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The Bolca *Fossil-Lagerstätten*:
A window into the Eocene World
(*editors* C.A. Papazzoni, L. Giusberti, G. Carnevale, G. Roghi, D. Bassi & R. Zorzin)

3. Geological and stratigraphical setting of the Bolca area

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Geological setting

Bolca is located in the eastern part of the Lessini Mountains, which are part of the Southern Alps, a structural element forming the northernmost part of the Adria (or Adriatic) Plate (e.g., Carminati et al., 2012).

During the early Paleogene, the Southern Alpine area was subdivided into two basins roughly separated by the present-day Brenta River. The Monte Baldo, the Monti Lessini, the Monti Berici, the Colli Euganei and the Vicenza Pre-Alps belonged to the western basin, whereas the eastern basin embraced the Belluno and Treviso areas (Bassi et al., 2008).

From Paleocene to Oligocene, the western basin was subjected to several pulses of volcanic activity (Barbieri et al., 1991; Barbieri & Zampieri, 1992; Zampieri, 1995) and large part of it allowed the shallowing of the seafloor, contributing to the growth of the carbonate platform called "Lessini Shelf" (Bosellini, 1989). This paleogeographic unit is characterized by widespread deposition of shallow-water carbonates starting from the Early Eocene (Luciani, 1989). The Lessini Shelf (Fig. 1), limited northwards by land and surrounded by deeper marine basins, partially covered the area that, in Jurassic times, was occupied by the shallow-water Trento Platform (Bosellini, 1989; Zampieri, 1995).

During the Paleogene, the central-eastern Lessini and western Berici formed a graben system known as "Alpone-Chiampo graben" (Barbieri et al., 1982), or "Alpone-Agno half-graben" (Barbieri et al., 1991), or "Alpone-Agno graben" (Zampieri, 1995). Since the late Paleocene this structure was bounded toward the west by the east-dipping Castelvero fault (Barbieri, 1972), which dammed the western accumulation of the basaltic volcanics and related subaqueous epiclastics (Fabiani, 1915; Piccoli, 1966a, b). The Bolca area is

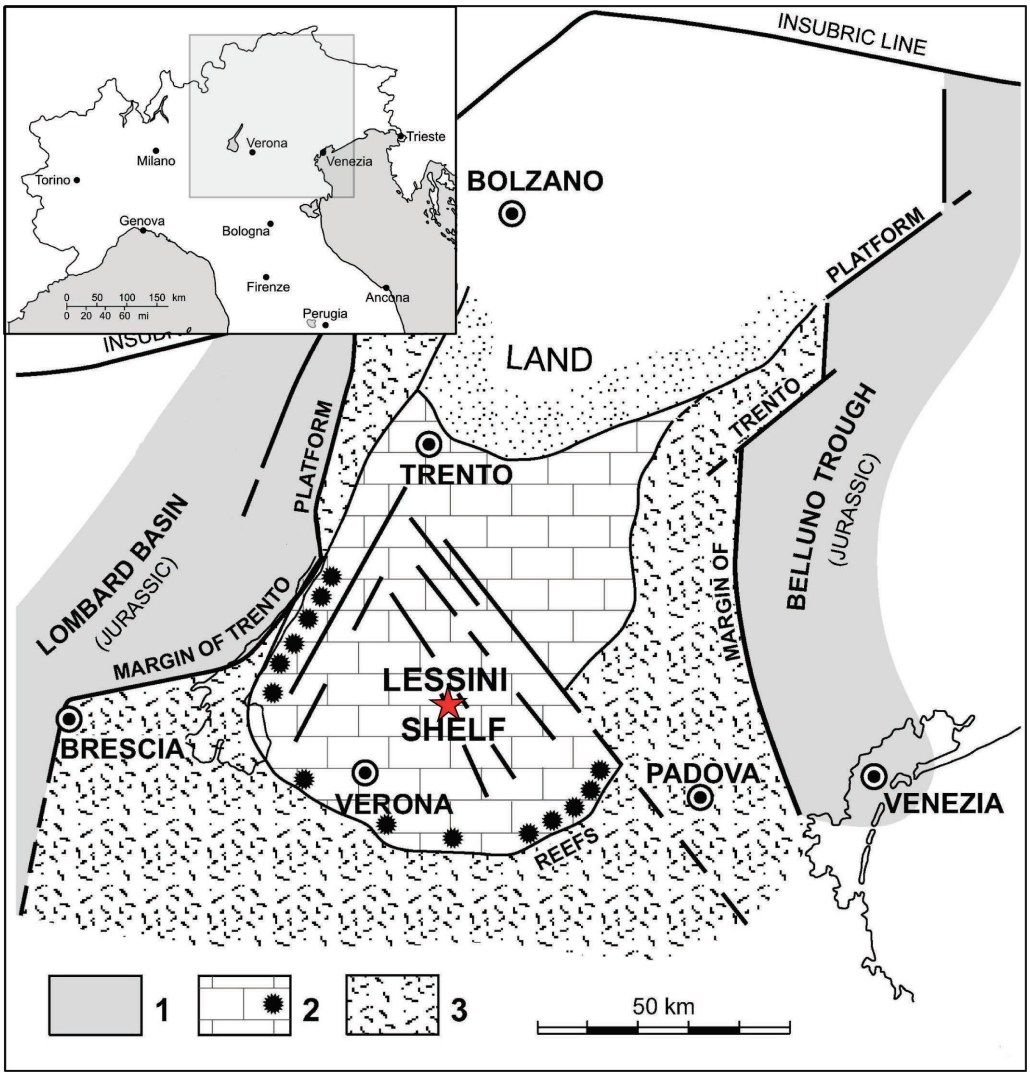

Fig. 1 - Paleogeographic reconstruction of the Lessini Shelf in the Southern Alps during the Paleogene (modified after Bosellini & Papazzoni, 2003). Bolca is indicated by the red star. Legend: 1) deep-water sediments in the Jurassic-Paleogene basins; 2) Paleogene shallow-water limestones with reefs (asterisks); 3) Paleogene deep-water sediments on the former Jurassic Trento Platform.

very close to the Castelvero fault whilst its western part is bounded by the Monte Postale fault (Barbieri & Medizza 1969; Dal Degan & Barbieri 2005; Schwark et al. 2009).

From the earliest Late Paleocene, this graben influenced the sedimentation on the Lessini Shelf, with two areas where different stratigraphic successions deposited (Antonelli et al., 1990): at first, on the eastern area (the graben), pelagic carbonates and resedimented calcarenites deposited, whilst on the western area (western Lessini) shallow-water marine carbonates dominated (De Zanche & Conterno, 1972; Mietto, 1975; Beschin et al., 1998) with the deposition of the 'Calcari Nummulitici' formation. East to the Castelvero fault, the subsidence was more active, and volcanic rocks (basaltic flows, hyaloclastites and volcaniclastics) intercalated with marine carbonate deposits

(Barbieri & Medizza, 1969; Barbieri, 1972; De Zanche & Conterno, 1972; Beccaro et al., 2001). Six volcanic stages were recognized by Barbieri et al. (1991), one from the Late Paleocene and the other five from the Early to the late Middle Eocene. The thickness of volcanics locally exceeds 400 m for the latter volcanic stage (Piccoli, 1966a, b; Barbieri et al., 1991; Zampieri, 1995).

During the Middle Eocene, close to the Lutetian-Bartonian boundary, the volcanic buildups lead to the emersion of the former graben. Therefore, in the Bartonian a volcanic ridge was substantially emerged, except for local and temporary marine episodes leading to the deposition of the so-called "Orizzonte di Roncà" (Fabiani, 1915).

During the Late Eocene the volcanic activity stopped within the graben and the Marne di Priabona Formation deposited in open marine, deep platform setting. This unit onlaps on the margins of the emerged volcanic ridge, with its base marked by a transgressive conglomerate (Barbieri et al., 1980; Mietto, 1992; Trevisani, 1997).

The still-emerging part of the Bartonian volcanic ridge and the whole eastern Lessini were then covered by the Lower Oligocene Calcareniti di Castelgomberto Formation, shallow-water carbonates probably deposited in the backreef of a rimmed platform, with the bioconstructed reef margin localized on the southeastern Berici Mts. (Frost, 1981; Bosellini & Trevisani, 1992; Mietto, 1992). Such peculiar depositional system lasted probably along the whole Rupelian (Geister & Ungaro, 1977).

In the western part of the Lessini Mountains the Oligocene is lacking, probably due to emersion (Luciani, 1989). In the eastern Lessini the carbonate shelf represented by the Calcareniti di Castelgomberto emerged only at the end of the Rupelian (Frost, 1981). The emersion surface of this platform, marked by evident paleokarst features, is interpreted as a 3rd order sequence boundary (Mietto, 1988; Gianolla et al., 1992; Dal Molin et al., 2001).

In the Lessini area, the Upper Oligocene-lowermost Miocene Arenarie e Calcari di S. Urbano Formation (Bosellini et al., 1967; Bassi et al., 2007, 2008; Bassi & Nebelsick, 2010) is overlain by the Lower Miocene Marne Argillose di Monte Costi Formation, only a few meters thick (Bosellini & Dal Cin, 1966; Bassi et al., 2007, 2008), which represents the last marine deposit of Cenozoic age in this area.

Stratigraphy

The Cenozoic stratigraphy of the Bolca area is not easy to reconstruct, because of the widespread occurrence of faults displacing the Eocene sedimentary succession into different blocks (the Castelvero Fault is close to this area), and also the presence of volcanic and volcaniclastic rocks intercalated or cutting the sedimentary succession (Fig. 2).

The first modern geological reports on the Bolca area date back to the 19th century (e.g., Suess, 1868; Bayan, 1870; Munier-Chalmas, 1891). Oppenheim (1894) studied the larger foraminiferal fauna, erecting among others the species *Nummulites bolcensis* and *N. spileccensis*, characteristic of this area.

Ramiro Fabiani (1912) defined the "Spileccian" stage after the name of the Spilecco hill, close to the Bolca village. He described in detail the geology of this area (Fabiani, 1914, 1915), drawing a stratigraphic sketch of the Monte Postale succession. The Fabiani's studies represent a cornerstone for the geological and stratigraphic interpretation of Bolca, being subsequently used and widely cited by all the researchers dealing with this locality. Among them, a mention is due to Schweighauser (1953), who studied the larger foraminifera from Spilecco and Monte Postale; to Malaroda (1954), who revised the mollusk fauna from the Monte Postale; to Hottinger (1960), who studied the alveolinids

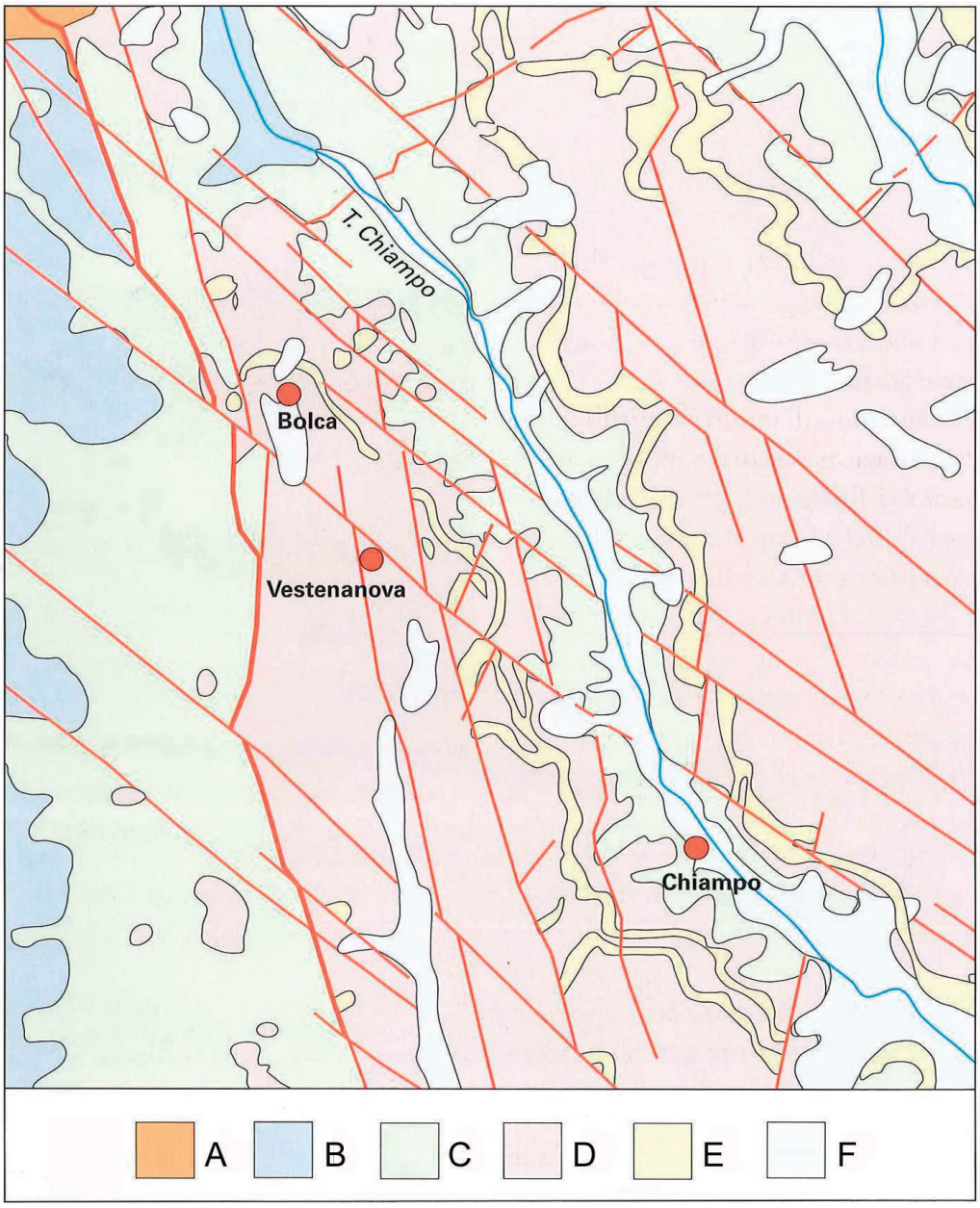

Fig. 2 - Simplified geological sketch map of the Bolca area (modified from Muscio & Tintori, 2005). A) Triassic dolostones; B) Jurassic limestones; C) Cretaceous limestones; D) Paleocene-Eocene volcanic rocks; E) Eocene limestones; F) Quaternary deposits.

from the Purga di Bolca, Brusaferri, Monte Postale, and Valecco; to Cita & Bolli (1961), who determined the biozonal assignment of the type-Spileccian by means of planktonic foraminifera; to Brönnimann et al. (1965), who studied planktonic foraminifera and calcareous nannoplankton from Spilecco and Purga di Bolca; to Barbieri & Medizza (1969), who re-studied the geology and stratigraphy of the Bolca area, even if they did not include the Monte Postale and Pesciara sites.

Fig. 3 - Panorama view of the Pesciara site.

The geological map by Bosellini et al. (1967) distinguished the Calcari di Spilecco formation, dated to the Paleocene-Early Eocene, from the Calcari Nummulitici formation (Middle Eocene). The former were restricted to the beds from Spilecco, whereas the Purga di Bolca and Monte Postale were included in the Calcari Nummulitici. Antonelli et al. (1990) retained the name 'Calcari Nummulitici' for both the biocalcarenites and organogenic limestones of the Monte Postale and the laminated calcilutites of Bolca (Pesciara; Fig. 3). Muscio & Tintori (2005) published a simplified geological sketch map of the surroundings of Bolca (Fig. 2). Dal Degan & Barbieri (2005) gave the most updated synopsis of the geology of the Bolca area, with a new detailed geological map (1:10,000) of Bolca and its surroundings. They distinguished the 'Calcare di Monte Spilecco' unit, dated at 56-58 Ma, the volcanic rocks (subdivided into several different units: lavas, basalt veins and breccias, hyaloclastics, epiclastics, caothic breccias, and volcaniclastics) and the Calcari Nummulitici. However, they used this term with restricted sense, apparently applying it only to the limestones which indeed contain nummulites. For the remaining limestones (mainly containing alveolinas or laminated beds with fishes and plants) they introduced the name "Formazione del Monte Postale-Pesciara".

All these lithostratigraphic units should be treated as informal ones, and the "Calcari Nummulitici" urgently need a revision, because it includes much different lithologies, paleoenvironments, and ages.

The biostratigraphy of the different localities (see Papazzoni et al., 2014, this volume) is currently under study.

The products of the volcanic activity are probably to be referred to the third phase recognized by Barbieri et al. (1991), but no radiometric ages are at present available for this material.

The fossiliferous sites of the Bolca area

Even if the most famous fossiliferous sites near the Bolca village are the Pesciara (Fig. 3) and the Monte Postale, several other localities with peculiar fossil contents and different stratigraphic settings are known (Fig. 4).

Among them, it is widely cited the Spilecco hill, or simply Spilecco. As mentioned above, it was the type locality of the local stage "Spilecciano", defined by Fabiani (1912) as equivalent to the whole Paleocene-Lower Eocene. The Spilecciano was retained in the literature until the end of 1960's (Bosellini et al., 1967; Barbieri & Medizza, 1969), but restricted to a short timespan within the latest part of the Paleocene (Schweighauser, 1953; Cita & Bolli, 1961) and then definitively abandoned. The characteristic gray-green limestones to reddish marly limestones of the Spilecco outcrops (poorly exposed at present) bear a rich fossil content made up mainly by planktonic foraminifera (in the gray-green limestones), larger foraminifera (nummulitids and orthophragminids) and macrofossils (in the reddish marly limestones); the glauconite is widespread in both lithologies. The larger foraminiferal fauna, containing among others *Nummulites*

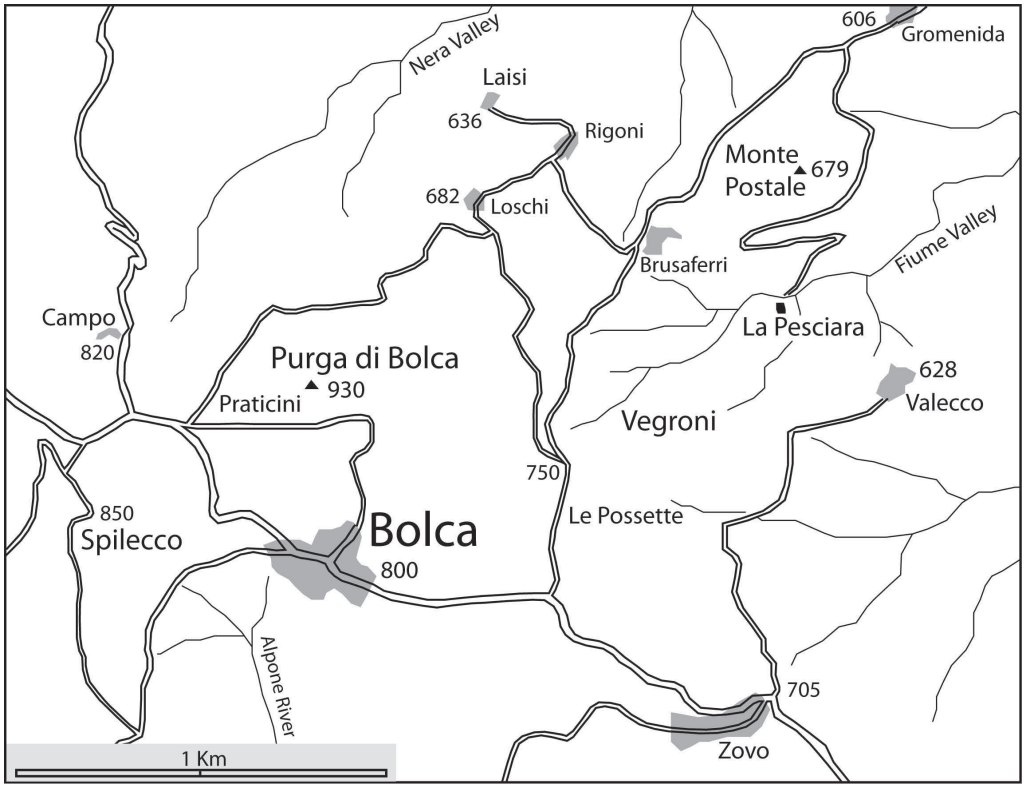

Fig. 4 - Location map of the main fossiliferous sites cropping out in the surroundings of Bolca (Verona).

bolcensis and *N. spileccensis*, allow to refer the Spilecco beds to the SBZ 7 (Trevisani & Papazzoni, 2003) of Serra-Kiel et al. (1998), or lower Ypresian, in good agreement with the nannoplankton zone NP 10 and the planktonic foraminifera zone P 5 (Barbieri & Medizza, 1969). The Spilecco beds represent the oldest Cenozoic evidence of shallow-water deposition in the Lessini Shelf (Trevisani & Papazzoni, 2003), even if they are indeed resedimented periplatform deposits. According to the chronology of volcanic phases (Barbieri et al., 1991), the Spilecco beds were deposited right after the first period of volcanic activity, so it is possible the volcano structures acted as areas of starting for small shallow-water platforms then coalesced into a larger one.

The Purga di Bolca is another important locality where a volcanic neck is preserved as a characteristic conical hill (Monte Purga). Barbieri & Medizza (1969) dated this neck to "post-Cuisian" times, giving a radiometric age of 36 Ma, or 'Early Oligocene'. No modern radiometric dating has been performed on this material, so this age needs confirmation. The neck cuts through 10-20 m of freshwater-brackish sediments (shales, siltites, lignites) containing ostracods, continental and brackish mollusks, crocodiles, and chelonians (Medizza, 1980). The sediments are in turn overlaid by volcaniclastic rocks with palm trees (*Latanites*). The sedimentary levels in the lowermost part of the succession bear calcareous nannofossils allowing their assignment to the NP 12 Zone (Barbieri & Medizza, 1969), in the middle Ypresian. The continental beds do not contain any marker, so their age is quite debated (see Giusberti et al., 2014, this volume), even if it could be still Ypresian (Sorbini, 1972; Medizza, 1980). The crocodile and turtle-bearing beds cropping out at Praticini mentioned by Blot (1969) probably correspond to the freshwater-brackish sediments of the Purga di Bolca. Other localities often cited as source of crocodiles and turtles include Loschi, Le Possette, and Valecco-Zovo (Blot, 1969), but no data about their geological setting and stratigraphy are at present available; maybe they represent the same levels present in the Monte Purga. Also the Vegroni locality, known for its beautiful palm trees, could probably be correlated with the Purga, but all these localities need further study to confirm or discard the correlation.

The Monte Postale succession, thoroughly described by Fabiani (1914, 1915), is the most complete in the Bolca area, spanning from the Cretaceous Scaglia Rossa Fm. up to the Ypresian-Lutetian(?) limestones with *Alveolina*, in their uppermost part containing also marine and continental-brackish mollusks, Lutetian according to Malaroda (1954), or more probably Cuisian according to the larger foraminiferal fauna (Hottinger, 1960). The lower-middle part of this section was recently re-studied by Papazzoni & Trevisani (2009), who attributed the *Alveolina* limestones to the SBZ 11 (middle Cuisian, or upper part of the Ypresian). At present, there are no updated biozonal assignments for the uppermost part of the Monte Postale section. In the lower-middle portion of this section there are laminated limestones very similar to the ones in the Pesciara, also bearing fish and plants.

Brusaferri is very close to the Monte Postale section. It gives its name to the so-called "horizon de Brusaferri" (Blot, 1969), or "calcari a *Numm. irregularis*" (Fabiani, 1915), rich in nummulites, assilinas, echinoids, and mollusks. According to Schaub (1981), this is the type locality of *Nummulites pratti* and it also indicates the middle Cuisian (SBZ 11 according to Serra-Kiel et al., 1998).

The Pesciara di Bolca is the most famous locality, and together with the laminated limestones of the Monte Postale, the major source of fossil fish and plants. In the old collections these two localities are often not separated and sometimes they are referred to as "Monte Bolca", even if this has no correspondence in any official toponym. The larger foraminifera from the Pesciara limestones, already mentioned by Hottinger (1960) and Schaub (1981), were recently re-studied (Trevisani et al., 2005; Papazzoni & Trevisani,

2006) and the section was entirely assigned to the SBZ 11 (Serra-Kiel et al., 1998). The nannofossils recognized in a single sample indicated the NP 14, also compatible with the uppermost part of the Ypresian (Medizza, 1975). The direct correlation between the Pesciara and Monte Postale sites is hampered because the Pesciara is an isolated block surrounded by volcanic and volcaniclastic deposits. Therefore, there is no continuity between the limestone of the Pesciara succession and the similar rocks of the Monte Postale, on the opposite side of the valley. A detailed stratigraphic and sedimentological study is needed to clarify the Pesciara-Postale relationships.

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