4. The Pesciara-Monte Postale *Fossil-Lagerstätte*: 1. Biostratigraphy, sedimentology and depositional model

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Biostratigraphy

The age assignment of the Monte Postale and Pesciara *Fossil-Lagerstätten* has been longly debated. Fabiani (1914, 1915) assigned all the strata to the Lutetian (Middle Eocene) (Fig. 1). Also Malaroda (1954) considered the mollusks from the Monte Postale as Lutetian.

Medizza (1975) studied the calcareous nannofossils on a single sample from the Pesciara, attributing it to the *Discoaster sublodoensis* Zone (NP 14 or CP 12), whose
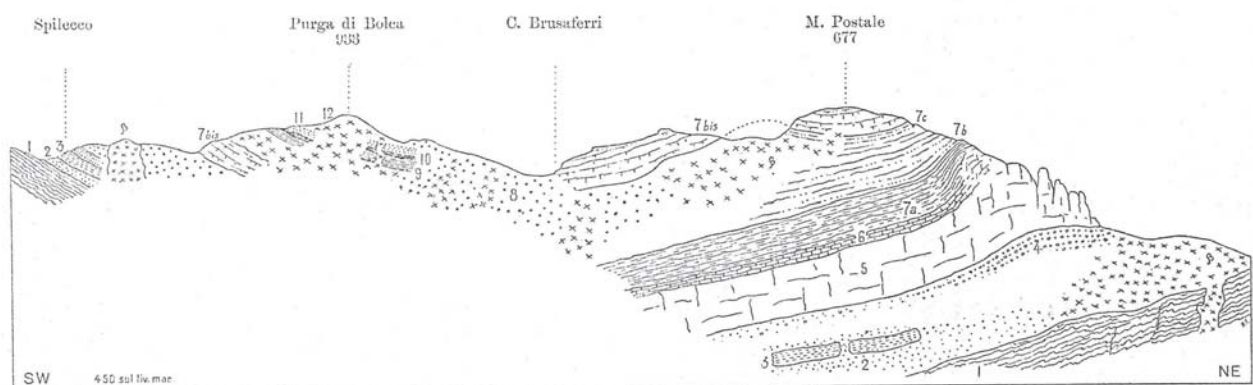

Fig. 1 - Monte Postale-Purga di Bolca-Spilecco profile and section according to Fabiani (1915). 1) "Senonian" (Upper Cretaceous) Scaglia Rossa; 2) "Early Eocene" (probably Upper Paleocene) tuffs; 3) "Early Eocene" (probably Upper Paleocene-lowermost Eocene) limestones; 4) basaltic breccias with red algae ("Nullipore"); 5) algal ("Nullipore") limestones; 6) laminated limestones with crustaceans; 7) *Alveolina* limestones: 7a) with plants and fishes; 7b) with marine mollusks; 7c) with marine, brackish, and terrestrial mollusks; 7bis) *Nummulites irregularis* limestones; 8) basaltic breccias; 9) Marls; 10) shales and lignite with *Crocodylus vicetinus*; 11) Tuffs with palm trees and freshwater-terrestrial mollusks; β) basalts.

range covers the uppermost Ypresian and lowermost Lutetian. This age contrasted with the larger foraminiferal *Alveolina dainellii* Zone determined by Hottinger (1960), which is well below the Lower/Middle Eocene boundary. Medizza (1975) stated that the larger foraminifera were reworked, as already declared by Sorbini (1967) and reaffirmed by Massari & Sorbini (1975).

Papazzoni & Trevisani (2006) found that the alveolinid tests are usually either quite well preserved or present a degree of abrasion consistent with a penecontemporaneous transport from a nearby area. Moreover, the taxonomic study of the whole fauna indicated a larger foraminiferal assemblage belonging to a single biozone, the SBZ 11 (middle Cuisian; Serra-Kiel et al., 1998), corresponding exactly to the *A. dainellii* Zone determined by Hottinger (1960). A single sample in the lowermost part of the Pesciara section bears surely reworked alveolinids from the *Alveolina oblonga* Zone (SBZ 10, early Cuisian; Papazzoni & Trevisani, 2006). The correlations among different biozonations allowed to better precise the age of the Pesciara limestones, restricting it to a narrow interval between the base of the NP 14 and the top of the SBZ11 (Fig. 2).

At present there are no published updated biostratigraphic data regarding the Monte Postale succession. A preliminary report assigning the lower-middle part of the Monte Postale to the SBZ 11 has been published by Papazzoni & Trevisani (2009).
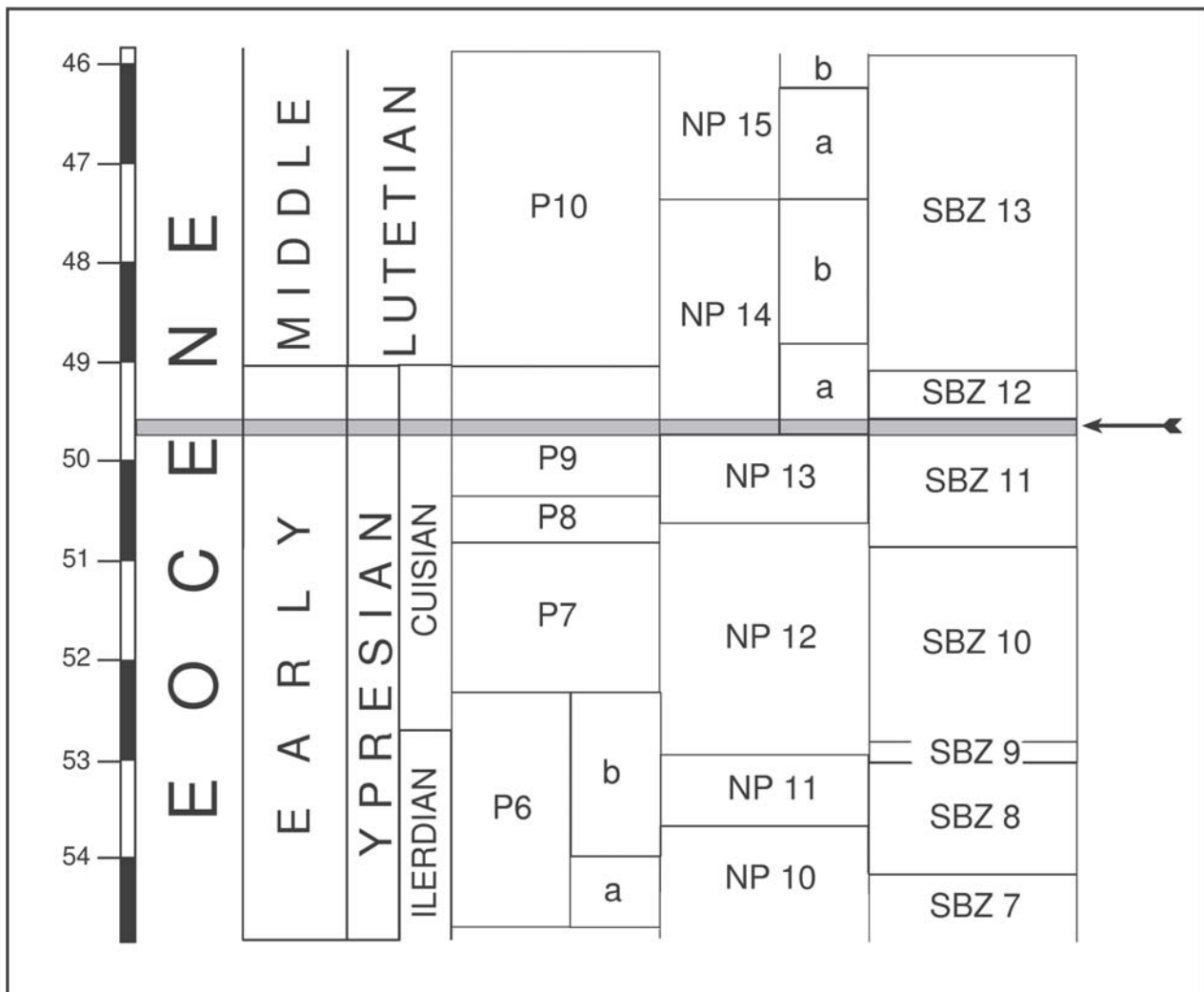

Fig. 2 - Correlation between the planktonic (P), calcareous nannofossils (NP) and the shallow benthic (SBZ) biozonations (modified after Serra-Kiel et al., 1998); the arrow indicates the estimated biostratigraphic assignment of the Pesciara section (after Papazzoni & Trevisani, 2006).

SEDIMENTOLOGY AND DEPOSITIONAL MODEL

Bolca is worldwide famous mainly for its fossil fish fauna, which comes entirely from the two localities of the Pesciara di Bolca and Monte Postale. The two localities are very close each other and, even if their stratigraphic relationships are still not completely understood (see above), they share common features, such as the presence of finely laminated limestone containing the fish and plant fossils. These lithologies are common in other *Fossil-Lagerstätten* of different ages, such as for instance the Jurassic Solnhofen lithographic limestone, where intra-platform depressions or basins were protected from the wash and wave action of the open ocean by one or several thresholds (Barthel et al., 1990; Papazzoni & Trevisani, 2006). Usually these deposits are assumed to have been developed in shallow water environments (less than 200 m depth), characteristic for most *Fossil-Lagerstätten*, though upper bathyal depths were proposed by Giusberti et al. (2014) for the recently described Early Eocene *Fossil-Lagerstätte* of Solane (Verona province), very close to Bolca both in time and space.

In these restricted basins the reconstructed paleoenvironment is commonly anoxic and eventually euxinic due to the lack of bottom dwellers, except for washed in organisms or rare currents marks. The conditions of scarce to absent oxygenation enhance the preservation of organic matter primarily produced within the water column by autotrophic organisms and also the production of floating or benthic microbial mats. However, the organic matter content of the Pesciara di Bolca limestone is rather low with Total Organic Carbon (TOC) < 0.5% (Schwark et al., 2009). In accordance with these data, exceptional fossilization in anoxic conditions does not appear to guarantee high organic matter contents. The investigation of the organic matter from the Pesciara *Fossil-Lagerstätte* provided important information about the paleoenvironmental parameters allowing the exceptional preservation of fossils in the laminated limestone (Schwark et al., 2009).

The fossil content of the fish-bearing beds includes, together with the fish, plant remains, algae, worms, crustaceans, insects, very rare jellyfishes, cephalopods, reptiles, and birds (Sorbini, 1972). In addition, the occurrence of amber has also been reported (Trevisani et al., 2005). The rarity of autochthonous benthic invertebrates may suggest that the Pesciara is a stagnation deposit according to the classification of Seilacher et al. (1985). The fish fauna, however, includes several benthic taxa (batoids, pleuronectiforms, eocottids, callipterygids, and lophiiforms) and many others which certainly were closely associated with the substrate (see Carnevale et al., 2014, this volume, for a more detailed discussion).

The high taxonomic diversity of the fish assemblage and its tropical shallow-water character have been traditionally interpreted as the evidences of a close link to a coral reef system (e.g., Blot, 1969). Moreover, the Bolca fish assemblage includes the earliest representatives of several families today closely associated with coral reefs. The morphology of the Bolca taxa belonging to reef fish families is extremely similar, if not undistinguishable, from that of their extant counterparts. For this reason, Bellwood (1996) and, subsequently Bellwood & Wainwright (2002), considered the fossil fishes of Bolca as the earliest clearly defined evidence of coral reef fish assemblage, documenting the starting point of the association between certain fish families and coral reef systems.

At the same time, based on auto- and synecological considerations, Landini & Sorbini (1996) assigned the Pesciara fossil fish assemblage to a perireefal system influenced by both the heterogenous coastal environments and the open sea. According to Landini & Sorbini (1996), the sedimentation of the laminated limestone took place in a silled depression located parallel to the coast at many dozens of meters of depth. In this model,

the overall physiographic context consists of a coastal area influenced by the open sea and characterized by fluvial systems, coastal lagoons and open expanses of *Halochloris* sand and seagrass beds surrounding reef zones.

A more recent model proposed by Papazzoni & Trevisani (2006) suggests that the Pesciara-Monte Postale laminated limestone were deposited in a subtropical lagoon, close to an emerged area with rivers and coastal swamps. The transition to the open sea was partially interrupted by a rising threshold, passing seawards to an oceanic setting testified by the presence of pelagic fishes (e.g., clupeids, paralepidids, carangids, ductorids, scombrids, blochiids, palaeorhynchids, euzaphlegids, pomatomids, etc.; Landini & Sorbini, 1996). The nature of this threshold is still uncertain: even if some coral-bearing limestones have been described in the past (e.g., Barbieri & Medizza, 1969), there are at present no reports of reefal bioconstructed limestones.

The facies analysis of the Pesciara limestones distinguished the evenly laminated micrite with fish and plant remains, interpreted as deposited in a lagoon with very low hydrodynamic energy, and the miliolid-dominated or *Alveolina*-dominated limestones, interpreted as detrital deposits generated by storm events wiping out the threshold, destroying part of it, and transporting into the Pesciara lagoon the washover sands. The alternating abundance or scarcity of this detrital deposition was explained as controlled by periodical relative sea-level oscillations influencing the effectiveness of the threshold in sheltering the lagoon (Papazzoni & Trevisani, 2006).

The total thickness of the Pesciara limestones is not easy to be measured, because of the uneven distribution of the detrital levels, which have laterally variable thickness and erosive base. Moreover, some slumps are clearly visible on the outcrop and at least in one case a fish-bearing level has been involved in synsedimentary deformation (Fig. 3). However, the total thickness measured by Papazzoni & Trevisani (2006) do not exceed 17 m at present. Other than the present-day four evenly-laminated limestones (L1-L4 in Fig. 3), there was in the past one more fish-bearing level (L5 in Fig. 3) above, but it has been completely destroyed by the digging activity for collecting fossil fishes.

The presence of drylands close to the Pesciara is also witnessed by the fossil continental plants (trees, bushes, herbs, coconuts, etc.; Massalongo, 1856, 1859; amber; Trevisani et al., 2005) and animals, e.g., insects (hymenopterans, orthopterans, termites, etc.; Massalongo, 1856; Omboni, 1886; Secretan, 1975), arachnids (a scorpion; Cerato, 2011), snakes (Janensch, 1904, 1906; Auffenberg, 1959), and birds (Omboni, 1885; Cerato, 2011).

According to the organic geochemical data, the predominant origin of kerogenous organic matter in the Pesciara sediments can be attributed to marine organisms with a minor admixture of terrigenous material. Biomarkers reveal that the terrigenic fraction is predominantly made up by land plant waxes that were transported into the depositional environment by eolian processes. Only in the lowermost fish-bearing level in the Pesciara the terrigenous-derived organic matter indicates significant terrestrial freshwater run-off (Schwark et al., 2009).

Molecular biomarkers indicate that the marine organic production was dominated by diatoms, even if they were never reported in the fossil assemblages. Their absence is tentatively attributed to dissolution of diatom tests under alkaline pore water conditions; the dissolved biogenic silica could be in turn the source of the observed silicified levels in different parts of the Pesciara succession. A potential role of benthic diatom mats in the preservation process of fossils has been speculated by Schwark et al. (2009), because of the low abundance of cyanobacteria inferred from the moderate amounts of mid-chain branched alkanes and other cyanobacterial biomarkers.

The depositional environment in the Pesciara paleobiotope was most probably anoxic though not euxinic, with a water column stratification due to episodic freshening of the
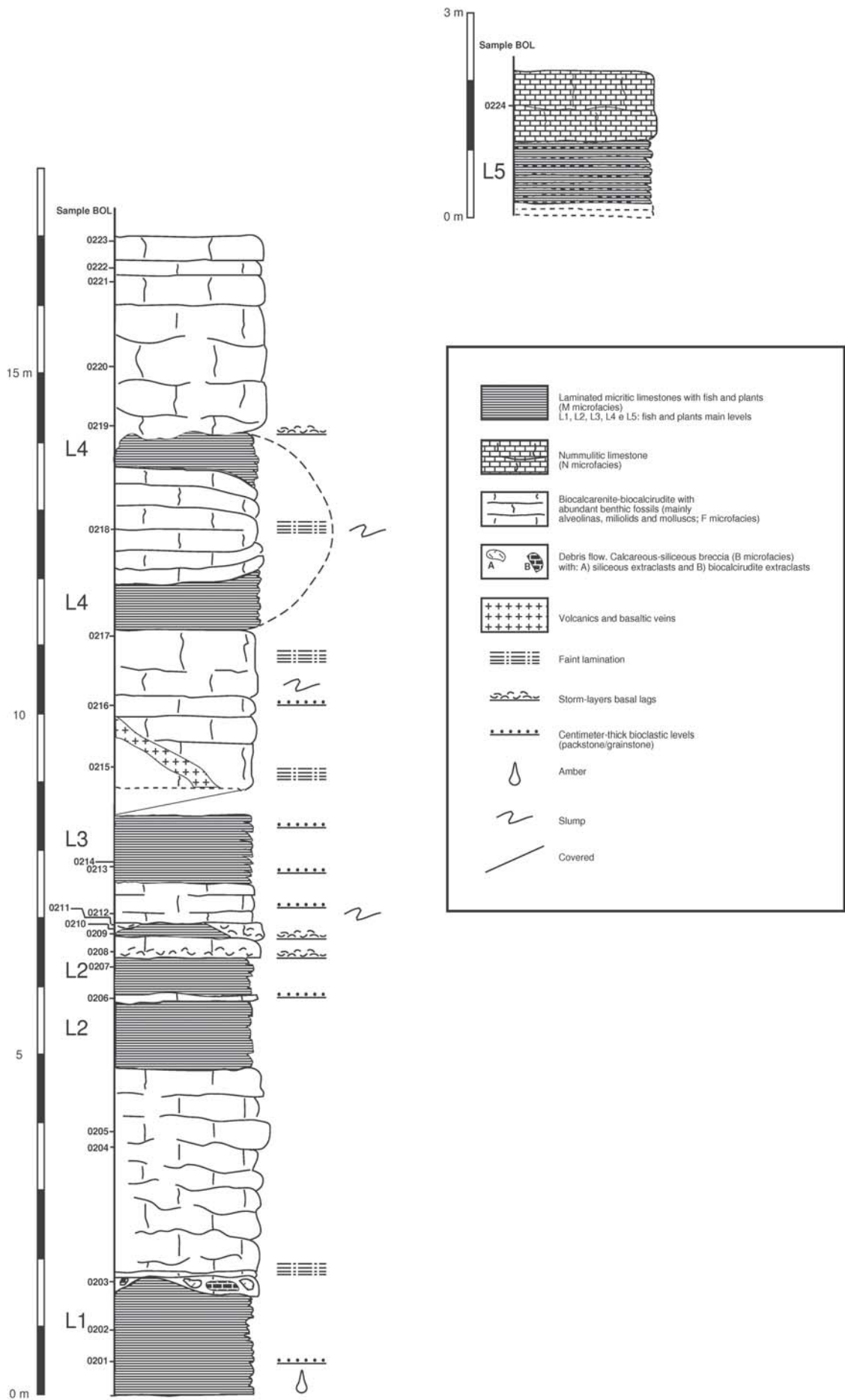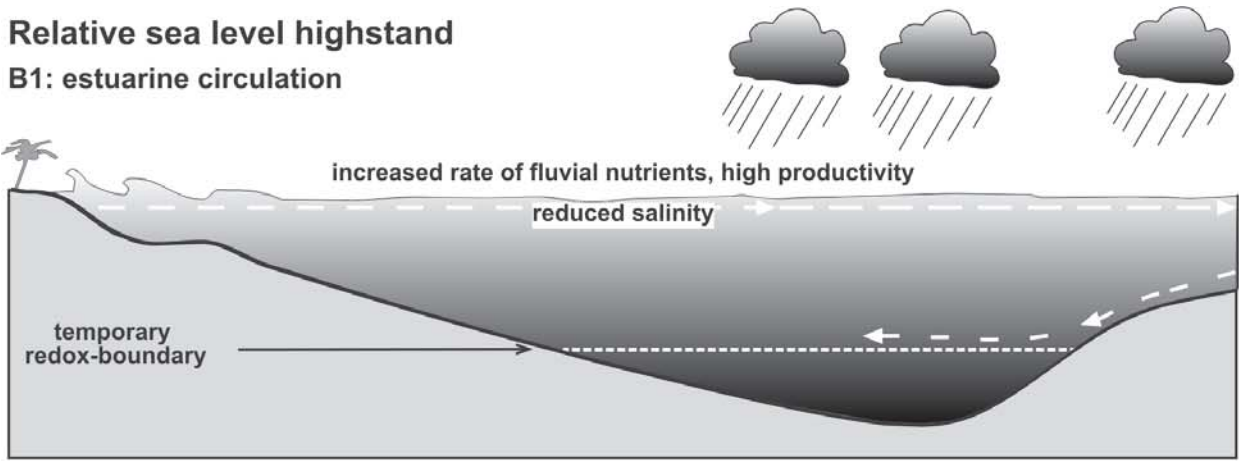
FIG. 3 - Stratigraphic column of the Pesciara section (after Papazzoni & Trevisani, 2006).
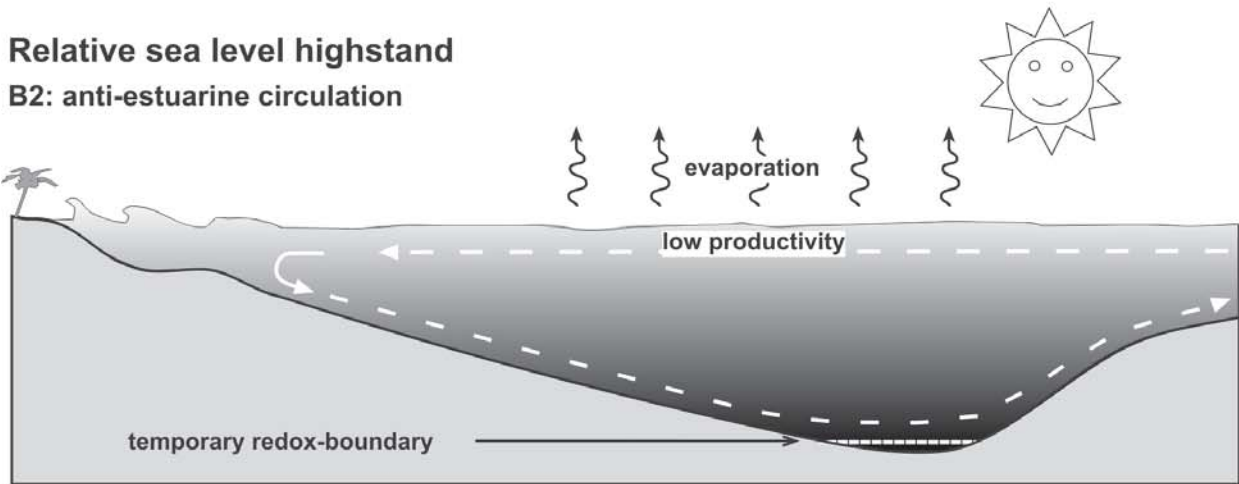
Relative sea level highstand
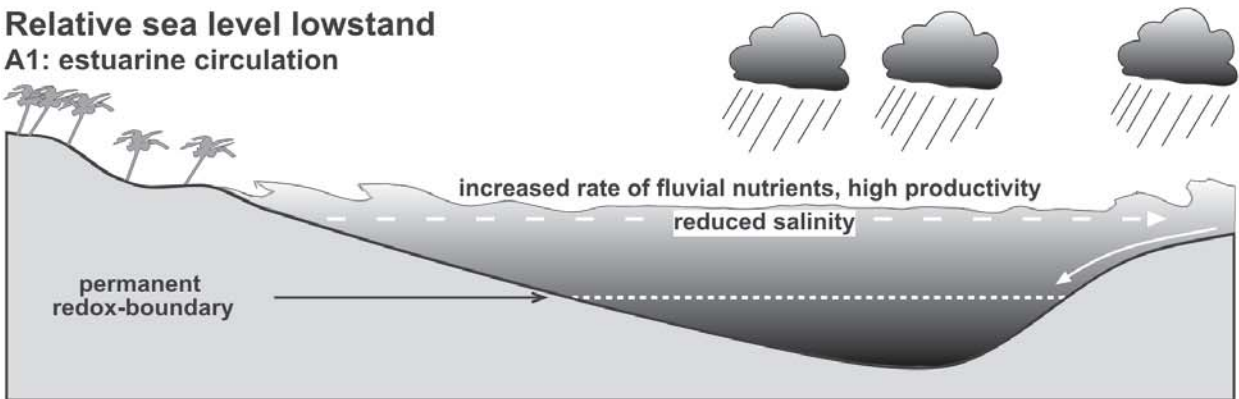**B1: estuarine circulation**

increased rate of fluvial nutrients, high productivity
reduced salinity

temporary redox-boundary

Relative sea level highstand
B2: anti-estuarine circulation

evaporation
low productivity

temporary redox-boundary

Relative sea level lowstand
A1: estuarine circulation

increased rate of fluvial nutrients, high productivity
reduced salinity

permanent redox-boundary

Relative sea level lowstand
A2: anti-estuarine circulation

evaporation
low productivity

permanent redox-boundary
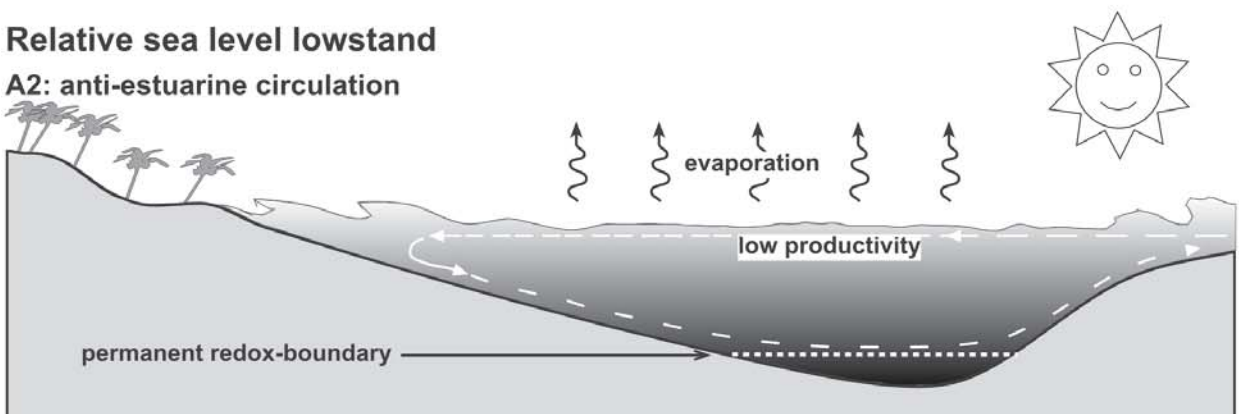
FIG. 4

upper water layers by monsoonal rain and terrestrial run-off, as shown by terrigenous biomarkers and fossils (Fig. 4). No organic markers of hypersaline bottom waters were found, though this condition is plausible as a consequence of high evaporation conditions in an equatorial carbonate platform. The very high (about 37°C) mean annual paleotemperature estimates for the nearby and nearly contemporaneous Solane *Lagerstätte* (Giusberti et al., 2014) suggest this hypothesis is not to be discarded.

The relative sea-level lowstands maximized the effectiveness of the threshold, inducing stagnation and very restricted circulation in the deeper parts of the basin (Fig. 4A). On the contrary, during relative sea-level highstand intervals the threshold was less effective, allowing to some extent admixing and slight oxygenation of the bottom waters with lower E_h values compared with the former (Fig. 4B).

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FIG. 4 - Interpretation of the Pesciara depositional environment, according to Schwark et al. (2009). A) Depositional setting during lowstand times, with effective threshold and permanent water stratification; these conditions are recorded in the lower part of the Pesciara section. B) Depositional setting during highstand times, with less effective threshold and temporary water stratification; these conditions are recorded in the upper part of the Pesciara section (after Schwark et al., 2009).

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