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THE PLANT RECORD OF THE DUNAROBBA AND PIETRAFITTA SITES IN THE PLIO-PLEISTOCENE PALAEOENVIRONMENTAL CONTEXT OF CENTRAL ITALY

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ABSTRACT: Dunarobba and Pietrafitta are two outstanding fossil sites, which provide us with a glimpse on central Italian palaeoenvironments during two different time spans. The still poorly dated Dunarobba succession is framed, mainly on the basis of continental mollusc biochronology, within the Piacenzian-Gelasian interval, whereas the Pietrafitta one is reliably dated to the Calabrian thanks to vertebrate biochronology. Here we add several new palaeobotanical data for the two sites and we provide for the first time an overview of the stratigraphic, sedimentological, palaeontological and palaeoenvironmental results so-far obtained. We also review the palaeobotanical evidence concerning the neighbouring sites of Cava Toppetti I/II, Fosso Bianco, Torre Picchio and Villa San Faustino. On the basis of the available datasets we conclude that the Dunarobba Fossil Forest, with several large conifer trunks in upright position, was produced by an ancient swamp vegetation dominated by *Glyptostrobus europaeus*, and including few other woody (*Alnus*, *Cephalanthus*, *Cornus*) and herbaceous (*Carex*, *Cladium*, *Schoenoplectus*) plants. Rich water-transported fruit and seed assemblages and pollen data indicate that the well-drained palaeoenvironments around the Dunarobba palaeo-swamp were covered by a forest having a floristic affinity to the modern Mixed Mesophytic Forests of East Asia, as proved by the occurrence of *Cryptomeria*, *Eurya*, *Sinomenium*, etc. The disappearance of the *Glyptostrobus* swamp forest was due to the establishment of well-drained palaeoenvironmental conditions, testified by a palaeosol profile.
The Pietrafitta site is characterized by a thick lignite seam, which embedded several carcasses of *Mammuthus meridionalis*, cervids, monkeys, rhinoceroses, etc. Sedimentological and palaeontological data indicate a lacustrine environment, as confirmed by newly studied fruit and seed assemblages dominated by such aquatic plants as: *Azolla*, *Najas*, *Nymphaea*, *Potamogeton*, etc. The pollen assemblage, studied in the 1960s-1970s, is still rich in exotic elements, and allows us to reconstruct a humid deciduous broadleaved forest, with a relevant subdivision of a bottom unit rich in *Taxodium* type pollen, and a top unit, lacking this pollen type and including all the lignite seam.

KEYWORDS: palaeobotany, palynology, sedimentology, local palaeovegetation, biochronology, Pliocene, Pleistocene, central Italy.

1. INTRODUCTION

The Pliocene-Early Pleistocene terrestrial palaeoflora of central Italy is documented by both palynomorphs (e.g. Lona & Bertoldi, 1972; Follieri, 1977; Bertini, 2003, 2010, 2013; Sadori et al., 2010; Magri & Palombo, 2013) and macroremains (e.g. Fischer & Butzmann, 2000; Martinetto, 2001; Teodoridis & Gregor, 2001; Girotti et al., 2003) from several fluvial and/or lacustrine sedimentary basins bordered by the Northern Apennine ridges (Fig. 1). The present paper is aimed at providing an updated overview of the palaeofloral data available for plant-bearing sites in the Tiberino Basin (Fig. 1), with special focus on the Dunarobba and Pietrafitta sites. Actually, the deposits of this last site are generally assigned to a minor basin, the Tavernelle-Pietrafitta Basin, that is considered as partly independent from the Tiberino Basin (see below).

The occasion of this paper was suitable for the compilation and critical revision of the most relevant palaeontological, stratigraphic and sedimentological data produced in the last thirty years.

2. GEOLOGICAL SETTING

During the Pliocene and the Pleistocene, central Italy was characterized by NW-SE trending extensional basins, roughly parallel to the uplift of the Apennine chain, which hosted marine and/or continental environments (Fig. 1) (e.g. Barchi et al., 1991; Martini & Sagri, 1993). The area surrounding the town of Perugia mainly coincided with two large structures: the Tiberino Basin to the East, and the South Valdichiana Basin, to the West, respectively associated with two major depositional settings, continental to the East and mainly marine to the West. The array of environments alternating

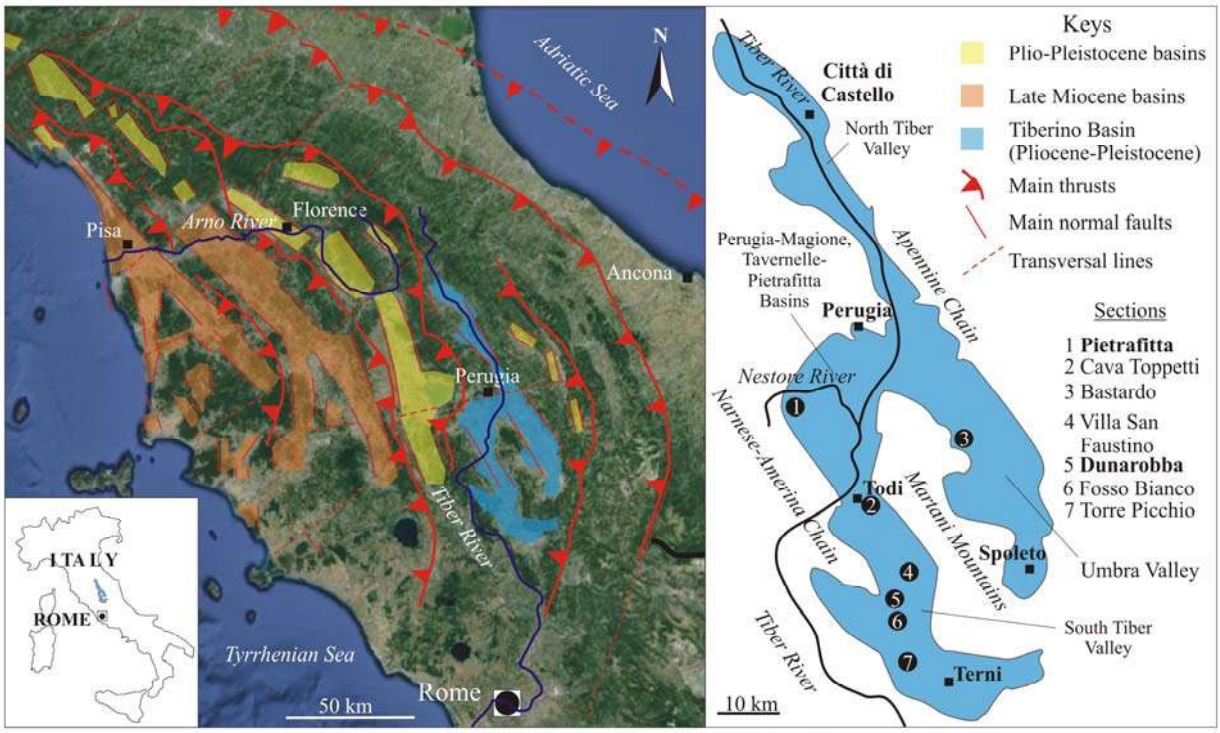


Fig. 1 - Simplified geo-structural scheme for Northern Apennine basins, evidencing the Tiberino Basin. To the right, location of plant-bearing sites treated in this paper within the Plio-Pleistocene Tiberino Basin in central Italy.

through time and space is likely to return a fairly complex stratigraphic framework, still under definition (Fig. 2). Three depositional cycles, respectively Early-Late Pliocene, Late Pliocene-Early Pleistocene and Middle-Late Pleistocene in age, have been described.

The Pliocene-Pleistocene Tiberino Basin (Fig. 1) was a subsiding, tilting extensional basin situated on the western edge of the Northern Apennine chain (Ambrosetti et al., 1995a). The basin stretches for 125 km in NW-SE direction, with a width of up to 20 km (Ambrosetti et al., 1995a). Across 19th and 20th centuries, a main coarsening upward sedimentary succession was described and associated with the fill up of a wide lake (the "Tiberino Lake": Lotti, 1917, 1926). The bottom of this succession is made up by clay, passing to sand and gravel at the top, locally interbedded with calcareous tufa and carbonate sand (Verri, 1879, 1901; Verducci, 1959; Jacobacci et al., 1970; Conti & Girotti, 1978; Ambrosetti et al., 1987a). Currently, four main areas, each one with its own history and sedimentary sequence, are recognized: a) North Tiber Valley, b) Perugia-Magione and Tavernelle-Pietrafitta minor basins, c) Umbra Valley, and d) South Tiber Valley (Fig. 1). Both unconformity-bounded units (synthems) and lithostratigraphic units have been used in the literature.

Lower Pleistocene deposits crop out in the middle (Magione and Ponte San Giovanni Units, Solfagnano synthem) and northern part (Fighille synthem) of the Tiber Valley, from Città di Castello to Deruta (Fig. 2; Pazzaglia, 2007; Pialli et al., 2009; Plesi et al., 2010; Argenti et al., 2013). Middle-Upper Pleistocene alluvial fan, fluvial and/or lacustrine sandy and/or gravely deposits crop out throughout the Tiber Valley. In the North Tiber Valley (Melelli et al., 2010), the complex geological dynamics determined the formation of several sub-basins (Fig. 1).

The eastern branch of the Tiberino Basin (Umbra Valley) mainly developed as an endorheic, isolated basin from the Pliocene to the Holocene, and two main depositional sequences, with alternating alluvial fan and lacustrine/swamp deposits, have been recognized (Coltorti & Pieruccini, 1997; Regione Umbria, 2005). The lower cycle (Morgnano synthem: Fig. 2), Pliocene in age, holds the Morgnano local vertebrate fauna (Pantanelli, 1886; Capellini, 1888; Cappuccino et al., 2006), assigned to the Triversa Faunal Unit, and is partially coeval with the lower part of the Fosso Bianco Unit. The upper cycle (Valle Umbra synthem: Fig. 2) had been usually dated to the Early Pleistocene (Esu & Girotti, 1974, 1991; Coltorti & Pieruccini, 1997; Regione Umbria, 2005), until palaeomagnetic data allowed extending it to the Middle Pleistocene, at least in the Bevagna area (Bizzarri et al., 2011).

2.1. The South Tiberino Basin

The South Tiberino Basin (Fig. 1) largely corresponds to the present-day South Tiber Valley. Basilici (1992, 1995, 1997, 2000a, b) and Ambrosetti et al. (1995a, b) distinguished four informal lithostratigraphic units (Fig. 2).

Fosso Bianco Unit (FBU) - This unit was mainly associated to a deep lacustrine environment with prevailing clay sedimentation. At the edge of the basin, clayey silt alternated to wavy- or cross-laminated silty

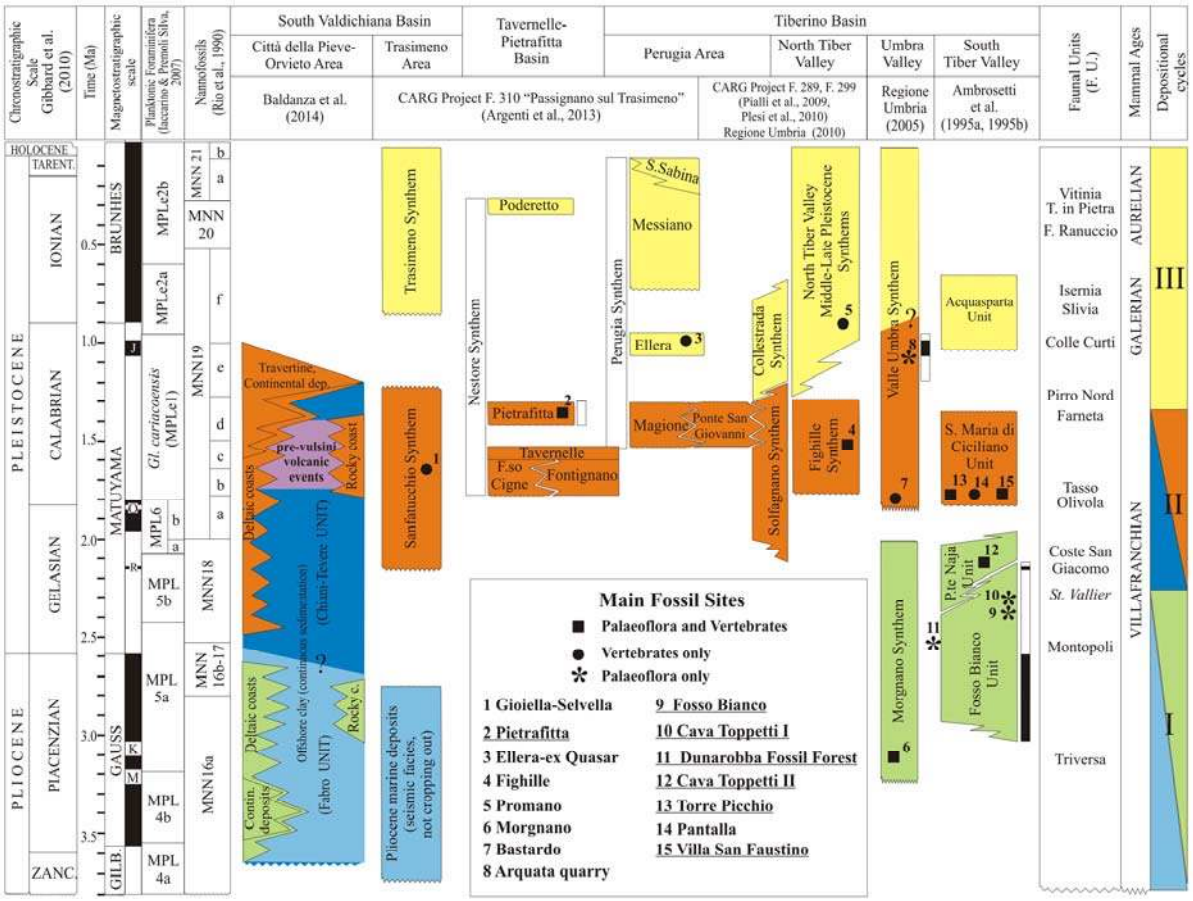


Fig. 2 - Synthesis of the stratigraphic schemes for Pliocene and Pleistocene deposits throughout the South Valdichiana Basin and the Tiberino Basin. See Fig. 1 for location of basins and main plant-bearing sections.

sand laminae, parallel-laminated silty clay, lignite-bearing clay deposits, and lenticular sand bodies crop out (Basilici, 1992, 1997; Ambrosetti et al., 1995a, b). They are interpreted as lower-shoreface deposits, marshy lacustrine shore deposits, and Gilbert-type delta deposits, respectively (Ambrosetti et al., 1995a, b; Basilici, 1997). According to magnetostratigraphy, carried out in Cava Toppetti I and Fosso Bianco main sections, a Piacenzian-Gelasian age was inferred (Ambrosetti et al., 1995b; Abbazzi et al., 1997).

Ponte Naja Unit - This unit was described only in the Todi area, where it is probably heteropic to the uppermost part of the FBU, although the stratigraphic contact was never recognized in outcrops, in particular in the Cava Toppeti II site, where this unit was best exposed during the 1990s. Several faults, indeed, affect the contact between the two units throughout the Todi hill (Basilici, 1992; Brozzetti & Basilici, 1998). The Ponte Naja Unit unit is associated to the distal or middle-distal end of an alluvial fan under humid climate, dominated by unchannelized flows (Basilici, 1992, 1995). The vertebrate fossil record allows attribution to the Villafranchian Mammal Age (Coste San Giacomo Faunal Unit: Abbazzi et al., 1997).

Santa Maria di Ciciliano Unit - This unit unconformably overlies the Ponte Naja Unit (close to the town of Todi) and the Fosso Bianco Unit (between Todi and Terni). It is mainly represented by up to 30 m thick sandy beds, interpreted as high-sinuosity river channels, alternated to massive or poorly laminated clay deposits with palaeosols, attributed to a floodplain. In this well-developed alluvial plain environment, deposits associated to crevasse-splays, small ponds, and carbonate sedimentation ponds, rich in Characeae, were also documented (Basilici, 1992, 1997, 2000a). Three sites (Pantalla, Torre Picchio, Villa San Faustino: Fig. 2) yielded late Villafranchian vertebrate fossil faunas (from the Tasso Faunal Unit to the Farneta Faunal Unit: Ambrosetti et al., 1995a; Sardella et al., 1995; Gentili et al., 1997; Petronio et al., 2002; Girotti et al., 2003; Argenti, 2004; Cherin et al., 2014), that provided evidence for an Early Pleistocene age of the Santa Maria di Ciciliano Unit.

Acquasparta Unit - This unit crops out mainly in the area of Acquasparta, where it overlays the Santa Maria di Ciciliano Unit with a concordant but sharp contact. The Aquasparta Unit consists of silty limestone and travertine deposits, formed in a lake or marsh, sometimes indicating emergence conditions. The unit was hypothetically referred to the Lower-Middle Pleistocene boundary or to the base of the Middle Pleistocene (Ambrosetti et al., 1995a).

2.2. The Tavernelle-Pietrafitta Basin and the lignites of Pietrafitta

The fossil-bearing lignites of Pietrafitta belong to the sedimentary succession of the Tavernelle-Pietrafitta Basin, in the upper valley of the Nestore River (Fig. 1). The basin extends in SW-NE direction for about 12 km, reaching a maximum width of about 5 km. The basins of Tavernelle-Pietrafitta and Perugia-Magione (Fig. 1) originated as minor intermountain basins, and presumably became part of a lateral branch of the main Tiberino Basin during the Early Pleistocene (Pazzaglia, 2007; Bizzarri et al., 2008; Cherin et al., 2012; Argenti et al., 2013; Pazzaglia et al., 2013). During the Early Pleistocene (and possibly the Late Pliocene), they underwent alternatively lacustrine/palustrine and alluvial plain conditions (Conti & Girotti, 1978; Conti & Esu, 1981; Ambrosetti et al., 1987a, 1989).

The lignites of Pietrafitta have been included in the Tiberino supersynthem and particularly in the Nestore synthem (CARG Project - F. 310 “Passignano sul Trasimeno”: Argenti et al., 2013). The Nestore synthem (Fig. 2) rests unconformably on the pre-Pliocene substrate and is unconformably covered by recent alluvial and/or colluvial deposits. It has been divided into two subsynthems: the lowermost Tavernelle subsynthem and the uppermost Pietrafitta subsynthem (Fig. 2). The Tavernelle subsynthem crops out in the whole area pertaining to the Nestore synthem. Lithologies vary from clay/silt to calcareous silts, sands and gravels/conglomerates. Two heteropic units (Fig. 2) are recognized: the Fosso Cigne unit, presumably deposited in a piedmont environment, and the Fontignano unit, which is related to a lacustrine and/or marshy depositional environment (Pazzaglia, 2007; Argenti et al., 2013). The Pietrafitta subsynthem (Fig. 2), which includes the fossil-bearing deposit described in this paper (see below), cropped out in the area affected by the extraction of lignite, near the homonymous village in the municipality of Piegaro.

3. MATERIAL AND METHODS

The present paper contains, on one hand, an assemblage of dispersed information on materials treated in several previous works. On the other hand, a quantity of new data is used here to provide a more extensive overview of the history, the fossil biota, the palaeoenvironment and the palaeoecology, especially of the Dunarobba and Pietrafitta fossil sites. The presentation of the methods mostly concerns this last data set, which includes palynological and palaeocarpological analyses, vegetation and palaeoclimatic analyses, sedimentological analyses, as well as information on the history of the discovery and preservation of the fossil sites.

3.1. Sedimentology and palaeopedology

Data were extracted from cores and outcrops. Several exposed sections, never thicker than 10 m, have been measured and described according to the facies analysis and palaeopedological methods, including description of colour, pedological structures, horizons, and biogenic features (Hodgson, 1978; Catt, 1990; Birkeland, 1999; Retallack, 2001). Samples from a palaeosol profile were collected for laboratory analyses, which concerned grain size and X-ray fluorescence analyses, to determinate textural and geochemical features, respectively.

3.2. Palynology

A critical review of the floristic and vegetational evidence from several pollen sites has been carried out in order to summarize and update the interpretation of the main palaeonvironmental and climatic changes at the Plio-Pleistocene transition in terrestrial settings around the 42° latitude and 12° longitude in central Italy.

The palynological documentation for the Tiberino Basin was provided by the Dunarobba S2 Core and by the following outcropping sections: Dunarobba Trunk and Dunarobba "Nuova Cava Fornaci Briziarelli Marsciano" (Simonetti, 1998), Fosso Bianco, Cava Toppetti I, Cava Toppetti II (Abbazzi et al., 1997; Pontini, 1997; Pontini & Bertini, 2000; Pontini et al., 2002).

All samples collected from previous sites were processed according to a standard procedure used at the Earth Sciences palynological laboratory of Florence (modified from Guillet & Planchais 1969 and Cour, 1974). For each sample at least 100 pollen grains were counted besides the dominant taxon. Details on pollen counts and number of identified taxa are specified below for each section. Data have been plotted in summary palynological diagrams where pollen taxa are organised into nine palyno-groups (Appendix 1) on the basis of the ecological and climatic requirements of their present correlatives.

Early palynological studies carried out on Dunarobba (Ambrosetti et al., 1995b), Pietrafitta (Ricciardi, 1961; Paganelli & Solazzi, 1962; Lona & Bertoldi, 1972) and Bastardo (GeMiNa, 1962) deposits were also taken in account for the discussion.

A floral list has been compiled on the basis of available data from Cava Toppetti I, Cava Toppetti II, three Dunarobba sections (i.e. S2 Core, Trunk Section and "Nuova Cava Fornaci Briziarelli Marsciano" Section), Fosso Bianco and Pietrafitta (Appendix 2).

3.3. Palaeocarpological analyses

For the preparation of this work we re-examined all the carpological material from Dunarobba and Pietrafitta sites, which had been prepared and analysed (sometimes only preliminarily) by Martinetto (1994, 1996, 2000, 2001) and Pauselli (2003). Most of the studied fruit and seed material is stored in the CENOFITA collection at the Earth Sciences Department of Turin, apart the samples DF5 and DF6, stored at the Physics and Geology Department of Perugia.

The sediment processing and fruit and seed extraction was similar for all samples, and followed the method described by Basilici et al. (1997). Only two Dunarobba samples (DC1a, DC1b) were prepared in the field, because of the large volume of sediment analysed. The abundance of carpological remains was counted or estimated (most frequent ones) for all sediment samples, and new comprehensive lists of plant taxa, with updated nomenclature, were compiled for Dunarobba (Tabs. 1-2) and Pietrafitta (Tab. 3). Taxa records from these two sites, which are reported in pre-

vious papers (Martinetto, 1994, 1996, 2000, 2001; Pauselli, 2003) but are not confirmed here, have to be considered erroneous.

3.4. Vegetation and palaeoclimate analysis

An elementary approach has been used to analyse the plant macrofossil assemblages following the indications of Wolfe (1971), already applied by Martinetto (1995) to some Italian Pliocene plant assemblages. This approach implies to compare the floristic composition of a vegetation type reconstructed on the basis of a fossil plant assemblage with the modern vegetation types, and pinpoints those ones which have the most similar floristic composition, indicated as the best vegetation analogs. Climatic data from the modern areas which host the best vegetation analogs are used to infer the palaeoclimatic conditions. In order to check the values of Mean Annual Temperature obtained from the best vegetation analogs, a comparison has been carried out with data provided by Grimm & Denk (2012) for individual plant taxa.

For the vegetational and climatic interpretation of pollen records, the principles indicated by Bertini (2001, 2010, 2013) have been followed. However, in this work we newly apply the Köppen-Geiger classification for the definition of climate types (Kottek et al., 2006). The somehow ambiguous term "subtropical" is used here with special reference to the southernmost part of the C climate belt of the northern hemisphere (comprised within the warm temperate climate according to Kottek et al., 2006). In this sense the "humid subtropical" climate and vegetation today is mainly found in southern North America and southern East Asia.

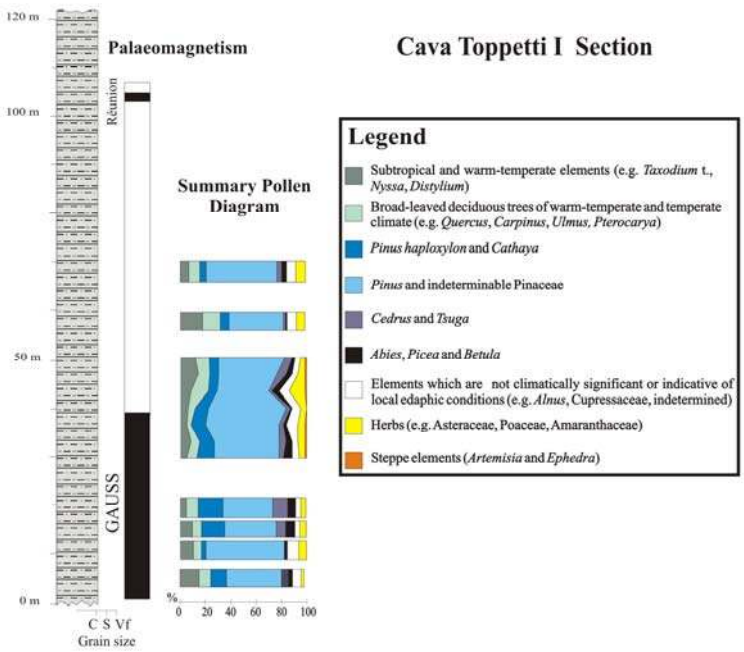


Fig. 3 - Summary pollen diagram of the Cava Toppetti I section, Fosso Bianco Unit (modified from Pontini et al., 2002). Sediment grain size: C, clay; S, silt; Vf, very fine sand.

4. POLLEN AND CARPOLOGICAL STUDIES IN THE PLIO-PLEISTOCENE OF THE TIBERINO BASIN

Pollen analyses were carried out in the studied area since the 1960s, with focus on lignite-bearing successions (Ricciardi, 1961; GeMiNa, 1962; Paganelli & Solazzi, 1962; Lona & Bertoldi, 1972). Additionally, Follieri (1977) analysed sediment samples from Monte Santo (near Todi) and Santa Maria di Ciciliano. She found that at Monte Santo *Taxodium* type (that includes also *Glyptostrobus*) and *Nyssa* were well represented, and accompanyied by *Dacrydium*, *Podocarpus*, *Sciadopitys*, *Sequoia*, *Keteleeria*, *Engelhardia*, *Rhus*, etc. With low frequencies were also present: *Carya*, *Pterocarya*, *Quercus*, *Zelkova*, *Ulmus*, etc.

Later on Abbazzi et al. (1997), Pontini (1997) and Pontini & Bertini (2000) studied a few sections of the south Tiberino Basin, as specified below. The pollen analyses permitted the collection of rich palaeofloral data (see Appendix 2). The occurrence of several genera, such as *Artemisia* and other Asteraceae, *Ephedra*, *Cedrus*, *Nyssa*, *Sciadopitys* and *Betula*, is not documented by other plant remains. In several cases the pollen taxa are also documented by carpological material (Martinetto, 1994, 1996, 2001), e.g., *Alnus*, *Fagus*, *Picea*, *Potamogeton, Sparganium*, "Taxodiaceae", *Tsuga.* Fruits and seeds also provide the documentation of several taxa not represented by pollen, such as entomophilous trees, climbers and shrubs (e.g. Lauraceae, Menispermaceae, Sabiaceae, Theaceae) or herbs with generalized pollen morphology (e.g. Cyperaceae). In two sites (Torre Picchio and Villa San Faustino) the analyses have been carried out on fruits and seeds alone.

In this paragraph we summarize results of previous palaeobotanical investigations for the main studied sites (Fig. 1), apart from Dunarobba and Pietrafitta which will be treated in detail below.

4.1. Cava Toppetti I Section

In this 70 m thick section, assigned to the Piacenzian/Gelasian transition (ca. 2.8 - 2.2 Ma) (Fig. 2; Pontini, 1997; Pontini et al., 2002), 15 pollen samples were collected, 7274 palynomorphs counted and 81 taxa identified. Pollen assemblages (Fig. 3) are dominated by arboreal elements, especially *Pinus*; its high occurrence (never below 30%) has been linked to taphonomic biases (over-representation) because of the palaeonvironmental context associated to a deep-water lake system. Along the pollen diagram the curve of *Taxodium* type always exhibits lower percentages with respect to those of *Pinus* and other bisaccate Pinaceae, and the same occurs for deciduous broad-leaved forest elements (e.g. *Quercus*, Juglandaceae, *Carpinus*, *Ulmus*, *Tilia*, *Acer*). Mediterranean elements are present with *Quercus ilex* type, *Olea* and *Pistacia*. From about 40 m, in correspondence of the top of the Gauss chron (Pontini et al.,

2002), an increase of herbs (mainly Amaranthaceae) is evident. A following rise, at about 50 m, of both *Taxodium* type and deciduous broad-leaved forest elements occurs, before a new expansion of bisaccate Pinaceae at about 66 m (Fig. 3).

Carpological material was collected by Martinetto (2001) from the top of this section, characterised by a slump deposit, which does not allow a precise dating of the plant-bearing layer. Few woody taxa so-far reported (Martinetto, 1996, 2001) indicate a plant assemblage of "subtropical" humid climate: *Ficus potentilloides*, *Liquidambar* cf. *europaea*, *Pseudotsuga* sp., *Sequoia abietina*, *Symplocos casparyi*, *Toddalia latisiliquata*, *Toddalia rhenana*.

4.2. Fosso Bianco Section

Integrated palynological and stratigraphical data (Sardella et al., 1995; Pontini, 1997, Ciangherotti et al., 1998; Pontini & Bertini, 2000; Napoleone et al., 2003) permit to frame the Fosso Bianco succession into the Gelasian interval between the 102 and 82 isotopic stages (i.e. within ca. 2.5 and 2.2 Ma), which also comprehends the Tiglian of North-West Europe (Zagwijn, 1963; 1974; 1996; Cohen & Gibbard, 2011). 56 samples were collected for pollen analysis; for each sample at least 100 pollen grains were counted besides the dominant taxon, nearly always exceeding 200 pollen grains. 17.752 palynomorphs (pollen grains and spores) were counted and 86 taxa identified. Reworked palynomorphs from Meso-Cenozoic sediments are frequent. The pollen flora is dominated by arboreal pollen grains, principally *Taxodium* type, followed by *Pinus* and *Quercus*. High percentages of *Abies* and *Picea* are found especially in the upper part. Herbs and shrubs (e.g. Poaceae, Amaranthaceae, *Ephedra, Artemisia* and other Asteraceae) are constantly present but generally below 30%. Four main pollen zones (I-IV) (Fig. 4) have been described by Pontini (1997) and Pontini & Bertini (2000).

ZONE I (0 m to 10.5 m). *Taxodium* type and *Pinus* dominate the pollen spectra. Deciduous forest elements are well represented especially by *Quercus* accompanied by *Ulmus; Carya, Pterocarya, Carpinus, Liquidambar* and *Acer* follow. *Ilex* is present up to 1.5%. Herbs, decidedly subordinated in comparison to arboreal elements, are principally represented by Poaceae, Ericaceae, Amaranthaceae and Asteraceae (included *Artemisia*). The climate of Zone I was definitely of C type (warm temperate *sensu* Kottek et al., 2006) and the abundance of pollen of *Glyptostrobus* and/or *Taxodium* (both genera produce pollen of the *Taxodium* type) suggests a humid "subtropical" character. The transition to Zone II is marked by the decrease of *Taxodium* type and other "Taxodiaceae"; at the same time *Abies, Pinus haploxylon* type and *Cathaya* slightly increase.

ZONE II (10.5 m to 26 m). It contains a significant amount of deciduous forest elements, whereas "Taxodiaceae" are scanty. At the same time herbs, including steppe elements (Poaceae, Amaranthaceae, Asteraceae, *Artemisia* and *Ephedra*), show successive expansions (up to ca 30%). Between the two major herbaceous expansions, respectively at 19.5 m and 24 m, a significant increase of deciduous forest elements is recorded, with a peak of *Quercus* preceding an expansion of altitudinal coniferous trees (principally *Picea*). The *Picea* acme phase coincides with the major event of sudden and drastic decrease of "Taxodiaceae" throughout the section, also corresponding to a significant frequency decrease of deciduous broad-leaved forest elements, *Cathaya* and *Pinus haploxylon* type. For Zone II a prevailing C type (warm temperate *sensu* Kottek et al., 2006) of climate can be reconstructed, possibly tending to a D snow climate during the *Picea* acme phase.

ZONE III (26 m to 65 m). The pollen assemblage of this zone is rather uniform from the bottom to the top, and is characterized by several elements which disappear from Europe during the Plio-Pleistocene, e.g.: "Taxodiaceae", *Carya, Pterocarya, Liquidambar, Nyssa, Myrica, Distylium, Engelhardia,* cf. *Panax* and *Symplocos*. The climate can definitely be referred to the C type (warm temperate *sensu* Kottek et al., 2006), with a humid "subtropical" character. The changes in abundances of *Taxodium* type and *Pinus* pointed out several sub-phases which probably related to both climatic and local palaeoenvironmental (lake level fluctuations) changes as a consequence of regional to global climate changes. Herbs (e.g. Asteraceae, Amaranthaceae, Poaceae, Brassicaceae, *Thalictrum*, Cyperaceae), with

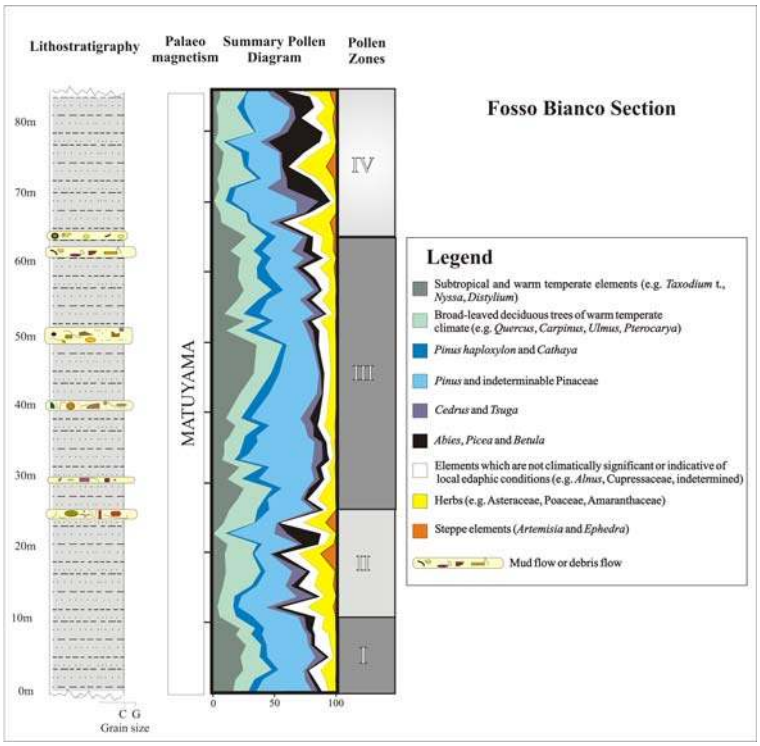


Fig. 4 - Summary pollen diagram of the Fosso Bianco section, Fosso Bianco Unit (modified from Pontini &m Bertini, 2000). Sediment grain size: C, clay; G, gravel.

steppe elements never above 1.5%, are in lower percentages with respect to the Zone II.

ZONE IV (65 m to 86 m) is characterized by a drastic reduction of “Taxodiaceae”, the absence of both *Ilex* and Ericaceae and a significant increase of the altitudinal arboreal elements. Deciduous elements are abundant (especially *Quercus*); they show two main phases of increase opposite to decreases of *Picea* and herbs. A small peak of steppe elements is apparent in the middle of this zone. The climate of Zone IV can be still mainly referred to the C type (warm temperate *sensu* Kottek et al., 2006), but the record of boreal conifers (*Picea*) and steppe elements (*Artemisia*) suggests a tendency to the D and possibly B climates.

Throughout the Fosso Bianco Section, the pollen record suggests repeated fluctuations in the plant assemblages, as shown in Fig. 4, which can be evaluated according to glacial/interglacial cycles and regional to local palaeoenvironmental changes. The vegetation is characterized, especially during the warmer phases, by several elements which disappear from Europe during the Plio-Pleistocene (e.g. “Taxodiaceae”, *Carya, Pterocarya, Liquidambar, Nyssa, Myrica, Distylium, Engelhardia,* cf. *Panax* and *Symplocos*). The major declines of thermophilous arboreal elements, including *Taxodium* type, and the simultaneous *Picea* acme testify a consistent decrease in temperature during glacial phases. Colder but still humid conditions, possibly tending to the D type snow climates (Kottek et al., 2006), are indicated by migration of *Picea* to lower altitudes, also penetrating the vegetation along the coastline, as attested by the observation (Pontini, 1997) of some pinaceous cones in silty strata, at the top of the section. Expansions of herbs (including *Artemisia)*, especially during pollen Zones II and IV, also prove a decrease of humidity, probably corresponding to the glacial acme. These extreme climatic conditions determined a strong reduction of swampy vegetation under the influence of temperature and humidity lowering. Probably both climatic parameters had a role on fluctuations of the local edaphic moisture and the lake level. Still in correspondence of pollen Zones II and IV, significant increases of deciduous broad-leaved forest elements are detected, which support climate amelioration phases, within a dominant C type climate (warm temperate *sensu* Kottek et al., 2006). However, “Taxodiaceae” stay in low proportions; in fact better edaphic conditions for the development of *Glyptostrobus/Taxodium* stands were only established during the long "subtropical" and humid phase of Zone III. This apparently long interval of stable climate conditions was tentatively related to the period of low amplitude variations occurring between the 96 and 86 isotopic stages (Pontini, 1997). Overlying cycles (zone IV) were referred to the 86 to 82 isotopic stages and the underlying ones (Zones I and II) to the stages 100 to 96.

Palynological and litho-sedimentological data suggest a quite diversified sedimentation rate, along the section. In particular, in correspondence of Zone IV (Fig. 4), the occurrence of the 40 kyr timescale in the glacial/interglacial cycles, approximately every 6 m, allowed to estimate a sedimentation rate of ca. 14 cm/kyr (Pontini, 1997).

4.3. Cava Toppetti II Section

In this 150 m thick section (Fig. 5) fossil vertebrate remains were recovered and assigned to the Sénèze faunal unit of the French biochronology (i.e the Italian Coste San Giacomo Faunal Unit., Abbazzi et al., 1997), which permits to frame the succession close to 2.1 Ma (Bellucci et al., in press).

Palynological analyses were carried out on palaeosols and sheet flow deposits (clayey sandy silt) of the Ponte Naja Unit (Pontini, 1997); in some cases the palaeosol top and the bottom of the subsequent sheet flow deposit were sampled.

Only 16 out of the 32 collected samples yielded a sufficient amount of pollen grains and spores, thus permitting to trace pollen spectra from 8 palaeosols and 8 sheet flow deposits (Fig. 5). The different proportion of pollen taxa between palaeosols (higher frequencies of herbs and *Pinus*) and sheet flow sediments (higher frequencies of *Taxodium* type and broad-leaved deciduous taxa) reflects apparent taphonomic biases.

As a whole rich and quite diversified pollen assemblages, very similar to those from both the Cava Toppetti I and the Fosso Bianco sections, are characterized by "subtropical" to warm temperate elements (*Taxodium* type principally, and *Nyssa*, *Distylium*, etc.) as well as

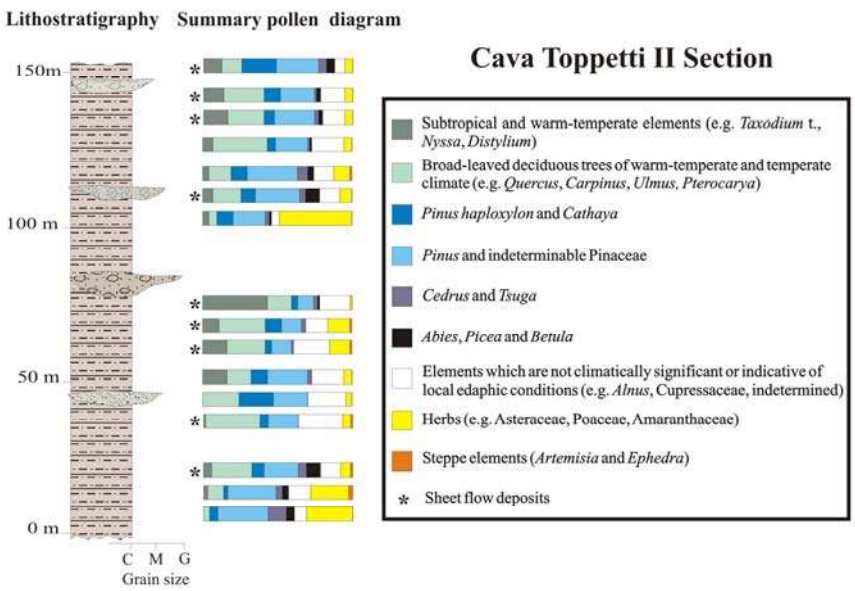


Fig. 5 - Summary pollen diagram of Cava Toppetti II Section, Ponte Naja Unit (modified from Abbazzi et al., 1997). Sediment grain size: C, clay; M, medium sand; G, gravel.

broad-laved deciduous elements (such as *Quercus*, *Carpinus*, *Ulmus*, *Pterocarya*, Araliaceae *Panax* type) typical of warm temperate climate (Kottek et al., 2006). Forest elements (broad-leaved deciduous dicotylendons plus *Taxodium* type) and herbs (especially Asteraceae Cichoroideae) show opposite phases of increase, over an interval of ca. 100 kyr, i.e the estimated time interval of deposition of the alluvial fan succession (Basilici, 1995). Steppe taxa (such as *Artemisia* and *Ephedra*) are not abundant during the dominant open vegetation phases.

One of the sheet flow deposits, in the middle of the section, also yielded a rather rich carpoflora (Martinetto, 2001). Woody taxa so-far reported indicate a "subtropical" humid climate: *Cephalotaxus* sp., *Mahonia staphyleaeformis*, *Magnolia cor*, *Sequoia abietina*, *Sinomenuim cantalense*, *Symplocos casparyi*, *Toddalia latisiliquata*.

4.4. Torre Picchio Section

This site of the South Tiber Valley, rich in fossils of plants and animals, is assigned to the Gelasian/Calabrian transition (ca. 2.0-1.5 Ma) by Girotti et al. (2003), who sampled and described a diverse fruit and seed association. It is characterised by the substantial lack of humid "subtropical" elements, and certainly reflects a palaeoflora which is significantly different from those of the older deposits of Cava Toppetti I and II. The palaeoflora of Torre Picchio was still significantly different from the present flora of central Italy, as evidenced by abundant remains of "exotic" trees, such as *Liquidambar*, *Liriodendron* and *Pterocarya*, and also by fruits of extinct herbaceous species, such as *Melissa elegans* and *Schoenoplectus* cf. *lacustroides*. This plant assemblage definitely indicates a warm temperate climate (Kottek et al., 2006).

4.5. Villa San Faustino Section

A few carpological remains from this deposit, assigned to the Gelasian/Calabrian transition (ca. 2.0-1.5 Ma: Ambrosetti et al., 1995a), were listed by Martinetto (1996, 2001). The palaeofloral association of Villa San Faustino is significant from the palaeoclimatic point of view because of the common occurrence of leaves and other macroremains of *Abies* and *Picea*. These genera are mainly linked to snow climates (Kottek et al., 2006), and the occurrence of macrofossils testify for their growth at low altitudes, thus indicating colder climatic conditions in comparison to the older palaeofloras of Cava Toppetti I-II. However, the presence of *Carpinus, Ostrya* and *Thymelaea* excludes a snow climate (Kottek et al., 2006), and would suggest a cold type of C climate, similar to the modern one of the areas where *Abies* and *Ostrya* grow together in the Mediterranean Basin (e.g. southern Apennines). The possible framing of the Villa San Faustino and Torre Picchio palaeofloras within the Early Pleistocene climate dynamics will be discussed below (see 7.2.).

5. THE DUNAROBBA SITE

The Dunarobba Fossil Forest (DF), in the territory of Avigliano Umbro (province of Terni, Umbria Region), represents a peculiar palaeontological heritage because of the excellently preserved remains of an *in situ* forest (Fig. 6), developed along the swampy lacustrine margin of the Tiberino Basin (Ambrosetti et al., 1995a). In the DF about 70 huge arboreal specimens (trees) in growth position have been so-far observed (Ambrosetti et al., 1995b; Baldanza et al., 2009).

The trunk remains are buried by silty and clayey sediments, with minor lignite and fine sand, belonging to the Fosso Bianco Unit, whose sedimentological features

Fig. 6 - Two panoramic views of the Dunarobba Fossil Forest at the end of the 1980s (courtesy of P. Ambrosetti, C. Benigni).

are described below. The observations carried out on several small oucropping sections (Fig. 7) allowed us to reconstruct a ca. 30 m thick succession. In addition, a drilling project realised during the years 1992-1995 (Ambrosetti et al., 1987a) furnished the continuous, ca. 110 m thick, S1 Core (Fig. 8). A shorter core, S2, correlates to the upper part of the S1 Core. The intergration of data from cores and outcrops let us to build up the Dunarobba Fossil Forest Synthethic Log (Fig. 8).

Most of the palaeobotanical studies on the Dunarobba Fossil Forest (Biondi & Brugiapaglia, 1991; Meneghini & Paganelli, 1994; Martinetto, 1996; Simonetti, 1998; Pauselli, 2003) were carried out on short sections, when the outcrop conditions were already deteriorated, so that a precise correlation of these sections to the Dunarobba Fossil Forest Synthethic Log (Fig. 8) is not easy. However, thanks to our observations during the 1980s, in good outcrop conditions, we provide here for the first time a syntetic correlation scheme of seven main sections (S1 Core, S2 Core, Road, Lignite, Forest, Trunk and Palaeosol: Fig. 8). Thus, all the palaeobotanical data, both published by other authors and collected by us, can be referred with certainty to one of these

Fig. 7 - Satellite image of the Dunarobba site, downloaded from GoogleMaps on May 25th, 2014. The location of all sections mentioned in this work is shown. DC, Dunarobba "New Quarry" Section; DW, Dunarobba West Section.

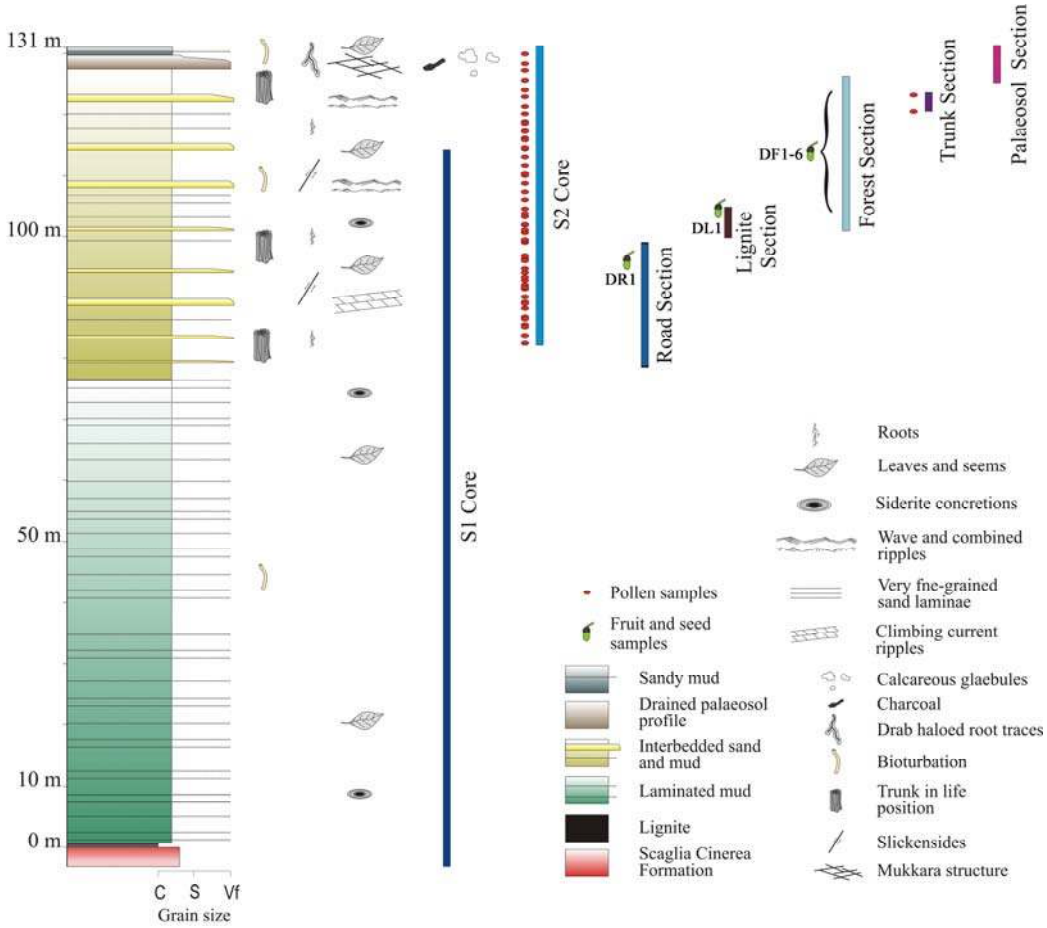


Fig. 8 - The reconstructed Dunarobba Fossil Forest Synthethic Log (to the left) showing the approximate stratigraphic position of seven main sections: S1 Core, S2 Core, Road, Lignite, Forest, Trunk and Palaeosol. The trunks of the Dunarobba Fossil Forest are found within interbedded sand and mud, for a thickness of ca. 50 m. Notice the position of pollen and carpological samples. Sediment grain size: C, clay; S, silt; Vf, very fine sand.

Fig. 9 - The Dunarobba "New Quarry" Section (DC, see location in Fig. 7), years 1990s. The asterisk indicates the sands from which sample DC1a was collected. The arrow indicates the thin lignite bed DC3.

sections.

We still need to point out that, about 700 m to the NW of the Forest Section, another outcrop was studied (Fig. 9). This was named by Basilici (1992) as "Dunarobba Cava Nuova" ("New Quarry"), and by Simonetti (1998) as "Nuova Cava Fornaci Briziarelli Marsciano". In this work it is indicated by the abbreviation DC (Fig. 7), and it is re-examined only from the palaeobotanical point of view. In fact, it provided rich macrofloral data, useful for a better understanding of the Dunarobba Fossil Forest palaeovegetational context. The correlation of the Dunarobba Fossil Forest Synthethic Log to the DC Section was not possible with stratigraphic methods, and will be discussed below on the basis of palaeobotanical data. Currently, the DC Section is no more exposed, but a 50 m thick clayey and silty succession, still pertaining to the Fosso Bianco Unit, crops out in a fresh section opened in the years 2010s (Dunarobba West, DW), 600 m to the West of the Forest Section (Fig. 7). A new sampling was carried out in the DW Section by two of the present authors (Baldanza, Bizarri) with the aim to investigate the ostracod and mollusc content and the formation of siderite nodules.

5.1. History of the discovery and fossil heritage preservation

Since its first discovery, the DF had to wait another 300 years to be rediscovered again: in fact the first reports date back to the early decades of the 16th century, to the work of the naturalist, and founder of the Accademia dei Lincei, Federico Cesi (Biondi, 1984). This researcher invited the academic Francesco Stelluti to investigate findings of arboreal specimens in the area of the DF, and the latter reported his observations in the work *"Trattato del legno fossile minerale nuovamente scoperto nel quale brevemente si accenna la varia et mutabil natura di detto legno"*, published in 1637. Stelluti, as a scientist, discussed the possible hypotheses on the formation of such wood on the basis of the evidence collected: "…*within the territory of Todi and Acquasparta there are four sites where this species of wood*, *which presents a large similarity with the cedar that is born in Mauritania, in Atlas Mountain (...), does occur. The formation of this wood is not from seed, or root of the plant, but solely by a kind of earth which looks much alike to the chalk, which gradually turns into wood .... and this, I believe, with the help of some heat from subterranean fires, that occur in those places. They grow underground, very often sending out a smoke, and sometimes flames, and especially during rainy days, with the help of sulfuric waters"*.

The beautiful drawings made by Stelluti during his research and observation of the woods (the "Metallofiti" of Cesi), were collected and stored, after Cesi's death in 1630, by Cassiano dal Pozzo (another member of the Accademia dei Lincei) in his "Paper Museum". The collection was acquired, over a century later, by King George III of England and is currently housed in Windsor Castle. Scott & Freedberg (2000) published a selection of drawings concerning fossilized woods and other geological specimens.

After these studies, the fossil wood in the region attracted foreign visitors to admire this wonder, especially after the Napoleonic Invasion, and visits of men of culture and science, or even just curious people, became more frequent. The wooden remains were well-known to local people, who, after surveys and excavations to find possible lignite seams, had to fight with the upright logs which prevented the digging of tunnels (Cerquaglia, 1996). Mining activities characterized the period following the First World War, providing work and a source of albeit minimal wealth for the miners. At the turn of 1950s and 1960s the mining technique changed by opening large open-cast mines, and also the material exploited changed, no more lignite but clay for the

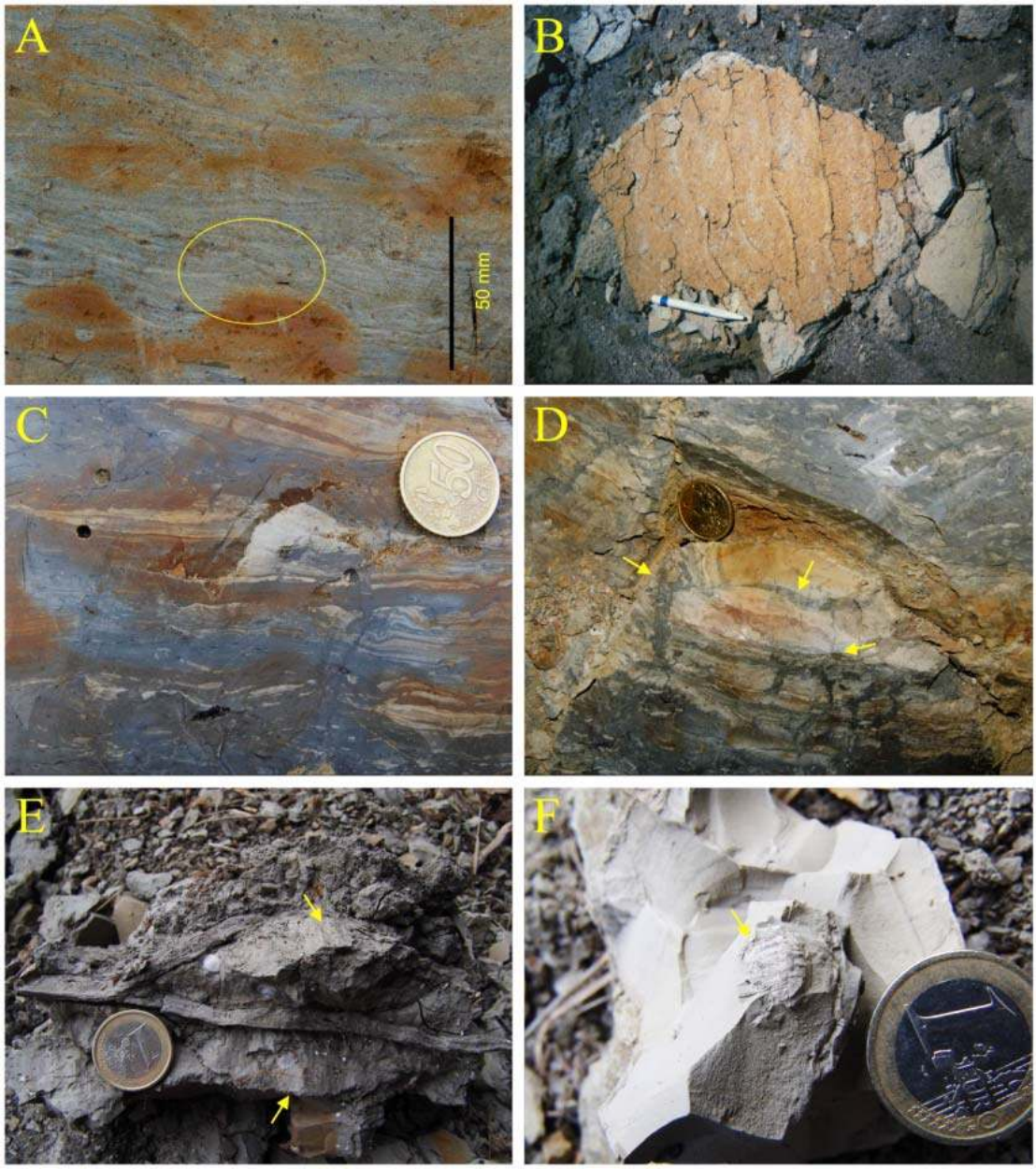


Fig. 10 - Dunarobba section, interbedded sand and mud intervals. (A) Laminated muddy sand showing structures produced by wave motion (circled in picture). (B) Wave ripples can be observed on the bedding surfaces, indicating the role of waves as transport and sedimentation agent on the wetland border where the Dunarobba Fossil Forest was located. Pencil: 0.145 m. (C) Deformed sandy laminae in mudstone. The deformation is likely due to bioturbation by roots. Coin: 24 mm. (D) Desiccation cracks (arrows) filled by bluish gray mud in wetland lake border subjected to frequent emersions. Coin: 24 mm. (E) Slickensides indicate common variation of water content in sediment probably linked to seasonal variations of the lake level. Coin: 23 mm. (F) Freshwater isopod (arrow); these fossils, as also freshwater fishes, crabs and gastropods, suggest at least periodical subaqueous conditions. Coin: 23 mm.

heavy clay industry. In 1986, with the progress of the work in the quarry of the Briziarelli Marsciano Brick Factory, large trunks in life position came to light, reaching heights of over eight meters. Since the discovery, the operators of the Archaeological Survey of Umbria carried out activities to preserve the fossils. After the imposition of a protection bond, according to the law, a first monitoring system has been activated in the 1990s (still in use), for the automated registration of changes in the environment as well as on some logs (Vergoni, 2000). The main requirement was, and is, to limit the damage caused by atmospheric and biological agents to the wood of the trunks, so that a climatic maxi-chamber was built around a group of specimens (named 25M), and

natural resin (colophony) was employed for the experimental treatment of some trunks.

5.2. Sedimentology and depositional palaeoenvironment

The sedimentary succession of the DF, which unconformably overlies Eocene-Oligocene clayey marl (Scaglia Cinerea Fm.), is 131 m thick and has been divided into five intervals (Ambrosetti et al., 1995b; Basilici, 1997, 2000b): 0.4 m of lignite, 76 m of laminated mud, 51 m of interbedded sand and mud, a 2.35 m thick palaeosol profile, and more than 1.5 m of sandy mud (Fig. 8). The interbedded sand and mud, which contains the trunks of the Fossil Forest, as well as the palaeosol profile and the sandy mud, are described and interpreted with the aim to understand the conditions of growth, death and preservation of the trunks.

Above the interval of 0.4 m of lignite, deposited in a wetland environment, 76 m of laminated muds suggest a lake depositional palaeoenvironment, located below the base of the wave action, where the sedimentation was controlled by low-density gravitational flows, with settling in disoxic conditions.

5.2.1. Interbedded sand and mud interval

The transition from laminated mud to the overlying interbedded mud and sand interval is gradual, and four lithofacies were described: sand, sandy mud, mud, and lignite (Ambrosetti et al., 1995b; Basilici, 1997, 2000b, 2008). The sand lithofacies is constituted of very fine-grained silty sand and fine-grained sand beds. In cross-section, small bedforms display pointed crests and chevron and bundled upbuilding cross-laminations (De Raaf et al., 1977) (Fig. 10A); on the bed surfaces, these structures appear as symmetrical ripples with rectilinear and pointed crest (Fig. 10B). The sandy mud lithofacies displays thin laminae, commonly interrupted and convoluted (Fig. 10C). Thin cracks, tapering downward, polygonal in shape on the depositional surface and filled of mud, are also observed (Fig. 10D). The mud lithofacies is structureless, but it is characterized by isolated calcareous nodules, <1-10 mm across, siderite nodules, up to 50 mm in diameter, and slickensides (Fig. 10E). Fossil remains of small fishes, crabs, and aquatic isopods are present (Fig. 10F). The lignite lithofacies, 0.2-1.5 m thick, is constituted of horizontal tree trunks and branches, and it is associated to mud beds.

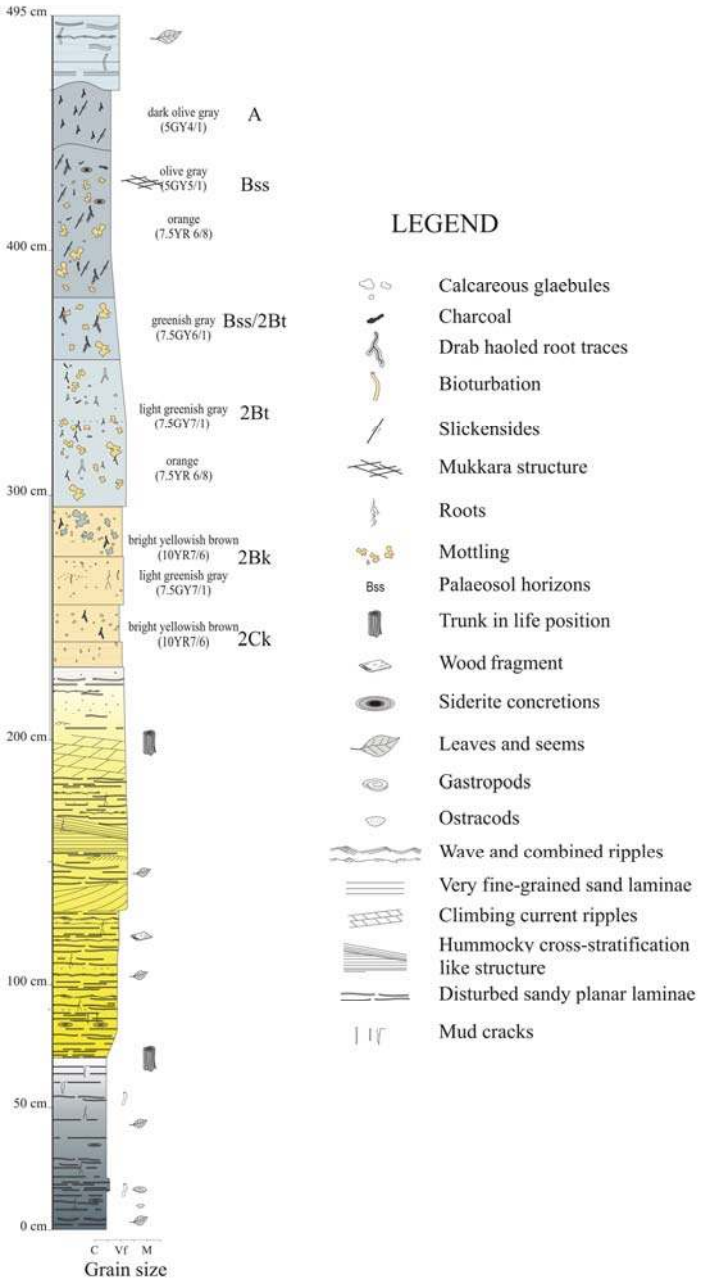


Fig. 11 - Palaeosol section, upper portion of the sedimentary succession of the Dunarobba Fossil Forest. Here the top of the interbedded sand and mud, drained palaeosols profiles, and sandy mud are represented in detail. Sediment grain size: C, clay; Vf, very fine sand; M, medium sand.

The outcrop conditions do not allow to well define the overall spatial relationships of these facies. However, in the upper portion of this interval sand, sandy mud and mud lithofacies are organized in a coarsening and thickening upward sequence (Fig. 11).

The sandy beds were deposited by traction and settling for oscillatory flows associated to unidirectional flows (combined flows). Grain size and horizontal geometry of the thin laminae of finer deposits indicate that they are the product of settling in calm water conditions. Lignite is interpreted as autochthonous organic deposit in a wetland. Emersion evidences (desiccation cracks) and palaeopedogenic features (partial disruption of the sedimentary structures, calcareous nodules, slickensides, roots, organic concentration, tree trunks) occur in all the facies, although they prevail in mud beds. These

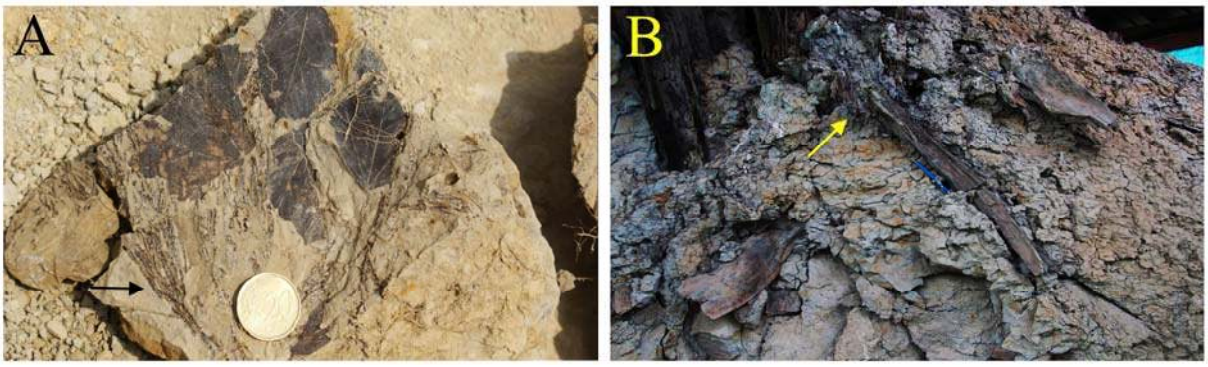


Fig. 12 - (A) *Glyptostrobus europaeus* shoots (arrow) and seeds can be found in sandy mud above the drained palaeosol, suggesting the continued presence of this species. Coin: 22 mm. (B) Sub-horizontal, flattened woody axis (arrow), possibly connected to a large trunk, well above the stump base. This same structure was interpreted as an adventitious root by Ambrosetti et al. (1995b). Pencil: 145 mm.

structures suggest periodical emersion and pedogenesis of the depositional surface, as a consequence of seasonal lowering of the water level and establishment of draining conditions. Nonetheless, the sand and mud interval lacks of clear well-defined palaeosol profiles, since the high rate of sedimentation overcomes the pedogenesis rate (Kraus, 1999).

Overall, based on the sedimentary aspects, the succession that contains the DF was interpreted (Ambrosetti et al., 1995b; Basilici, 1997, 2000b) as a wetland characterized by a coastal lacustrine palaeoenvironment at the margin of a large and deep lake, in which the largest part of the Fosso Bianco Unit was deposited.

In lake margins, the wave action decreases towards the coast for the influence of vegetation, that attenuates the wave energy, hinders the formation of a sandy foreshore, and promotes the deposition of mud and organic matter on the inner coastal areas (e.g. distribution of lithofacies for the lacustrine palaeoenvironment of the Horton Bluff Formation-Lower Carboniferous, Nova Scotia: Martel & Gibling, 1994). The proposed lateral lithofacies model (facies tract) for the DF depositional system is characterized by the progressive decreasing of the grain size and increasing of the emersion evidences towards the coast (Ambrosetti et al., 1995b; Basilici, 1997).

5.2.2. Palaeosol profile and sandy mud

The upper portion of the DF sedimentary succession is formed of a 2.35 m thick palaeosol profile, overlain by a more than 1.5 m thick mud deposit (Fig. 11). The lower transition of the palaeosol profile interval is gradual, whereas its upper boundary is sharp, but non erosional. Bioturbation and root traces, with preserved organic matter and drab haloes, occur in all the horizons, but they are concentrated in A and Bss horizons, together with charcoal. The high concentration of slickensides in A and Bss horizons defines angular blocky peds, which identify a structure called mukkara (Retallack, 2005). In this sense, the undulating surface of the top of the A horizon may be interpreted as gilgai superficial microrelief. High concentrations of clay, and mukkara and gilgai structures are features typical of Vertisols.

The palaeosol profile interval indicates an interruption of the sedimentary processes, which did not extend for more than hundred years, because low concentration of calcareous nodules (Machette, 1985) and clay in B horizons, as well as absence of pedogenic structures (with the exception of mukkara), evidence poor soil development (Wright, 1989). Calcareous nodules, orange mottling, and clay accumulation within the palaeosol profiles are the evidences of the establishment of drained conditions that caused the extinction of the wetland where the forest lived. Drained conditions cannot be attributed to climate changes, because (1) calcareous nodules are small, isolated and not abundant, differently of arid environments, (2) slickensides and clay concentration in Bss and Bt horizons, respectively, indicate rain precipitation, and (3) drab haloed root traces indicate temporary water stagnation. The upper sandy mud interval represents the re-establishment of the previous palaeoenvironmental conditions, related to a lacustrine margin wetland. However, *in situ* tree trunks were not found in this interval, and only fossil leaves and conifer shoots occur (Fig. 12A).

5.2.3. Changes in the sedimentary environment

The sedimentary intervals described reveal a succession of events that led to the growth, death and preservation of a swamp forest. The trees lived in a wetland lacustrine margin, where high quantity of muddy and sandy sediments was constantly introduced by combined flows, generated by wave activity. Cumulative palaeosols with A horizon up to 3 m thick and absence of B horizon testify for a high sedimentation rate, which prevented the formation of well-developed soil profiles (Kraus, 1999). Some large sub-horizontal woody axes were observed laterally to the tree trunks (Fig. 12B) and interpreted as adventitious roots by Ambrosetti et al. (1995b). The poorly-developed Vertisol, that overlies the coastal lacustrine deposits, exhibits drained palaeoenvironmental conditions, which caused the disappearance of the wetland and the swamp forest. The high rate of sedimentation in the sand and mud interval that contains the DF is due to high accommodation space creation, probably generated by tectonics. Indeed, clear evidences of tectonics activity during sedimentation are provided by Gilbert-type deltas in contemporaneous

deposits of the Fosso Bianco Unit (Basilici, 1997) and high frequency cycles of immature palaeosols and sheet flow deposits in a contemporaneous alluvial fan (Ponte Naja Unit: Basilici, 1995) .

The successive restoration of the wetland conditions did not allow the preservation of *in situ* tree trunks: probably the rate of space accommodation and/or sedimentary supply were no more suitable to create conditions for the preservation of a new fossil forest.

5.3. Fossil invertebrates

The most common invertebrates reported from the Dunarobba sections are molluscs and ostracods; apart from these, only a few insects have been studied in the Forest Section (Principato & Principato, 2000).

Two malacological associations were distinguished in the deposits of the Forest Section: 1) pulmonate gastropods, found in clays near the trunks (hydromorphic palaeosols lithofacies), which indicate a wooded environment with highly hydric soil (swamp), and 2) an association dominated by freshwater Prosobranchia, which characterizes running, loosely flowing or standing waters (Ambrosetti et al., 1995b; Ciangherotti et al., 1998). Both associations suggest a warm temperate climate. The first association shows strong affinities with Pliocene mollusc associations of NW Italy, France and Germany; the second association includes endemic species also found in the sections (see Fig. 1) of Fosso Bianco (Fosso Bianco Unit) and Cava Toppetti I (Ponte Naja Unit). The rich fossil snail assemblage of the Forest Section (Fig. 7) consists of about twenty species, some of great palaeontological and biogeographical interest (Manganelli et al., 1989, 1990; Esu & Girotti, 1991; Esu et al., 1993; Ambrosetti et al., 1995a; Manganelli & Giusti, 2000). Only five species have been investigated in detail: *Eostrobilops aloisii* Manganelli, Delle Cave et Giusti 1989, *Leiostyla* cf. *gottschicki* (Wenz 1922), *Lauria* cf. *cylindracea* (Da Costa 1778), *Gastrocopta (Albinula) acuminata* (Klein 1846) and *G.* (*Vertigopsis*) *moravica* (Petrbok 1959) (Manganelli et al., 1989, 1990; Manganelli & Giusti, 2000). Recently, the new species *Staurodon cianfanellianus* Manganelli, Benocci, Esu et Giusti 2008 was described (Manganelli et al., 2008).

Medici & Gliozzi (2008) reported in the Dunarobba Forest Section a more diversified ostracofauna with respect to Cava Toppetti I and Fosso Bianco sections, including Candonidae, Limnocytherinae, Ilyocyprididae, Cytherideinae and Cyprididae. As a whole, the Tiberino Lake ostracod assemblages seem to be characterised by a marked endemism, particularly in the deep lacustrine facies (up to 83%) and, among the Candoninae, intralacustrine speciation is recognizable for genera *Candona (Neglecandona)*, *Sirmiella* and "*Caspiocypris*". Within the Dunarobba ostracod fauna, only 2 species are new (*Paralimnocythere* n. sp. and *Hemicypris* n. sp.) while the remaining 14 species were already known, and display a broad European distribution. The presence of *Cypris subglobosa* Sowerby 1840, and of the genus *Hemicypris*, suggests that the Tiberino Lake littoral waters were warmer than the present-day lakes of central Italy (Medici & Gliozzi, 2008).

During the recent sampling of the DW Section by

Fig. 13 - *Glyptostrobus europaeus* cone and shoot imprints highlighted by reddish minerals, sample photographed in an unmarked position of the Forest Section of Dunarobba. Coin diametre = 2 cm.

Fig. 14 - Compressed leaf of the fern *Osmunda* from the Forest Section (photo O. Pauselli). Scale = 1 cm.

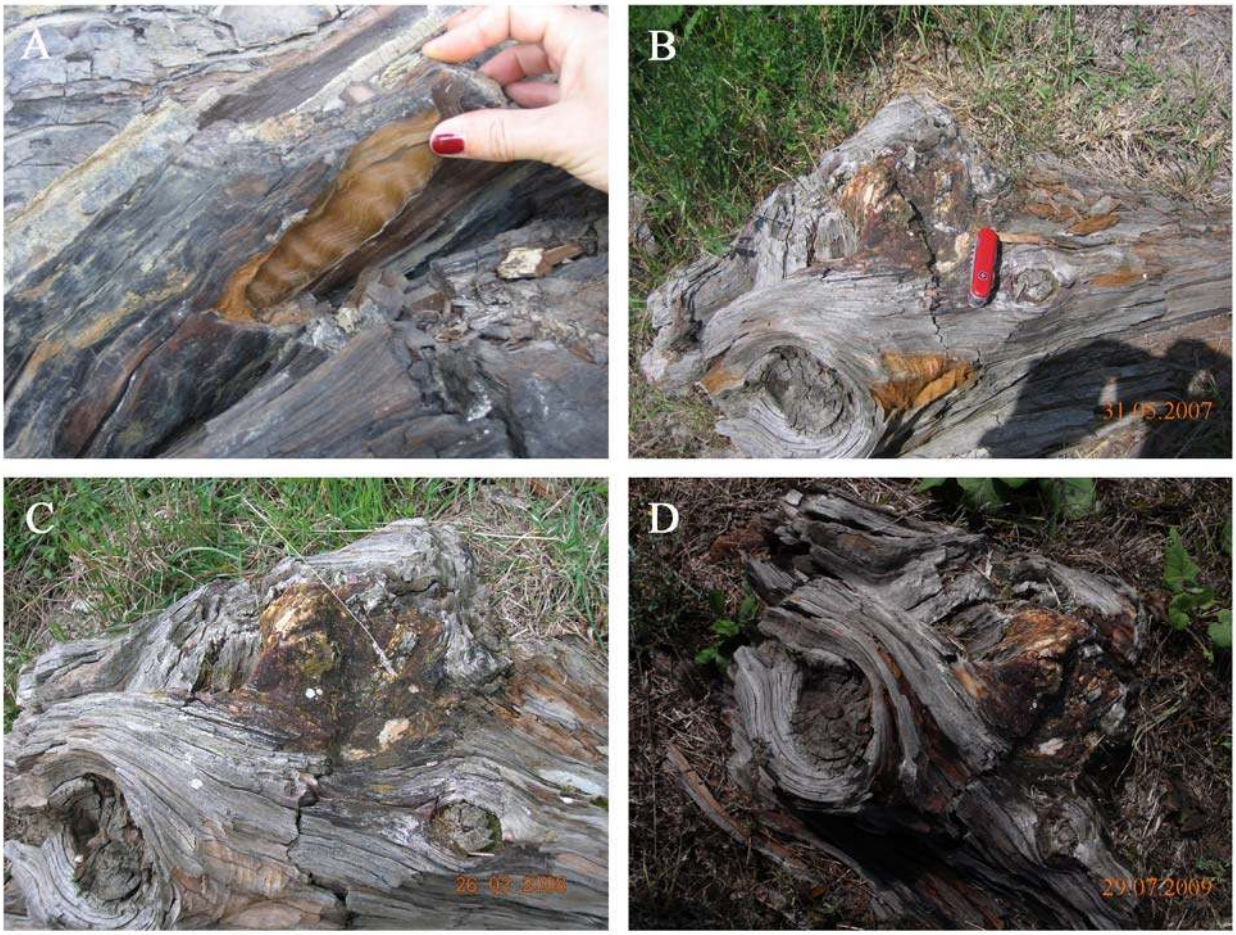


Fig. 15 - A) Detail of the wood original color in Dunarobba trunks. B-D) Comparison of the same trunk fragment (from 2007 to 2009), analysed by Baldanza et al. (2009), evidencing a massive loss of wooden material and the formation of dark brown ring around the mineralized area.

A. Baldanza, R. Bizzarri, E. Gliozzi and F. Posati, some preliminary data on the ostracod assemblages have been collected. The association was exclusively made up by Candonidae, including the dominating species *Candona neglecta* Sars 1887, accompanied by common *Caspiocypris* spp., and seems to confirm the occurrence of the species flock event hypothesized by Medici & Gliozzi (2008).

5.4. Fossil plants

Data on the trunks of the Dunarobba Forest Section were collected by Ambrosetti et al. (1995b). The diameter size of the trunks was measured from 1.5 to 2.5 m, and the visible height between 2 and 8 m. The trees were presumed having grown to heights of about 35 m and the older ones probably have lived for 2000-3000 years. Thanks to the mapping of the *in situ* trunks of the Forest Section (Ambrosetti et al., 1995b), a density of 43 trees/hectare was estimated.

Due to the rapid burial and the dysoxic environment, the wood is still perfectly preserved (mummified), with very limited mineralization in just a few specimens (Scott & Collinson, 2003; Nowak *et al*., 2007); in many of the large, intact trunks original cellulose and lignin were detected (Baldanza et al., 2009). Several papers were devoted to Dunarobba wood analyses, spacing from chemotaxonomy (Staccioli *et al*., 1996; Menchi *et al*., 1997; Staccioli & Bartolini, 1997) to mineralogy of inorganic compounds (Boyce *et al*., 2001; Staccioli *et al*., 2001; Scott & Collinson, 2003) and, finally, to the role played by organic compounds for permineralization (Nowak *et al*., 2007).

According to wood-anatomical analyses, Biondi & Brugiapaglia (1991, 2000) assigned all of the trunks to a single morphospecies, *Taxodioxylon gypsaceum* (Goeppert) Krausel, which shows similarities to the modern wood of *Sequoia sempervirens*.

In the sediments embedding the fossil trunks several smaller plant remains have been observed: roots, woody axes, conifer shoots, leaves, small cones and tiny seeds. The conifer shoots are all of the same type and can be referred to *Glyptostrobus europaeus* (Fig. 13), observed from the bottom to the top layers of the Forest Section. The nearest living relative of this extinct conifer species is the East Asian tree *Glyptostrobus pensilis*. Angiosperm leaves are often tightly packed and

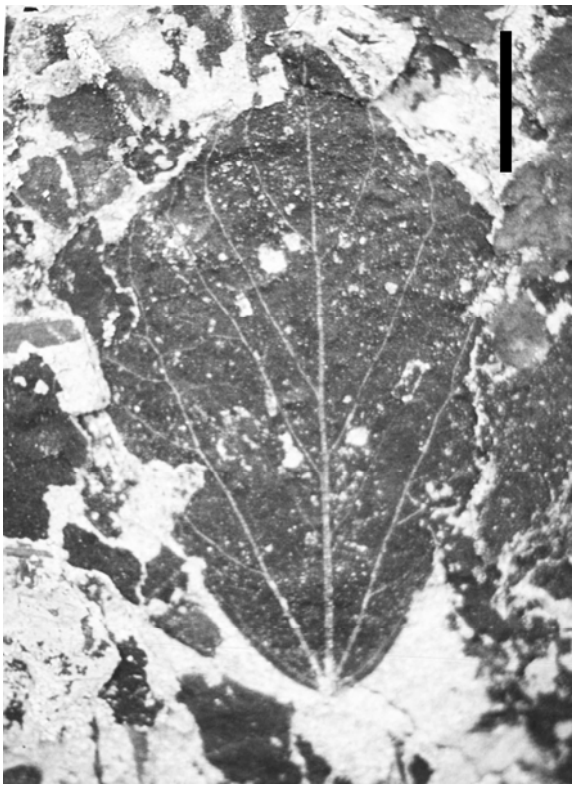


Fig. 16.- Compressed leaf (Hamamelidaceae?) on a bedding plane of the fine sands of the DC Section. Scale = 1 cm.

the morphology is difficult to be recognized. Only a few compressed leaves showed significant morphological features as to be assigned to *Acer* sp. and *Osmunda* sp. (Fig. 14).

The plant remains sampled at the top of the Palaeosol Section (Fig. 12A), in the upper sandy mud interval above the palaeosol, have been assigned to *Glyptostrobus europaeus* (shoots with scale-like leaves and a few seeds) and to *Acer* sp. (trilobate leaves).

A still unstudied collection of leaf impressions of uncertain stratigraphic position is preserved at the reception centre of the DF (Centro di Paleontologia Vegetale), and contains interesting fern and angiosperm leaves. The macropalaoebotanical research carried out in the Dunarobba sections was mainly devoted to fruit and seed analysis (palaeocarpology, see 5.4.2.).

5.4.1. Wood research and preservation

The finding of trunks in life position testifies that the trees underwent conservative and reducing conditions soon after death or even during life. The soft clayey sediments protected the trunks from the attacks of bacteria and fungi, also preventing the circulation of mineralizing fluids. A natural resistence of the Dunarobba wood to the attacks by fungi and insects was reported by Palanti et al. (2004), and the high content of cellulose (Brugnoli et al., 2000) testifies for a good preservation state. Moreover, the ^{13}C and ^{12}C isotopic composition, measured both on rings and on extracted holocellulose, evidenced many important fluctuations related to palaeoenvironmental variations (i.e. water availability and temperature). The Dunarobba trees registered a progressive enrichment of ^{13}C in the annual rings, and Brugnoli et al. (2000) concluded that such isotopic variation was due to a physiological response of the trees to stressed palaeoenvironmental conditions, also responsible for a decrease in the tree growth. Several papers were devoted to Dunarobba wood analyses spacing from chemotaxonomy (Staccioli et al., 1996; Menchi et al., 1997; Staccioli & Bartolini, 1997) to mineralogy of inorganic components (Boyce et al., 2001; Staccioli et al., 2001; Scott & Collison, 2003) and, finally, to the role played by organic compounds for permineralization (Nowak et al., 2007). Recent mineralogical research (Baldanza et al., 2009) assessed that exposure to the atmosphere produced a significant alteration of the wood (Fig. 15). Two different types of wood are identified, one suffering from an incipient mineralization with calcium carbonate, and one non-mineralized in which the original organic material is preserved. Natural weathering effects, of the "once buried-now exposed" mummified trunks, are responsible for significant decay effects on the exposed trees; it was highlighted that the environmental conditions transform the iron sulfides into iron oxides and hydroxides, with production of sulfuric acid. This process of widespread alteration, with the formation of new mineral phases and their volume increase, is one of the probable causes aggravating exfoliation of the many phenomena that afflict the trunks of the DF. Observations carried out during the years 2007-2009 (Fig. 15), on the same trunk

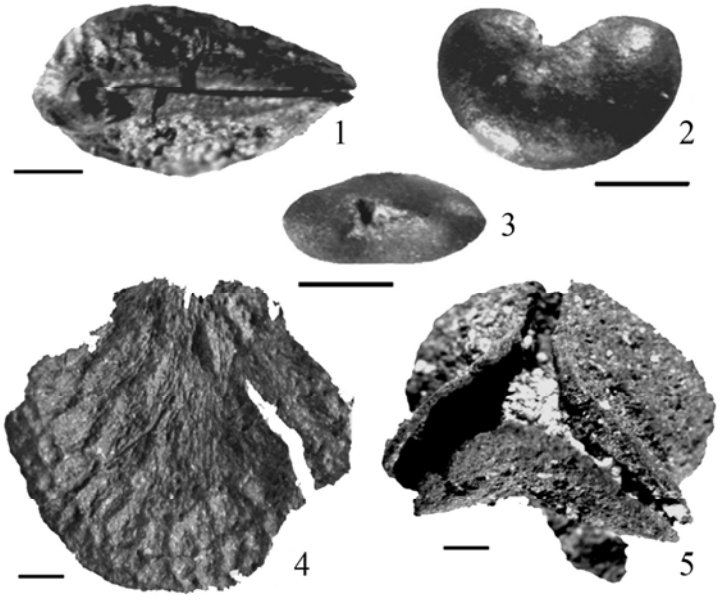


Fig. 17 - Fossil carpological remains from the Dunarobba DC Section, belonging to plants which are rare in post-Miocene sediments of central-eastern Europe: 1) *Zanthoxylum ailanthiforme*, seed; 2, 3) *Toddalia rhenana*, seeds; 4) *Sabia europaea*, fragmentary endocarp; 5) *Tetraclinis salicornioides*, cone. Scale 1 mm.

fragment, evidenced a massive loss of wooden material and the formation of dark brown ring around the mineralized area.

5.4.2. Palaeocarpological studies

Rich assemblages of fruits, seeds and related structures have been sieved out from several sediment samples of the Road Section, Lignite Section, Forest Section and from four layers of the adjoining DC Section (Figs. 7 and 8). In the Forest Section, three sediment samples were collected in the 1990s (labels DF1-3), and partial results were already reported by Martinetto (1994, 1996, 2000). This sampling phase also regarded a layer of lignite (DL1) cropping out at the entrance of the DF protected area, in the Lignite Section (corresponding to section 3 of Basilici, 1992, p. 178). Another sample of consolidated sandy mud (DR1) from a lower layer of the Road Section was kindly provided by Dr. Patrizia Argenti (this sample was precisely placed at the height of 20.8 cm in section 7 of Basilici, 1992, p. 7). About ten years later, Pauselli (2003) analysed other four samples from the Forest Section. The stratigraphic position of all of these samples was marked into short stratigraphic sections (1-2 m thick), which fall in the interval between 90 and 125 m of the Dunarobba Fossil Forest Synthethic Log (Fig. 8). The fine-scale stratigraphic correlation of the sampled layers is not easy, however DR1 is definitely the oldest sample, immediately followed by DL1, whereas the remaining samples are certainly located no more than 20 m above DL1 (Fig. 8).

In the DC Section, field observations permitted to detect abundant wood and leaf remains (Fig. 16), but only the fruits and seeds have been analysed to reconstruct the palaeoflora. Four layers were sampled in the 1990s (Martinetto, 1996), and precisely:

- sands (composite bed DC1, samples DC1a, 8 dm^3 and DC1b, 20 dm^3) laying 3-4 m below the base of the lignite layer DC3;
- sandy silt (layer and sample DC2, 4 dm^3) laying 1.6 m below the base of the lignite layer DC3;
- lignite (layer and sample DC3, 5 dm^3);
- lignite and poorly consolidated carbonate deposits (composite bed and sample DC4, 3 dm^3), corresponding to the same layer of the DC3 sample (and part of the layer above it), in a site where its thickness was less than 10 cm.

We did not consider for the present work the unpublished carpological material from Dunarobba deposited by D.H. Mai in the collection of the Museum fuer Naturkunde of Berlin, because it was sampled from an uncertain stratigraphic position (year 1999, with E. Martinetto).

The results of palaeocarpological investigations show that the assemblages of the Road, Lignite and Forest sections contain the same taxa as those found in the richer DC assemblages (Tab. 1). All of the identified taxa (e.g., Plate I) correspond to fossil species commonly found in the Neogene successions of transalpine Europe, and in the Pliocene of northern and central Italy. These data suggest that the Tiberino Basin area, at the time when the DF grew, belonged to the same palaeofloral region as Central Europe, namely the "Westeuropean Region" of Mai & Walther (1988). Particularly remarkable is the absence of Mediterranean elements or plants indicating periodically dry conditions. An astonishing feature, in consideration of a possible Early Pleistocene age, is that several Dunarobba taxa (Fig. 17) were considered to disappear from central-eastern Europe at the end of the Miocene (e.g. *Tetraclinis salicorniodes*, *Zanthoxylum ailanthiforme*), and others at the and of the Early Pliocene (*Toddalia rhenana*, *Sabia europaea*). The meaning of their occurence in the Dunarobba section will be discussed below at the light of the role of refuge area played by central Italy in the Pliocene-Early Pleistocene (Martinetto, 2001).

The layers of lignite and of mudstones with compressed plant macroremains (DC3, DC4 DF1-6, DL1) have provided fruit and seed assemblages dominated by a few very common species (see Plate I): *Alnus* sp., *Carex psedocyperus, Cephalanthus dorofeevi, Cladium paleomariscus, Glyptostrobus europaeus, Schoenoplectus isolepioides, Cornus* aff. *amomum*. In accordance with what is argued elsewhere (Martinetto, 1994), this lack of variety can be explained by a limited range of post-abscission dispersion, so that the fruits and seeds must belong to a few species adapted to specific soil conditions, which formed the local palaeovegetation. These fruit and seed assemblages (DC3, DC4, DF1-6, DL1) were most probably generated through a simple vertical fall of the diaspores or a short lateral transport by air or water, so they can be classified as autochthonous (or hypoauthochthonous).

The DR1 sample, consisting in consolidated sandy mud of the Road Section, differed from the others for the dominance of diaspores adapted to animal dispersal (endozoochory), and selective transport by animals is the probable cause of the peculiar composition of this species-poor assemblage, which does not allow the reconstruction of an ancient plant community.

As for the two associations from silty sand layers of the "New Quarry" Section (DC1, DC2), a more consistent drift of fruits and seeds can be argued. These contain a mixture of hygrophilous plants (*Cladium, Glyptostrobus, Schoenoplactus, Sparganium*) and taxa that can be assigned to mesic palaeocommunities of well-drained soils (*Fagus, Liriodendron, Zanthoxylum*), thus suggesting that the plant remains were collected from several types of mesic and wetland vegetation, and transported till to a lake-shore environment, resulting in a higher species diversity of these assemblages (Tab. 2).

5.4.3. Palynology

At the Dunarobba Fossil Forest site pollen analyses were carried out on 52 samples (Simonetti, 1998), collected throughout the 53.5 m thick S2 Core (Fig. 8), which crossed the sediments of the Fosso Bianco Unit (Fig. 18). Also two samples from the Trunk Section (Figs. 7, 8) were analyzed. Moreover, 7 palynological samples were collected throughout the DC Section (Fig. 7), which includes 10 m of clastic deposits (Fig. 18) with wave-dominated coastline sands at the bottom and two meters of calcareous strata at the top (Fosso Bianco

Site: **Dunarobba**				**Section**	**Road**	**Lign.**	**Forest**					**DC (New Quarry)**				
				Sample labels in this work	**DR1**	**DL1**	**DF1**	**DF2**	**DF5**	**DF6**	**DF3**	**DC1a**	**DC1b**	**DC2**	**DC3**	**DC4**
				Labels in Martinetto (1996)	D7	DF4	DF1	DF2	/	/	DF3	/	DC1	DC2	DC3	DC4
				Labels in Pauselli (2003)	/	/	/	/	C39V	C11V	/	/	/	/	/	/
Age: uncertain, Late Pliocene or Early Pleistocene, ca. 3.5-1.5 Ma				Labels in CENOFITA	DU7 A4I	DU10 A0U	DU1 A0S	DU1 A4D	DU1 /	DU1 /	DU1 A4E	DU20 B1L	DU20 A3T	DU23 A4H	DU21 A4G	DU25 A4F
				Volume analysed (dm^3)	/	**2.2**	**1.3**	**0.1**	**2.5**	**2.5**	**1.5**	**8**	**20**	**5**	**4**	**3**
Taxa	**e/n**	**hab**	**a/h/m**	**NLRs distribution**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Alnus sp. (fem. amenta)	n	t	h	cosmopolitan				7		12						
Alnus sp. (fruits)	n	t	h	cosmopolitan		0	0	63	0	2	14	1				
Carex aff. *aquatilis* Walenbg.	n	h	h	cosmopolitan			3		2					1		
Carex pseudocyperus L.	n	h	h	Holarctic			16		4	0	1					
Carex spp.	n	h	h	cosmopolitan			1		0	1			2			
Cephalanthus dorofeevii Arbuzova et Zhil.	e	s	h	cosmopolitan						4	35			17	0	3
Cladium paleomariscus Dorofeev	n	h	h	cosmopolitan			24		9	0		4	1	0	1	
Cornus aff. *Amomum* Mill.	n	s	m/h	NE America		29	1	7	0	4			4	12	1	17
Decodon globosus (E. M. Reid) Nikitin	e	h	h	NE America			0		0							3
Ficus potentilloides Mai	e	t/s	m	pantropical					0			7	6	0	8	4
Glyptostrobus europaeus (Brongniart) Unger	e	t	h	SE Asia | Remains = cones		4	3	11	1	10	21		1	16	1	9
Glyptostrobus europaeus (Brongniart) Unger	e	t	h	SE Asia | Remains = seeds		64	10	11	0	61	18		1	30	7	35
Hypericum sp.	e	h/s	m/h	cosmopolitan			0						1	1	1	
Itea europea Mai	e	s	h	SE Asia-NE America		1	0			2	2					
Ludwigia cf. *palustris* L.	e	h	a	Holarctic					0	1		0				
Lycopus cf. *europaeus* L.	n	h	h	Holarctic		0									0	
Magnolia allasoniae Martinetto	e	t	m (h?)	E Asia-NE America	11		0					5	3	0	0	2
Meliosma wetteraviensis (Ludwig) Mai	e	t	m (h?)	SE Asia- central America		0					1					
Potamogeton spp.	n	h	a	cosmopolitan						1	1	0		3		2
Proserpinaca reticulata C. et E.M. Reid	e	h	a	NE America						0				4		0
Pterocarya limburgensis C. et E.M. Reid	e	t	m	SE and SW Asia		2						4	3	0		
Rubus cf. *semirotundatus* Lancucka-Srodoniowa	n	s	m/h	cosmopolitan							0					
Rubus microspermus E.M. Reid	n	s	m/h	cosmopolitan					0	0	4	1		2		
Saurauia sp.	e	t	m	SE Asia- central America							0					
Schoenoplectus isolepioides Mai et Walther	n	h	h	cosmopolitan			41		84				2		64	6
Solanum dulcamara L.	n	h	m/h	cosmopolitan						0				4		
Sparganium cf. *neglectum* Beeby	n	h	h	cosmopolitan						0		0	2			
Tilioideae (cf. *Craigia*)	e	t	m	cosmopolitan							2					
Urticaceae	/	h	m/h	cosmopolitan						0						
Viola	n	h	m/h	cosmopolitan						0		1				
Vitis parasylvestris Kirchheimer	e	c	m	Holarctic	3	0							2			1
Total nr. specimens					**139**	**818**	**488**	**27**	**286**	**326**	**2999**	**229**	**103**	**310**	**442**	**282**

Tab. 1 - List of fruit and seed taxa detected in samples of both the Forest Section and the New Quarry (DC) Section of the Dunarobba site; occurrences in the Road and Lignite sections are also reported.The column "e/n" is referred to the Nearest Living Relatives, e = exotic, n = native; hab = habitus: t = tree, s = shrub, h = herb, c = climber; a/h/m = aquatic, hygrophilous, mesic. The values represent the taxon's percentual frequency in each sample.

Unit). As a whole, rich and well preserved pollen assemblages have been detected, that provide accurate floristic and vegetational evidence.

S2 Core

76 taxa representatives of 49 families were identified (Simonetti, 1998; Appendix 2). "Subtropical" to warm temperate arboreal taxa are abundant. Among them, *Taxodium* type, a typical swamp element, dominates the pollen assemblages in association with *Alnus*, *Pterocarya* and *Nyssa*. Some herbaceaous taxa, such as Poaceae, Cyperaceae, *Sparganium*, *Potamogeton*, were also present but never in high abundance. Successive fluctuations in the percentage curves of swamp elements, as well as of *Pinus,* possibly reflect variations of the lake water level. Pollen of deciduous broad-leaved mixed forest elements (e.g. *Quercus*, *Ulmus*, *Fraxinus*, *Pterocarya*, *Carya*) is more abundant in those layers where a decrease in inundation phases was attested by sedimentological evidence (less waterlogged conditions). The origin of *Cathaya*, *Pinus*, and *Cedrus* pollen is attributed to the closer middle altitude mountain belt; *Tsuga* is not a significant component. Among microthermic conifers *Picea* is subordinated to *Abies*; they are especially present in correspondence of the lacustrine lithofacies at the bottom of the core otherwise usually strongly reduced. The increase of *Cathaya*, the appearance, though with scanty pollen grains, of *Sciadopitys* and the concomitant decrease of *Taxodium* type and of the broad-leaved mixed forest elements in the upper portion of S2 was related to a cooling trend (Simonetti, 1998). If not climate-induced such change in proportion of the plant assemblages could rather be related to a major lake level increase, which in its turn determines an over-representation of bisaccate pollen grains and the flooding of the wetland vegetation. Herbaceous elements, always in low quantities, consist in large part of hydrophytes such as *Typha latifolia*, *Spar-*

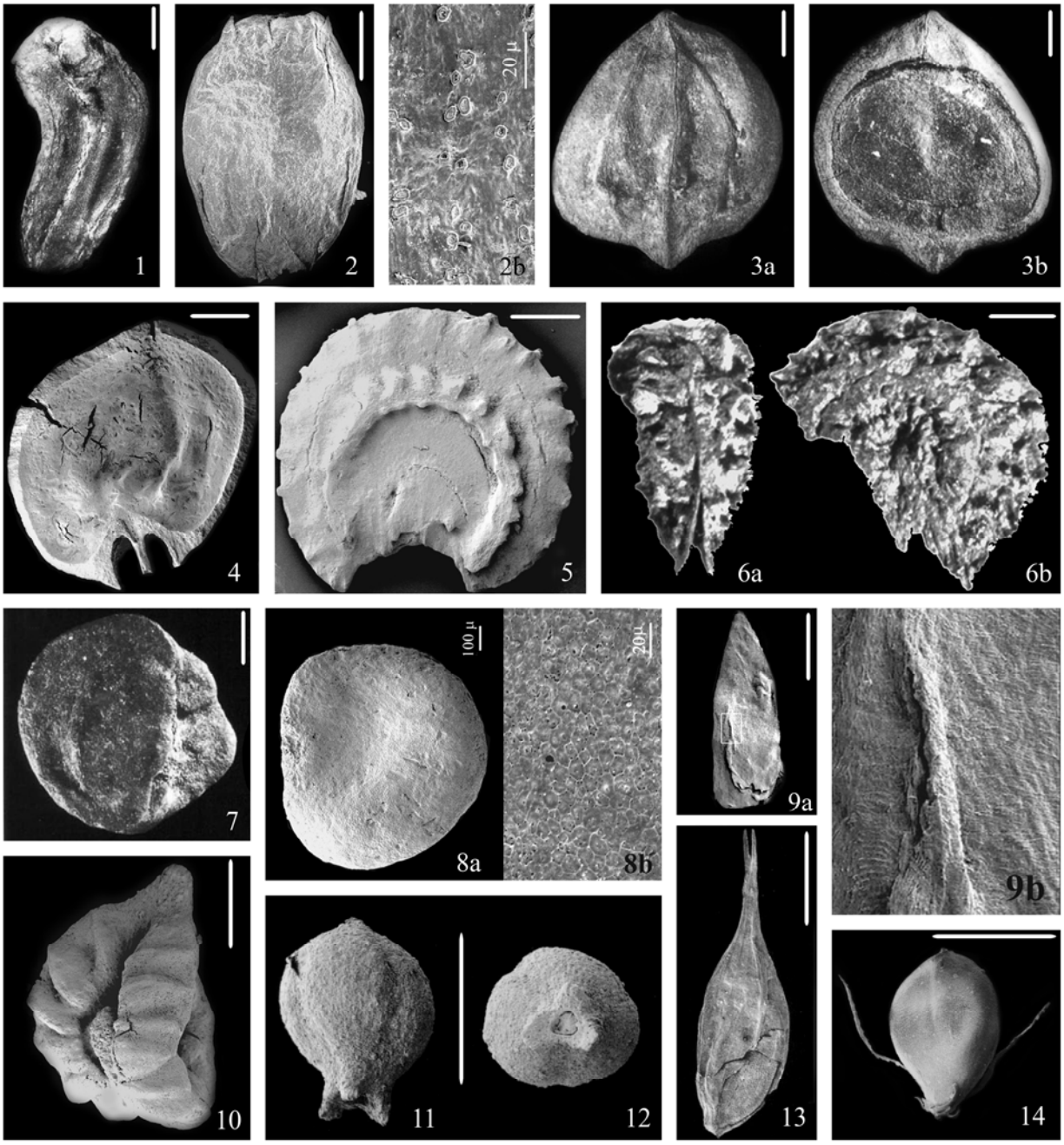


Plate I - Fossil fruits and seeds (apart *Tetraclinis*) from the Dunarobba sites (Road, Lignite, Forest and DC sections): 1) *Glyptostrobus europaeus*, seed; 2) *Tetraclinis salicornioides*, shoot article with detail of the stomata (2b) at the SEM; 3) *Cornus* aff. *amomum*, endocarp from both sides, showing one of the 2 seed locules and internal septum (3b); 4) *Magnolia allasoniae*, internal view of a seed; 5) *Sinomenium cantalense*, endocarp; 6) *Cyclea palatinati-bavariae*, endocarp fragment in two views; 7) *Meliosma wetteraviensis*, small endocarp; 8) *Ficus potentilloides*: 8a, endocarp morphology; 8b, detail of cells; 9) *Cephalanthus dorofeevi*: 9a, endocarp morphology; 9b, detail of the surface with striation; 10) *Ampelopsis ludwigii*, seed; 11, 12) *Cladium paleomariscus*, endocarps in lateral and basal views; 13) *Carex pseudocyperus*, utricle partly opened as to show the achene inside; 14) *Schoenoplectus isolepiodes*, achene with two bristles. Scale bar = 1 mm, when not differently indicated.

Site: **Dunarobba**				**Section**	Road	DC (New Quarry)				
				Sample labels in this work	DR1	DC1a	DC1b	DC2	DC3	DC4
				Labels in Martinetto (1996)	D7	/	DC1	DC2	DC3	DC4
				Labels in CENOFITA	DU7	DU20		DU23	DU21	DU25
Age: Late Pliocene or Early Pleistocene, ca. 3.5-1.5 Ma					A4I	B1L	A3T	A4G	A4H	A4F
				Volume analysed (dm^3)	?	8	20	4	5	3
Taxa	**e/n**	**hab**	**a/h/m**	**NLRs distribution**	%	%	%	%	%	%
Acer sp.	n	t	m/h	Holarctic		2				
Actinidia faveolata C. et E.M. Reid	e	c	m	Est Asia		0				
Ajuga antiqua C. et E.M. Reid	n	h	m	Holarctic		2		2		
Alangium sp.	e	t	m	SE Asia-NE America			1	0		
Alisma sp.	n	h	h	cosmopolitan			1			
Ampelopsis ludwigii (A. Braun) Mai	e	c	m	SE Asia-N America	1	0	5		0	
Apiaceae	n	h	m	cosmopolitan				0		
Araliaceae	n	s	m	cosmopolitan				0		
Carex cf. *flagellata* C. et E.M. Reid	n	h	h	cosmopolitan		0				
Carpinus betulus L.	n	t	m	Europe and W Asia		10	5			
Carpolithes minimus (Szafer) Mai				cosmopolitan		0	1	1		
Chamaecyparis sp.	e	t	m/h	E Asia-N America		1	1	0		
Cryptomeria rhenana Kilpper	e	t	m	E Asia		10	17			
Cyclea palatinati-bavariae Gregor	e	c	m	pantropical-S Palearctic	0	2				
Cyperus sp.	n	h	h	cosmopolitan				9		
Eleocharis sp.	n	h	h	cosmopolitan				0		
Euphorbia sp.	n	h/s	h	cosmopolitan		0				
Eurya stigmosa (Ludwig) Mai	e	s	m	E Asia and Indonesia		3	1			
Fagus sp. (cup.)	n	t	m	Holarctic			1			
Hamamelidoideae	e	s/t	m	Asia, Indonesia and Madagascar			1			
Liquidambar cf. *europaea* Al. Braun	n	t	m	SE and W Asia, America		0				
Liriodendron geminata Kirchheimer	e	t	m	E Asia-NE America		1	1			
Litsea sonntagii Gregor	e	t	m	E Asia-NE America	72	0	5	0		
Lobelia pliocenica (Dorofeev) Mai	e	h	h	Holarctic				0		
Magnolia cf. *ludwigii* Ettingshausen	e	t	m	E Asia-NE America		1				
Mahonia staphyleaeformis Mai et Walther	e	s	m	E Asia-NE America		1			0	
Meliosoma canavesana Martinetto	e	t	m	Asia, Indonesia, central America			1			
Melissa elegans E.M. Reid	e	h	m	Holarctic				0		
Morus germanica Mai	?n	t	m	E Asia		1	1			16
Myrica sp.	e	s	h	Holarctic				0		
Ocotea sp.	e	t	m	Macaronesia-S America			0			
Olea sp.	n	t	m	Asia-Mediterranean		0				
Origanum cf. *vulgare* L.	n	h	m	Holarctic				0		
Phytolacca salsoloides Martinetto	e	s	m	E Asia			0			
Pinus	n	t	m	cosmopolitan					0	
Platanus sp.	n	t	m/h	S Holarctic		1				
Poaceae indet. (stem)	n	h	m/h	cosmopolitan					1	
Quercus spp. (cupule)	n	t	m	Holarctic			1	0	0	
Sabia europaea Czeczott et Skirgiello	e	c	m	SE Asia		1	1			
Sambucus pulchella	n	s	m	cosmopolitan		3		0		0
Sambucus sp.	n	s	m	Holarctic			2			
Sassafras ludwigii Mai	e	t	m	E Asia-NE America		1	2		0	
Scirpus cf. *radicans* Schkuhr	n	h	h	cosmopolitan				0		
Scirpus sp.	n	h	h	cosmopolitan			2			
Selaginella gr. *pliocenica* Dorofeev	n	h	m	cosmopolitan			1	1		
Sequoia abietina (Brongniart) Knobloch	e	t	m	California and Oregon					1	
Sinomenium cantalense (E.M. Reid) Dorofeev	e	c	m	E Asia		11	7			0
Sparganium nanum Dorofeev	n	h	h	cosmopolitan	8	6	6	1	0	1
Stemona germanica Mai	e	c	m	E Asia		1	1			
Sympolocos casparyi Ludwig	e	t/s	m	SE Asia, cemtral and NE America		3	1			
Ternostroermia reniformis (Chandler) Mai	e	t/s	m	SE Asia, cemtral and NE America		1				
Tetraclinis salicornioides (Unger) Kvacek	n	t/s	m	Mediterranean		4	2		6	
Toddalia latisiliquata (Ludwig) Gregor	e	c	m	Africa and SE Asia			1			0
Toddalia rhenana Gregor	e	c	m	Africa and SE Asia		3	3		0	
Verbena sp.	n	h	m	cosmopolitan				1		
Zanthoxylum ailanthiforme (Gregor) Gregor	e	t	m	SE Asia- central America		0	2			
Nr. specimens					**139**	**229**	**103**	**310**	**442**	**282**

Tab. 2 - List of fruit and seed taxa detected only in the samples of the Road and DC sections of Dunarobba. See Tab. 1 for explanation.

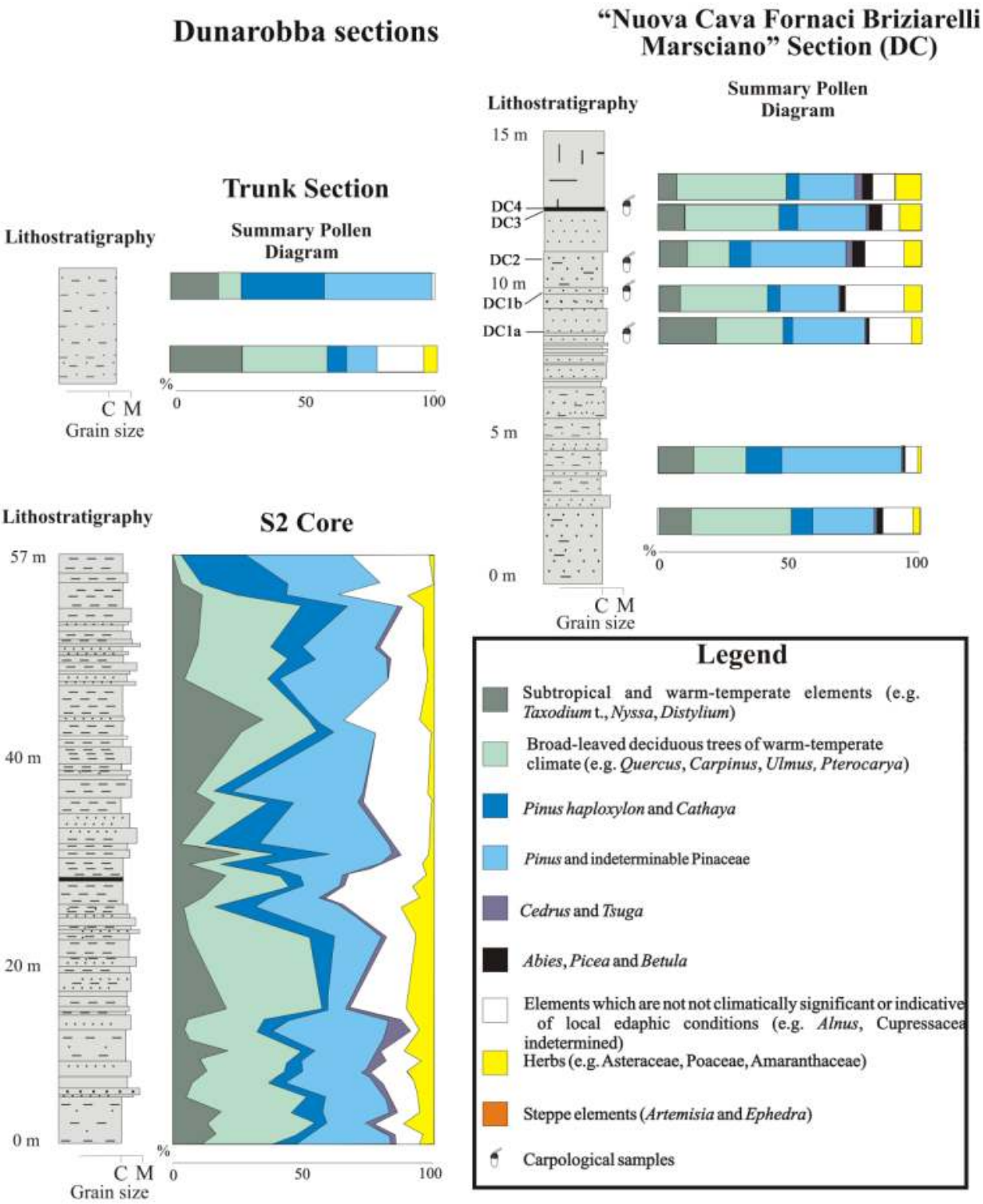


Fig. 18 - Summary pollen diagrams of three sections sampled at Dunarobba, Fosso Bianco Unit (modified from Simonetti, 1998). Steppe elements are represented by *Artemisia*, but they do not figure out in the diagram due to the very low percentage. Sediment grain size: C, clay; M, medium sand.

ganium, *Potamogeton*, Poaceae (p.p.). Abundant spores of Pteridophyta (Polypodiaceae, Osmundaceae) were also detected.

Trunk Section

The stratigraphically lower pollen spectrum from the Trunk Section is dominated by *Taxodium* type and broad-leaved mixed forest elements, whereas Pinaceae are strongly reduced. On the other hand the Pinaceae are frequent in the upper pollen spectrum of this section (clay inglobing the trunk). This second spectrum shows very few non arboreal taxa, and the highest percentanges are reached by *Pinus* (including the *haploxylon* type). The discrepancies detected in the two samples suggest a considerable taphonomical bias, so that the discussion of the pollen results will be mostly based on the several S2 Core samples.

A previous analysis by Meneghini & Paganelli (1994), carried out on a 350 cm thick part of the Forest Section, is similar to the lower spectrum of the Trunk Section, even if the frequent "Taxodiaceae" pollen (11-34%) has been mainly attributed to *Sequoia* type. The floristic list included also some other taxa such as: *Sciadopitys*, *Taxodium* type, *Celtis*, *Eucommia*, *Tsuga*, Juglandaceae.

"Nuova Cava Fornaci Briziarelli Marsciano" Section (DC)

Pinaceae are largely present with *Pinus* reaching the maximum value of 42.5 % at ca. 4 m, in this position also *Cathaya* shows an increase up to ca. 8%. *Taxodium* type is constantly present with the higher values (ca. 18%) at 8.4 m. *Sequoia* type is scanty. Broad-leaved deciduous forest taxa are principally represented by *Quercus,* which reaches a maximum (20%) at 13.3 m. *Ulmus*, *Carya* and *Pterocarya* follow. *Alnus* shows several fluctuations never depassing 5.4%. Meso - to microthermic conifers are usually present in low percentages (e.g. *Cedrus* and *Tsuga*), even if *Abies* shows a good increase toward the top of the section at 12.8 m reaching values up to 4%. Herbaceous elements are principally represented by Poaceae and Asteraceae. Brassicaceae follow.

6. THE PIETRAFITTA FOSSIL SITE

6.1. History of the discovery and fossil heritage preservation

Since the 1860s there have been news regarding the presence of the lignite deposit in Pietrafitta. In a document dated 1862, a project mentioned Pietrafitta as a possible place for lignite exploitation (Ambrosetti, 1992b). It is quite possible that lignite was since long time exploited by the population at a non-industrial level, as fuel for domestic use and for local manufacturing companies, thanks to the presence of a number of accessible outcrops (Ambrosetti, 1992b). These moderate excavation activities, between the second half of the 19th century and the first decades of the 20th century, lead to the discovery of the first fossil vertebrate remains, which are now scattered in numerous European museum collections. In the open-cast mine of Pietrafitta,

Fig. 19 - The Pietrafitta lignite seam in the Poderone outcrop, year 1994. An unpublished stratigraphic section measured in the year 1994 is shown to the left, also reporting the position of the fruit and seed assemblages PF1 and PF2. The white objects at the bottom of the picture indicate the PF1 layer. Sediment type: C, clay; L, lignite.

the industrial production of lignite started in the early 20th century, but assumed a significant role, on both a local and national level, essentially in correspondence with the two World Wars, and particularly with the inauguration of the ENEL (the National Electricity Corporation) thermo-electric power-plant in 1959, situated near the lignite deposit (Ambrosetti, 1992b). In view of the poor quality of the lignite, the exploitation of the deposit in Pietrafitta, thanks to the limited depth of seam top, has always been carried out in the open air, both in the period of manual excavation, until 1923, and during the mechanization of lignite extraction from 1923 until the end of the 20th century.

The lignite seam of Pietrafitta (Fig. 19) had an extension approaching 200 hectares, with a slight slope and a thickness between 5 and 8.5 metres. The sediments capping the lignite seam consisted of sand, clay and silt with a thickness varying between 5 to 8 metres.

It the year 1966 Mr. Luigi Boldrini (friendly known as *Gigino*), an assistant head miner and shift-worker, while systematically and continuously inspecting the excavations of the lignite deposit, began to set up the first palaeontological collection of Pietrafitta (Gentili et al., 2000a). In 1930, at the early age of 14, Luigi Boldrini began working in the mine. This miner "lover of palaeontology" (Sorbini, 1990) spent more than 55 years hunting for fossils in the lignite mines of Pietrafitta, both as an employee and later as a pensioner. Although fossils were mostly recovered through simple techniques, *Gigino*'s strong passion permitted to build up the bases of the present day impressive collection. He dug up tonnes of lignite, with axes and chisels, thus rescuing hundreds of plant and animal fossil remains from being damaged by the large excavating machines. The findings were kept partly in the mine and partly in *Gigino*'s home. People like Boldrini call to mind the fossil hunters of past centuries whose collections laid the basis for the most important museums in Europe (Findlen, 1977; Sorbini, 1990).

It was only in the 1980s that the ENEL company and the Archaeological Survey for Umbria, with the scientific support of the University of Perugia, under the direction of Prof. Pierluigi Ambrosetti and Prof. Lucilia Gregori of the Department of Earth Sciences, began the systematic collection and conservation of the fossil findings. The Archaeological Survey for Umbria delegated the task of conservation and maintenance of the fossils to the ENEL company, while the University of Perugia was entrusted with overseeing the operations of research, excavation, recovery and archiving of the specimens. This is how the palaeontological importance of Pietrafitta was at last recognized "only" 20 years after Luigi Boldrini's intuition.

The direct intervention of the ENEL and the University led to a significant increase in the number and diversity of fossils retrieved (for instance, traces and remains of insects: Odonata, Diptera, Coleoptera, Lepidoptera, Neuroptera).

The Pietrafitta deposit is characterized in particular by:

- a great abundance and diversity of fossils, with over two thousand specimens in the collections (Gentili, 1991);
- macro- and micro-mammal species occurring together in the same lignite levels (Gentili et al., 1996);
- fossils in a good state of preservation even in the small morphological details, although they were affected by fragile-type deformation (Ambrosetti et al., 1992a);
- lignite deposits accumulating over a short time span, perhaps no longer than 40,000 years (Martini, personal communication);
- the possibility of a rapid recovery of large mammals, whose fossil skeletons have been extracted *en bloc* together with a part of the embedding lignite (Ambrosetti et al., 1987, 1993).

To give an idea of the richness of the palaeontological site it is enough to mention that in three years (from 1989 to 1991), from the "Poderone" mine alone, over 1200 vertebrate skeletal elements were recovered and identified (Gentili, 1991).

Actually, this collection can be considered as one of the most important in the Quaternary of Europe (Gentili et al., 1997; Zucchetta et al., 2003; Petronio et al., 2005).

At the end of the 1980s the scientific community was informed for the first time about the idea of establishing a palaeontological museum at Pietrafitta (Ambrosetti et al., 1987b). Finally, thanks also to the great work of project coordination carried out over the past few years by the Archaeological Survey for Umbria, and in particular thanks to Dr. Maria Cristina De Angelis, *Gigino*'s dream has come true and the Palaeontological Museum "Luigi Boldrini" was set up near the town of Pietrafitta and opened to the public in 2010. Certainly, this was made possible thanks to the contribution of the Community of Pietrafitta, which, in recent years, has continuously identified itself with its palaeontological heritage (Gentili et al., 2000a, b).

Nowadays, the educational itineraries carried out in the exhibition areas of the Museum allow visitors to have a direct, not just virtual, experience with the problems regarding the strategies and methods for the study and reconstruction of past environment and life, in particular by analysing the taphonomic data. Thus, the Museum offers a view of palaeobiology "in the field", inserted into the social and cultural context of the Pietrafitta area (Gentili et al., 2003).

6.2 Stratigraphy and previous palaeoenvironmental interpretations

As reported above, the fossil assemblages discussed in this paper originate from the Pietrafitta subsynthem, whose primary thickness was about 30 m. The Pietrafitta subsynthem is in angular unconformity on the underlying Fontignano unit (Pazzaglia, 2007; Argenti et al., 2013), and it is poorly visible today because most of it was removed during the cultivation of lignite, and the remaining part is covered by backfill, or is hidden below the artificial "Pietrafitta Lake". Currently, the only outcrop is located in "Poderone", the last mining site in the 1990s (Fig. 19), before the abandonment of the quarries and the reconversion of the power station. The geometry of the lignite seam was reconstructed in the 1960s thanks to a series of perforations and geoelectric analy-

ses (Pazzaglia, 2007). It had a thickness varying between 6 and 12 m and was located at a maximum depth of 25 m below the ground level, mainly cropping out in the central part of the basin due to erosion of the cover (Pazzaglia, 2007). According to Ambrosetti et al. (1987b), lignites belonging to the Pietrafitta subsynthem mainly consist of herbaceous remains of Cyperaceae and Poaceae deposited *in situ*, with no evidence of neither transport nor root remains. Rare logs, up to 10-15 m long, strongly compressed due to the sediment load, were found especially in the area of "Poderone". According to the facies analysis, Ambrosetti et al. (1992a) referred the lignite deposits to a marshy area with abundant organic production. The marsh was probably located on the edge of a lake with fine clastic sedimentation (Conti & Girotti, 1978; Ambrosetti et al., 1987b). Lignite is intermingled with thin layers of organic clay bearing intraformational clasts, freshwater molluscs (Ambrosetti et al., 1992a) and oligohaline ostracods (Gliozzi et al., 1997), which may have been produced by high-energy events, such as storms, which remobilized the sediment of the lake bottom towards the marginal swamp (Pazzaglia, 2007).

6.3. The Early Pleistocene vertebrates of Pietrafitta

The remains from Pietrafitta constitute the richest collection of fossil vertebrates in the Umbria Region as well as the most important Italian local faunal assemblage referred to the Farneta Faunal Unit (Late Villafranchian; about 1.5 Ma). Most of the collection comes from the stratigraphic interval shown in Fig. 19 and is formed by macro- and, secondly, micromammals. Additionally, the discovery of a considerable number of interesting - although often fragmentary - skeletal remains of bony fishes, amphibians, reptiles and birds is noteworthy.

The fish remains are represented by isolated bones, pharyngeal teeth and few articulated skeletons preliminarily referred to the genera *Tinca*, *Scardinius* and *Leuciscus* (family Cyprinidae; Corvetti, 2004).

The 89 amphibian skeletal elements are attributed to two Anura taxa: *Latonia* cf. *L. regei* and *Rana* ex gr. *R. ridibunda* (Delfino et al., 2004). The large frog *Latonia* appears in the Oligocene of France and is quite abundant in the European Neogene, whereas today is represented by a single species living in Israel (Biton et al., 2013). The report from Pietrafitta is the last occurrence of this genus in Europe.

Reptile remains are very rare at Pietrafitta, but at least four taxa are recognized: three snakes (*Vipera* cf. *V. ammodytes*, *Natrix* sp. and Colubrines indet.; Delfino et al., 2004) and the European pond turtle *Emys orbicularis* (Kotsakis & Gregori, 1985). The latter species is represented by a number of well-preserved carapaces and plastrons and testifies the presence of a shallow, clear freshwater palaeoenvironment.

About one hundred of postcranial bones and bone fragments are referred to nine bird taxa: *Podiceps* sp., *Phalacrocorax* sp., cf. *Ixobrychus*, *Cygnus* sp., *Anas* sp. (large size), *Anas crecca/querquedula*, *Aythya* sp., *Somateria* aff. *S. mollissima*, Rallidae indet., cf. *Gallus* (Zucchetta et al., 2003). This bird assemblage is one of the richest in the Early Pleistocene of Europe. It is composed mainly by aquatic taxa, but cf. *Gallus* is a true terrestrial form related to thick forest environments (Zucchetta et al., 2003).

The micromammals are poorly represented at Pietrafitta. A small insectivore (*Sorex* cf. *S. minutus*) and a lagomorph (*Oryctolagus* cf. *O. lacosti*) are reported (Argenti & Kotsakis, 2009). The arvicolid species *Mimomys pusillus*, *Microtus* (*Allophaiomys*) cf. *M.* (*A.*) *ruffoi* and *M.* (*A.*) *chalinei* (the latter represented by a single mandibular fragment) confirm the Late Villafranchian (i.e., Early Biharian) age of the site (Gentili et al., 1996). The abundant cranial and postcranial remains of a larger rodent are referred to *Castor fiber plicidens*, chronologically limited to the Tasso and Farneta Faunal Units (Barisone et al., 2006).

The rich sample of monkey skeletal remains (about 78 elements belonging to at least eight individuals) is attributed to *Macaca sylvanus florentina* (Gentili et al., 1998).

Carnivores are quite rare at Pietrafitta. Most of the specimens are referred to the medium-sized bear *Ursus etruscus*, whose morphology (especially in the teeth) shows a number of more derived characters than the specimens from older Italian Late Villafranchian sites, such as Olivola and Upper Valdarno (Rustioni & Mazza, 1993). The presumed occurrence of the felid *Panthera gombaszoegensis* needs to be confirmed by further studies. The carnivore assemblage is completed by the mustelid *Pannonictis nestii*, represented by isolated teeth, postcranial elements and a nearly complete cranium with associated mandible (Rook, 1995).

The Pietrafitta collection includes two partial skeletons and some isolated skeletal elements of a small-sized rhinoceros. Mazza et al. (1993) recognize some tooth similarities with *Stephanorhinus etruscus*, while the analysis of the postcranial material highlights strong affinities with *S. hundsheimensis*. Because of the absence of well-preserved cranial remains, the authors refer the material to *Stephanorhinus* cf. *S. hundsheimensis*.

The artiodactyl sample from Pietrafitta is mostly constituted by a medium-sized bovid belonging to the Plio-Pleistocene genus *Leptobos*. The overall morphology of the skull and teeth is similar to that of *L. vallisarni* from the Upper Valdarno and Val di Chiana, but some differences in the horn cores and the absence of a sufficiently-complete comparative sample among the Tuscan collections bring Gentili & Masini (2003) to refer the material to *Leptobos* aff. *L. vallisarni*.

Two cervid species are recorded at Pietrafitta: the medium-sized *Pseudodama farnetensis* and the very large *Praemegaceros obscurus*, both represented by well-preserved cranial and postcranial remains. A nearly complete cranium with articulated antlers of a sub-adult *P. obscurus* is one of the most remarkable specimens in the collection. Azzaroli & Mazza (1993) report a third taxon, *Eucladoceros* sp., whose actual occurrence needs to be confirmed.

Finally, the sample of *Mammuthus meridionalis* from Pietrafitta is one of the richest in Italy. In the light of the supposed chronologic correspondence between the Pietrafitta local fauna and those from Farneta (Val di Chiana) and Scoppito (L'Aquila), the Pietrafitta elephantid has been often referred to the derived *M. meridion-*

Fig. 20 - Possible fern rhizomes photographed in the Pietrafitta lignite.

Fig. 21 - Fruits of *Trapa* cf. *natans* extracted from layer PF1, below the Pietrafitta lignite seam. Scale 1 cm.

alis vestinus. However, this subspecific attribution cannot be confirmed because of the lack of complete crania (Ferretti, 1999 and references therein). On the contrary, the abundant molars from Pietrafitta do not show significant differences with those of *M. meridionalis meridionalis* from the Upper Valdarno (Ferretti, 1999).

6.4. Macropalaeobotanical data for the Pietrafitta succession

A general survey of the plant macrofossil content of the whole lignite-bearing succession of Pietrafitta, exposed for a thickness of 9.5 m, was carried out in the field during the year 1994. These observations showed that most lignite layers were made up by massive fine-grained (humified?) plant material, and morphologically identifiable plant remains, e.g. angiosperm leaves or fern axes (Fig. 20), were restricted to a few layers. Very few fruits and seeds were directly visible in the field, and most of these were concentrated in a precise layer characterised by high clay content (PF1), laying 4.5 m below the base of the main lignite seam. The largest fruits (Fig. 21) can be assigned to *Trapa* cf. *natans* (a species of the modern Italian flora), as suggested by a preliminary analysis of the material by J. Wojcicki. Conversely, other

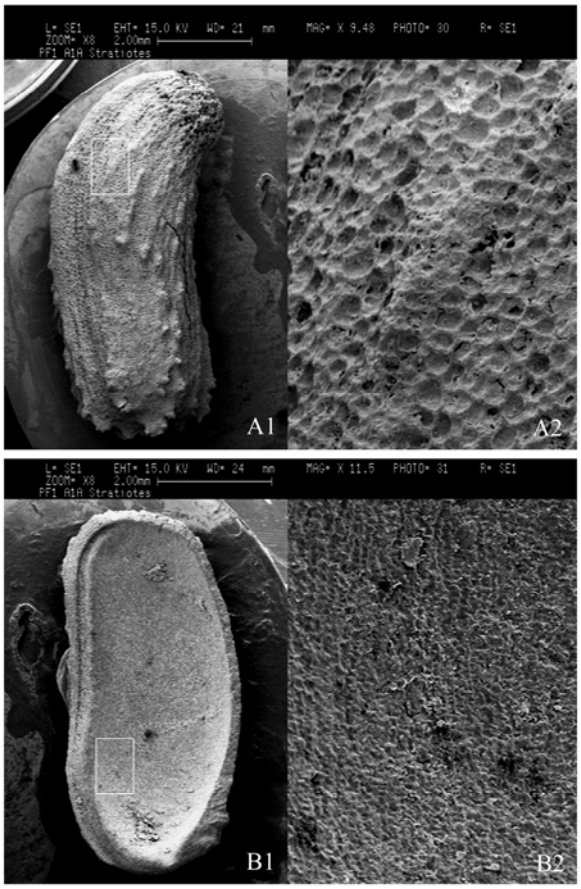


Fig. 22 - Seeds of *Statiotes* cf. *intermedius* extracted from layer PF1, at the base of the Pietrafitta Section. A1) Seed in external view; A2) detail of the cells on the outer surface; B1) Seed in internal view; B2) detail of the cells on the inner surface.

Fig. 23 - Leaves from the Pietrafitta mine, Boldrini collection, most probably originating from the silty-sandy layers above the lignite seam. All the specimens can be assigned to *Quercus*, and that indicated by the arrow to *Q.* cf. *cerris*.

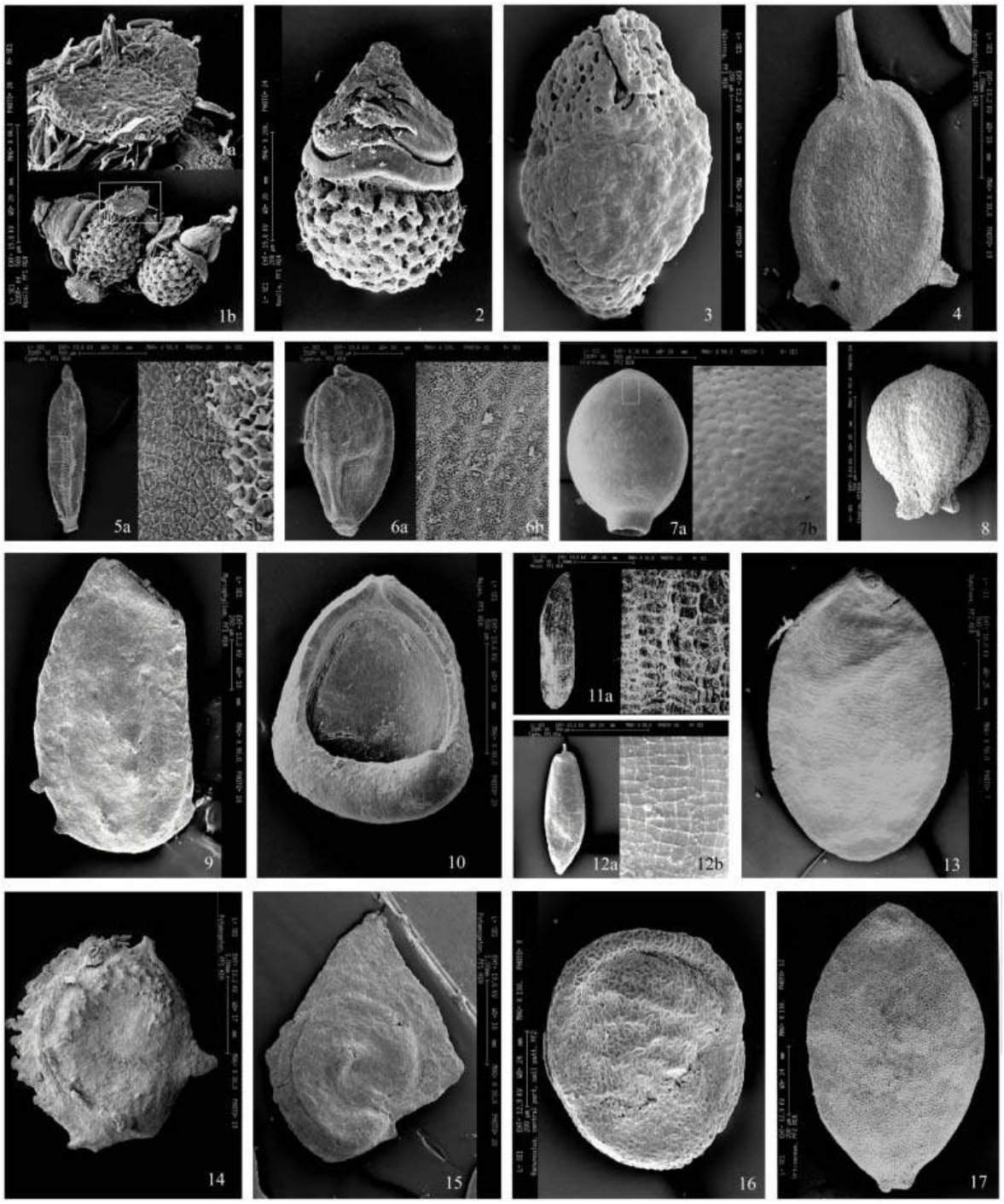


Plate II - Fossil megaspores, fruits, and seeds from the Pietrafitta site: 1, 2) *Azolla filiculoides*: 1a, microspore from a group (massula) including also 2 megaspores; 1b, general view of the massula; 2, isolated megaspore; 3, *Salvinia* cf. *natans*, megaspore; 4) *Ceratophyllum demersum*, fruit; 5) *Cyperus glomeratoides*: 5a, achene morphology; 5b, detail of the epidermal cells; 6) *Cyperus* cf. *longus*: 6a, achene morphology; 6b, detail of the epidermal cells; 7) *Aldrovanda* cf. *zussii* T. V. Jakub.: 7a, seed morphology; 7b, detail of the epidermal cells; 8) *Cladium mariscus*, endocarp; 9) *Myriophyllum spicatum*, endocarp in lateral view; 10) *Decodon globosus*, seed which has lost the germination valve, seen in ventral view; 11) *Najas minor*: 11a, seed morphology; 11b, detail of the epidermal cells; 12) *Typha* cf. *latifolia*: 12a, seed morphology; 12b, detail of the epidermal cells; 13) *Nymphaea borysthenica* Dorofeev, compressed seed; 14) *Potamogeton pannosus* Dorofeev, fruits with apparent remains of the exocarp, such as the flanges on the dorsal side, covering the endocarp; 15) *Potamogeton* cf. *crispus,* complete fruit which distinctly shows the outline of the endocarp; 16) *Ranunculus sceleratus*, fruit; 17) *Urtica dioica*, seed. Length of the scale bar reported for each specimen.

Site: **Pietrafitta**				**Bed**	**PF0**	**PF1**	**PF1**	**PF2**
Age: Early Pleistocene, Calabrian, ca. 1.5-1.3 Ma				**Sample label**	/	**A1A**	**A8W**	**A1B**
				Volume analysed (dm^3)	**0**	**2**	**0.1**	**0.5**
Taxa	**e/n**	**hab.**	**a/h/m**	**NLRs distribution**		**%**	**%**	**%**
Aldrovanda cf. *zussii* T.V. Jakub.	n	h	a	sub-cosmopolitan		0		5
Sium cf. *latifolium*	n	h	h	Europe		0		
Apiaceae indet.	n	h	/	cosmopolitan		0		
Azolla filiculoides Lam.	e	h	a	America		0	32	55
Carex cf. *elata* All.	n	h	h	Eurasia	0			
Carex cf. *panicea* L.	n	h	h	Eurasia	0			
Carex pseudocyperus L.	n	h	h	sub-cosmopolitan		1	1	0
Carex sp.	n	h	h	cosmopolitan		0		
Ceratophyllum demersum L.	n	h	a	cosmopolitan		4		3
Characeae	n	h	a	cosmopolitan		2		
Cladium mariscus (L.) Pohl.	n	h	h	cosmopolitan		3	1	
Cyperus glomeratoides Veichkievich et Zast.	n	h	h	palaeosubtropical		10		
Cyperus longus L.	n	h	h	palaeotemperate		4		
Decodon globosus (E. M. Reid) Nikitin	e	h	h	NE America		12	39	8
Euryale (?) *nodulosa* C. et E.M. Reid	e	h	a	E Asia		0		
Lemna sp.	n	h	a	cosmopolitan		0		0
Lycopus cf. *exaltatatus* L.	n	h	h	Eurasia		0		
Mentha cf. *aquatica* L.	n	h	h	cosmopolitan		0		
Myriophyllum spicatum L.	n	h	a	sub-cosmopolitan		2		
Najas marina L.	n	h	a	cosmopolitan		24	5	1
Najas minor L.	n	h	a	palaeotemperate		8	5	
Nymphaea borysthenica Doroveev	n	h	a	Eurasia		5	1	15
Oenanthe cf. *aquatica* L.	n	h	a	Eurasia		1		3
Poaceae indet.	n	h	h	cosmopolitan		0		
Potamogeton cf. *crispus* L.	n	h	a	cosmopolitan		5		
Potamogeton pannosus Dorofeev	n	h	a	cosmopolitan		1		
Potamogeton ?	n	h	a	cosmopolitan		0		
Ranunculus sceleratus L.	n	h	h	palaeotemperate		5		
Rubus sp.	n	h	h/m	cosmopolitan		0		
Salvinia cf. *natans* L.	n	h	a	Eurasia		1		1
Schoenoplectus tabernaemontani (Gmel.) Pal	n	h	a/h	cosmopolitan		0		
Stratiotes cf. *intermedius* Hartz	n	h	a	Eurasia		6	1	
Typha cf. *latifolia* L.	n	h	a/h	cosmopolitan		3	13	4
Trapa cf. *natans* L.	n	h	a	cosmopolitan		0		
Urtica dioica L.	n	h	h/m	cosmopolitan				4
Vitis vinifera L. ssp. *sylvestris* Gmelin	n	h	m	Mediterranean		0		
Total nr. specimens					/	**300**	**77**	**271**

Tab. 3 - List of fruit and seed taxa detected in four samples of the Pietrafitta Section. See Fig. 19 for the stratigraphic position of samples PF1 and PF2. The precise position of PF0 is unknown, but it falls definitely within the main lignite seam. See Tab. 1 for explanation of abbreviations.

two forms of cm-sized seeds, observed in the field in the same layer (PF1), represent extinct species: *Stratiotes* cf. *intermedius* (Fig. 22) and *Euryale(?) nodulosa* [the question mark after the generic name expresses the possible assignment of this species to the extinct genus *Pseudoeuryale* Dorofeev].

The analysis of bulk sediment samples from the *Trapa*-bearing bed (PF1), and from another layer (PF2), located ca. 5 m above PF1, at the base of the main lignite seam, evidenced fossil fruit and seed assemblages which testify for the occurrence of consistently diverse palaeocommunities of freshwater macrophytes in the Early Pleistocene lake. A sample collected from an uknown position (PF0) is just mentioned here because of the occurrence of *Carex* cf. *elata*, a species with possible biochronologic relevance (Martinetto et al., 2012, in press). The precise determination allowed by the morphological characterisation of fruits and seeds provided a good taxonomic framing of the lacustrine palaeoflora (Plate II). At the state of the art, 23 species have been identified (Tab. 3), and 15 of them represent plants still growing in Italy today. Other 8 species are believed to represent extinct plants, and 2 of them belong to genera (*Azolla, Decodon*) which are absent in the European native flora of the Holocene, even if their fossil remains are reported in Middle Pleistocene inter-

glacial sediments (Velichkevich & Zastawniak, 2006, 2008).

Most of the Pietrafitta species were already reported for several Early Pleistocene localities of central and/or Eastern Europe, but a few ones were previously recorded only in East European localities. For example, the perfectly preserved seeds of *Aldrovanda*, an aquatic genus with a single living species (which is now strongly endangered in Italy), share all of the diagnostic characters with *A. zussii* T. V. Jakub. (Plate II, 7), an extinct species whose seeds were found in a single Pleistocene locality of Belarus (Velichkevich & Zastawniak, 2008). The occurrence of plant species with East-European affinity had been already pointed out for the Early Pleistocene of Northeastern Italy (Martinetto et al., 2012).

The non-aquatic plants are represented in the Pietrafitta assemblages by a few taxa which produce wind- or animal- transported fruits (e.g. *Vitis* sp.). These findings are too scarce and do not contribute to the reconstruction of the ancient mesic vegetation growing around the depositional basin, which is documented by pollen assemblages.

Plant macrofossils originating from mesic communities were definitely present within silty layers covering the brown coal, which unfortunately never underwent a detailed macropalaeobotanical study. These contained angiosperm leaves, as proved by a few samples of this material, preserved in the Boldrini collection (Fig. 23), showing irregularly and acutely-lobed lanceolate leaves, which we assign to *Quercus* cf. *cerris*.

6.5. Palynology

The Pietrafitta lignite-bearing succession has been submitted to palynological studies since 1961, when Ricciardi published the first data which concentrated especially on clay overlying the lignite seam. However some samples were also collected from the lignites as well as at the top of the underlying clay. The author pointed out the rarity of *Pinus haploxylon* type, the absence of *Picea orientalis* type and the sporadic occurrence of *Fagus*. On the other hand *Carya* was abundant as well as *Quercus*; *Ulmus*, *Pterocarya*, *Zelkova*, *Tsuga*, *Corylus* followed. *Liquidambar* was exceptionally abundant, but not in the lignites, which were associated to cooler and moister conditions. The increase of *Abies alba* just at the top of the section was related to a climate change towards oceanic conditions by Ricciardi (1961).

The palynological contribution of Paganelli & Solazzi (1962) was carried out on a 16.50 m thick section below a sandy pebble stratum, including 8.10 m of clay, a lignite bank (approx 7.50 m thick) and about 1 m of humic clay rich in shells of molluscs.

Later Lona & Bertoldi (1972) carried out a study on an outcrop including the lignite bank; the underlying clay was drilled and studied in core. In Fig. 24 the original pollen plates of Lona & Bertoldi (1972) are reported. Seven main pollen zones were described in the pollen diagram (Fig. 25), which is split into two main parts by the strong and drastic reduction of "Taxodiaceae".

The lower part of the Pietrafitta pollen record shows, in fact, a constant occurrence of "Taxodiaceae", but also Pinaceae, followed by *Liquidambar*, Magnoliaceae, *Castanea*, Sapotaceae, Celastraceae, Podocarpaceae, Ginkgoaceae, Arecaceae. The upper part includes *Pinus*, *Abies*, *Picea*, *Tsuga*, Juglandaceae, Ulmaceae, *Eucommia*, Betulaceae, Aracaceae. Moreover, the components of the so-called *Quercetum* and *Carietum* are quite abundant.

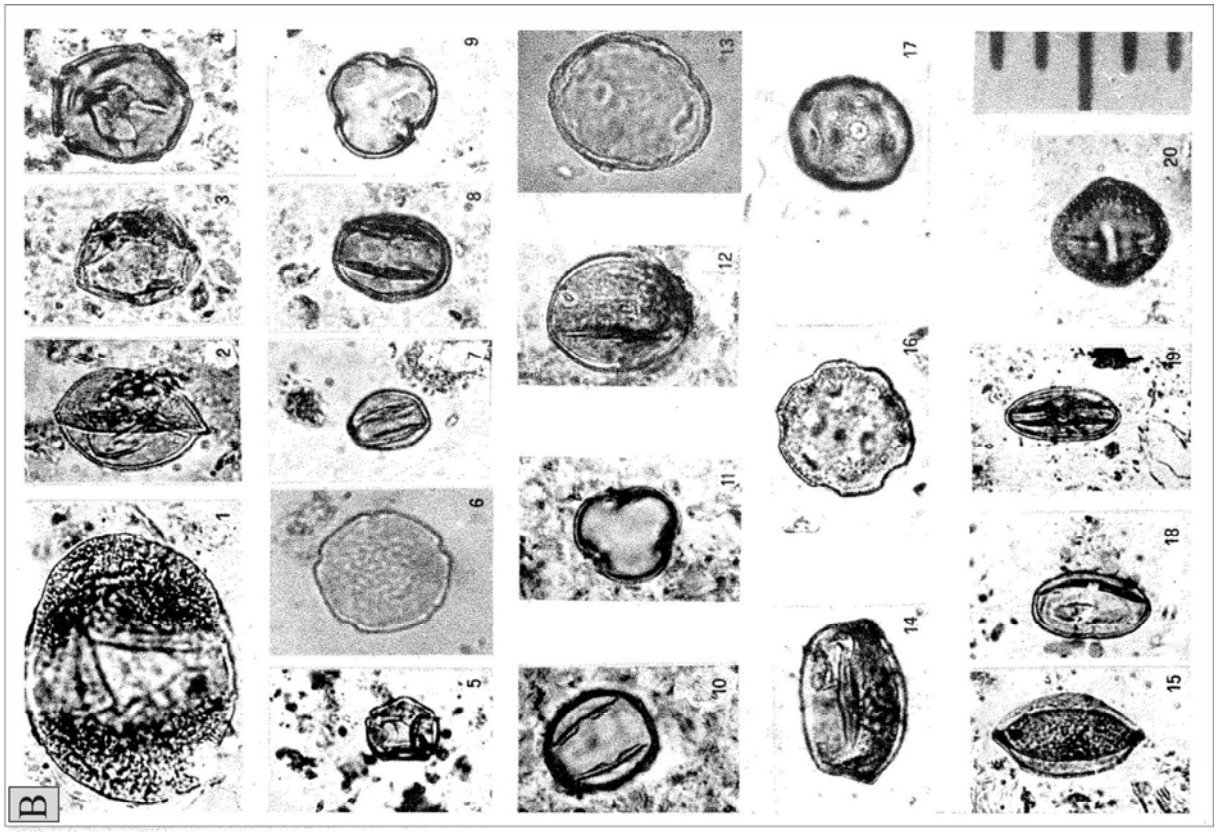
Herbaceous plants show successive phases of increase of *Artemisia* and other Asteraceae, *Ephedra*, Amaranthaceae, Poaceae, Caryophyllaceae, etc.

The boundary between the lower and upper part of the pollen diagram was named "Tiberian boundary" and correlated with the central European "Taxodiaceae" disappearance event. The Tiberian boundary was also described in marine deposits, i.e at Stirone (Lona et al., 1969; Lona & Bertoldi, 1972) and Le Castella (Bertoldi, 1977). However, further evidence (see Bertini, 2010 and references therein) demonstrated: 1. the recurrent sudden falls in the pollen percentages of "Taxodiaceae" throughout the Gelasian; and 2. the persistence of "Taxodiaceae" after 1.8 Ma in many Italian sites.

7. DISCUSSION

The plant record of the two main fossil sites of Pietrafitta and Dunarobba, with the addition of Cava Toppetti I and II, Fosso Bianco, Torre Picchio and Villa San Faustino sections, provide us with a good glimpse on the central Italian palaeoenvironments. Dunarobba is one of the few sites in the world yielding upright trunks in a mummified fossil forest. Other famous examples, apart Bukkabrany (in Hungary, 7.7-6.3 Ma: Kàzmér, 2008; Csaszar et al., 2009; Erdei et al., 2009; Gryc & Sakala, 2010; Erdei & Magyari, 2011), bear definitely shorter trunks, for example in the Arctic region of Canada (Axel Heiberg Island, about 45-40 Ma: Bigras et al., 1995; Williams et al., 2008), and in NW Italy (Stura di Lanzo Fossil Forest, ca. 3.0 Ma: Martinetto et al., 2007; Vassio et al., 2008). Yet, the Dunarobba site is unique, not only for the presence of the Dunarobba Fossil Forest, but also for having provided the highest number of fruit and seed species so-far detected in the Pliocene-Early Pleistocene of the Italian Peninsula. Thus, the palaeocarpological dataset here consistently integrates the pollen record, available for many other sites (Lona & Bertoldi, 1972; Urban et al., 1983; Pontini & Bertini, 2000; Pontini et al., 2002; Bertini, 2010, 2013; Magri et al., 2010; Sadori et al., 2010; Magri & Palombo, 2013),

Fig. 24 - Microphotographs of some pollen types from Pietrafitta as documented by Lona & Bertoldi (1972). A, original plate IV by Lona & Bertoldi (1972): 1, 2. *Sequoia* type; 3. *Sciadopitys*; 4-10. *Taxodium* type; 11. *Taxodium* type; 12. *Keteleeria*; 13. *Tsuga*; 14. "small" *Picea*. B, original plate V by Lona & Bertoldi (1972): 1. *Pinus haploxylon* (*s.s.*) type; 2. Cupressaceae; 3. Inaperturate grain; 4. *Pterocarya*; 5. cf. *Platycarya*; 6. *Zelkova*; 7. *Quercus ilex* type; 8-11. *Eucommia*; 12. *Celtis*; 13. *Celtis reticulata* Torr. (modern); 14. Magnoliaceae; 15. Monocolpate grain; 16-17. *Liquidambar*; 18. cf. *Aesculus*; 19. *Tricolporopollenites cingulum* cf. *fusus* (R. Potonie) Th. et Pf.; 20. *Hedera* type.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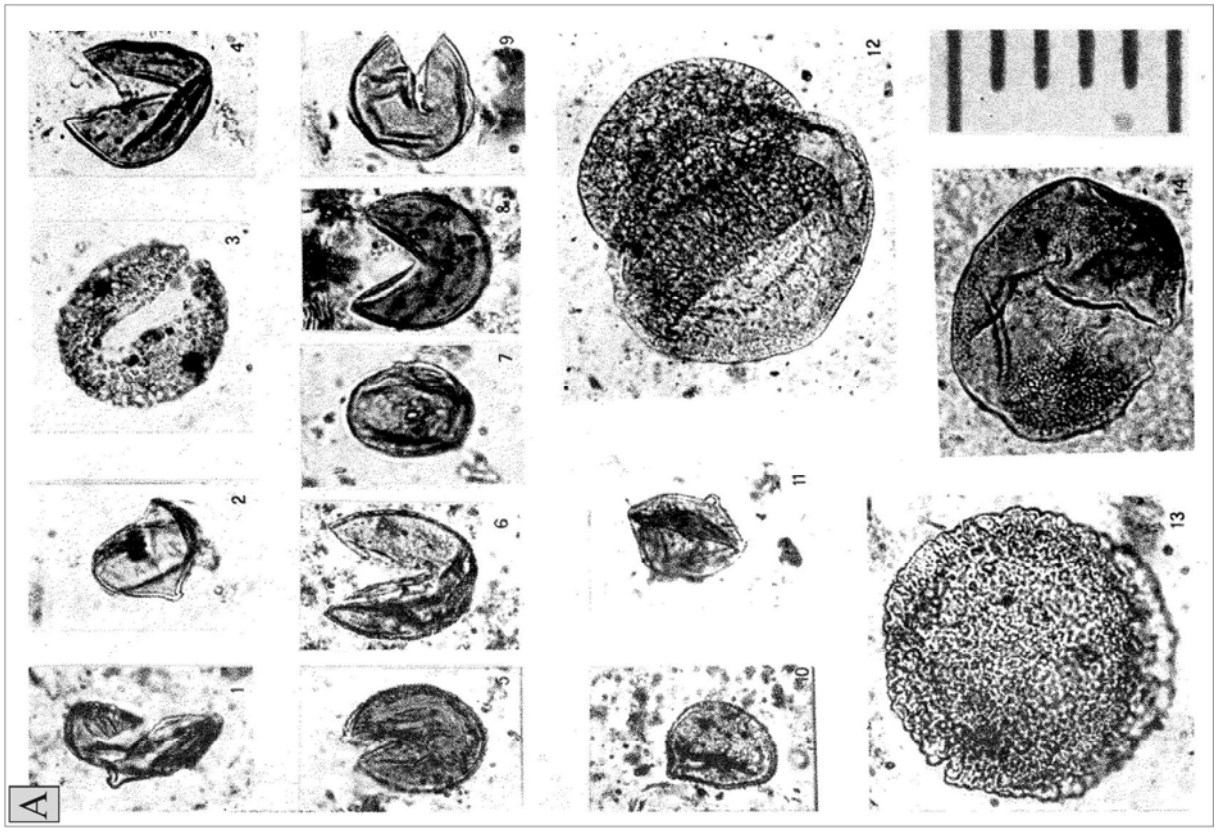
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and makes the Dunarobba palaeoflora very rich of palaeovegetational and palaeoclimatic information, despite its still uncertain age.

The macrofossil plants of the Pietrafitta site are not exceptional for their preservation state, but for the context in which they were found, being associated to a rich vertebrate palaeofauna. The diversity of the aquatic palaeoflora is remarkable, and a few species (*Aldrovanda* cf. *zussii*, *Potamogeton pannosus*) are documented here for the first time in Italy. Further studies would be needed to assess their relevance in biogeography as well as biochronology.

The common feature of the two studied localities is the occurrence of autochthonous fruit and seed assemblages both in Dunarobba (in 3 sections and several layers) and in Pietrafitta, whose analysis can throw light on the floristic composition of the local vegetation of these waterlogged palaeoenvironments. The reconstruction of extralocal vegetation and climate changes are provided by the integration of pollen data.

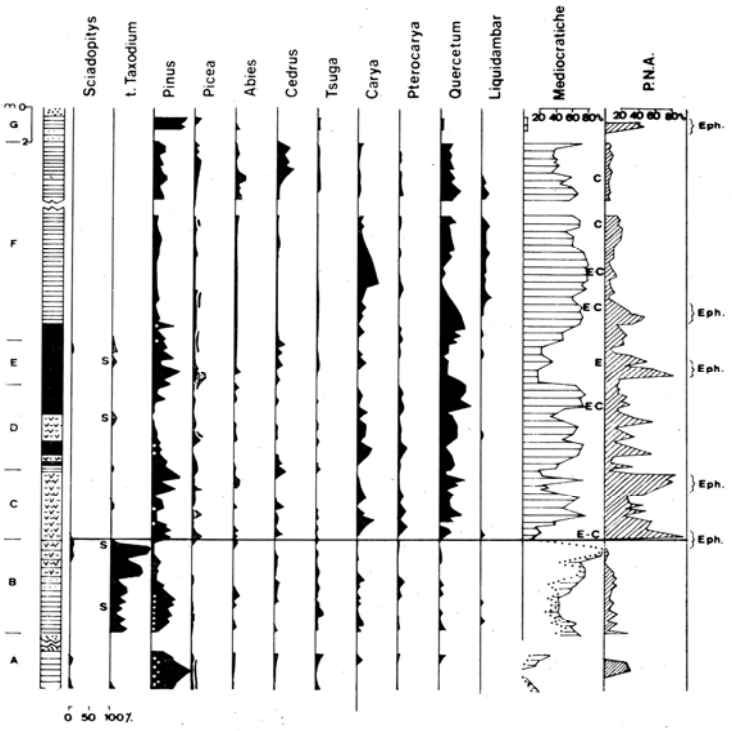

Fig. 25 - Pollen diagram published by Lona & Bertoldi (1972) based on the study of a succession drilled in the 1960s in the Pietrafitta site. Seven pollen zones were distinguished (A-G). P.N.A. = non-arboreal plants.

7.1 Local palaeovegetation

Studies on autochthonous fruit and seed assemblages in modern lakes and mires (Birks, 1973; Collinson, 1983; Greatrex, 1983; Dunwiddie, 1987; Spicer & Wolfe, 1987; Thomasson, 1991; Dieffenbacher Krall & Halteman, 2000) showed that a high-medium frequency of certain species, and their occurrence in several samples of the same deposit, usually indicates their participation in the local palaeovegetation.

In the samples of lignite and muddy sediments of the Dunarobba Lignite and Forest sections, fruit and seed assemblages show a scanty representation of plants from well-drained substrates, and the hydrophytes are almost completely absent, except for sporadic fruits of *Potamogeton*. These probably underwent a short transport, coming from slightly deeper areas. In consideration of the generalised dominance of the hygrophilous plants we can conclude that the palaeoenvironmental context was probably characterised by large areas covered by wetland vegetation, and the closest mesic communities were growing at least several hundred meters apart (Basilici, 1992, p. 80).

The large floristic similarity of the DF1-6 plus DL1 (Lignite and Forest sections) and DC3 (DC Section) assemblages (Tab. 1) proves that the same type of palaeoflora existed during the sedimentation of the DC Section and of the succession embedding the Dunarobba Fossil Forest trunks. Both in the DF1-6 plus DL1 and in the DC3 ancient plant communities, the following woody elements had to be present: *Alnus* sp., *Cephalanthus dorofeevi, Cornus* aff. *amomum* and *Glyptostrobus europaeus*. Among the herbaceous forms, *Carex pseudocyperus* was important only in certain areas and/or phases of development of the Forest Section, while *Cladium paleomariscus* and *Schoenoplectus isolepioides* occurred in both the Forest Section and the DC3 palaeocommunities. The latter species would participate to the herbaceous layer of swamp forests, and/or form a distinct sedge palaeocommunity. Among the aquatic taxa, *Potamogeton* fruits occur in both the Forest Section and DC Section assemblages, and in this last section it is represented also by pollen. The nearest living relatives (NLRs) of the aforementioned species (*Alnus* spp., *Cephalanthus occidentalis, Cornus amomum*, *Cladium mariscus*, *Schoenoplectus* spp.) correspond to typical plants of waterlogged environments. The pollen spectra of the part of the Forest Section which contains the trunks are very rich in *Taxodium* type pollen, which confirms the result of wood analysis as for the dominance of a Taxodioid plant in the local swamp forest. For a more accurate determination of the dominant Taxodioid species in the DF, it useful to point out that all the samples with autochthonous/parauthochtonous remains contained seeds and cones of a single species, *Glyptostrobus europaeus*. Two other species of Taxodioidaeae (*Cryptomeria rhenana* in DC1a-b and *Sequoia abietina* in DC2) appear only in allochthonous assemblages and would therefore originate from the extralocal palaeovegetation. Therefore, the hypothesis (Martinetto, 1994; Basilici, 2008) that the *in situ* stumps and logs belong to the "*Glyptostrobus europaeus* whole plant" (Vassio et al., 2008) takes on greater support. Yet, the wood-anatomical assignment of the large Dunarobba trunks to *Taxodioxylon gypsaceum* (Biondi & Brugiapaglia, 1991) is problematic, because the wood of

the "*Glyptostrobus europaeus* whole plant" should be assigned to the wood morphospecies *Glyptostroboxylon rudolphii* Dolezych et Van der Burgh (see Teodoridis & Sakala, 2008). In view of the recent description of this last morphospecies (Dolezych & Van der Burgh, 2004), we suggest that a revision of the wood anatomy of the Dunarobba trunks is badly needed.

We consider the evidence provided by shoots, cones and seeds (Tab. 1) as sufficient to reconstruct extensive *Glyptostrobus* swamp forests in the Dunarobba site, at the margin of the ancient Tiberino lake (Fig. 26). Even the deposition of the lignite layer DC3 of the DC Section (Fig. 7), despite not having observed the presence of *in situ* trees, can be traced back to a marginal area of a *Glyptostrobus* swamp forest, due to the abundance of macroremains of this plant which has been detected in the bulk sediment sample (Tab. 2).

Fossil forests dominated by *Glyptostrobus europaeus* are known from other Pliocene sites of Italy, e.g. the above-mentioned Stura di Lanzo Fossil Forest, and an Upper Valdarno site (Le Matole) in Tuscany (Martinetto, unpublished data). The record of such forests is probably also reflected in some pollen diagrams showing a high percentage of *Taxodium* type (also including *Glyptostrobus*), such as the Zanclean and early Piacenzian diagram of the Stirone Section (Bertini, 2003) and the Piacenzian diagram of the Upper Valdarno Basin (Santa Barbara section: Bertini, 2013). The *Taxodium* type occurs, with progressively reduced percentages, also in some Early Pleistocene sections of northern Italy, e.g. the Leffe Section (Ravazzi & Rossignol Strick 1995) and the Lamone Section (Fusco, 2007).

At Pietrafitta, two plant macrofossil assemblages document freshwater macrophyte palaeocommunities with relevant similarities to the ones of modern Italian lakes (Tab. 3). Nevertheless, the detailed morphological analysis of fossil fruits and seeds allows us to recognize precise morphospecies (e.g.: *Cyperus glometratoides*, *Decodon globosus*, *Nymphaea borysthenica*), which most probably represent extinct plants (Velichkevich & Zastawniak, 2003, 2006).

Plant assemblages with this same species association are known in Eastern Europe (Velichkevich & Zastawniak, 2003, 2006), and similarities can be found also in a palaeoflora described from NE Italy (Martinetto et al., 2012), because of a characteristic association between taxa of Miocene origin (*Decodon globosus*), the rare Pliocene-Pleistocene element *Nymphaea borysthenica*, and the "younger" ones (possibly post-Piacenzian immigrants) *Carex* cf. *elata* and *Cyperus glometratoides*. Another very similar palaeofloral association has been detected in the "*Trapa* layer" flora of Buronzo, in NW Italy, interpreted as Gelasian (Martinetto, 1999; Martinetto & Festa, 2013); on the other hand we cannot cite any assemblage with the same characteristics in central and western Europe.

As discussed above, studies on modern fruits and seeds in bottom sediments of lakes and ponds showed that the composition of the assemblages reflects rather faithfully the local vegetation (within a few tens of metres), and the record of the regional vegetation is scanty.

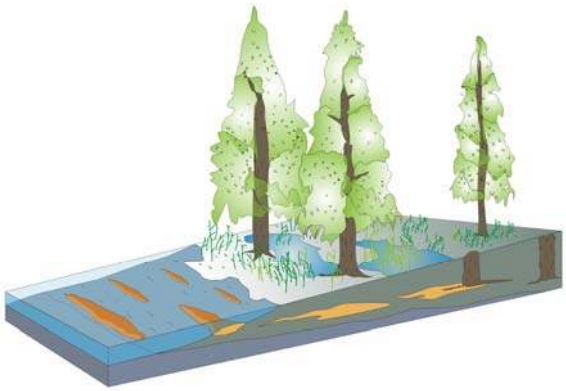

Fig. 26 - Reconstruction of the sedimentary context and plant cover at the ancient lacustrine margin of Dunarobba.

This explains the dominance of fruits and seeds of aquatic plants in the Pietrafitta assemblages, which would reflect the floristic composition of the local plant communities growing in the ancient lake. The diaspores of submerged (*Aldrovanda, Ceratophyllum, Myriophyllum*, *Najas, Stratiotes*), rooted (*Nymphaea*, *Potamogeton*, *Trapa*) or free-floating (*Azolla*) macrophytes are dominant in the Pietrafitta sediments, but some emergent aquatic plants (helophytes, such as *Cyperus, Decodon* and *Typha*) are also not rare. Two plants (*Nymphaea, Najas*) require at least 1 m deep water in a standing-water environment. The non-aquatic plants are represented by a few taxa which produce wind- or animal- transported fruits (e.g. *Vitis* sp.), whose findings are rare and do not contribute to the reconstruction of the ancient mesic vegetation, growing around the depositional basin, which is documented by the pollen assemblages.

As a whole, these freshwater macrophytes permit to accurately characterize the ancient vegetation of the two analysed layers of the Pietrafitta lacustrine basin (PF1, PF2), that show minor floral differences (Tab. 3). The carpological remains found in each layer allow us to recontruct at least tre belts ot lake margin vegetation: a shallow-water belt with *Carex*, *Decodon* and *Typha* (with the addition of *Cladium*, *Cyperus, Ranunculus* and *Schoenoplectus* for PF1, and *Urtica* for PF2), an intermediate belt with *Aldrovanda, Azolla*, *Ceratophyllum* and *Oenanthe* (with the addition of *Myriophyllum*, *Potamogeton*, *Salvinia* and *Stratiotes* for PF1), and a deeper -water belt with *Najas* and *Nymphaea* (and possibly *Myriophyllum*, *Potamogeton, Stratiotes* and *Trapa* for PF1).

7.2. Extralocal palaeovegetation and palaeoclimate

As for Dunarobba, the macrofloral record of the extralocal vegetation is mainly provided by pollen assemblages from both DC and Forest sections, accompanyied by rare fruits and seeds of the Forest Section, and by much more abundant ones from the DC1-2 layers of the DC Section, with transported (allochthonous) plant assemblages. As discussed above, the carpological assemblages of the DC1-2 layers and of the studied layers of the Forest Section show a high floristic similarity (Tab. 1), and most probably reflect the same phase

of vegetation development, so we will discuss together their record.

At the present state of knowledge the concomitant record of pollen and carpoflora is not yet rich enough to propose the reconstruction of vegetation transects as in Bertini & Martinetto (2011). A useful information to define the features of the extralocal vegetation is provided by the reconstructed habit of the mesic elements: both in the Forest Section and DC Section plant assemblages (Tabs. 1, 2) they mostly belong to woody plants, in particular trees. This means that the zonal vegetation was a forest, and there is no evidence of herbaceous formations of regional importance. Only in the hygrophilous palaeocommunities the herbaceous plants were important and diversified.

From the biogeographical point of view, many of the genera found in the Dunarobba sections are currently confined to East Asian Regions: *Cathaya, Cryptomeria, Glyptostrobus, Pterocarya* (also West Asia), *Sabia*, and *Sinomenium*. On the contrary, the genera exclusively growing in North America are *Cephalanthus, Decodon, Proserpinaca* and *Sequoia*. The remaining exotic genera have today a palaeotropical (*Sabia* and *Toddalia*), pantropical (*Cyclea*, *Eurya*, *Ficus*, *Magnolia, Meliosma, Saurauia*) or disjunct Asian-American distribution (*Alangium, Chamaecyparis, Liriodendron, Sassafras, Symplocos, Zanthoxylum*).

The modern vegetation of some East Asian regions shows a closer affinity to the Dunarobba palaeofloras and is used as a model, also for the climatic interpretation (as in Gregor et al., 1989). From the floristic point of view, the association of the genera *Ampelopsis, Cryptomeria, Magnolia, Sinomenium, Styrax* and *Symplocos* allows us to establish a link between the Dunarobba palaeofloras and the modern "Mixed Mesophytic Forest" of Japan (Mai & Walther, 1988), but also of China (Wang, 1961). On this basis, we can tentatively reconstruct a Mixed Mesophytic Forest vegetation type, sensu Wang (1961) and Wolfe (1971), i.e. a prevalently deciduous forest with high species diversity, growing within the warm temperate Cfa climatic zone (Kottek et al., 2006).

More in detail, the presence of such humid "subtropical" elements (Zagwjin, 1990) as *Cyclea* (DR1, DC1a), *Ficus, Eurya* (DC1a-b), *Meliosma canavesana* (DC1b), *Symplocos casparyi* (DC1a-b) and *Toddalia* (DC1a-b, DC3, DC4) would indicate a type of "Mixed Mesophytic Forest" similar to that growing today close to the transition to the "Evergreen Broad-leaved Forest", which is richer in evergreen trees (Hou, 1983). Martinetto (1996), referring to the diagram of Wolfe (1971), supplemented with data from Hou (1983), Numata (1974) and Satoo (1983), obtained the following climatic parameters for the Dunarobba palaeofloras (transition Mixed Mesophytic Forest/Evergreen Braoad-leaved Forest):

- Average annual temperature around 13-14 °C.
- Average annual rainfall in the range 1000-3000 mm.

The above temperature estimation is not in contrast with the new temperature data provided by Grimm & Denk (2012), which define an interval between 9 °C and 21 °C for the plant taxa occurring at Dunarobba (see climatic data in Fig. 27), tentatively restricted to the interval 14-21 °C according to the whole dataset reported in Fig. 27 (excluding the relic genus *Tetraclinis*, >15°C).

Finally, the Dunarobba palaeofloras are framed in the context of a warm and humid temperate palaeoclimate (Cfa *sensu* Köppen-Geiger: Kottek et al., 2006), and the presence of "subtropical" elements allows us to exclude severe winter frost.

The long pollen record from the Dunarobba S2 Core (Fig. 18) shows successive phases of reduction vs expansion of *Taxodium* type (followed by some elements of the mixed deciduous broad-leaved forest) and *Pinus*. Such pattern supports the image of a landscape submitted to humidity fluctuations, but within a prevalent humid, warm temperate climate. Also the chemical and physical features of the palaeosols demonstrate that climate conditions did not change remarkably from the bottom of the Forest Section to the top of the Palaeosol Section (Fig. 8). In fact the absence of important expansions of herbs in the pollen diagram indicates that humidity fluctuations were never dramatic, and there is no definite evidence of glacial/interglacial cycles. The Pinaceae pollen increase during the relatively moister phases can be attributed to lake level rises (larger basin = over-representation of *Pinus* pollen). Successively, the pollen curve of the *Taxodium* type shows a definite increase, which indicates an expansion of swamps. The following phase of humidity lowering determined the expansion of mixed deciduous broad-leaved forest in the areas closest to the lake coast.

In synthesis, the vegetation and climate reconstructed for the Dunarobba sections are similar to those of the Cava Toppetti I Section, the Zone III of the Fosso Bianco pollen diagram, and the warmest phases of the Cava Toppetti II pollen diagram. However, the Cava Toppetti II and Fosso Bianco pollen records show more apparent vegetation and climate changes (see 4.2. and 4.3.), whereas the Cava Toppetti I and Dunarobba pollen records indicate fairly stable conditions.

In the Pietrafitta succession the extralocal vegetation is only documented by pollen. The long pollen diagram of Lona & Bertoldi (1972) shows consistent variations in the pollen percentage of taxa indicating different vegetation types. A progressive increase of *Taxodium* type, till to a complete dominance, would suggest a warm temperate climate (Kottek et al., 2006) of "subtropical" type. The abundance of *Taxodium* type also indicates the local establishment of a taxodiod swamp forest, possibly similar to the Dunarobba one, even if here we have no macrofossil record of such a plant community. Later on the *Taxodium* type nearly disappears, marking the so-called "Tiberian boundary" of Lona & Bertoldi (1972). From this horizon onwards the pollen of the so-called "*Quercetum*" taxa dominates, together with *Carya* and *Pterocarya*. The extralocal vegetation of the this pollen zone, comprising the basal part of the lignite seam, was a mixed deciduous broad-leaved forest indicating a warm temperate climate (Kottek et al., 2006) and sufficient humidity. At the top of the diagram there is a prevalence of *Pinus* and herbaceous pollen, suggesting a cool phase with conifer forests and open vegetation, possibly growing under a snow climate (Kottek et al., 2006).

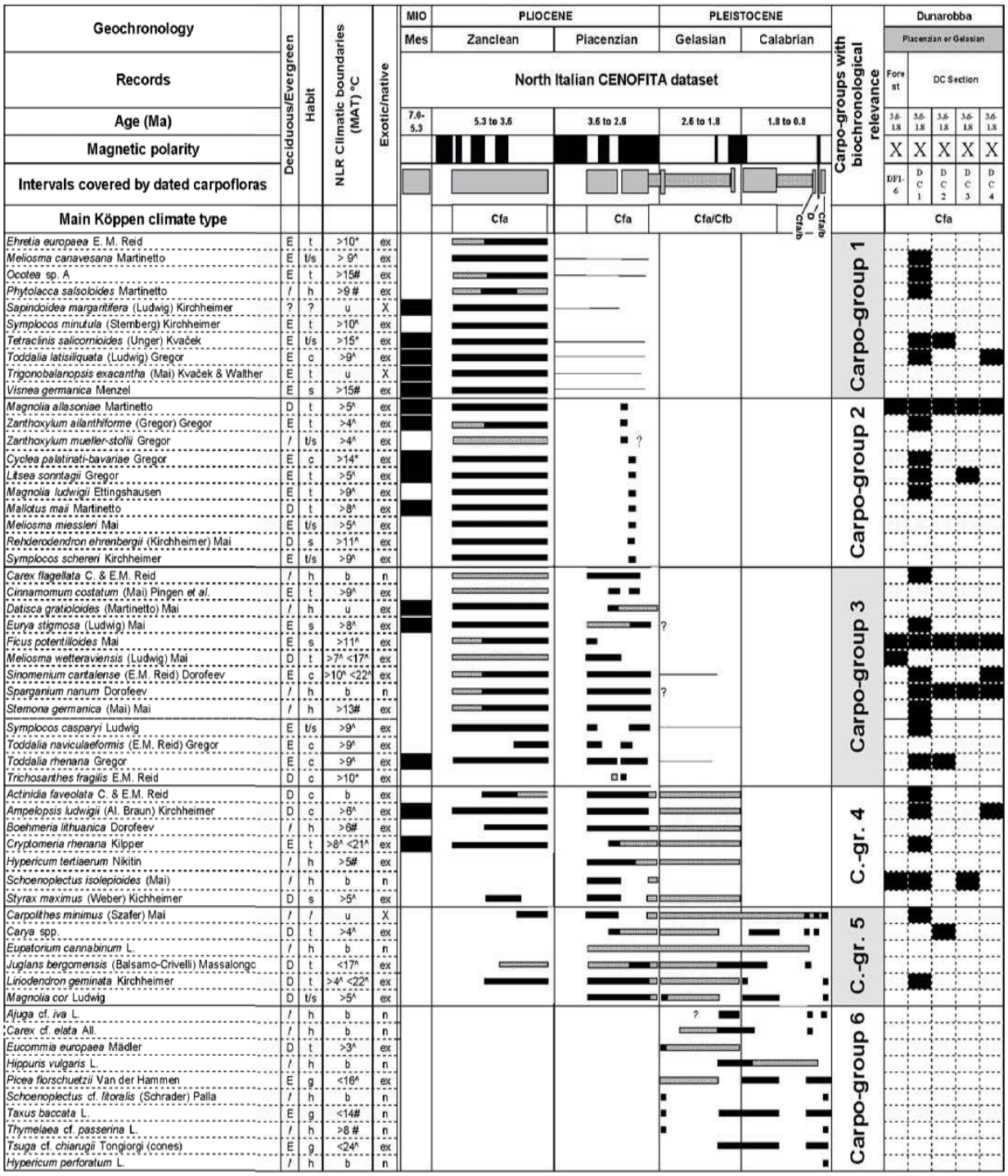

Fig. 27 - Biochronological chart of selected fruit and seed species based on data from Northern Italy. The black boxes to the right side (Dunarobba columns) indicate occurrence in our samples (see Tabs. 1, 2). Mes = Messinian; Gel = Gelasian. The listed taxa have been gathered in 6 main Carpo-groups, according to Martinetto et al., in press. A simple characterisation of the growth forms of the listed taxa is reported in the two columns named respectively "Deciduous/Evergreen" and "Habit", where "c", "h", "s" and "t" stand for climber, herb, shrub and tree. The thermal climatic requirements of each species have been synthetically expressed by the boundary values of Mean Annual Temperature (NLR Clim. boundaries), e.g.: >13 = distribution of Nearest Living Relatives (NLRs) mainly in areas where the MAT is higher than 13°C; <14 = distribution of NLRs mainly in areas where the MAT is lower than 14°C; u = uncertain, b = broad climatic distribution (literature sources: ^Grimm & Denk, 2012; *Utescher and Mosbrugger, 2013; #other sources, reported in Martinetto et al., in press). The column "exotic/native" (ex/n) is referred to the NLRs, and "X" means no-NLR (extinct genus or morphogenus).

The Pietrafitta pollen diagram (Fig. 25), when compared to that of the Dunarobba S2 Core (Fig. 18), distinctly differs for a significant increase of herbaceous pollen in the C Zone, with dominance of the steppe element *Artemisia.* Similar phases of steppe elements increase occur in the Fosso Bianco pollen diagram (Fig. 4). At the light of the vegetation dynamics pointed out by the long pollen record from Pietrafitta, the macrofloral data provided by the Torre Picchio Section (Girotti et al., 2003) can be referred to a mixed deciduous broad-leaved forest phase, indicating a warm temperate climate and sufficient humidity. The Villa San Faustino macroflora (Martinetto, 1996) can be referred to a colder phase with mixed conifer (*Abies*, *Picea*) and deciduous broad-leaved forests, even if the climate was still possibly of C type according to the Köppen-Geiger classification (Kottek et al., 2006).

7.3. Biochronology of plant assemblages

The stratigraphic study of the pollen assemblages in late Cenozoic successions of Italy led to the proposal of biostratigraphic schemes (Lona & Bertoldi, 1972; Bertoldi, 1990; Bertoldi et al., 1994), in which a few units were distinguished on the basis of the progressive disappearance, or extreme reduction, of some thermophilous plants. These schemes were also used to interpret the chronology of the even more apparent disappearance of thermophilous plants seen in fruit and seed assemblages (Martinetto, 1995, 1999). More recent studies posed the necessity of a revision of such disappearance times (Bertini, 2010; Martinetto et al., in press), and put forth the longer persistence of some species in central Italy with respect to the northern part of this country (Martinetto, 2001). This means that it is very difficult, in central Italy, to assess the age of a deposit on the basis of the assemblage of extinct plants that it contains.

The analysis of the distribution in northern Italy (Martinetto et al., in press) of the fruit and seed species of Dunarobba (Fig. 27) shows how several "Zanclean" (Carpo-group 1) or "Zanclean-Piacenzian" (Carpo-groups 2 and 3) elements are still found in the Dunarobba sediments (*Alangium deutschmannii, Cyclea palatinati-bavariae*, *Litsea sonntagii, Meliosma canavesana, Magnolia allasoniae, Tetraclinis salicornioides, Toddalia latisiliquata* and *Zanthoxylum ailanthiforme*). This situation may be explained in 2 ways:

1) the Dunarobba succession has a Zanclean or Piacenzian age;
2) several elements of Carpo-groups 1-3 persisted after the end of the Piacenzian in central Italy.

If the second case is true, the Dunarobba succession may well have a Gelasian age, as proposed by Bizzarri et al. (2011). However, the Gelasian is well-known for the instauration of glacial/interglacial cycles, and the analysis of the Dunarobba S2 Core pollen diagram (Fig. 18) does not provide any evidence of such cycles (i.e. alternations among deciduous broadleaved forest and steppe or microtermic coniferous forest). Rather, the continuos curve of the *Taxodium* type would fit better within the Pliocene.

On the other hand, the onset of well defined glacial/interglacial cycles has been observed troughout both the Fosso Bianco and the Pietrafitta sections, and fits very well with the age of these sections, respectively Gelasian and Calabrian.

The early Gelasian glacial phases, as detected in the Fosso Bianco section, are often characterized by the expansion of *Picea* and *Abies*, and the decrease of the thermophilous elements, such as *Taxodium* type. Sometimes they correspond to the expansion of herbs, including *Artemisia*, whose increase, however, preceedes that of *Picea*. For these features such glacial phases show an intermediate pattern between those described for the central Mediterranean littoral (e.g. at Vrica: Combourieu-Nebout, 1993) and the North Apennine ones (Bertini, 2001; Fusco, 2007).

At Pietrafitta there are no elements of Carpo-groups 1-4, and only *Carex* cf. *elata* was listed by Martinetto et al. (in press) as an element of Carpo-group 6, distributed from the Gelasian to the Holocene. However, several extinct carpological species occur (*Aldrovanda* cf. *zussii*, *Cyperus glometratoides*, *Decodon globosus*, *Nymphaea borysthenica, Potamogeton pannosus, Euryale(?) nodulosa, Stratiotes* cf. *intermedius*), and form a characteristic assemblage, similar to those assigned to the Late Pliocene-Early Pleistocene in East Europe (Velichkevich & Zastawniak, 2003), and to an Early Pleistocene assemblage in West Asia (Melamed et al., 2011).

At the present state of the art the association of fruit and seed species of Pietrafitta, although characteristic, does not provide definite biochronological indications, and further studies are needed in two directions: 1) the improvement of the taxonomic accuracy (e.g. *Aldrovanda* cf. *zussii*, *Carex* cf. *elata, Salvinia* cf. *natans*, *Stratiotes* cf. *intermedius*, *Trapa* cf. *natans*); 2) the study of a larger number of well-calibrated Early Pleistocene sections with carpofloras. However, vertebrate biochronology (see 6.3.) permitted to assign to a definite part of the Calabrian (1.5-1.3 Ma) the stratigraphic intervals including both the carpological sample PF1 and PF2.

8. CONCLUSION

The plant remains of the Dunarobba and Pietrafitta sites provide abundant information on two different phases of palaeofloral development in central Italy. The Dunarobba sections are assigned, mainly on the basis of continental mollusc biochronology, to the Piacenzian-Gelasian interval, whereas the Pietrafitta Section, till to 6 m below the lignite seam, is reliably dated to the middle part of the Calabrian thanks to vertebrate biochronology. The age of the non-outcropping layers rich in *Taxodium* type pollen, laying ca. 8 m below the lignite seam bottom, is still uncertain.

At Dunarobba, information provided by autochthonous fruit and seed assemblages has been combined with physical stratigraphic data to conclude that the remarkable Fossil Forest was produced by an ancient swamp vegetation dominated by *Glyptostrobus europaeus,* a conifer species whose nearest living relative is the East Asian tree *Glyptostrobus pensilis*. The Dunarobba trees grew in a wetland with high sedimentation

rate, bordering the ancient Tiberino Lake. The disappearance of the wetland and the *Glyptostrobus* forest was due to the establishment of well-drained palaeoenvironmental conditions, testified by a palaeosol profile. Chemical and physical features of the palaeosols demonstrate that climate conditions did not change, so this palaeoenvironmental variation was probably caused by local morphological changes induced by tectonics. The successive restoration of the wetland conditions was not sufficient for the preservation of *in situ* tree trunks.

The well-drained palaeoenvironments around the palaeo-swamp of the Dunarobba Fossil Forest were covered by forests having a floristic affinity to the modern Mixed Mesophytic Forests of East Asia, as proved by rich, water-transported fruit and seed assemblages. So, in the warm phases of the Pliocene-Pleistocene transition, the vegetation in central Italy was very similar to the one which was present, in older times (pre-Piacenzian), in central-western Europe. The relative uniformity of the pollen curves in a 50 m long diagram suggests that the extra-local vegetation and climate remained stable for a long time span. Conversely, the Pietrafitta pollen record suggests that, during the Calabrian, the East-Asian character of the extra-local vegetation was less apparent, and more frequent, sometimes abrupt, vegetation changes occurred. The vertebtrate-bearing lignite seam was initially deposited in a humid warm temperate phase, when the Pietrafitta palaeolake was surrounded by broad-leaved deciduous forests. The aquatic and wetland plant communities still comprised several exotic plants (e.g. *Azolla*, *Decodon*, *Euryale*(?), etc.) and extinct species of East European affinity (e.g. *Cyperus glomeratoides, Nymphaea borysthenica, Potamogeton pannosus*).

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APPENDIX 1

INFORMAL PALYNO-GROUPS USED IN THE SUMMARY POLLEN DIAGRAMS OF FIGURES 3-5 AND 18

Palyno-group 1 Mega-mesothermic elements. *Taxodium* type is the main component (plus rare pollen grains of *Sequoia* -type and *Sciadopitys*); *Nyssa*, Arecaceae, *Engelhardia*, *Myrica*, *Distylium* and other Hamamelidaceae tricolpate pollen grains are subordinated.

Palyno-group 2 Mesothermic elements requiring a humid climate but tolerating seasonal contrast in humidity and temperature. *Quercus* is the principal component. Juglandaceae (*Juglans*, *Carya*, *Pterocarya*), *Liquidambar*, *Ilex*, *Carpinus*, *Castanea*, *Ulmus*, *Tilia*, *Acer*, *Fraxinus*, *Viburnum*, Araliaceae (*Panax* type) and *Celtis* are subordinated. The Mediterranean evergreens, represented by only few pollen grains of *Quercus ilex*-type, *Olea*, and *Pistacia*, are included in this Palyno-group.

Palyno-group 3 *Cathaya* plus *Pinus haploxylon*-type. *Cathaya* is a SE Asian gymnosperm tolerating low temperature but requiring an high humidity along all the year.

Palyno-group 4 *Pinus* and undetermined Pinaceae saccate pollen grains, with variable ecological and climatic requirements.

Palyno-group 5 Meso-microthermic conifers such as *Cedrus* and *Tsuga*.

Palyno-group 6 Microthermic elements such as *Abies* and *Picea* plus *Fagus* and *Betula*.

Palyno-group 7 Undetermined and indeterminable pollen grains as well as elements with local significance such as *Alnus* and *Salix* plus Cupressaceae.

Palyno-group 8 Non arboreal elements, principally herbs such as Poaeeae, Asteraceae (except *Artemisia*), Amaranthaceae, Ericaceae, Ranunculaeeae (*Thalictrum*), Brassicaceae, Caryophyllaceae, Plantaginaceae, Lamiaceae, cf. Fabaceae, Polygonaceae (*Rumex*), Plumbaginaceae (*Armeria*).

Palyno-group 9 Steppic taxa such as *Artemisia* and *Ephedra*.

APPENDIX 2

PALYNO-FLORAL LIST FOR THE PLIO-PLEISTOCENE SITES OF THE TIBERINO BASIN

Legend: CT I, Cava Toppetti I Section; CT II, Cava Toppetti II Section; DU, Dunarobba sections; FB, Fosso Bianco Section; PF, Pietrafitta Section.

Floral list		CT I	CT II	DU	FB	PF
GYMNOSPERMS						
Cupressaceae	Cupressaceae indet.	*	*	*	*	*
	cf. *Chamaecyparis*					*
	Sequoia t.	*	*	*	*	*
	Taxodium t.	*	*	*	*	*
Ephedraceae	*Ephedra*	*	*		*	*
Ginkgoaceae	Ginkgoaceae indet.					*
Pinaceae	Pinaceae indet.	*	*	*	*	*
	Abies	*	*	*	*	*
	Cedrus	*	*	*	*	*
	Cathaya	*	*	*	*	
	Keteleeria					*
ANGIOSPERMS						
Aceraceae	*Acer*	*	*	*	*	*
Actinidiaceae	*Actinidia*					*
Alismataceae	*Alisma*	*			*	
Altingiaceae	*Liquidambar*	*	*	*	*	*
Amaranthaceae	Amaranthaceae indet.	*	*	*	*	*
Anacardiaceae	*Pistacia*	*	*			*
	Rhus					*
Apiaceae	Apiaceae indet.	*	*	*	*	*
	Buplerum					
Aquifoliaceae	*Ilex*	*	*	*	*	*
Araliaceae	Araliaceae indet.	*	*	*	*	*
	Hedera	*	*	*		*
	Panax t.	*	*	*	*	
Arecaceae	Arecaceae indet.	*	*	*	*	*
	Chamaerops					*
	Phoenix					*
	Sabal					*
Asteraceae	Asteraceae Asteroideae	*	*	*	*	*
	Artemisia	*	*	*	*	*
Asteraceae	Asteraceae	*	*	*	*	*
Berberidaceae	cf. *Mahonia*	*				
Betulaceae	*Alnus*	*	*	*	*	*
	Betula	*	*	*	*	*
	Carpinus	*	*	*	*	*
	Corylus					*
	Ostrya			*	*	*
Boraginaceae	Boraginaceae indet.				*	
Brassicaceae	Brassicaceae indet.	*	*		*	
Butumaceae	*Butomus*			*	*	
Buxaceae	*Buxus*	*	*		*	*
Caprifoliaceae	*Viburnum*	*	*		*	
	Lonicera	*			*	
Caryophyllaceae	Caryophyllaceae indet.	*	*		*	*
Celastraceae	Celastraceae indet.	*			*	*
	Evonymus					
Cistaceae	*Helianthemum*					*
Convolvulaceae	*Convolvulus*				*	
Cyperaceae	Cyperaceae indet.	*	*		*	
Dipsacaceae		*	*			*
Eleagnaceae	*Eleagnus*					*
Ericaceae	Ericaceae indet.	*	*		*	
Eucommiaceae	*Eucommia*					*
Fabaceae	*Acacia*					
Fagaceae	*Castanea*	*	*		*	*
	Fagus	*	*	*	*	*
	Quercus	*	*	*	*	*
	Quercus ilex t.	*	*	*	*	*
Geraniaceae	*Erodium*				*	
Haloragaceae	*Myryophillum*				*	*
Hamamelidaceae	Hamamelidaceae indet.	*	*		*	
	Distylium	*	*		*	
	Parrotia	*	*		*	
	Parrotiopsis				*	
Hypericaceae	Hypericaceae indet.				*	
	Hypericum	*				
OTHERS						
Tricolporopollenites cingulum cf. subsp.						*
PTERIDOPHYTA						
Lycopodiaceae	Lycopodiaceae indet.	*	*	*		*
Ophioglossaceae	Ophioglossaceae indet.	*	*	*		
Osmundaceae	*Osmunda*	*	*	*	*	*
Polypodiaceae	Polypodiaceae indet.	*	*	*	*	*

Floral list		CT I	CT II	DU	FB	PF
Pinaceae cont	*Picea*	*	*	*	*	*
	Pinus diploxylon t.	*	*	*	*	*
	Pinus haploxylon t.	*	*	*	*	*
	Pseudolarix					*
	Pseudotsuga					*
	Tsuga	*	*	*	*	*
	Pinaceae sacc. indet.	*	*	*	*	*
Podocarpaceae	*Dacrydium*					*
	Podocarpus					*
Sciadopityaceae	*Sciadopitys*	*	*	*	*	*
Taxaceae	cf. *Taxus*					*
Inaperturated		*	*	*	*	*
Juglandaceae	Juglandaceae indet.	*	*	*	*	*
	Carya	*	*	*	*	*
	Engelhardia	*	*		*	
	Juglans	*	*	*	*	*
	Platycarya					*
	Pterocarya	*	*	*	*	*
Lamiaceae	Lamiaceae indet.	*	*		*	
Lauraceae	*Laurus*					*
Lemnaceae	*Lemna*					
Liliaceae	Liliaceae indet.	*	*		*	*
Loranthaceae	Loranthaceae indet.				*	
Magnoliaceae	Magnoliaceae indet.					
	Liriodendron					*
	cf. *Drymis*					*
Myricaceae	*Myrica*	*	*		*	
Myrtaceae						*
Nympheaceae	Nympheaceae indet.				*	
Nyssaceae	*Nyssa*	*	*		*	
Oleaceae	Oleaceae indet.			*		*
	Olea	*	*		*	
	Fraxinus					*
	Phillyrea					*
Plantaginaceae	Plantaginaceae indet.	*	*	*	*	
	Plantago					
Platanaceae	Platanaceae indet.					
	Platanus	*	*		*	*
Plumbaginaceae	*Armeria*				*	
Polemoniaceae	*Polemonium*					
Poaceae	Poaceae indet.	*	*	*	*	*
Polygonaceae	*Rumex*	*	*		*	
Ranunculaceae	Ranunculaceae indet.	*	*		*	
	Thalictrum	*	*	*	*	*
	Helleborus					
Rhamnaceae	*Rhamnus*					
Rutaceae	Rutaceae indet.	*	*		*	
	Phellodendron					
Salicaceae	*Populus*	*			*	
	Salix	*	*	*	*	*
Sapindaceae	*Aesculus*					*
Sapotaceae	Sapotaceae indet.					*
Saxifragaceae	Saxifragaceae indet.				*	
Scrophulariaceae	Scrophulariaceae indet.					
Sparganiaceae	*Sparganium*					*
Symplocaceae	*Symplocos*				*	
Tiliaceae	*Tilia*	*	*	*	*	*
Typhaceae	*Typha*	*			*	*
Ulmaceae	*Celtis*				*	*
	Ulmus	*	*	*	*	*
	Zelkova	*	*	*		*
Valerianaceae	Valerianaceae indet.				*	
Vitaceae	*Vitis*				*	
	Parthenocissus	*	*		*	
Zosteraceae	*Potamogeton*			*		
Pteridaceae	Pteridaceae indet.	*	*	*		*
Alete spores	Alete spores	*	*	*	*	*
Monoletes spores	Monoletes spores	*	*	*	*	*
Triletes spores	Triletes spores	*	*	*	*	*