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Early Eocene amber from the "Pesciara di Bolca" (Lessini Mountains, Northern Italy)

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Abstract

The occurrence of amber from the world-famous fossil-lagerstätte of Pesciara di Bolca (Verona province) is here reported for the first time. This amber has been carefully analysed by means of infrared spectrophotometry (FTIR), thermogravimetric analysis (TG), differential thermogravimetric analysis (DTG), and elemental chemical analysis. Then, the amber from Bolca has been compared with other ambers of similar age. Among them, a sample from the Cava Rossi quarry (Monte di Malo, Vicenza province) shows striking similarities in all the physical–chemical characters.

The fossil content of the amber levels of the Pesciara and Cava Rossi was examined with respect to the palynomorphs and larger foraminiferans. This permitted to ascertain that the two amber levels are substantially isochronous, within the resolution power of the larger foraminiferan biozones. According to the shallow benthic biozonation, the age is in both cases SBZ 11, or Middle Cuisian (Early Eocene).

Moreover, the fossil assemblages allowed to reconstruct the palaeoenvironments, stressing they were in both case on a shallow carbonate platform, relatively close to the shoreline. The Pesciara palaeoenvironment was very close to the continental areas and with peculiar conditions allowing the exceptional preservation of the fishes. Instead, the Cava Rossi palaeoenvironment was more distal and open to marine influxes.

Keywords: Amber; Fossil-lagerstätte; Physical–chemical properties; Biostratigraphy; Early Eocene

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1. Introduction

The stratigraphy of the fossil sites of Pesciara di Bolca and nearby Monte Postale (Verona province, Northern Italy) is currently under revision by the Museo di Storia Naturale di Ferrara and Dipartimento del Museo di Paleobiologia e dell'Orto Botanico dell'Università di Modena e Reggio Emilia. During this work, we found some yellow-green amber nodules within the lowermost of the fish-bearing levels of the Pesciara outcrop (Trevisani et al., 2002).

Notwithstanding the ancient knowledge of this section, this is the first time that amber is signalled from this site. The literature reported the occurrence of amber from potentially coeval beds in the Cava Rossi quarry near Monte di Malo, Eastern Lessini Mts. (Boscardin and Violati Tescari, 1996). Therefore, we started to analyse the fossil content (larger foraminiferans, palynomorphs, dinoflagellate cysts), the biostratigraphy of the sections, and the physical—chemical characters of the two ambers to verify the possible connections between the localities (about 15 km from each other; Fig. 1).

1.1. Occurrence of amber in the Southern Alps

In the present study we use the term "amber" sensu lato, in the meaning of "fossil resin". In origin, the word amber was first used exclusively to indicate a fossil resin occurring only in Northern Europe (Beck, 1999), but subsequently it was used to identify any sedimentary organic material derived from fossilized resins of higher plants. Therefore, we refer to "amber" and "fossil resin" as interchangeable terms.

In Italy amber has been reported since ancient times, especially from Tertiary rocks of the Northern Apennines and of the Sicily.

From the Southern Alps, since recent times, the occurrence of amber has been cited only sporadically. The first record is a letter, dated 1827, where Catullo informed Brugnatelli about a "fossil forest", including fossil resin, discovered in a valley near Roana, on the Asiago Plateau (Catullo, 1827). Unfortunately, we have no further information about this discovery. Then, Stoppani (1886) reported that amber was collected from the Chattian beds at the base of the Monte Brione Formation, near Riva del Garda (Trento province).

There are also some reports of amber from the Dolomites by Koken (1913) and Zardini (1973), but here the age is Triassic.

During the last decade, more comprehensive descriptions of amber findings have been published. Here follows a list of these reports:

- near Redagno and Pietralba (Bolzano province) some millimetric granules of amber from the Arenarie della Val Gardena Fm., upper Permian (Maffi and Maffi, 1992);
- near Cortina d'Ampezzo (Belluno province), and in Val Badia (Bolzano province) some reddish "drops" of amber from the Dürrenstein Fm., Carnian (Gianolla et al., 1998; Roghi et al., 2002; Ragazzi et al., 2003);
- at Cava Rossi quarry, Monte di Malo (Vicenza province), some centimetric amber nodules from the marly limestones of the lower-middle Eocene (Boscardin and Violati Tescari, 1996);
- in the Chiavon stream, near Salcedo (Vicenza province) some millimetric granules of amber from the Oligocene beds (Ragazzi and Roghi, 2003);
- similar fragments were collected also from the Oligocene of Sedico (Belluno province) (Ragazzi and Roghi, 2003).

1.2. Geological settings

Bolca is located into the Alpone River Valley, eastern Lessini Mts., about 25 km north-east of Verona. The Pesciara outcrop and the Monte Postale are on the opposite sides of Val del Fiume, about 2 km north-east of Bolca (Fig. 1A). The Bolca area gives many problems in reconstructing its stratigraphy, because of the widespread volcanic rocks, among which the sedimentary beds are scanty, often dismembered, and displaced by tectonic movements.

The Pesciara outcrop appears as a limestone "spot" surrounded by volcanic rocks. The limestone beds cover an area of some hundred square metres; they are less than 20 m thick, and plunge towards south-east (Figs. 2 and 3). The extraordinary fossil content of these limestones, from which more than 250 species of fishes were extracted, made it the most famous fossil fish locality all over the world,

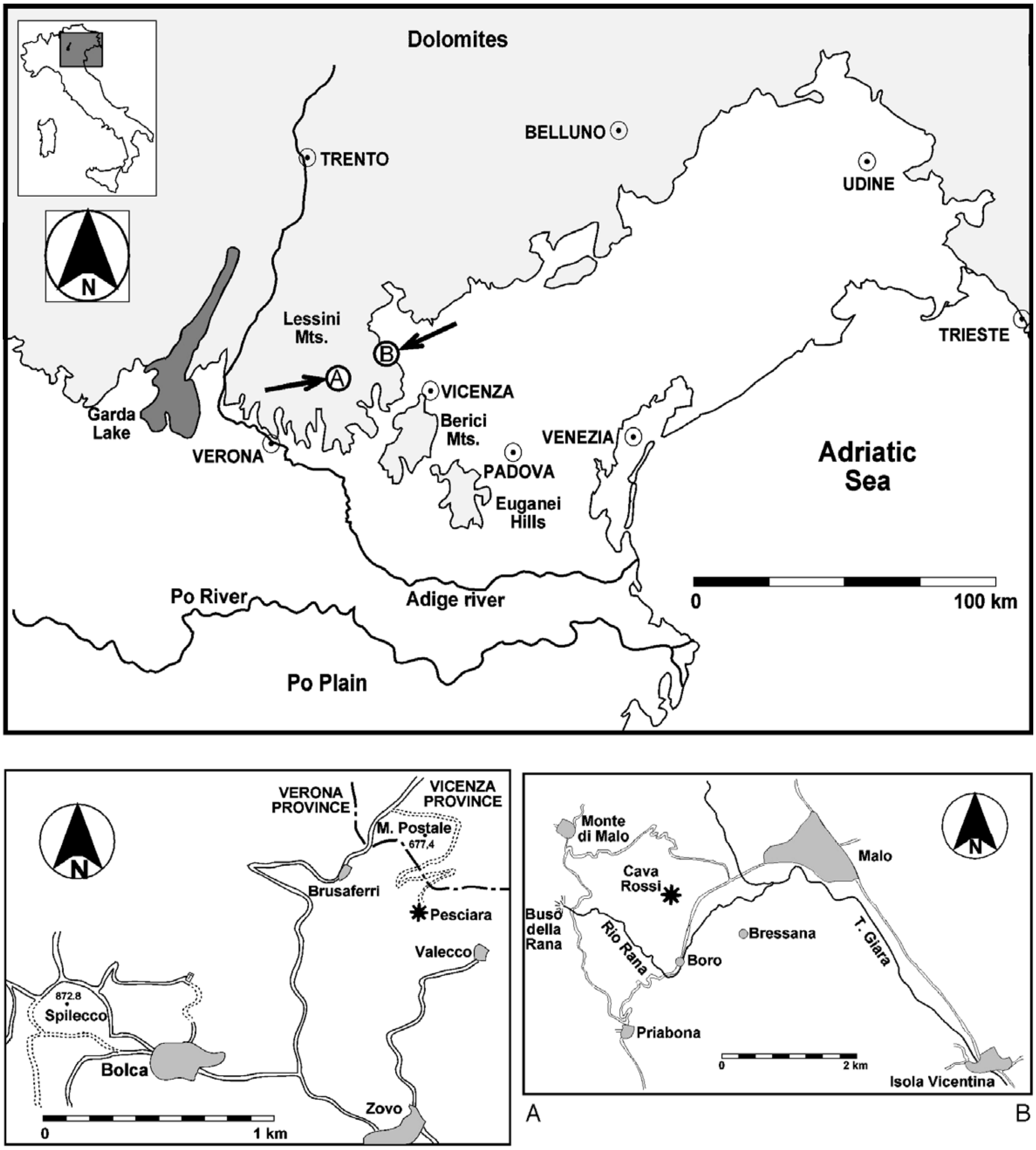

Fig. 1. Map showing the location of the study sites. (A) Pesciara di Bolca; (B) Cava Rossi near Monte di Malo.

known since the half of the XVI century. Apart from the fishes, it provided a very rich flora (both marine and continental), and an incredibly diverse fauna including foraminiferans, molluscs (bivalves, gastropods, cephalopods), worms (polichaetes), jellyfishes, corals, insects, crustaceans, reptiles, and birds (Sorbini, 1972). The renown of this locality induced Bolca to be the only Italian fossil site candidate to enter into the World Heritage List (Wells, 1996), the prestigious list compiled by the UNESCO to preserve the areas with exceptional cultural or natural value.

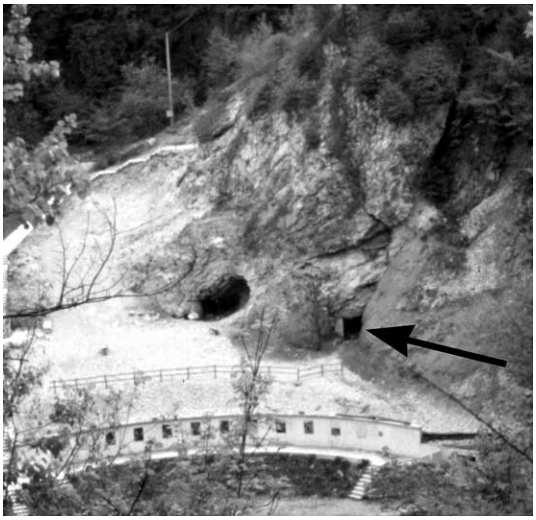

Fig. 2. The Pesciara di Bolca; the arrow points to the tunnel opening into the lowest (first) fish-bearing level.

The Pesciara amber occurs as greenish, centimetre-sized nodules (Fig. 4A). At present, we examined three samples, coming from the lowermost fish-bearing level of the Pesciara limestone. The thin sections made on the rhythmites of this level show submillimetric granules, yellowish in colour with parallel nicols and isotropic with crossed nicols; we assume they also could be amber "drops".

The Cava Rossi quarry is in Calcara locality, close to Monte di Malo, along the provincial road connecting Priabona to Malo (Fig. 1B). The quarry cuts a calcareous-marly succession, with tuffs intercalated, dated to the Middle Cuisian–Late Lutetian (Beschin et al., 1998; Beccaro et al., 2001).

The Cava Rossi amber was collected from two levels (Fig. 5): the lower one is a marly limestone, very rich in vegetal remains, with widespread amber as small, subcentimetric nodules; the upper one is a biocalcarenite, where the amber is more rare, but with larger-sized nodules (up to some centimetres; Fig. 4B).

The Cava Rossi succession, as the Pesciara one, could be ascribed to the Lower-Middle Eocene informal lithostratigraphical unit named "Calcari nummulitici". This unit in fact represents a "basket" containing different rocks, locally distinguished by their lithology, palaeoenvironment, palaeogeography, etc. A comprehensive revision of this stratigraphical interval on a regional scale urges, also because it represents the time when the first Paleogene carbonate platforms set up in the Venetian area, after a long period of basinal sedimentation represented by the widespread Scaglia Rossa Fm.

2. Materials and methods

To establish the age of the Pesciara succession, more than twenty samples have been taken both

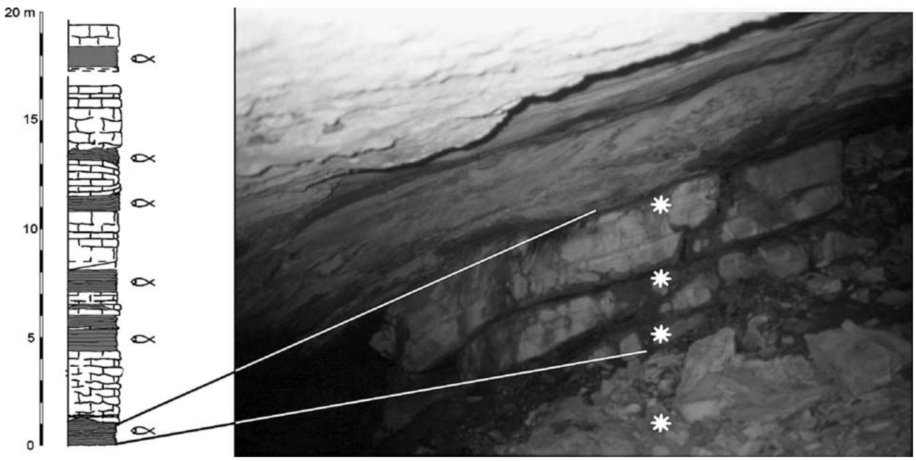

Fig. 3. Simplified stratigraphic section of the Pesciara di Bolca on the left; first fish-bearing level on the right (the asterisks indicate the position of the samples).

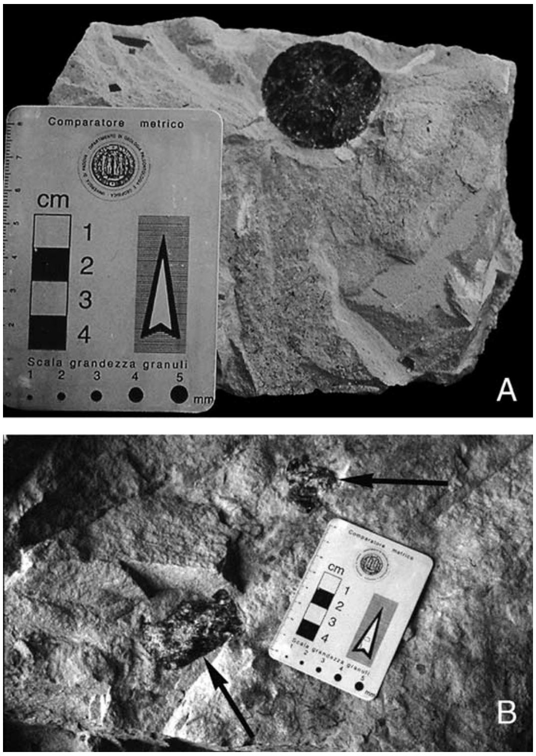

Fig. 4. (A) Amber nodule (diameter 3.5 cm) from the laminated limestones of the first fish-bearing level of the Pesciara di Bolca; (B) two amber nodules on a bed surface from Cava Rossi (Monte di Malo; MCZ 1169).

from the fish-bearing levels and from the intercalated coarse-grained biocalcarenites–biocalcirudites with molluscs and foraminiferans. In the Cava Rossi succession, about fifteen samples have been collected from the lowermost part of the quarry. All these samples have been treated with the standard methods to study the larger foraminiferans, i.e. thin sections for the hard limestones and washing for the marly rocks.

The age has always been referred to the standard Shallow Benthic Zonation (SBZ of Serra-Kiel et al., 1998).

The physical–chemical properties of the amber have been determined with respect to the fluorescence in under UV light, fracture, solubility in common solvents, and application of a hot point. Moreover, the Fourier-Transform Infrared (FTIR) analysis, thermal analysis (TG and DTG), and elemental analysis of the amber have been made.

Solid-state Fourier-Transform Infrared analysis was performed on freshly powdered samples of amber included in potassium bromide pellets. A Perkin Elmer 1600 Series FTIR Spectrophotometer was used in the wavelength range 2.5–15.5 μm (4000–645 cm^{-1}).

TG and DTG patterns were obtained in the Institute of Geosciences and Earth Resources of the Italian National Council of Research (IGG-CNR, Padova, Italy, Dr. Aurelio Giaretta) by using a prototypal instrument, consisting of a thermocouple placed in an electric furnace. Samples (500 mg) were pulverized in an agate mortar and inserted in a platinum crucible, placed on a quartz glass support interfaced with a Mettler Toledo AB 104 balance. The heating rate was 10 °C/min from room temperature to 700 °C. Analytical data were recorded by using a software written in LabView 5.1 language, and thermal profiles edited by using Grapher 2 software.

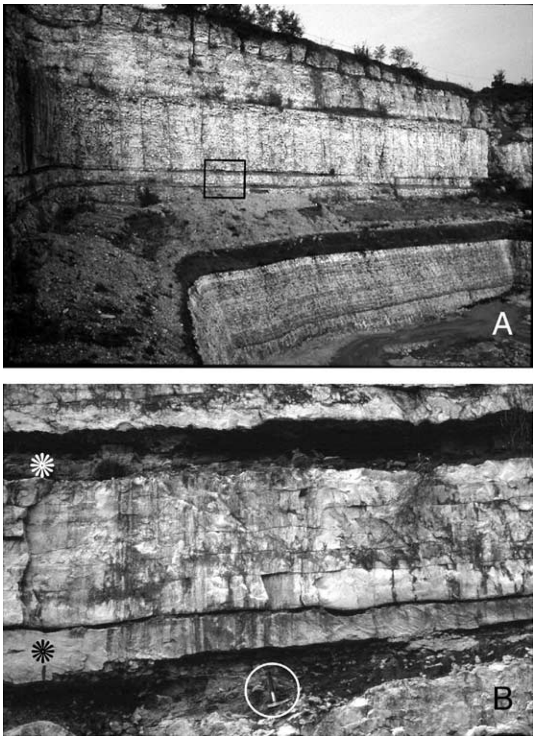

Fig. 5. (A) Cava Rossi Quarry (Monte di Malo); (B) enlargement of (A), the asterisks on the left side indicate the amber-bearing levels (encircled hammer for scale).

The carbon, hydrogen, nitrogen and sulphur content of amber was determined by using a CE-Instruments EA 1110 automatic elemental analyzer, equipped with AS 200 autosampler and Mettler Toledo AT 21 Comparator.

The palynological analysis was carried out on five samples obtained from clay interlayers of Pesciara di Bolca and from amber-bearing marls of Cava Rossi of Monte di Malo. The samples were processed by the palynological standard method (HCl, HF and HNO_3) methodologies to identify pollens, spores, and dinoflagellates, useful to increase the knowledge about the palaeoenvironment. The slides are stored in the Department of Geology, Paleontology and Geophysics of Padova University.

3. Biostratigraphy

The Pesciara succession has been since now dated to the boundary between the Early and the Middle Eocene according to the study of the calcareous nannoplankton on a single sample (Medizza, 1975). The biozone recognized is the *Discoaster sublodoensis* Zone (NP 14, or CP 12). This contrasts with the data by Hottinger (1960), who reported a larger foraminiferal assemblage with *Alveolina cremae*, *A. rugosa*, *A. distefanoi*, *A. rutimeyeri*, characteristic of the *Alveolina dainellii* Zone, which in turn is surely older than the Early/Middle Eocene boundary. The alveolinas were found within the so-called "detrital limestones" intercalated with the fish-bearing levels. Medizza (1975) stated that the alveolinas were not useful for the age determination, because they show clear signs of reworking, as reaffirmed by Massari and Sorbini (1975).

The first results of the stratigraphical revision of the Pesciara and Monte Postale (Papazzoni and Trevisani, 2002) substantiate a quite different picture. In most samples, the wear habit of the alveolina tests is consistent with a penecontemporaneous and limited transport from nearby areas, so excluding a stratigraphically significant reworking. We recognised *A. cremae* Checchia-Rispoli, *A.* aff. *croatica* Drobne, *A. decastroi* Scotto di Carlo, *A. distefanoi* Checchia-Rispoli, *A. levantina* Hottinger, *A.* cf. *minuta* Checchia-Rispoli, and *A. rugosa* Hottinger. Moreover, some nummulites were determined on thin sections from samples in the uppermost portion of the succession. They are *Nummulites* cf. *leupoldi* Schaub, *N.* cf. *prelucasi* Douvillé, *N.* cf. *pratti* d'Archiac and Haime, and *N.* cf. *rotularius* Deshayes. Both the assemblages corroborate what reported by Hottinger (1960), that is the SBZ 11 biozone (Middle Cuisian) in the Serra-Kiel et al. (1998) scheme. According to the last, we could now combine the different biozonation scales, because the SBZ 11 finishes just above the base of the NP 14 (*Discoaster sublodoensis* Zone). Therefore, the age of the Pesciara succession could even be restricted to the topmost part of the SBZ 11, or to the base of the NP 14.

The Cava Rossi succession has been dated to the Middle Cuisian–Late Lutetian interval according to the planktonic and benthonic foraminiferal assemblages, covering the time between the *Nummulites nitidus* Zone (SBZ 11, Middle Cuisian) and the *Morozovella lehneri* Zone (P12, Late Lutetian) (Beschin et al., 1998). Beccaro et al. (2001), studying the planktonic foraminiferans, found the *Morozovella aragonensis* biozone (P8, Middle Cuisian) in the lower beds of the quarry. Moreover, they found the calcareous nannoplankton zone NP 14 (*Discoaster sublodoensis* Zone) in the middle part of the quarry.

Recently, the quarry front was deepened, partially obliterating the reference points reported in the papers of Beschin et al. (1998) and Beccaro et al. (2001).

Nevertheless, the biostratigraphical analysis of the larger foraminiferal assemblage in a sample collected between the two amber levels of Cava Rossi allowed the recognition of *N. cantabricus* Schaub, *N.* aff. *manfredi* Schaub, *N. pratti* d'Archiac and Haime, *N. praelevigatus* Schaub, *N. rotularius* Deshayes, and *Assilina* aff. *cuvillieri* Schaub. This assemblage attests the SBZ11 biozone, or Middle Cuisian. The study of the larger foraminiferal fauna of this section is in progress, but we can affirm that other species of the genus *Nummulites* and some *Orbitoclypeus* are present.

Our stratigraphical data are at present sufficient to affirm that, within the limits of the larger foraminiferal biostratigraphical resolution, the amber levels at the Pesciara di Bolca and at the Cava Rossi are substantially isochronous.

4. Physical–chemical properties of Bolca amber and Monte di Malo amber

Bolca amber occurs as small rounded masses, with a maximal size of a few centimetres, with the surface finely fractured, included in a limestone matrix. Its colour is transparent greenish-yellow, and under ultraviolet light (365 nm) it displays an intense yellowish glow. The fracture is vitreous and the hardness 2–3 of the Mohs scale. The application of a hot point causes the resin to burn and emit a resinous odour. It is not soluble in ethanol, nor in acetone, by holding a small drop of solvent on the sample for 30 s, and looking for any dissolution of the surface (this being a method of distinguishing between amber and other less mature resins; see Currie, 1997). Also leaving the fossil resin in the solvent for a longer time (up to 24 h), it does not significantly dissolve; conversely, diethyl ether is able to soften the fossil resin just after a few minutes.

The amber of Monte di Malo has been found in fairly good amounts as nodules of a few centimetres in diameter, with fractured surface, included in a limestone matrix; it has also been found as smaller nodules (of the size under a centimetre) included in a marly matrix with abundant vegetal remains. The colour is light yellow to brownish, fluorescent to ultraviolet light; the fracture is vitreous and the hardness 2–3 of the Mohs scale; the fossil resin shows solubility properties similar to those of Bolca amber.

4.1. FTIR analysis of Bolca amber

The FTIR spectrum of Bolca amber is presented in Fig. 6 and it is typical of a fossil resin. The first absorption band is at 2.9 μm (3500 cm^{-1}) (band marked as A in Fig. 6), assigned to the stretching of hydrogen–oxygen bonds (Langenheim and Beck, 1968; Broughton, 1974), such as phenolic and carboxylic hydroxyl functional groups; part of these hydroxyl groups responsible of the band pre-exists in the resin, but may also be due to the water vapour assumed by the sample during the preparation for the analytical procedure (Beck et al., 1966). The bending motion of the same bonds (Langenheim and Beck, 1968) causes the weak absorption band near 6.1 μm (1650 cm^{-1}) (band D in the spectrum of Fig. 6).

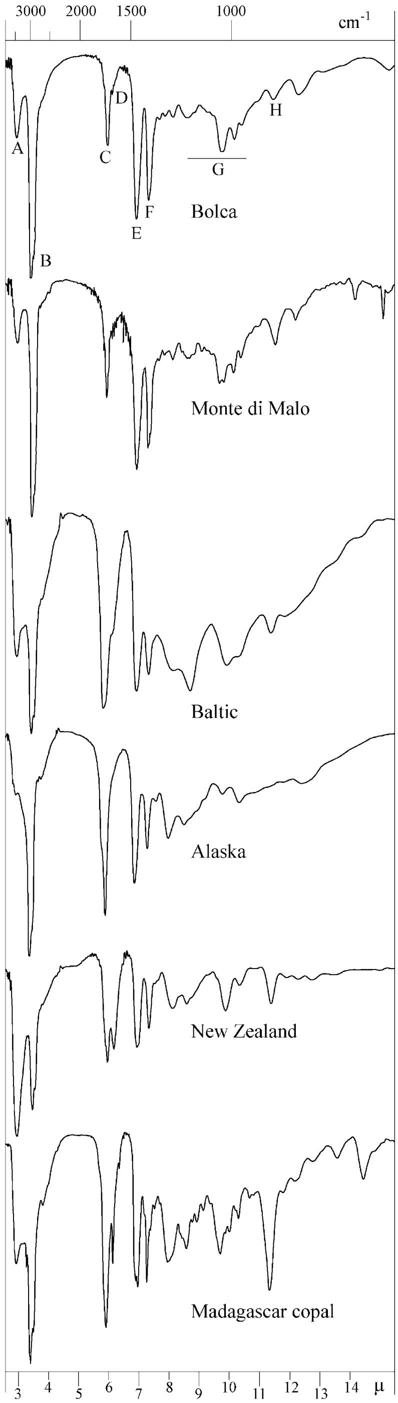

Fig. 6. Infrared spectrum of amber from Bolca and Monte di Malo, compared to the spectra of other fossil resins of similar age, and of a recent sample of Madagascar copal (Leguminosae of genus *Hymenaea*).

The strong band at 3.4 μm (2950 cm^{-1}) (band B in Fig. 6) is caused by the stretching of aliphatic carbon–hydrogen bonds (Langenheim and Beck, 1968) and is considered diagnostic of resinous structures (Broughton, 1974). Bending of the same bonds produces an absorption peak near 6.8 μm (1470 cm^{-1}) (band E) and 7.25 μm (1380 cm^{-1}) (band F) (Langenheim and Beck, 1968).

In the spectrum of Bolca amber another strong absorption band is detected near 5.8 μm (1700 cm^{-1}) (band C), called "carbonyl band" (Langenheim and Beck, 1968), also typical of all fossil resins, caused by stretching movements of carbon–oxygen double bonds.

The above described absorption bands are found in all fossil resins, and therefore do not possess a strong diagnostic interest; however, they are useful to confirm the presence of a fossil resin.

The upper part of the infrared spectrum, higher than 8 μm, is difficult to interpret in terms of chemical structure (Langenheim and Beck, 1968), but it is more useful than the lower region of the spectrum because it varies among the different resins. The region between 8 and 10 μm (1250–1000 cm^{-1}) (G region in the Fig. 6) presents absorption bands caused by carbon–oxygen single bonds (Langenheim and Beck, 1968; Vávra and Vycudilik, 1976). It is difficult to assign the absorption bands of this region to a specific structure, because the vibrations are influenced by the carbon skeleton of the whole molecule. However this region is very useful as a "fingerprint" of a specific fossil resin (Langenheim and Beck, 1968). In this part of the spectrum, Baltic amber (also called *succinite*) shows the typical "Baltic shoulder" (Beck et al., 1964; Langenheim and Beck, 1965; Beck, 1986; Vávra and Vycudilik, 1976) (see Fig. 6, Baltic amber spectrum); it consists of a single carbon–oxygen deformation band near 8.6–8.7 μm (about 1160–1150 cm^{-1}), preceded by a more or less flat shoulder between 8 and 8.6 μm (1250–1160 cm^{-1}), attributed to absorption of ester group of polyester-like structures (Vávra and Vycudilik, 1976; Matuszewska and Karwowski, 1999). The shoulder appears horizontal in well-preserved Baltic amber, but it can present a slope in samples that have been subject to oxidation (Beck, 1986). The Baltic shoulder has been assigned to succinic acid esters (Beck, 1986) and has not been found in the spectra of other European ambers (Beck, 1986). However, it can be detected in the spectra of fossil resins from North America (Langenheim and Beck, 1968; Broughton, 1974; Beck, 1986). In the infrared spectrum of Bolca amber the described morphology of Baltic shoulder is not present, suggesting a different structure in comparison to Baltic amber.

Absorption near 11.3 μm (885 cm^{-1}) (band H in Fig. 6) is typical of out-of-plane bending movements of two hydrogen atoms in a terminal methylene group (Langenheim and Beck, 1965, 1968), and may be attributed to resin acids (for example copalic acid and agathic acid) also found in recent resins, such as in Madagascar copal (Fig. 6), which is produced by species of the genus *Hymenaea* (Leguminosae/Fabaceae family). Some fossil resins, such as Mexican and Dominican amber (Oligocene–Miocene), also originated from the genus *Hymenaea* (Poinar, 1991; Poinar and Brown, 2002), present an absorption band near 11.3 μm (Langenheim, 1969), although of weak intensity, as expected in consequence of resin maturation. The absence of this band (and of others strictly related, such as those at 3.25 and 6.1 μm, due to stretching of carbon–hydrogen bonds (Vávra and Vycudilik, 1976) has been considered as the result of progressive oxidation by atmospheric oxygen, or may indicate that the resin never had a terminal methylene group (Langenheim and Beck, 1965, 1968). The Bolca amber spectrum does not have strong infrared absorption near 11.3 μm, as well as Baltic amber (also mentioned in Beck, 1999), suggesting scarceness (acquired or primitive) of the above mentioned functional groups.

An absorption band near 14.2–14.4 μm (705–695 cm^{-1}), due to unassigned skeletal frequency, is found in recent resins of the genus *Hymenaea* and *Styrax* (Langenheim and Beck, 1965), as confirmed by the spectrum of Madagascar copal (Fig. 6). However, the maturation of the resin during the process of fossilization causes reduction or disappearance of the band, as in the spectrum of Mexican amber (Langenheim, 1969) and of Bolca amber (Fig. 6).

The spectrum of amber from Monte di Malo was considered and compared to that of Bolca amber. Monte di Malo amber has been previously described by Boscardin and Violati Tescari (1996), also under the infrared aspect. Our data (Fig. 6), show a close relationship between Bolca and Monte di Malo amber specimens. Since the age of the two deposits is similar, a common paleobotanical origin can be hypothesized.

Comparing the infrared spectra of different fossil and recent resins published in the literature (for example in Langenheim and Beck, 1968; Langenheim, 1969), an overall similarity can be found among Bolca and Monte di Malo amber with resins of the above mentioned Angiosperm genus *Hymenaea* (Leguminosae/Fabaceae family) producing Madagascar copal and Dominican and Mexican amber. Also the spectrum of the resin of the genus *Protium* (Langenheim, 1969), another arboreal Angiosperm which is known to produce large quantities of resins in tropical regions, shows an overall similarity with the spectrum of Bolca and Monte di Malo amber.

A closer similarity can be observed between the IR spectrum of our fossil resins and the spectrum of the fossil resin identified as "glessite" (Kosmowska-Ceranowicz et al., 1993; Kosmowska-Ceranowicz, 1994, 2001), a dark-brown fossil resin found in Germany (Bitterfeld mine, Saxony-Anhalt, and Lusatia), which has been attributed to the family Burseraceae; another glessite occurrence has been reported in Borneo and its paleobotanical origin is believed to be of the family Dipterocarpaceae (Hillmer et al., 1992; Kosmowska-Ceranowicz, 1994). Comparing the fingerprint region (G region in Fig. 6) of the spectrum of Bolca and Monte di Malo amber, a considerable similarity can be observed with the spectrum of glessite, both from Burseraceae and Dipterocarpaceae families, reported by Kosmowska-Ceranowicz (Kosmowska-Ceranowicz et al., 1993; Kosmowska-Ceranowicz, 1994).

No close relationship was found in the fingerprint region of the infrared spectrum of Baltic amber compared to that of Bolca and Monte di Malo amber. Baltic amber is typically found in Tertiary deposits (Upper Eocene–Lower Oligocene of "blue earth") (Kosmowska-Ceranowicz, 1984, 1999; Poinar, 1992; Blazhchishin, 2001). Earlier literature designated the amber-producing tree as *Pinites succinifer* (Göppert, 1836), later named *Pinus succinifera* (Conwentz, 1890), a conifer considered similar to a living species of pine. More accurate chemical determination of the components of the fossil resin suggested an affinity with the Araucariaceae family, probably of the genus *Agathis*, similar to the *Agathis australis* which grows in New Zealand and produces kauri resin (Mills et al., 1984; Beck, 1993). Beck (1993, 1999) observed that this amber contains mainly bicyclic diterpenic acid of the labdane-type (abundant in *Agathis* resin), and little abietic acid or its derivatives (prevalent in *Pinus* resin), excluding a pine as the amber-producing species. Baltic amber has been also related to a species linked to present-day cypresses (*Cedrus atlantica*) (Pielinska, 1998; Kosmowska-Ceranowicz, 1999); another possible species is from the genus *Pseudolarix* (Grimaldi, 1996).

To compare Bolca amber with other kinds of Tertiary amber, the infrared spectrum of two other nearly coeval fossil resins was obtained. The first specimen is from Alaska, near Sutton, Evan Jones Mine, dated as Late Upper Paleocene–Early Eocene (kind gift from Dr. Roland Gangloff, University of Alaska Fairbanks, sample AK-2694-P-01, accession # 1999 P-02). No paleobotanical attribution has been possible. The second specimen is from New Zealand, found at Brunner Coal Measures, between Greymouth and Westport, late Middle to Late Eocene in age (Bortonian to Kaiatan New Zealand stages that correspond to late Bartonian to Priabonian international stages) (kind gift of Dr. Hamish Campbell, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand). Due to the geographical location of the discovery, a paleobotanical origin from the genus *Agathis* is possible (Currie, 1997). Interestingly, fossil kauri resin is believed to differ from succinite only in that it does not contain succinic acid, and the carbon skeleton is identical with that of succinite (Beck, 1999). Both samples produced an infrared spectrum (Fig. 6) that in the fingerprint region appears different from that of Bolca and Monte di Malo amber.

It is difficult, using the sole infrared spectrum, to attribute a paleobotanical affinity to fossil resin found at Bolca and Monte di Malo, without a strict association of the amber with fossil vegetal remains which are taxonomically identified.

It should be noted that the chemical composition of fossil resins undergoes several changes during the process of resin maturation (Anderson et al., 1992), also named *amberization*. The rate at which these processes proceed are strictly dependent on temperature, the age and thermal history of the sample. Therefore resins with similar paleobotanical origin may present different compositions, as indicated by infrared spectrum, in consequence of several taphonomic variables.

A relevant finding, however, is the strict similarity between the FTIR spectra of Bolca and Monte di Malo amber. Further research is needed to find a significant association of amber with vegetal remains, in order to clarify the paleobotanical issue that now is only a working hypothesis.

4.2. Thermogravimetric (TG) and Differential Thermogravimetric (DTG) analysis

The thermal analysis, namely thermogravimetric (TG) and differential thermogravimetric (DTG) analysis, has been recently applied to the study of fossil resins (Rodgers and Curie, 1999; Ragazzi et al., 2003). Thermal analysis provides a rapid and quantitative method to examine the overall pyrolysis process and to estimate the effective rates of overall decomposition reactions, related to the chemical structure and degree of resin polymerization during the amberization process.

Bolca amber and Monte di Malo amber show a TG combustion profile starting after 200 °C; total combustion occurred before 600 °C (Fig. 7). DTG showed a main combustion event, as consequence of maximal rate of weight loss, very similar in both fossil resins, 382 and 390 °C for Bolca and Monte di Malo ambers, respectively (Fig. 7). Another lower peak was observed near 550 °C.

According to published data (Rodgers and Curie, 1999; Ragazzi et al., 2003), DTG main peak is proportional to the age of fossil resin and the degree of maturation. Comparison of thermal behaviour of Bolca and Monte di Malo amber with that of other resins (Ragazzi et al., 2003) indicates that the main thermal peak is similar to that of Dominican amber (400 °C) and Baltic amber (402 °C), both belonging to Tertiary period, mainly Eocene (for Baltic amber) and Miocene (for Dominican amber).

4.3. Elemental analysis

As reported in Table 1, Bolca amber has a relatively high content of sulphur as compared with Monte di Malo amber where the element is completely lacking.

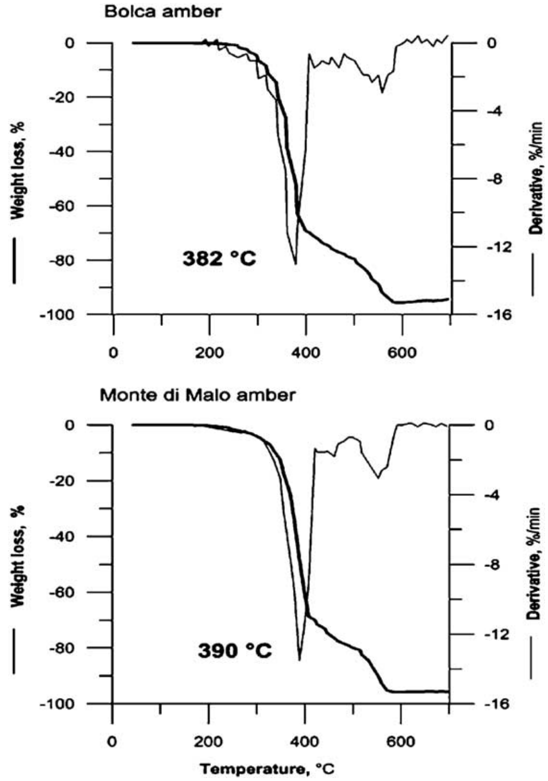

Fig. 7. Thermogravimetric (TG, thick line) and Differential Thermogravimetric (DTG, thin line) analysis of Bolca and Monte di Malo (Cava Rossi) amber.

In Bolca amber the content of oxygen and other trace elements is higher, and the carbon content lower, in comparison with Monte di Malo amber.

The higher sulphur content may be the consequence of high content of the element in Bolca layers, possibly linked with the peculiar taphonomic event which permitted the exceptional conservation of fossils in the site. Alternatively, the high level of the element might be related to an elevated paleoenvironmental content of sulphur, such as in a site near volcanic activity. From Upper Paleocene to Oligocene, several periods of basic volcanic activities have been documented in the Veneto region (Barbieri et al., 1981), as demonstrated by the occurrence of tuffaceous layers, also present in Cava Rossi, in the same sections yielding amber. Moreover, the amount of resin secretion from trees could have been increased in regions affected by volcanic eruptions, as suggested by published theories from Polish authors (Prof. Kosmowska-Ceranowicz, personal communication).

Table 1
Elemental analysis of Bolca and Monte di Malo (Cava Rossi) amber

	C%	H%	N%	O% and other trace elements	S%
Bolca amber	82	11	0.025	4.5	2
Monte di Malo amber	86	11	0.03	2	0

It can be speculated that the yellow-greenish colour of Bolca amber may be due to the presence of sulphur in the fossil resin.

5. Palynology

The samples yielded pollen, spores and dinoflagellates, with foraminiferal chitinous rests and scolecodonts. Palynological assemblages often showed deteriorated morphology and were not enough for a quantitative analysis, but supplied useful information about the distance from lands and suggestions on the possible paleobotanical source of amber.

5.1. Terrestrial components

Specimens from Bolca area were richer in pollen and spores with respect to those found at Monte di Malo. In Monte di Malo section only a few spores of Pteridophyte (*Gleicheniidites*, *Leiotriletes*) were found (Table 2).

In the Pesciara di Bolca section, the lowest fish-bearing level yielded Briophyta (*Stereisporites*) and Pteridophyta (*Gleichenidiites*, *Leiotriletes*, *Cicatricosisporites*, *Echinatisporis*). Among the Gymnosperms, coniferalean pollen attributed to the Araucariaceae family (*Araucariacites*) was found, while among Angiospermae some specimens of Juglandaceae (*Caryapollenites*), probably of Cyrillaceae (*Tricolporopollenites*) and unidentified dycotiledons were observed (Table 2).

5.2. Marine components

In Bolca samples badly preserved dinoflagellates belonging to *Operculodinium* (Gonyaulacaceae) and ?*Wetzeliella* (Peridiniaceae) were found.

Samples from Monte di Malo (CAVRO amber e CAVRO 3) were richer in biostratigraphically useful dinoflagellate forms. Commonly found genera were *Operculodinium*, *Impagidinium*, *Leptodinium* and *Hystrichokolpoma* (Gonyaulacaceae). Among *Hystrichokolpoma*, the species *H. cinctum* was observed. This form showed its first occurrence, in the lower and middle latitudes, during the Ypresian (53 My). The forms *Homotriblium* sp. and *Cerebrocysta* sp. (Goniodomaceae), and *Selenopemphix* sp. ind. (Protoperidiniaceae) were also found.

5.3. Paleobotanical affinity of Bolca and Monte di Malo amber

On the basis of the physical–chemical and palynological analysis of the sites studied in the present work, some hypotheses were proposed about the paleobotanical origin of the fossil resins.

Among Angiosperms, the family of Leguminosae (Fabaceae), which is well represented in Bolca flora, has been recognized to include abundant resin-producing trees. This datum is confirmed by the FTIR spectrum which is compatible with a Leguminosae origin of the fossil resin, considering the close correlation of the spectrum morphology of Bolca and Monte di Malo amber with Madagascar copal

Table 2
Palynological content of the amber-bearing layers of Pesciara di Bolca and Cava Rossi at Monte di Malo

	Bolca	Cava Rossi
Bryophyta gen. *Stereisporites*	X	
Filicophyta, Gleicheniaceae gen. *Gleichenidiites*, *Echinatisporis*	X	X
Pteridophyta, Schizaeaceae gen. *Leiotriletes*, *Cicatricosisporites*	X	X
Pteridophyta, Polypodiaceae		X
Lycophyta, Selaginellaceae	X	
Coniferophyta		
Coniferales, Araucariaceae, gen. *Araucariacites*	X	
Angiospermae		
Juglandaceae gen. *Caryapollenites*	X	
?Cyrillaceae gen. *Tricolporopollenites*	X	
Dicotyledons not identified	X	

(tropical species of the genus *Hymenaea*, belonging to Leguminosae). A probable affinity with this group of plants is supported also by the Early and Middle Eocene distribution of the paleoflora, when the maximum expansion of tropical and paratropical flora (including Leguminosae) occurred, up to 50–60° of latitude North (Stewart and Rothwell, 1993).

Although a palynological quantitative analysis was not possible in the studied samples, the presence of several Angiosperm pollen at Bolca site, also testified by the macroflora described by Massalongo (1856, 1859a,b), is consistent with a fossil resin derived from some Angiosperm groups.

A correlation between amber and Araucariaceae family (common conifers that produced abundant resin during Cretaceous) seems to be excluded by the FTIR analysis, although pollen of this family was found in Bolca samples (but not in Monte di Malo section). Palynological analysis did not show any other form attributable to conifers.

The paleobotanical affinities of amber found in sites of similar geological age suggest an origin from different plants. Baltic amber has been related to *Pinites succinifer* (Göppert, 1836), *Pinus succinifera* (Conwentz, 1890), species of the genus *Agathis*, *Cedrus atlantica* (Kosmowska-Ceranowicz, 1999), and *Pseudolarix* (Grimaldi, 1996), all species belonging to conifers. Lower Eocene amber from Paris Basin (Le Quesnoy, France), was found in association with wood, flowers, fruits and seeds, pollen and spores (Nel et al., 1999; Cavagnetto, 2000; De Franceschi and De Ploëg, 2003). This amber has been preliminarily attributed to Combretaceae or Leguminosae-Caesalpiniaceae (Nel et al., 1999). Further studies have suggested that the amber-producing tree could be related to Caesalpiniaceae (De Franceschi and De Ploëg, 2003). However, FTIR data published on Eocene amber from France (Savkevitch and Popkova, 1978) seem to exclude similarity with our samples.

According to data in the literature and to the findings presented in this study, a paleobotanical origin of amber can be hypothesized in relation to the latitude where the amber-producing trees lived. The forests that yielded Baltic amber were located more towards the north (around 55–60° N; see map in Beck, 1986, 1999), and therefore compatible with a Gymnosperm origin (or more stressed Angiosperms), in comparison with the area of France (35–40° N) and of Bolca (35° N), where the considered plants were located, that is more southern and in an inner continental location, possibly allowing a greater diffusion of Angiosperms.

6. Conclusions

The presence of amber, never reported before, in the Pesciara di Bolca increases the already abundant fossil documentation of this unique paleontological site. The presence of amber in Cava Rossi at Monte di Malo, about 15 km from Bolca, allows a correlation between the two sites and significantly contributes to increase the paleogeographical and paleoenvironmental knowledge.

The close similarity of the physical–chemical properties of amber from both sites, together with the biostratigraphical correlation by means of larger foraminiferal biozones, permits us to hypothesize on the occurrence of an amber layer substantially isochronous.

On the contrary, the paleoenvironments which can be reconstructed on the basis of fossil assemblages show significant differences.

At the Pesciara di Bolca, the fish assemblages indicates a strict relationship with a reef environment (Bellwood, 1996; Landini and Sorbini, 1996), relatively close to variously articulated emerged lands. The abundant rests of continental plants (Massalongo, 1856, 1859a,b), insects (Hymenoptera, Orthoptera, Isoptera, etc.) (Massalongo, 1856; Omboni, 1886; Secretan, 1975), and amber itself, confirm this interpretation and suggests that fossil resin had not been subjected to any reworking. The abundance of well-preserved fossil fishes and plants in Bolca site suggests that also the resin can belong to a primary deposit. The remnants of aquatic plants, such as *Eichorniopsis* sp. and *Maffeia* sp., of insects such as dragonflies (typical of freshwater), and fishes such as *Eolates* sp., *Scatophagus* sp. and *Cyclopoma* sp. (which probably could live in brackish water near the mouth of rivers), suggest the probable presence of fluvial systems and coastal ponds. The larger foraminiferal assemblages, although transported, derives from a relatively shallow marine environment (prevalence of miliolids and alveolinids), confirming the closeness to the ancient coastal line. This is perfectly coherent with paleobotanical data from the study of pollen, spores and dinoflagellates (as above reported).

Regarding Cava Rossi of Monte di Malo, the knowledge of paleoenvironments is surely less complete in comparison to the Pesciara di Bolca; however it is possible to hypothesize some differences. Here the very peculiar conditions of a restricted basin, which permitted the exceptional preservation of fossils of the Pesciara, failed. Several indications of a paleoenvironment more influenced by open sea have been found, although typical of relatively shallow carbonatic platform. The dominant larger foraminiferans are nummulites, assilines, "ortophragmines" (discocyclinids and orbitoclypeids), while alveolinids are almost absent.

Moreover, paleobotanical analysis showed a scarce continental component and relative abundance of more frankly marine dinoflagellates.

It appears likely that Cava Rossi represents the evidence of a more open and distal facies (although relatively nearby) with respect to the location of emerged lands during Middle Cuisian.

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