraclasts) becoming thicker and more frequent upwards (packstone with peloids, miliolids, molluscs, and alveolinids). These carbonate rocks are cut through by one of the more conspicuous basaltic dykes which cross the whole Pesciara succession.

Then, there is a 3 m-thick slump made up of laminated micrites with ostracods and plant remains. The syndepositional folding affected the fourth fish-bearing level (L4, see Fig. 3): fishes collected from this level are always distorted.

A massive biocalcarentic level, 1.8 m thick, cuts through the top of the underlying slump. The biocalcarentic is roughly graded, with a lumachelle basal lag (packstone with bivalves and alveolinids, also containing miliolids, peloids, and intraclasts) fading upward into a wackestone with miliolids, alveolinids, molluscs, peloids, and intraclasts.

The succession ends with 1 m of packstones–wackestones (arranged in 20–40 cm-thick beds) with peloids, miliolids and plant remains.

The current top of the Pesciara limestone is an undulated bed-surface made up by non-laminated micrites (mudstone) with plant remains and rare miliolids. Probably in past times, this level represented the base of the fifth fish-bearing level (L5).

At last, an isolated boulder dislocated in the lowermost part of the Pesciara outcrop was sampled,

because it came from the limestones capping in the past the L5 (Massimo Cerato, personal communication). It is made up of packstones with abundant nummulites (often silicified) and assilinas, containing also red algae, small benthic and rare planktonic foraminifers.

#### 4. Biostratigraphy

Notwithstanding the ancient knowledge of the Pesciara *Lagerstätte*, the data about its age are surprisingly scanty. Usually, its age has been referred to the early/middle Eocene transition, according to the study of the calcareous nannoplankton carried out by Medizza (1975) on a single sample of the succession. He assigned this sample to the *Discoaster subloensis* Zone (NP 14 or CP 12). However, this age was in contrast with that suggested earlier by Hottinger (1960) on the base of larger foraminiferal assemblages including *Alveolina cremae*, *Alveolina rugosa*, *Alveolina distefanoi*, and *Alveolina rutimeyeri*, indicating the *Alveolina dainellii* Zone, well below the early/middle Eocene boundary. Medizza (1975) solved the apparent contradiction stating that these alveolinids show clear signs of reworking. This was reaffirmed by Massari and Sorbini (1975).

In the Pesciara succession, alveolinids occur in almost all the bioclastic intervals separating the fish-bearing levels. The tests are usually either quite well preserved or present a degree of abrasion consistent with a penecon-

temporaneous transport from a nearby area (Papazzoni and Trevisani, 2002). Moreover, the taxonomic study of the whole fauna indicates a time-consistent assemblage belonging practically to a single biozone. All the exceptions come from extraclasts clearly distinguished from the main sediment (*Alveolina schwageri* from silicified extraclasts in the lower portion of the section).

The larger foraminiferal assemblage includes *Alveolina* ex gr. *canavarii*, *A. cremae*, *A. aff. croatica*, *A. decastroi*, *A. distefanoi*, *A. levantina*, *A. cf. minuta*, *A. rugosa*, *Assilina* spp., *Asterocyclina* spp., *Discocyclina* spp., *Idalina* sp., *Nummulites pratti*, *N. prelucasi*, *N. cf. rotularius*, *Orbitoclypeus* sp., and *Orbitolites* spp. This assemblage is consistent with the one reported by Hottinger (1960), indicating the *A. dainellii* Zone, or SBZ 11 biozone (middle Cuisian; Serra-Kiel et al., 1998).

In a single sample, at the top of L1, we found surely reworked alveolinids; here there are silicified black extraclasts bearing among others *A. schwageri*, marker of the *Alveolina oblonga* Zone (SBZ 10, Early Cuisian). Obviously, this has no consequences on the dating of the Pesciara succession, which remains firmly within SBZ 11.

According to Kapellos and Schaub (1973), Schaub (1981), and Serra-Kiel et al. (1998), the SBZ 11 can be correlated to the whole NP 13 and the lowermost part of NP 14 Zone. This implies that the age of the Pesciara limestones could be restricted to a narrow interval between the base of the NP 14 and the top of the SBZ

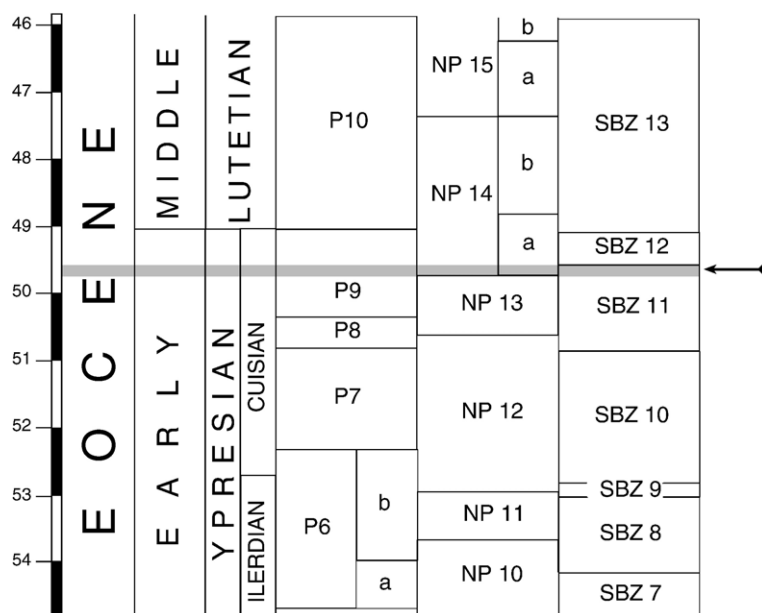


Fig. 8. Correlation between the planktonic (P), calcareous nannoplankton (NP) and the shallow benthic (SBZ) biozonation (modified after Serra-Kiel et al., 1998); the arrow indicates the estimated age of the Pesciara sediments.

11 (Fig. 8). The time-resolution could hardly be so high, given the uncertainties in correlating different biozonation systems. Nevertheless, we underline the agreement between our results and the age based on nannoplankton reported by [Medizza \(1975\)](#).

## 5. Facies analysis and palaeoenvironmental reconstruction

The Pesciara limestone needs a careful investigation before reaching some conclusion about its palaeoenvironmental setting. Several *Fossil-Lagerstätten* of different ages show a “black shale” facies allowing their interpretation as poorly oxygenated depositional environments, with high amounts of organic carbon. Even if the fish-bearing levels of the Pesciara limestones contain some pyrite and bituminous material, their overall light colour is not consistent with a massive accumulation of organic matter. On the other hand, the exceptional preservation of fossil fishes requires the absence of scavengers and reducing conditions within the sediment. The nearly complete absence of benthic fauna from these levels (except for some transported tests) points to the extension of the reducing conditions above the water–sediment interface. The most common explanation for this is the more or less marked lack of oxygen, but we cannot exclude that abnormally high salinity could give the same result. For instance, this interpretation has been proposed for one of the best studied *Fossil-Lagerstätten*, the Solnhofen Plattenkalk of Late Jurassic age (e.g., [Keupp, 1977](#); [Barthel et al., 1990](#); [Viohl, 1994](#)). Both anoxia and hypersalinity are currently associated with the presence of algal mats made up by cyanobacteria, presumably thriving in the Pesciara sediments (e.g., microfacies M2, and possibly also M1).

The fossil content of the fish-bearing levels includes, together with the fish, plant remains, algae, worms, crustaceans, insects, very rare jellyfish, cephalopods, reptiles, and birds ([Sorbini, 1972](#)). In addition, recently the occurrence of amber has been reported ([Trevisani et al., 2002, 2004, 2005](#)). The lack of autochthonous benthic biota suggests that the Pesciara is a stagnation deposit of the classification of [Seilacher et al. \(1985\)](#). It is unclear whether the pelagic fauna could live within the water column immediately above the anoxic (hypersaline?) bottom waters or it has been transported from adjacent areas. Instead, the transport is obvious for continental and freshwater organisms.

The biocalcarene levels were traditionally neglected as “barren” or simply referred to as “mollusc layers” ([Sorbini, 1972](#)). They actually yield a diverse biota especially rich in foraminifers (microfacies F and N).

[Landini and Sorbini \(1996\)](#) assigned the fossil fish fauna from the Pesciara to a reef system (see also [Bellwood, 1996](#)), or at least to the transition between a reef and a pelagic system. The former authors also presented a palaeoenvironmental model. Here we propose a similar model by using data from the literature, together with our own observations.

First of all, we need to advocate a physiography allowing rapid changes between high and low water-energy levels. The more likely hypothesis is that of a subtropical lagoon, close to an emerged area ([Dercourt et al., 2000](#)). This was possibly represented by an archipelago, primarily of volcanic origin. The subaerial environment probably included rivers and coastal swamps. The transition to the open sea was partially interrupted by a rising threshold, passing seawards to an oceanic ramp. The presence of an open, relatively deep basin is inferred from the taxonomic composition of the fish assemblages, including different families of pelagic fishes, such as the Clupeidae ([Landini and Sorbini, 1996](#)).

Regarding the origin of the threshold, data are very few. We have some clues from the bioclastic levels of the Pesciara: they give no indications about a real coral reef. So, we prefer to adopt neutral terms such as threshold, or carbonate buildup (according to [Wilson, 1975](#)), excluding any genetic implication.

The facies analysis demonstrates that, except for the evenly laminated micrite with fishes and plant remains (M microfacies), the greater part of the limestones in the Pesciara succession is made up of tempestites (corresponding to the F microfacies). The storm events wiped out the threshold carbonate buildup, destroying part of it and transporting into the Pesciara “basin” the washover deposits. The resedimented limestone contains miliolid-dominated or *Alveolina*-dominated foraminiferal assemblages. This is consistent with its provenance from back-reef or very shallow inner platform according to current palaeoenvironmental models (e.g., [Arni, 1965](#); [Serra-Kiel and Reguant, 1984](#); [Buxton and Pedley, 1989](#); [Jorj et al., 2003](#); [Beavington-Penney and Racey, 2004](#)). Since the main fish-bearing levels have a thickness reaching 1 m or more, we could assume that, over relatively long time spans, the lagoon had very low hydrodynamic energy. Because it is unlikely the storm events were lacking for such a long time, we may assume that periodical sea-level oscillations were crucial in making more or less effective the sheltering of the threshold.

Of the impressive Pesciara flora and fauna here we consider mainly the palaeoecological significance, whereas the systematics of the fishes has been widely reported in a vast literature. Instead, some additional



details are given on the “minor fauna”, especially the foraminifers.

The palaeoenvironment of the Pesciara could be compared with (but not completely assimilated to) a reef-linked depositional system, with some emerged areas of unknown extension nearby. This is deduced more from the palaeoecological analysis than from the sedimentary evidences, because the last are constrained by the very small outcrop area. For instance, we have no direct evidence of a reef facies *sensu stricto*, whereas some ecological guilds of fishes recognized by Landini and Sorbini (1996) clearly advocate a reef palaeoenvironment.

The Pesciara “basin” was surrounded by very shallow, normally oxygenated sea bottoms, colonised by *Alveolina*- or miliolid-dominated foraminiferal assemblages. The *Nummulites*–*Assilina*-dominated assemblages were not found in the Pesciara limestones, with the single exception of the L5-capping limestone (N microfacies). This kind of assemblage indicates the open, deeper part of the carbonate platform (e.g., Beavington-Penney and Racey, 2004 and references therein), which was therefore probably not directly connected with the stagnating Pesciara bottom.

There are numerous evidences testifying to an emerged land close to the Bolca area: continental plant remains (trees, bushes, herbs, coconuts, etc.; Massalongo, 1856, 1859a,b), continental animals, e.g., insects (hymenopterans, orthopterans, termites, etc.; Massalongo, 1856; Omboni, 1886; Secretan, 1975), and amber (Trevisani et al., 2005).

The freshwater palaeoenvironment (rivers and coastal swamps) is also documented by fossils of water plants like *Eichornia* sp. and *Maffea* sp., freshwater insects (dragonflies), and some fishes like *Eolates* sp., *Scatophagus* sp., and *Cyclopoma* sp., which probably lived in brackish waters close to river mouths.

## 6. Depositional model

The depositional model for the Pesciara “lagoon” arises from partially speculative arguments, but it agrees with all the palaeoecological evidences reported in literature, and also with the facies analysis.

We assume that, during a relative sea-level lowstand, the barrier buildup sheltered very effectively the lagoon. Here the restricted circulation produced the ideal environment for the exceptional preservation of the fossils. On the contrary, when there was a sea-level highstand, the barrier buildup could not completely

shelter the lagoon; instead, the barrier itself was partially dismantled and resedimented into the lagoon. At present, we cannot establish whether the relative sea-level oscillations were due to the glacio-eustatism or to volcanic/tectonic movements.

To explain the exceptional preservation observed in the fish-bearing levels in the Pesciara (which could be compared to “black shales”) we must assume a restricted circulation and very low water-energy conditions. However, this is not sufficient: the amazing preservation of the soft tissues, the even lamination, the presence of pyrite and bitumen, the almost complete absence of bottom dwellers and bioturbation, all indicate that during the deposition of the fish-bearing levels the Pesciara sea bottom was under anoxic (disaerobic) conditions. Once again, relative sea-level oscillations and consequent changes in the sheltering effect of the barrier buildup justify the variation in the position of the reduction-oxidation surface within the sedimentary basin of the Pesciara, and the variable conditions of oxygenation at the sea bottom.

The depositional model (Fig. 9) relies first on the seasonal alternation of wet and arid conditions.

During highstand times, in the wet season (Fig. 9A) an estuarine circulation set up, so the river inflows established a low-salinity superficial current seawards, counterbalanced by a normal-salinity undercurrent coastward. The net result is a density layering of the water body. The increasing river inflows raised the nutrient concentration (making possible even a water eutrophication, according to Sorbini, 1972) and consequently increasing primary productivity, with organic material accumulating on the sea bottom. The decay of this material consumed the dissolved oxygen, raising the redox boundary and increasing the sea-bottom anoxic layer thickness. Conversely, during the dry season (Fig. 9B) an anti-estuarine circulation set up, so the high evaporation rates and the low river inflows concentrated salts raising the nearshore density. The hypersaline water sank seawards, counterbalanced by a normal-marine water flux near the surface. Therefore, the density layering was destroyed and the redox boundary sank, making the sea bottom more oxygenated.

On the contrary, during lowstand times, the interchanges between the open sea and the lagoon were extremely reduced due to some kind of threshold. In these conditions, during the wet season (Fig. 9C) the estuarine circulation was characterised by strong superficial current seawards and weak undercurrent lagoonwards; during the dry season (Fig. 9D) the anti-estuarine circulation surely sunk to some extent the



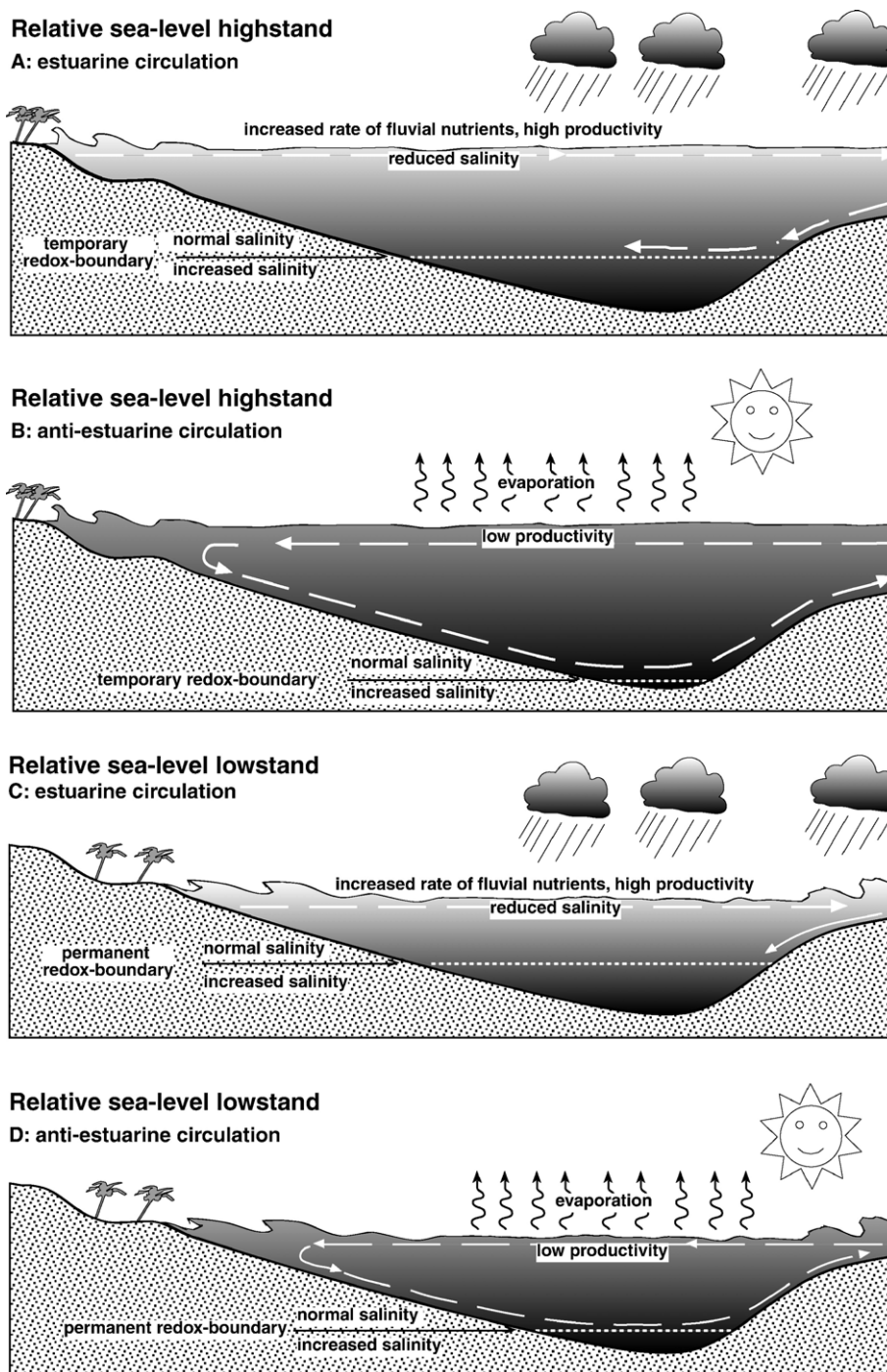


Fig. 9. Sketch showing the depositional model for the Pesciara. For details, see the text. Note that, during highstand times, water mixing occurred (especially in the dry season); conversely, during lowstand times, the circulation patterns did not allow substantial water mixing, producing the best conditions for the exceptional preservation of fishes. The grey tones of the water indicates, from dark to light, decreasing salinity.

redox boundary, but could not completely mix up the water leaving the pycnocline substantially untouched. Consequently, during the relative sea-level lowstand times the water body stagnated, with permanent sea-

bottom anoxia, only sporadically interrupted by very short episodes of benthic colonisation, presumably triggered by water mixing after strong storms. These short oxygenated intervals are recorded by rare tracks of

benthic organisms and rare mollusc and brachiopod faunas (Mellini and Quaggiotto, 1999).

## 7. Conclusions

As yet, the biostratigraphy of the “Pesciara” *Fossil-Lagerstätte* relies on a single nannoplankton age determination (Medizza, 1975). The age determined by Hottinger (1960) by means of alveolinids was generally disregarded both because the foraminifers were considered reworked and because it did not fit with the NP zone of Medizza (1975). Our new study of the larger foraminifers allowed us to refer the whole Pesciara sediments to SBZ 11 (middle Cuisian, i.e., late Ypresian, about 50 ma ago; Serra-Kiel et al., 1998). Hints of an older carbonate platform are given by silicified extraclasts containing alveolinids of the underlying SBZ 10 (Early Cuisian). Therefore, all the fish-bearing limestones intercalated with the coarser foraminiferal limestones are of early Eocene age (not early–middle Eocene as formerly indicated).

Facies analysis allowed us to distinguish between autochthonous micritic limestones (M microfacies) and allochthonous biocalcarenes–biocalcirudites (F, N, and B microfacies). We stress that the allochthonous sediments are not reworked (except for some elements of the B microfacies): they come from nearby areas exactly as the fishes did not live on the autochthonous micritic muds.

The depositional model involves a restricted “basin” (this term does not imply a greater depth), where the interchange of water was very low, affecting the oxygen content. In this basin, sedimentation was mainly micritic (microfacies M), possibly with occasional stromatolite-like bacterial mats (microfacies M2). The coarser grained deposition of foraminifer-rich limestones (microfacies F and possibly N) was triggered by sea-level oscillations and storms. The Pesciara basin was very close to some emerged land (the extension of which we cannot estimate), as witnessed by the abundant continental fossils both of plants and animals.

Some clues could suggest a coral reef (Landini and Sorbini, 1996), which could be a candidate to build the threshold isolating the basin from the open sea. Nevertheless, a real coral reef was never found near the Pesciara.

## Acknowledgements

We thank the reviewers for their critical reading, which substantially improved the manuscript. Thanks to D. Massetti (Trieste University) for his kind help in

some microfacies interpretation. We are grateful to the Comunità Montana della Lessinia for allowing us access to the Pesciara site. Many thanks to the whole Cerato family for their collaboration, in particular to Massimo Cerato for his useful suggestions and great kindness. Work financed with the research grants of the Società Paleontologica Italiana (Fondo per la Tutela del Patrimonio Paleontologico), Miur PRIN 2004 (resp. Prof. A. Russo), and of the Museo Civico di Storia Naturale di Ferrara.

## References

- Arni, P., 1965. L'évolution des *Nummulitinae* en tant que facteur de modification des dépôts littoraux. *Mémoires du Bureau de Recherches Géologiques et Minières* 32, 7–20.
- Barbieri, G., 1972. Sul significato geologico della Faglia di Castelvero (Lessini veronesi). *Atti e Memorie dell'Accademia Patavina di Scienze. Lettere ed Arti* 84, 297–302.
- Barbieri, G., Medizza, F., 1969. Contributo alla conoscenza geologica della regione di Bolca (Monti Lessini). *Memorie dell'Istituto di Geologia e Mineralogia dell'Università di Padova* 27, 1–36.
- Barbieri, G., De Zanche, V., Medizza, F., Sedeà, R., 1982. Considerazioni sul vulcanismo terziario del Veneto occidentale e del Trentino meridionale. *Rendiconti della Società Geologica Italiana* 4, 267–270 (1981).
- Barbieri, G., De Zanche, V., Sedeà, R., 1991. Vulcanismo paleogenico ed evoluzione del semigraben Alpone-Agno (Monti Lessini). *Rendiconti della Società Geologica Italiana* 14, 5–12.
- Barthel, K.W., Swinburne, N.H.M., Conway Morris, S., 1990. Solnhofen. A Study in Mesozoic Paleontology. Cambridge University Press, Cambridge.
- Bayan, F., 1870. Sur les terrains tertiaires de la Venetie. *Bulletin de la Société Géologique de France* 27 (2), 444–486.
- Beavington-Penney, S., Racey, A., 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. *Earth-Science Reviews* 67, 219–265.
- Bellwood, D.R., 1996. The Eocene fishes of Monte Bolca: the earliest coral reef fish assemblage. *Coral Reefs* 15 (1), 11–19.
- Buxton, M.W.N., Pedley, H.M., 1989. A standardized model for Tethyan Tertiary carbonate ramps. *Journal of the Geological Society, London* 146, 746–748.
- Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju-Duval, B., Brunet, M.F., Cadet, J.P., Crasquin, S., Sandulescu, M., 2000. Atlas Peri-Tethys Palaeogeographical maps. CCGM/CGMW, Paris.
- De Vecchi, G., Sedeà, R., 1995. The Paleogene basalts of the Veneto region (NE Italy). *Memorie di Scienze Geologiche* 47, 253–274.
- De Zanche, V., Conterno, T., 1972. Contributo alla conoscenza geologica dell'orizzonte di Ronca nel Veronese e nel Vicentino. *Atti e Memorie dell'Accademia Patavina di Scienze. Lettere ed Arti* 84, 287–295.
- Fabiani, R., 1912. Nuove osservazioni sul Terziario fra il Brenta e l'Astico. *Atti dell'Accademia delle Scienze Veneta-Trentino-Istria* 5 (1), 7–36.
- Fabiani, R., 1914. La serie stratigrafica del Monte Bolca e dei suoi dintorni. *Memorie dell'Istituto di Geologia della Regia Università di Padova* 2, 223–235 (1913).

- Fabiani, R., 1915. Il Paleogene del Veneto. Memorie dell'Istituto di Geologia della Regia Università di Padova 3, 1–336.
- Hottinger, L., 1960. Recherches sur les Alvéolines du Paléocène et de l'Eocène. Schweizerische Paläontologische Abhandlungen 75–76, 1–243.
- Jorry, S., Davaud, E., Caline, B., 2003. Controls on the distribution of nummulite facies: a case study from the Late Ypresian El Garia Formation (Kesra Plateau, Central Tunisia). *Journal of Petroleum Geology* 26 (3), 283–306.
- Kapellos, C.C., Schaub, H., 1973. Zur Korrelation von Biozonierungen mit Grossforaminiferen und Nannoplankton im Paläogen der Pyrenäen. *Eclogae geologicae Helvetiae* 66 (3), 687–737.
- Keupp, H., 1977. Ultrafazies und Genese der Solnhofener Plattenkalke (Oberer Malm, Südliche Frankenalb). Abhandlung der Naturhistorischen Gesellschaft Nürnberg e.V. 37, 1–128.
- Landini, W., Sorbini, L., 1996. Ecological and trophic relationships of Eocene Monte Bolca (Pesciara) fish fauna. In: Cherchi, A. (Ed.), *Autecology of Selected Fossil Organism: Achievements and Problems*. Bollettino della Società Paleontologica Italiana, special vol. 3, pp. 105–112.
- Massalongo, A., 1856. Studi Paleontologici. Antonelli, Verona.
- Massalongo, A., 1859a. Specimen photographicum quorundam plantarumque fossilium agri veronensis. Vicentini-Franchini, Verona.
- Massalongo, A., 1859b. Syllabus plantarum fossilium hucusque in formationibus tertiariis Agri Veneti detectarum. Merlo, Verona.
- Massari, F., Sorbini, L., 1975. Aspects sédimentologiques des couches à poissons de l'Éocène de Bolca (Vérone–Nord Italie). IX Congrès International de Sédimentologie 55–61.
- Medizza, F., 1975. Il nannoplancton calcareo della Pesciara di Bolca (Monti Lessini). Studi e Ricerche sui Giacimenti Terziari di Bolca 2, 433–444.
- Mellini, A., Quaggiotto, E., 1999. Aggiornamenti sulla “fauna minore” della Pesciara di Bolca (Verona). Studi e Ricerche-Associazione Amici del Museo-Museo Civico “G. Zannato”, 23–30.
- Munier-Chalmas, E., 1891. Étude du Tithonique, du Crétacé et du Tertiaire du Vicentin. These, Paris.
- Omboni, G., 1886. Di alcuni insetti fossili del Veneto. Atti Regio Istituto Veneto Scienze Lettere ed Arti (ser. 6) 4, 1421–1435.
- Papazzoni, C.A., Trevisani, E., 2002. Risultati preliminari dello studio delle Alveoline della Pesciara di Bolca (VR). In: Tintori, A. (Ed.), *Giornate di Paleontologia 2002*, Riassunti, 40.
- Schaub, H., 1981. Nummulites et Assilines de la Thétyss Paléogène. Taxonomie, phylogénèse et biostratigraphie. Schweizerische Paläontologische Abhandlungen 104, 1–236.
- Secretan, S., 1975. Un Orthoptère fossile du Monte Bolca. Studi e Ricerche sui Giacimenti Terziari di Bolca 2, 427–431.
- Seilacher, A., Reif, W.-E., Westphal, F., 1985. Sedimentological, ecological and temporal patterns of fossil *Lagerstätten*. *Philosophical Transactions of the Royal Society London B* 311, 5–24.
- Serra-Kiel, J., Reguant, S., 1984. Paleoeological conditions and morphological variation in monospecific banks of *Nummulites*: an example. Benthos '83; 2nd International Symposium on Benthic Foraminifera (Pau, April 1983), pp. 557–563.
- Serra-Kiel, J., Hottinger, L., Caus, E., Drobne, K., Ferrández, C., Jauhri, A.K., Less, G., Pavlovec, R., Pignatti, J., Samsó, J.M., Schaub, H., Sirel, E., Strougo, A., Tambareau, Y., Tosquella, J., Zakrevskaya, E., 1998. Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin de la Société Géologique de France* 169 (2), 281–299.
- Solinas, G., 1971. Bolca e i suoi fossili. *Natura Alpina* 22, 39–74.
- Sorbini, L., 1967. Contributo alla sedimentologia della “Pesciara” di Bolca. Memorie del Museo Civico di Storia Naturale di Verona, 15, pp. 213–221.
- Sorbini, L., 1972. I fossili di Bolca. Museo Civico di Storia Naturale di Verona.
- Suess, E., 1868. Ueber die Gliederung des vicentinische Tertiärgesbirges. Sitzungsberichte der K. Akademie der Wissenschaften, I Abtheilung 58, 265–280.
- Trevisani, E., 1994. Evoluzione paleogeografica e stratigrafia sequenziale del margine orientale del Lessini Shelf durante l'Eocene inferiore-medio (Prealpi Venete). *Memorie di Scienze Geologiche* 46, 1–15.
- Trevisani, E., Papazzoni, C.A., Ragazzi, E., Roghi, G., 2002. Presenza di Ambra nell'Eocene Inferiore delle Prealpi Venete (Province di Vicenza e Verona). IX Riunione annuale GIS, Raccolta dei Riassunti, pp. 90–91.
- Trevisani, E., Papazzoni, C.A., Ragazzi, E., Roghi, G., 2004. Amber event in the early Eocene of the Lessini Mountains (northern Italy). 32nd International Geological Congress, Electronic Version Posted On-line on July 20, 2004, pt. 2, sez. 211–10, p. 983.
- Trevisani, E., Papazzoni, C.A., Ragazzi, E., Roghi, G., 2005. Early Eocene amber from the “Pesciara di Bolca” (Lessini Mountains, Northern Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology* 223 (3–4), 260–274.
- Viohl, G., 1994. Fish taphonomy of the Solnhofen Plattenkalk—an approach to the reconstruction of the palaeoenvironment. *Geobios Mémoire Special* 16, 81–90.
- Wells, R.T., 1996. Earth's Geological History a Contextual Framework for Assessment of World Heritage Fossil Site Nominations. IUCN-UNESCO.
- Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer Verlag, New York.