Available online http://amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Alpine and Mediterranean Quaternary, 31 (1), 2018, 87 - 104 https://doi.org/10.26382/AMQ.2018.14

NEW INTEGRATED DATA FROM CLAY LACUSTRINE DEPOSITS OF THE DUNAROBBA AREA (UMBRIA, CENTRAL ITALY)

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ABSTRACT: This paper is aimed to illustrate and discuss new data from the clayey deposits collected in the Dunarobba area (Umbria, central Italy), and to better understand some features of the “Fosso Bianco” Unit lacustrine stage inside the South Tiberino Basin, during its latest (presumably Early Pleistocene) phases. Data come from a newly cultivated quarry area (Cava Nuova), only partly considered in previous works; the new section extends well inside the deep lake depositional stage of Fosso Bianco Unit, previously not directly described in outcrop in the Dunarobba area, but only reported from well logs. Selected samples from the Cava Nuova section were analyzed from sedimentological, geotechnical, chemical, mineralogical and biostratigraphical point of view. Sedimentological and geotechnical analyses, including density measurements, particle-size analysis, Atterberg limits and organic matter content, as well as XRF and XRPD analyses, resulted the most suitable techniques to identify the main features, at least for prevailing clayey deposits. Facies analysis and sedimentological data lead to recognize a clear depositional transition from relatively deep to shallow lacustrine deposits, which was only rarely documented formerly through a single section. On the other hand, both geotechnical and mineralogical data indicate a compositional homogeneity for clay sediments, which does not correspond with facies lateral and vertical variability nor with palaeoenvironmental complexity. Despite its preliminary nature, this integrated method looks very promising to characterize the paleodepositional context, and some hypotheses on sediment source were also evaluated. Integrated data from Cava Nuova section, as well as minor well-logs in the immediate surroundings, were discussed and compared with existing data outcoming from the whole Dunarobba area. On the heels of the recent literature, this paper is aimed to put a new light on the complexity of the Fosso Bianco paleoenvironment.
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Keywords: Dunarobba clays; geotechnical properties; XRF; XRPD; early Pleistocene

1. INTRODUCTION

Inside the Pliocene-Pleistocene evolution of the Tiberino Basin (Umbria, central Italy, Fig. 1), the older evolution phases were testified by the diffuse occurrence of clayey sediments, particularly in the southern sector. Deposits were associated to lacustrine environment, from the ancient idea of the “Tiberino Lake” (Lotti, 1917, 1926), to the definition of the informal “Fosso Bianco” Unit (Ambrosetti et al., 1995a; Basilici, 1997), finally to the recent hypothesis of a “Paleo-ancient Lake” (Medici & Gliozzi, 2008; Spadi, 2018; Spadi et al., 2018a, 2018b), a relic from the late Messinian salinity crises. In this scenario, the Dunarobba area was always considered one of the key-point. The clayey deposits widely crop out in the area and they were studied since the beginning of the 20th century, due to the cultivation of lignite mines until 1950, and the production of bricks from 1950 onwards (Fig. 2; Cerquaglia, 1996). In this area, at about the half of eighties, the Dunarobba Fossil Forest (DFF in Figure 1) was discovered, which is now considered one of the most relevant geosites in Italy, due to the preservation in life’s position of more than forty mummified trunks, buried inside lacustrine clay deposits. Dunarobba is one of the few sites in the world yielding mummified and upright fossil forests, including (regardless to age) Axel Heiberg Island, in the Arctic region of Canada (45-40 Ma: Bigras et al., 1995; Williams et al., 2008), the Bukkabrany swamp cypress forest in Hungary (7.7-6.3 Ma: Kàzmér, 2008; Csaszar et al., 2009; Erdei et al., 2009; Gryc & Sakala, 2010; Erdei & Magyari, 2011), and the Stura di Lanzo Fossil Forest, in NW Italy (~3.0 Ma: Martinetto et al., 2007; Vassio et al., 2008).

Due to its geological and environmental interest, the Dunarobba Fossil Forest is under consideration for inclusion in the World Heritage List (UNESCO), and most of the previous studies in the area converged on it. Previous works, indeed, were mainly focused on sedimentological and paleontological features (Manganelli et al., 1989, 1990, 2008; Biondi & Brugiapaglia, 1991; Esu & Girotti, 1991; Martinetto, 1994; Ambrosetti et al., 1995b, 1997; Basilici, 1997; Ciangherotti et al., 1998; Manganelli & Giusti, 2000; Medici & Gliozzi, 2008; Marti-

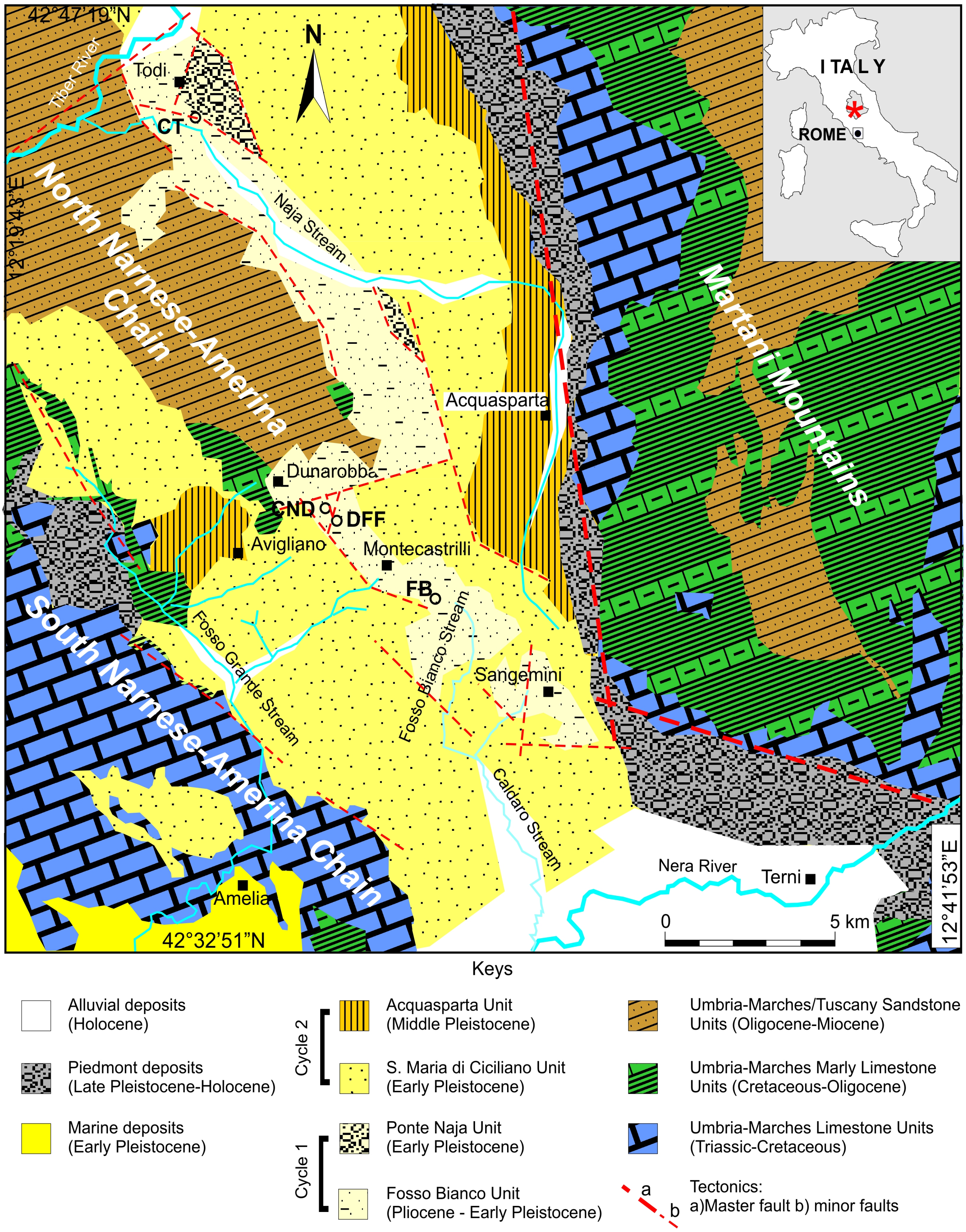

Fig. 1 - Geographic localization and simplified geological scheme for the study area. CND=Cava Nuova; DFF=Dunarobba Fossil Forest; CT=Cava Toppetti; FB=Fosso Bianco (see text for details).

netto et al., 2014; Spadi, 2018; Spadi et al., 2018a, 2018b), on both the site area and the Fosso Bianco Unit outcropping area. Nonetheless, only few researches have conducted integrated multidisciplinary study. A research, carried out by Valentini et al. (1997), was aimed to define the geological, hydrogeological and geochemical processes, which allowed the preservation of unaltered wood, making the Dunarobba Fossil Forest an outstanding example of natural analogue, in the perspective of evaluating the confinement conditions of geological sites for radioactive waste disposal. Barbieri et al. (1997) and Bozzano et al. (2000) presented a set of geotechnical and mineralogical data obtained on samples collected from four boreholes and one open pit quarry, defining two main facies: deep lacustrine and swampy lacustrine coast facies associations. The latter was characterized by samples with abundant sandy fraction (loam range) or with clay fraction (paleosol levels and clay range strata containing the tree trunks). These facies associations are strictly comparable with the sedimentological restoration proposed by Ambrosetti et al. (1995b, 1997) and Basilici (1997). The originary location of boreholes is shown in Figure 2.

Since it was discovered (or rediscovered), the Dunarobba Fossil Forest began to show preservation problems, not only directly related to weathering (Baldanza et al., 2009; Martinetto et al., 2014). Among the factors listed by Valentini et al. (1997) as responsible for the preservation of fossil trunks, the main and, unfortunately, the only strongly modified by excavation were the sealing properties of the clay mass.

Unfortunately, in order to preserve the geosite, new invasive analyses are avoided inside the perimeter of the Dunarobba Fossil Forest from 1995 onwards. None-

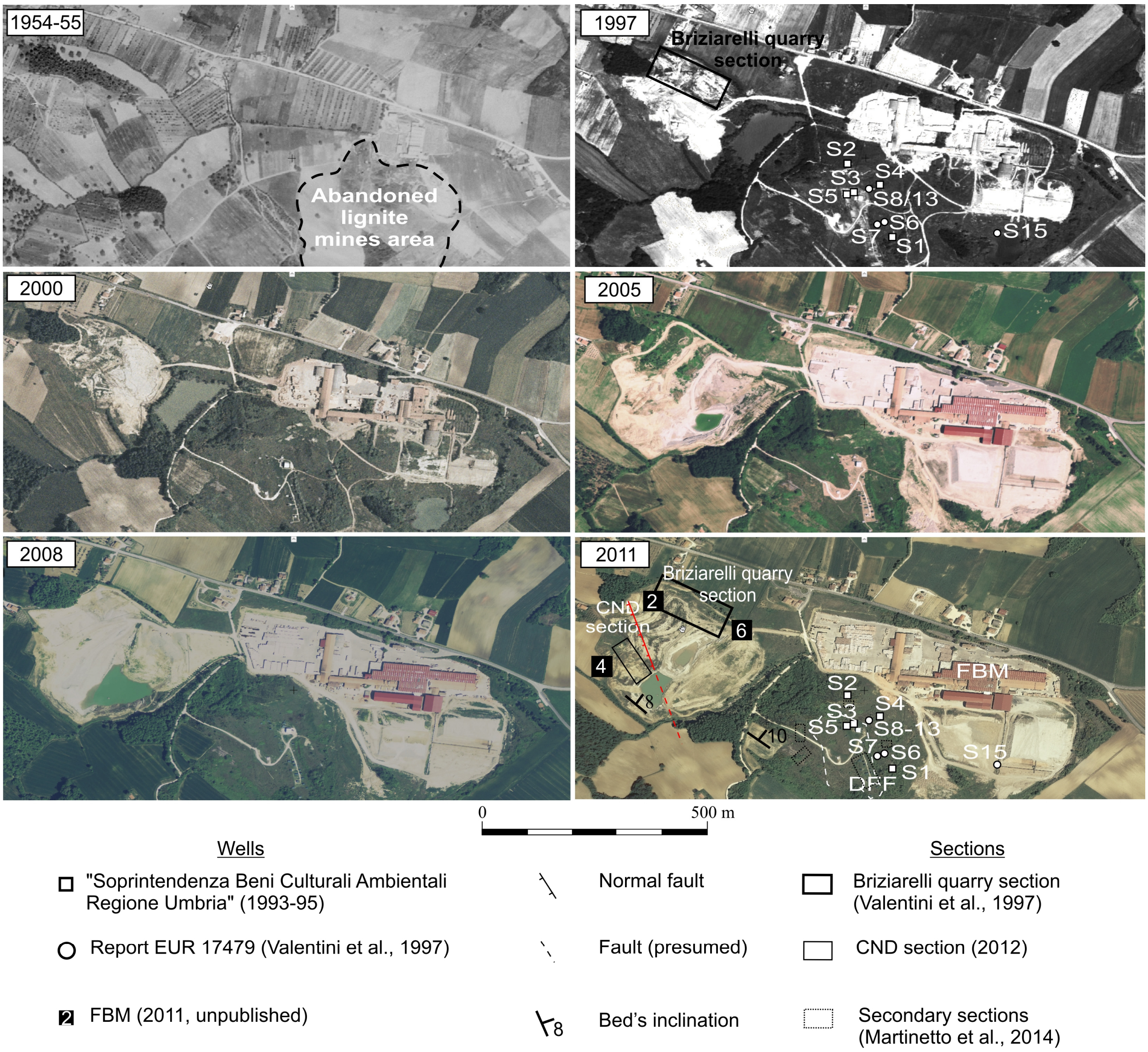

Fig. 2 - Evolution of the Cava Nuova quarrying area (CND) and of the Dunarobba Fossil Forest area (DFF) through time. Positions of stratigraphic sections and wells are reported.

Fig. 3 - Panoramic view of the Cava Nuova quarry area, as it appeared in January, 2012.

theless, due to the enlargement of neighbouring excavation area starting from 2011, new outcrops of clayey deposits were discovered in the surrounding area, only partly investigated during previous research activities. In this framework, a new geognostic campaign was carried out between 2011 and 2012, making disposable lithostratigraphic, sedimentological, geological-technical and chemical-mineralogical data in the neighbouring Cava Nuova (CND in Figure 1) area. The present work - by using an integrated multidisciplinary approach - illustrates and discusses new and old data from the Dunarobba Fossil Forest area aiming to better understand some of the features of the "Fosso Bianco" lacustrine stage during the latest evolution of the Tiberino sedimentary basin, to try to re-discuss age constrains, and to propose some hypothesis on sediment provenance, based on mineralogical and sedimentological analyses. Although the preservation problems and the possible protection interventions are beyond the aims of this paper, all data collectable in this area are crucial not only for the correct paleoenvironmental restoration and geological evolution of the Tiberino Basin, particularly at the beginning of Early Pleistocene, but also in the light of the Dunarobba Fossil Forest preservation strategies.

2. GEOLOGICAL SETTINGS

The study area is situated in southern Umbria, central Italy, inside the present-day southern Tiber Valley (Fig. 1). Through the Pliocene and the Pleistocene, this area pertained to the southwestern branch of the Tiberino Basin (also indicated as South Tiberino Basin), one of the NW-SE trending extensional basins, roughly parallel to the Apennine chain in lifting which characterized the evolution of Northern Apennine from Miocene to recent (Barchi et al., 1991; Martini & Sagri, 1993). The geological and stratigraphic model for the South Tiberino Basin evolved through time, from the initial idea of the fill up of a wide lake (the "Tiberino Lake": Lotti, 1917, 1926) to the definition of a lithostratigraphic succession of informal units divided according to sedimentological and biochronological data (Ambrosetti et al., 1995a, 1995b; Basilici 1997, 2000a, 2000b). Now substantial agreement lays on the individuation of two main depositional cycles: 1) the lacustrine phase, Pliocene to Early Pleistocene in age, and 2) the alluvial plain phase, Early Pleistocene to Middle Pleistocene in age. Relationships among units belonging to the two cycles are both marked by faults and/or by unconformities (Ambrosetti et al., 1995a; Basilici, 1997). The uppermost cycles is largely represented by the "S. Maria di Ciciliano" Unit and, locally, by the "Acquasparta" Unit (Ambrosetti et al., 1995a; Basilici, 1997). For an updated review and the state of the art, as well as for more detailed geological and stratigraphic schemes, we remind to Martinetto et al. (2014, 2017). The Dunarobba area lies inside the lowermost cycle and belongs to the informal Fosso Bianco Unit, which outcropping part is attributed to the Piacenzian-Gelasian interval according to magnetostratigraphy (Abbazzi et al., 1997). The unit was mainly associated to a deep lacustrine environment with prevailing clay sedimentation (Facies association A: Ambrosetti et al., 1995a, 1995b, 1997; Basilici, 1997). Locally, clayey silts alternated to wavy- and/or cross-laminated silty sand laminae, parallel-laminated silty clay, lignite-bearing clay deposits, and lenticular sand bodies crop

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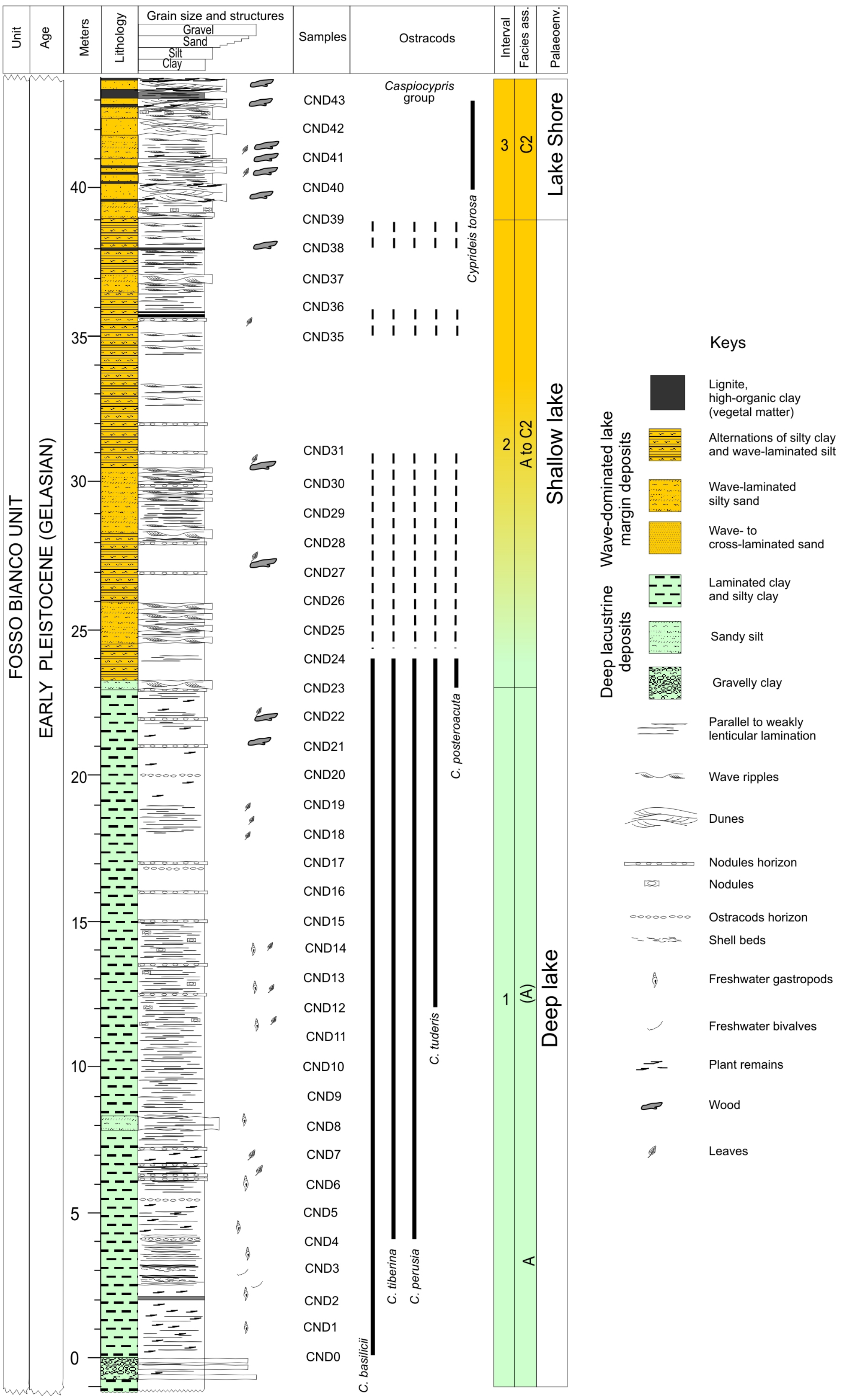
Fig. 4 - Cava Nuova sedimentological-lithostratigraphic section. Facies associations refer to Basilici (1997).


Unit
Age
Meters
Lithology
Grain size and structures
Gravel
Sand
Silt
Clay
Samples
Ostracods
Interval
Facies ass.
Palaeoenv.
FOSSO BIANCO UNIT
EARLY PLEISTOCENE (GELASIAN)
0
5
10
15
20
25
30
35
40
CND0
CND1
CND2
CND3
CND4
CND5
CND6
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CND29
CND30
CND31
CND35
CND36
CND37
CND38
CND39
CND40
CND41
CND42
CND43
Caspiocypris group
C. basilicii
C. tiberina
C. perusia
C. tuderis
C. posteroacuta
Cyprideis torosa
1
2
3
A
(A)
A to C2
C2
Deep lake
Shallow lake
Lake Shore
Keys
Wave-dominated lake margin deposits
Deep lacustrine deposits
Lignite, high-organic clay (vegetal matter)
Alternations of silty clay and wave-laminated silt
Wave-laminated silty sand
Wave- to cross-laminated sand
Laminated clay and silty clay
Sandy silt
Gravelly clay
Parallel to weakly lenticular lamination
Wave ripples
Dunes
Nodules horizon
Nodules
Ostracods horizon
Shell beds
Freshwater gastropods
Freshwater bivalves
Plant remains
Wood
Leaves

out. They were interpreted as Gilbert type delta deposits (Facies association B), marshy lacustrine shore deposits (Facies association C1, lithofacies a-e), and sandy lower shoreface deposits (Facies association C2, lithofacies f-i), respectively (Ambrosetti et al., 1995b; Basilici, 1997). A fourth type of deposits (Facies association D), related to distal alluvial fan environment, is somehow associated to the same depositional cycle, although it was firstly indicated as "Ponte Naja" Unit (Ambrosetti et al., 1995a; Basilici, 1997).

The Cava Nuova section (Figs. 3, 4), inside the Fornaci Briziarelli Marsciano quarry, is the accessible outcrop of Fosso Bianco Unit closest (0.5 km) to the Dunarobba Fossil Forest. It was recently measured and sampled, for a total thickness of 44 m. Other 16 m, in continuity with the uppermost part, were previously described (Ambrosetti et al., 1995b, 1997; Basilici, 1997), while other six surveys wells were realized recently in the same area (Figs. 2, 5, 6). Sedimentological and geological features of some selected sections are shown in figure 5.

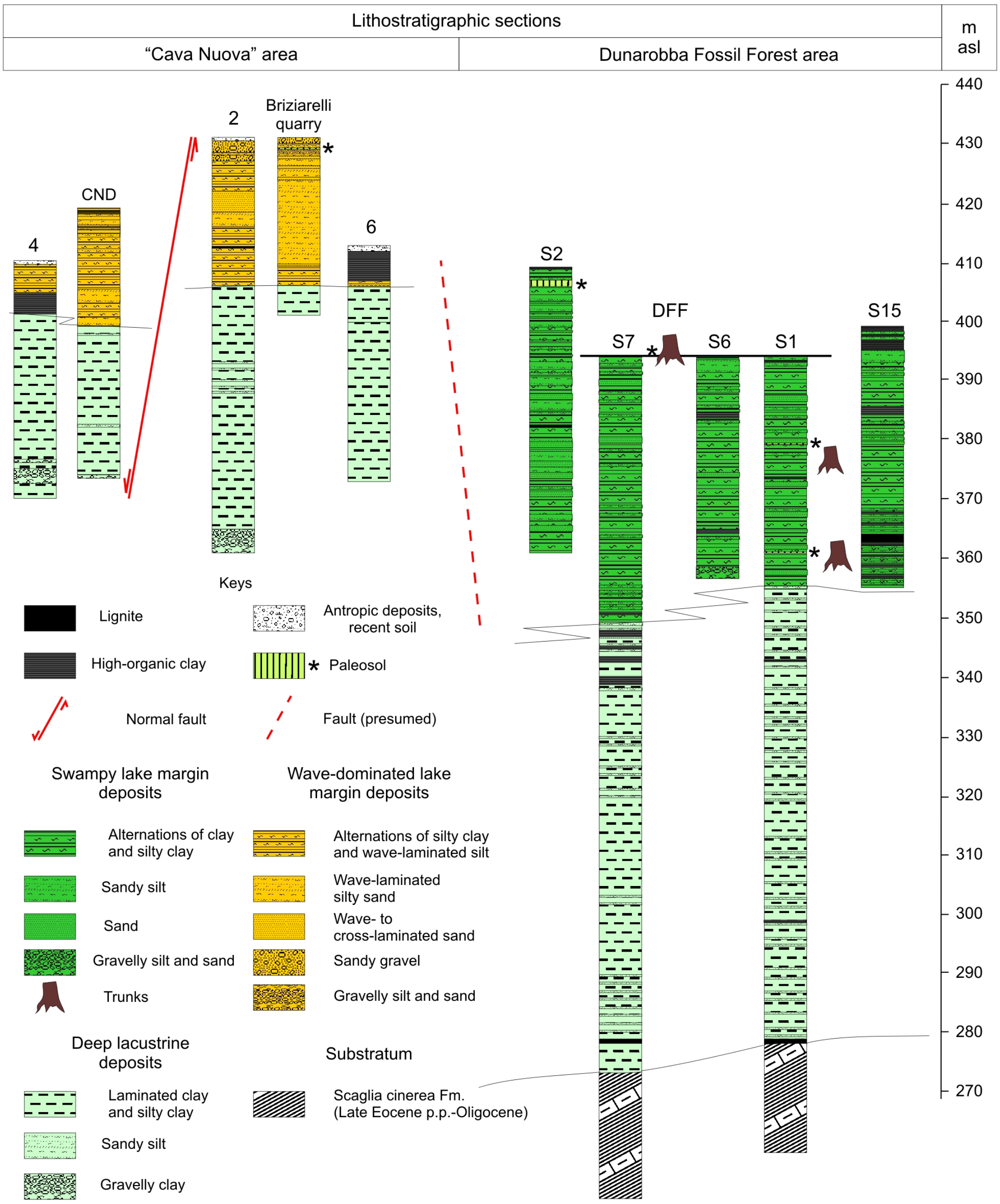

Fig. 5 - Comparison of selected lithostratigraphic columns in the Dunarobba area from recent and further data.

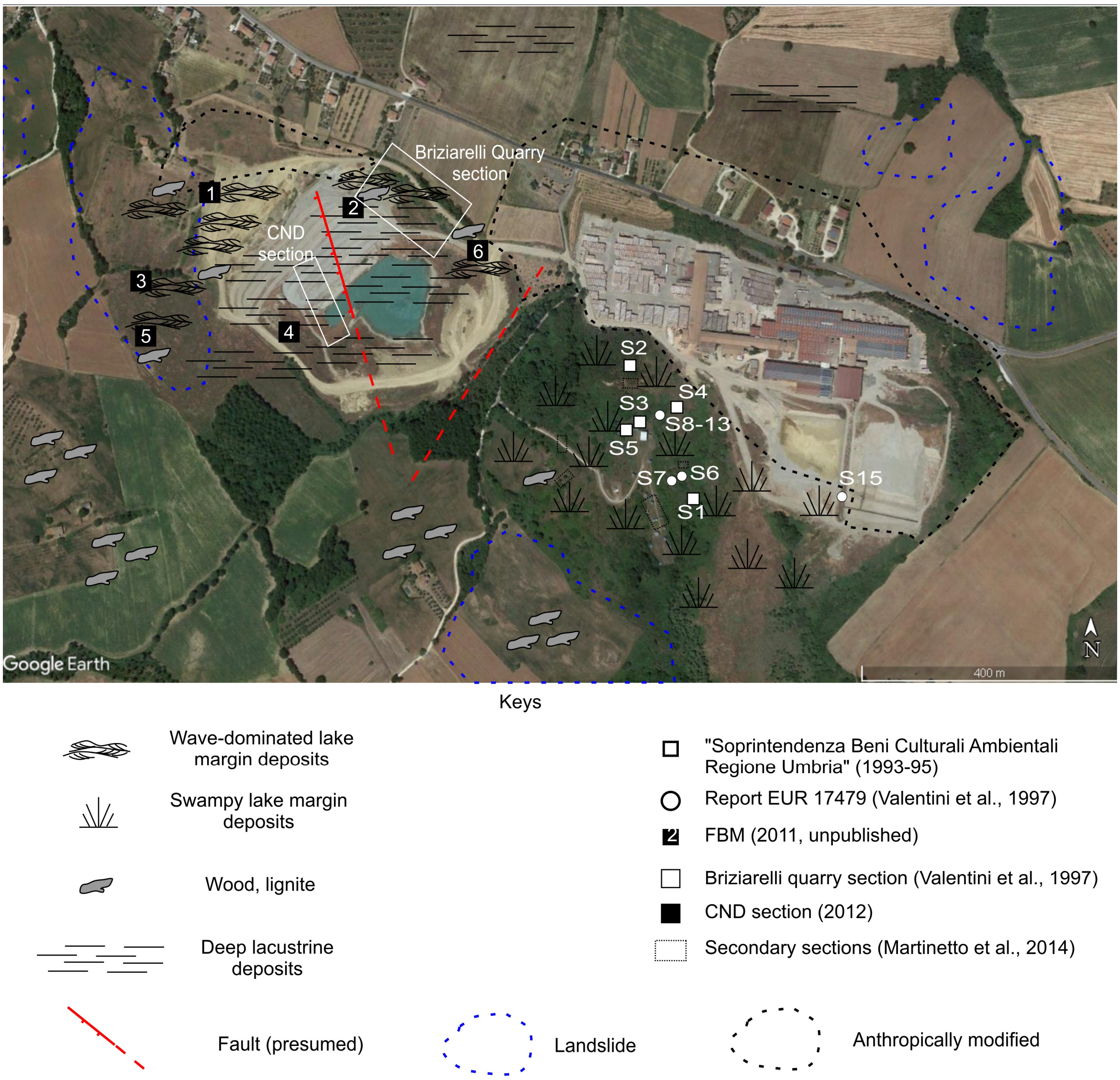

Fig. 6 - Schematic distribution of facies across the Cava Nuova and the Fossil Forest areas. Landslide and anthropically-modified sectors are also perimetered.

3. MATERIALS AND METHODS

A preliminary facies description was carried out directly on the field, and a meter-stepped sampling was performed, with the collection of 44 samples, indicated as CND both in the stratigraphic section and in the tables (Fig. 4, Tabs. 1-4). All samples were considered for microfossil content. About 500 g of each sample were washed in a hydrogen peroxide solution 30% in water and filtered through a Satylon 63 µm sieve. The retained material was dried and observed under a stereomicroscope model Nissan optical equipped with optical fibres. Micropaleontological investigations allowed to identify on washed residues the biological component (mainly ostracod valves and molluscs). On twelve samples, selected according to the preliminary facies description, sedimentological and geotechnical analyses were performed, including soil particle density measurement, particle-size analysis, Atterberg limits and organic matter content, following the ASTM D7263, ASTM D422, ISO/TS 17892-12:2004 and ASTM D2974 standards, respectively. All the analyses were performed at the Applied Geology Laboratory (Department of Physics and Geology, University of Perugia). Although the European Standard (CEN ISO/TS 17892-12 2004) requires the cone penetrometer technique for Liquid Limit determination and indicates the Casagrande cup as an alternative method, the latter was used in the present work. Despite the Casagrande cup method is much operator depending than the cone penetrometer device (e.g., Di Matteo, 2012; Di Matteo et al., 2016), it has been chosen here in order to compare data with those presented by previous works (Candio et al., 1992; Barbieri et al., 1997; Bozzano et al., 2000).

The selected twelve samples were also analyzed for determining their chemical and mineralogical compositions. Major, minor and trace chemical components of the selected samples were determined by X-ray Fluorescence (XRF) on pressed powder pellets utilizing an ARL 9400 XP+ sequential X-ray spectrometer under the instrumental conditions reported in Lezzerini et al. (2013). Within the range of the measured concentrations, the analytical uncertainties are <5% for all the components except for Na_2O, P_2O_5, CaO, TiO_2 and MnO which may occasionally attain <10% for very low concentrations (Lezzerini et al., 2013, 2014). The total amount of volatile components was determined as loss on ignition (LOI in 105-950°C temperature range). The CO_2 content was measured by using the calcimetry method (Leone et al., 1988) on 300 mg of finely powdered samples previously dried at 105±5°C. The difference between LOI and CO_2 values was entirely ascribed to structural water (H_2O).The qualitative mineralogical composition of the selected samples was obtained by X-ray powder diffraction analysis (XRPD) using a diffractometer with a Bragg-Brentano geometry. XRPD patterns were recorded using a Philips PW 1730 automatic diffractometer with the following settings: CuK_α radiation obtained at 40 kV and 20 mA; slits: 1° divergence and scatter, 0.2 mm receiving; scan speed: 1°2θ/min; step size of 0.2°θ and counting time of 2s per step.

Mineralogy of bulk samples was investigated on randomly oriented whole-rock powder.

Oriented mounts of the <2μm fraction deposited on glass slides (2 mg/cm^2: Lezzerini et al., 1995; Moore & Reynolds, 1997) were used in order to identify the clay mineral assemblages. The clay mineral assemblage was studied on Mg^{2+} and K^+ saturated oriented aggregates of the <2μm fraction. The Mg^{2+} saturated specimens were measured in air-dried (AD) and glycolated (EG) states. For some Mg^{2+}-saturated mounts, glycerol solvation was also performed. K^+ saturated mounts were measured in air-dried conditions and after heating at 60, 110, 300 and 550°C. The basal reflections of clay minerals (including mixed-layer phases) were analyzed by DIFFRAC.EVA suite for phase analysis. The XRPD analysis of the main phyllosilicates was carried out following the procedures described by Moore & Reynolds (1997). Quantitative mineralogical composition of the selected samples was obtained by combining XRF and XRD data as suggested by Leoni et al. (2008).

4. CAVA NUOVA SECTION INTEGRATED DATA

4.1. Sedimentological and geotechnical features

On the bases of lithological features, three main intervals are recognized already starting from the description on the field (Figs. 3, 4):

Interval 1 (from the base of the section up to 23 m): silty clay deposits, massive to slightly parallel-laminated. Fossil record is represented by rare gastropods, ostracods, bivalves, plant remains (leaves and wood's fragments). Thin horizons of vegetal remains ("lignite" *s.l.*) and high-organic clay, black to deep brown in colour, also occur. In the interval between 6 and 19 meters, iron -enriched reddish horizons, crusts and nodules are common inside clay, as reported by Gallo et al. (2014). Studies are still in progress, and the preliminary data associated these features to Fe-carbonate ($FeCO_3$, siderite). Deposits in which nodules occur are associated to a relatively deep lacustrine environment, below the wave base; particularly in the lowermost section, features already correspond to these reported by Basilici (1997) for Facies association A. Nonetheless, the presence of siderite crusts and nodules looks here particularly pervasive, on respect to the local, occasional occurrence already reported (Ambrosetti et al., 1995b, 1997; Basilici 1997). Studies on the origin and meaning of siderite nodules are still in progress, and their complete descrip-

Sample	Sieve analysis (%)				LL	PL	PI		Organic matter	USCS
	Clay	Silt	Sand	Fines P#200	%	%	%	Gs	content (wt%)	Class.
CND1	58.0	41.0	1.0	99.9	67	26	41	2.67	2.48	CH
CND4	56.0	43.8	0.2	99.8	65	26	39	2.69	2.68	CH
CND7	58.0	41.5	0.5	99.9	66	25	41	2.76	2.54	CH
CND8	62.0	37.8	0.2	99.8	64	25	39	2.72	2.59	CH
CND14	65.0	34.9	0.1	99.9	70	26	44	2.70	2.88	CH
CND15	61.0	38.7	0.3	99.2	68	25	43	2.79	2.64	CH
CND20	64.0	35.8	0.2	99.9	70	26	44	2.69	2.60	CH
CND25	65.0	34.8	0.2	99.9	71	26	45	2.72	3.18	CH
CND27	41.0	58.8	0.2	99.9	55	24	31	2.72	2.34	CH
CND30	50.0	49.8	0.2	99.9	62	25	37	2.72	2.55	CH
CND36	41.0	58.5	0.5	99.8	57	22	35	2.72	2.58	CH
CND42	41.0	57.3	1.7	99.8	56	21	35	2.72	2.15	CH
CND42b	26.0	57.0	17.0	85.3	44	20	24	2.72	2.04	CL

Tab. 1 - Sedimentological and geotechnical data of selected samples. Index properties of the CND soil samples are reported from the bottom (CND1) to the top (CND42) of the section. LL = liquid limit; PL = plastic limit; PI = plasticity index. PI is the difference between the liquid limit and the plastic limit (PI = LL-PL). Soils with a high PI tend to be clay, those with a lower PI tend to be silt. In case of PI=0, soils are considered to have little/no clay or silt and called non-plastic soil. A soil is also considered non-plastic when LL or PL cannot be determined (N.P.). Gs = specific gravity (pycnometer test); USCS = Unified Soil Classification System (CH = clay of high plasticity - LL > 50; CL = clay of low plasticity - LL <50). Samples CND42 and CND42b refer to the same bed, and are reported as an example of variability in sand/silt/clay fractions according to lateral facies variation.

tion is beyond the aims of this paper: at the moment, we choose to assign siderite-enriched layers to a local, not yet described variant inside Facies association A of former authors.

Interval 2 (from 23 m to 38 m): silty clay deposits, alternated to fine sand and/or silty beds. Sands are usually ripple-laminated. The same thin horizons made of vegetal remains (from charcoal to decimetric wood fragments), described in Interval 1, as well as the high-organic darkish clay, are still commonly documented inside clay, as well as the occurrence, although less frequent, of iron-enriched reddish horizons. Deposits are still referable to a lacustrine environment, showing clear shallowing upward trend, intermittent interaction with wave motion and re-sedimentation processes. Also these deposits can be inserted in the facies description of Basilici (1997): sandy/silty laminated beds are organized as coupled lithofacies f-g, inside the Facies associations C2, while silty clay beds are still referable to Facies associations A. We assume Interval 2 may probably represent a transition between these two Facies associations.

Interval 3 (from 38 m to 44 m): in this interval, deposits are characterized by alternations of sand and silt, from parallel-laminated to cross-laminated. Plant remains, frequently including leaves, are common as well as lignite horizons. Deposits are associated to a lake margin subjected to wave motion, and can be still assigned to some features of Facies association C2 of Basilici (1997), although only lignite beds were previously reported.

The same facies variation, as well as the same depositional architecture, are detectable in the six well-logs all-around the Cava Nuova section (Fig. 5), although the transition, represented by Interval 2 in the main section, is here less defined. These entire supplementary sections grade from clay deposits (presumably referable to relatively deep lacustrine facies) towards sand and silt coastal deposits, locally enriched in vegetal remains and/or high-organic sandy clay. Minor variations are imputable both to lateral facies variation and tectonics (Fig. 5).

Geotechnical data are useful to carry out an integrated analysis with sedimentological and mineralogical ones. Table 1 summarizes the collected geotechnical data for the 12 soil samples from the Cava Nuova section.

Grain size analyses confirm the preliminary field description, with occurrence of three main distributions. Lowermost samples (Interval 1), approximately until meter 25 (CND25 in Table 1), show constant percentages of clay (about 60%) and silt (about 40%) fractions. The silty component increases in the intermediate section (Interval 2), while the sand fraction, which is steadily less than 1%, prevails in the last meters (Interval 3). Figure 7 shows the location of soils on Skempton's activity chart taking into account also the characteristics of soils published by Candio et al. (1992) and Barbieri et al. (1997), also belonging to fluvial-lacustrine deposits of

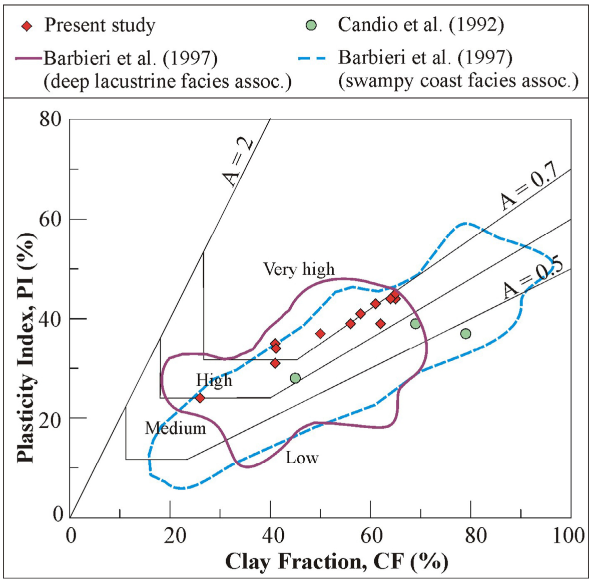

Fig. 7 - Skempton's activity chart (modified after Williams & Donaldson, 1980) for soils in Table 1 and those from Candio et al. (1992). Data from Barbieri et al. (1997) were elaborated from original graph (only boundaries of data were represented).

Dunarobba Fossil Forest area. Soil samples of Cava Nuova falls along the 0.7 Activity (A) line and are characterized by high to very high swelling potential; they fall in the transition zone between deep lacustrine associations and swampy coast facies as defined by Barbieri et al. (1997). Moving from the bottom to the top of the Cava Nuova section, PI values tend to gradually increase up to the medium part of the section (Interval 1), then they decrease upward reaching about 36% in Interval 2 and 24% in Interval 3, where -due to the low silt-clay fraction -a reduction of about 20 percentage points is observed in the last meters.

Although minimal variations in grain size distribution are also related to facies variability, this fact does not affect neither the general trend nor the distribution within the chart of Figure 7. Samples 42 and 42b (Tab. 1) are reported as an example: index properties depend from the percentage of clay fraction rather than from a difference in clay mineralogy.

4.2. Fossil content

Throughout the section (Fig. 4), the fossil content is very poor and represented by rare freshwater gastropods (mainly *Emmericia umbra* specimens) and bivalves, and by ostracods.

The ostracod assemblages, although very poor, found along the Cava Nuova section are mainly represented by the occurrence of genera belonging to the Candonidae family (*Candona neglecta* and *Caspiocypris* group), by the spotted occurrence of *Cytherissa lacustris*, and by the dominance of *Cyprideis torosa* in uppermost samples. The new species of *Caspiocypris*, recently identified (inside both FB and CT sections, see Figure 1) by Spadi et al. (2018a), and considered as endemic of the grey clays of Fosso Bianco Unit, also occur through the Cava Nuova section. Particularly,

Sample	H_2O	CO_2	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
CND1	6.48	10.91	0.29	2.64	11.43	42.36	0.13	2.08	16.24	0.72	0.11	6.61
CND4	6.26	13.17	0.25	2.39	10.55	36.63	0.15	2.01	18.36	0.65	0.17	9.41
CND7	8.66	7.32	0.32	2.81	12.23	44.27	0.12	2.19	14.37	0.78	0.11	6.82
CND8	6.92	8.85	0.25	2.58	11.82	42.35	0.14	2.35	14.66	0.79	0.15	9.14
CND14	7.96	9.66	0.20	2.24	10.74	39.08	0.15	2.14	17.92	0.73	0.15	9.03
CND15	7.23	3.20	0.28	3.27	14.43	55.83	0.11	2.51	6.47	0.93	0.06	5.68
CND20	7.75	8.46	0.21	2.62	12.19	42.27	0.13	2.35	15.14	0.83	0.15	7.90
CND25	7.05	9.21	0.19	2.61	12.31	41.04	0.16	2.21	13.71	0.75	0.16	10.60
CND27	6.61	7.12	0.42	2.95	12.85	47.67	0.14	2.13	11.84	0.82	0.13	7.32
CND30	6.82	7.14	0.37	2.91	13.32	46.46	0.14	2.25	11.23	0.84	0.16	8.36
CND36	5.95	6.66	0.43	2.87	12.38	48.60	0.14	2.39	11.08	0.90	0.15	8.45
CND42	5.82	7.16	0.48	2.70	12.40	47.95	0.16	2.04	11.66	0.75	0.17	8.71

Tab. 2 - Major and minor elements of the analyzed samples (wt.%).

Caspiocypris basilicii and *Caspiocypris tiberina* are documented from the base, followed by *Caspiocypris tuderis* and *Caspiocypris posteroacuta* starting from samples CND12 and CND 23 respectively. In the Interval 1 (Facies association A), the *Caspiocypris* group dominates the assemblages, only with few specimens of *C. neglecta*. A sharp decrease in *Caspiocypris* spp. abundance is detected from sample CND24 (about 24 m from the base of the section) onwards, in correspondence of the progressive increase in the sandy fraction and environmental energy, evidenced by wave ripples and cross laminations structures. From sample CND24 to CND39 (Interval 2), species of the *Caspiocypris* group occurs sporadically, with very low abundances. From sample CND40 (deposits of Interval 3), a sudden increase in the abundance of the ostracods is noted: assemblages are represented by *Cyprideis torosa* (90%) and, for the remaining 10%, by *C. neglecta* and *C. basilicii*. Thus, *C. torosa* characterizes assemblages associated to shallow lake/lake shore paleoenvironmental condition. With regard to the taxon *Cytherissa lacustris*, it is found inside Interval 1 and Interval 3 with two isolated presence (samples CND 15 and CND 42); the low frequencies (no more of 5 valves) suggest a passive transport (wind action and/or dispersion by birds).

4.3. Chemistry and mineralogy

Major, minor and trace chemical data are reported in Tables 2 and 3, respectively.

The observed values indicate a relatively homogenous chemical composition for all the studied samples through the stratigraphic sequence, except for CND1, CND4 and CND15.

In detail (Tab. 2), at the bottom of the sequence the samples CND1 and CND4 exhibit the highest levels of CO_2 and CaO, as well the lowest SiO_2 content. As a rule, SiO_2 and Al_2O_3 slightly increase upwards, while contemporarily CaO tend to decrease. This datum agrees with the increase upwards in the sandy fraction, enriched in quartz and feldspars.

On the contrary, the sample CND15, in the middle of the sequence, shows a very low amount of CaO, with consequently high tenor of the other chemical components. Finally, noteworthy is that Fe_2O_3, which can be considered slightly constant through the section, ranges between 5.68 (CND15) and 10.60 wt.% (CND25): iron is probably a significant component in sediments and/or originary water, and variations are related to the occurrence of levels enriched in siderite nodules. According to major and minor element trends, trace element keep comparable levels over the sequence; an exception is represented by sample CND15, characterized by low Sr, and high Cr, Ni and Ba, due to its high clay/silt+sand ratio (see Tab. 1). Nonetheless, barium keeps relatively high values throughout the section. The derived Rb/Sr ratio (Tab. 3), almost show the same trend, allowing to identify a marked peak at sample CND15.

Sample	V	Cr	Co	Ni	Rb	Sr	Y	Zr	Nb	Ba	La	Ce	Rb/Sr
CND1	128	213	13	< 5	115	261	21	111	100	200	< 20	81	0,441
CND4	129	216	14	< 5	115	278	17	130	88	163	< 20	65	0,414
CND7	136	229	14	< 5	127	247	22	115	88	241	< 20	62	0,514
CND8	136	233	12	< 5	136	257	20	138	95	239	< 20	46	0,529
CND14	128	208	16	< 5	118	283	21	131	94	181	< 20	85	0,417
CND15	142	264	24	53	145	183	19	111	85	442	< 20	91	0,792
CND20	136	222	12	< 5	130	247	23	130	96	206	< 20	69	0,526
CND25	139	238	15	< 5	131	257	18	152	87	238	< 20	32	0,510
CND27	126	215	27	21	120	247	22	146	85	285	< 20	55	0,486
CND30	133	239	16	15	130	231	22	156	93	278	< 20	49	0,563
CND36	126	225	19	26	131	238	23	167	75	264	< 20	57	0,550
CND42	117	216	18	20	113	225	23	178	70	263	< 20	52	0,502

Tab. 3 - Trace elements of the analyzed samples (ppm).

Based on X-ray diffraction analysis on oriented mounts (Fig. 8), the clay mineral assemblage is due to illite (10 Å), kaolinite (7 Å) and expansible minerals (also detectable from the Skempton's activity chart: Fig. 7); in particular, the latter ones consist in illite/smectite mixed layers (according to Cesarano et al., 2018).

The quantitative mineralogical composition determined by combining XRPD and XRF data (Tab. 4) evidence a slight decreasing of calcite with a concomitant increasing of quartz contents over the sequence, from bottom to top. Out of trend is the sample CND15, for which the lower calcite and the higher quartz tenors are calculated.

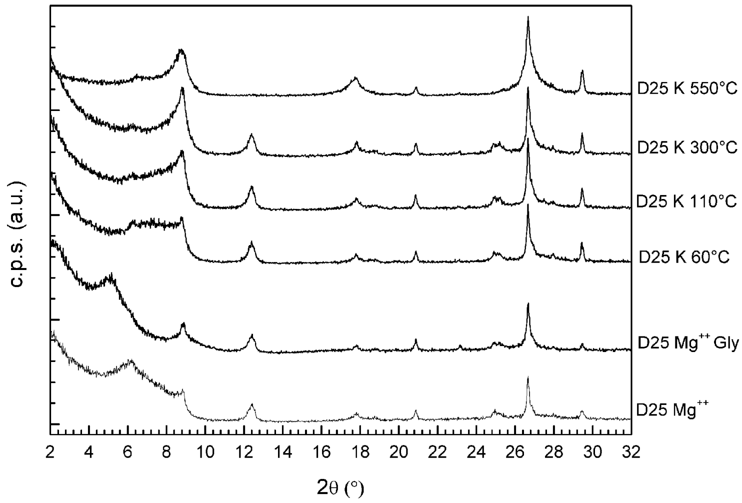

Fig. 8 - XRD patterns collected on oriented mounts of CND25 sample, saturated with Mg++and K+, as example.

4.4. Paleoenvironmental restoration

Facies associations recognized in the Cava Nuova area are only partly comparable with these formerly described (Ambrosetti et al., 1995b, 1997; Basilici, 1997). On the other hand, swamp lacustrine coastal deposits looks circumscribed at the Dunarobba Fossil Forest area. All the sedimentological, geotechnical and paleoecological data from the Cava Nuova section confirm the description and interpretation of facies initially made on the field, and the paleoenvironmental transition from relatively deep lake to coastal lacustrine is reliable. The lowermost section is characterized by fine-grained sediments (clay and silt), indicating a very low water energy and prevalence of decantation processes. The oligotypic assemblages lead to reconstruct the physical and chemical paleoenvironmental parameters. The data on ostracofaunas agree with those reported by Spadi (2018) and Spadi et al. (2018b), where the new proposed *Caspiocypris* species are reported as endemic of the "Paleolake Tiberino". More generally, the common occurrence in assemblages of *Caspiocypris* group indicates deep lacustrine condition, with a minimum depth of at least 50 m (Spadi et al., 2018b), or >40 m (Ruiz et al., 2013). On the other hand, *C. neglecta* is widespread in springs, brooks and ponds connected to springs, and lakes (from shallow littoral to great depths).The species is distributed throughout the Holarctic (Meisch, 2000). The lake was characterized by cool and relatively deep waters, and by a silty to clayey floor, grading upwards to shallower depths, with higher water energy, relatively warmer temperature, and a coarse-grained (sandy/silty) floor. *Candona neglecta*, as well as some species of *Caspiocypris* (as *C. pontica*), tolerate very low salinity conditions (0.5-6‰: Medici & Gliozzi, 2008; Spadi et al., 2018a; 2018b); *C. neglecta* can also sustain low oxygen values (Meisch, 2000; Ruiz et al., 2013), and prefers alkaline to weakly acid pH (Ruiz et al., 2013).

Basin waters were probably moderately to well oxygenated, showing low salinity (between 0.5 and 6‰), neutral pH and low concentration of $CaCO_3$. As lowermost clay samples are enriched in both CO_2 and Calcite (Tabs. 2, 4), this probably reflects the petrology of the mother rocks (source of sediments) rather than the water chemistry. This is not surprising, and a main provenance of fines from Cretaceous to Oligocene marly limestone Units (Figs. 1, 5) is highly probable.

Sample	Calcite	Feldspar	Illite	Smectite	Kaolinite	Other	Quartz
CND1	30	2	22	14	11	4	17
CND4	33	2	21	13	10	7	14
CND7	26	3	23	15	12	4	17
CND8	26	2	25	13	10	7	17
CND14	33	2	22	11	9	7	16
CND15	12	2	26	18	15	2	25
CND20	28	2	25	13	11	5	16
CND25	25	2	23	14	13	8	15
CND27	21	4	22	16	14	4	19
CND30	20	3	24	16	14	5	18
CND36	20	4	25	15	10	5	21
CND42	21	4	21	14	13	6	21

Tab. 4 - Mineralogical composition of bulk samples based on XRD and XRF data.

As the grain-size, the geotechnical parameters and the fossil record are steady throughout the lower section, stable and long-lasting deep lacustrine conditions can be assumed. Time inferences imply considerations on stratigraphic constrains and sedimentation rate, which are discussed later (see § 5.2).

Deposits in the intermediate section (from sample CND23 to CND38) show a coarsening upward trend, with increase of the silt fraction, and the decrease in ostracods specimens. These data are interpreted in terms of shallowing trend and progradation of coastal systems; the prevalence of silty fraction in respect to the clay presumably conditioned the ecology of benthic forms.

In the uppermost section (samples CND39-CND43), the coarsening upward trend proceeds, with a prevailing sandy fraction, and a high content in plant remains, both testifying for the increase in energy and the reduction in depth. The fossil content is dominated by *C. torosa*, species related to transitional waters, shallower depths and/or sandy floor. Deposits are associated to a wave-influenced lacustrine coastal environment. As for the lower section, chemical and physical parameters (water temperature, oxygen content, salinity, pH and concentration of $CaCO_3$) seem to be steady in these two other portions. On the other hand, the increase in sandy portion clearly indicates a coastal shift: in this sense, a higher sedimentation rate is expected.

Throughout the section, mineralogical data show high values in trace elements values (Tab. 3), particularly for barium, reaching 441 ppm in sample CDN15, but constantly over 200 ppm. As evidenced by Muller (2014), barium appears to play an important role in bacterial metabolism, as well as iron and other trace elements. Local condition could be related to the development of freshwater algal, protozoan, and bacteria, all organisms able to produce intracellular barite from geological material like clay (Muller, 2009, 2014, with references therein).

5. DISCUSSION

Inside the wide outcropping area of “Fosso Bianco” Unit (Fig. 1), Cava Nuova section and Dunarobba Fossil Forest areas represent single, although related, observation point, and this bias needs to be considered in generalizing the results of analyses. Nonetheless, some points can be highlighted.

5.1. Relationships between Cava Nuova and Fossil Forest areas

A crucial point in every paleoenvironmental restoration lies on the originary vertical and lateral relation between deposits pertaining to the two areas of Cava Nuova and Fossil Forest, respectively. Although they are really close (Figs. 2, 5, 6), facies cropping out in the two areas are almost different. A detailed facies description and redefinition is beyond the aims of this work, and we choose still to refer to Facies associations proposed by previous authors (Ambrosetti et al., 1995b, 1997; Basilici, 1997, 2000b): nonetheless, some differences were remarked, and, in our opinion, a partial integration is probably needed. A simplified chart of facies cropping out (Fig. 6) reveals how Swampy lake margin deposits and Wave-dominated lake margin deposits (Facies associations C1 and C2 of Basilici, 1997, respectively) seem to be confined to the two areas. Both types of deposits overlay Deep lacustrine deposits (Facies association A, with variations: Basilici, 1997), which are recognized only on quarry fronts and well-logs (Fig. 5). In the fields all around (Fig. 6), the occurrence of plant remains (mainly large wood fragments) were commonly documented (F. Famiani, pers. comm. 2018), although they can be alternatively related to both types of lake margin. As firstly proposed by Ambrosetti et al. (1995a) and Basilici (1997), the relations between the two areas at least partly result from Late Pleistocene and Holocene tectonics. As shown in the transect reconstructed across the Cava Nuova and the Fossil Forest areas (Fig. 5), minor faults are documented only in the fresh-exposed quarry fronts, while, according to the facies distribution, deposits all-around the Fossil Forest look undisturbed. Thus, a NE-SW striking fault, with a presumed transtensive component, associated to the main fault system (Fig. 1) and dividing the two areas (Cava Nuova and Dunarobba Fossil Forest), although reasonable, it is not directly detectable on the field and can only be presumed. Moreover, the direction of movement and the amount of dislocations are not easy to quantify. As discussed later, and according to sedimentation models formerly proposed (Ambrosetti et al., 1995b, 1997; Basilici, 1997; Martinetto et al., 2014; Spadi et al., 2018b), the two types of lake margin could be strictly related, thus tectonics can be considered a secondary factor in present-day distribution of facies on the field.

5.2. Stratigraphic constrains

A definitive age attribution for deposits of Fosso Bianco Unit cropping out in the Dunarobba area is still debated. A time range from ~3.1 to ~2.0 Ma is commonly accepted for the whole unit, although its base was never clearly identified, nor in outcrop or in wells. According to Ambrosetti et al. (1995a), the southern branch of the Tiberino Basin accommodated ~1 km of post-Miocene deposits; assuming, for the sedimentation rate, the mean values reported in the previous section, it implies a possible ~5 Ma duration for deposition inside the basin. Thus, Fosso Bianco Unit could be extended downwards fairly closer to the Miocene-Pliocene boundary. On the other hand, only two sections were calibrated to magnetostratigraphic scale (Abbazzi et al., 1997; Pontini & Bertini, 2000; Pontini et al., 2002; Martinetto et al., 2014): the Cava Toppetti section, near Todi, and the Fosso Bianco section, south from Dunarobba Fossil Forest (CT and FB in Figure 1, respectively). As the first one documents the Gauss (successive to Kaena) - Matuyama (nearly successive to Reunion) magnetostratigraphic interval (between about 2.8 and 2.02 Ma), the second only records 87 m-thick reversal interval, calibrated to the Gelasian portion of the Matuyama chron (about 2.5-2.2 Ma). Pontini & Bertini (2000), by meant of pollen record, also remark the occurrence of four short but clearly recognizable “climatic” phases, in which the climate oscillated between ”temperate-warm” (pollen zones II and IV) and “subtropical humid” (pollen zones I and III). These four intervals took place between the 102 (or 100) and 82 isotopic stages (i.e.: between 2.56-2.52 and 2.16 Ma).

The recent phyletic revision of *Caspiocypris* group lead on by Spadi et al. (2018 a, 2018b), and their stratigraphic, although local, use, also shade a new light in the study of Fosso Bianco deposits. The tentative of phylogenetic relations within the *Caspiocypris* species flock of the Palaeolake Tiberino suggested by Spadi et al (2018a) evidenced that the appearance of *C. tuderis* is a remarkable local event that took place inside the lower (but not basal) Early Pleistocene (Gelasian), in both Cava Toppetti and Fosso Bianco sections. Inside Cava Nuova section, this event is documented in the middle portion of Interval 1 (sample CND12, Fig. 4), where the assemblages are characterized by *C. basilicii*, *C. tiberina* and *C. perusia*, in the same stratigraphic position as in the other two sections. Although this local event could be time-tansgressive, and new confirmations are expected, its relevance for local stratigraphy and correlations appears evident.

As pointed out by previous authors, the deep lacustrine deposits (Facies association A) inside Fosso Bianco Unit record significant fluctuations in sedimentation rate, depending on the stratigraphic and the paleoenvironmental/paleogeographical situation (Abbazzi et al., 1997; Pontini & Bertini, 2000; Pontini et al., 2002; Martinetto et al., 2014). Average values vary from 14-15 cm/kyr at Cava Toppetti, to 21-28 cm/kyr at Fosso Bianco (CT and FB sections in Fig. 1, respectively). According to these values, the *C. tuderis* local event should be dated to about 2.5-2.45 Ma, in both the sections. Assuming the same sedimentation rates for the lowermost, deep lacustrine deposits at Cava Nuova, the first 23 m could have been deposited in a time between about 80-100 kyr (sedimentation rate of 21-28 cm/kyr) and about 155-160 kyr (sedimentation rate of 14-15 cm/kyr). Thus, the deep lacustrine phase cropping out at Cava Nuova should be comprised between about 2.58-2.55 and 2.4-2.37 Ma.

Thus, a Gelasian age can be finally assumed also for the lowermost, deep lacustrine deposits (Interval 1) cropping out at Cava Nuova. As the section shows a continuous facies transition inside a shallowing-upward trend (Fig. 4), an almost continuous decreasing in age is also expected, with no major time gaps and hiatus. Assuming the same sedimentation rate values also for Intervals 2 and 3, the whole section (43 m) should record a 150 to 280 kyr time interval. That is, the top of the section should be dated between 2.4 and 2.3 Ma. On the other hand, throughout that facies transition variations in sedimentation rate are expected. Although the alternation of dryer and wetter intervals recorded in Fosso Bianco section seems not to find a direct sedimentological and/or paleontological correspondence at Cava Nuova (Fig. 4), the lowermost section (Interval 1 and part of Interval 2) records cool water conditions, and it could be associated to pollen zone II of Pontini & Bertini (2000). This hypothesis looks consistent with the geochemical peak in Rb/Sr ratio noted in sample CND15 (Tab. 3). This ratio may reflect mother rock compositions, as well as the Sr content could result from different processes, such as primary carbonate productivity, or early diagenetic calcite dissolution. Nonetheless, it could also be cautiously considered as indicative of the prevalence of physical or chemical weathering in the catchment area (for example, see Xu et al., 2010). Although data are too scarce to reconstruct a climatic trend, in our opinion the hypothesis that this peak could be related to a moment of cool/arid climate, which favoured physical weathering, and which falls shortly after the *C. tuderis* local event (around 2.45 Ma), should be considered in paleoenvironmental restoration.

In this way, part of Interval 2 and Interval 3 could be associated to at least part of pollen zone III, and an age about 2.24 for the top of the section could be reliable.

To assign an age to deposits from the Fossil Forest area is even more speculative; nonetheless, some hypotheses need to be considered. Ambrosetti et al. (1995b), mainly on the base of paleoecologic/paleoclimatic topics, firstly proposed a Piacenzian age for the Fossil Forest. Assuming the sedimentation rates previously discussed, and its top being not younger than 2.588 Ma, the base of the composite section (extending from top of S2 to substrate in S1-S7 sections: Fig. 5) should be dated between about 3.49 and 3.06 Ma. It implies the Fossil Forest area records the very beginning of sedimentation inside the Fosso Bianco Unit, which was never documented otherwise. The older deposits inside Cava Toppetti section, indeed, are dated to about 2.8 Ma. In central Italy, so ancient deposits were documented in the Valdarno Basin (Napoleone et al., 2003), and in the eastern branch of the Tiberino Basin (fossil record inside the lignites of Morgnano, attributed to Triversa Faunal Unit: Bizzarri et al., 2018, and references therein). Although this hypothesis cannot be totally abandoned, some question arises. The presence of such old deposits in a restricted area, fairly close surrounded by younger (Gelasian) deposits, and both older and younger deposits indifferently overlaid by the same lithostratigraphic unit (S. Maria di Ciciliano Unit: Ambrosetti et al., 1995a), can be justified only in terms of main tectonic displacement, occurring in a very short time interval (200 kyr) between Gelasian and Calabrian (Early Pleistocene tectonics). As synthesized in Figure 1, the present geological setting seems to be mainly related to Middle-Late Pleistocene tectonics, and to the occurrence of an important NE-SW oriented strike-slip area between Dunarobba and Acquasparta villages (see also geological schemes proposed by Ambrosetti et al., 1995a, Basilici, 1997, and Spadi et al., 2018b).

The same shallowing-upward trend, from deep lacustrine deposits to coastal deposits, is documented in both the Cava Nuova and Fossil Forest areas, and in both cases idealized composite stratigraphic sections do not record the occurrence of a second, superimposed cycle. That is, both situations appear to record a "final", although local, evolutive step. This cannot be easily justified if the ages are significantly different, and the presence of several overlapping sedimentary cycles should be expected.

On the bases of ostracofauna, Spadi (2018) and Spadi et al. (2018b) proposed deposits of the Fossil Forest area are almost coeval to the Ponte Naja Unit (2.2-2.0 Ma: Abbazzi et al., 1997; Pontini et al., 2002). As discussed in Martinetto et al. (2014), the Dunarobba

Fossil Forest record, particularly pollen record from S2 section, can be also correlated with the pollen zone III of Fosso Bianco section (Pontini & Bertini, 2000). In this way, Cava Nuova Section and Dunarobba Fossil Forest paleofloristic records were recomprised in the persistence of "humid thermophilous plant taxa of East Asian affinity" (HUTEA) as "Pliocene relics", and inside their progressive disappearance through Early Pleistocene in southern Europe, as proposed by Martinetto et al. (2017). As the local trend of progressive decrease in depth, although with different evidences, is recorded in all the sections of the Fossil Forest and Cava Nuova areas (Fig. 5), the hypotheses the two areas are coeval, and that both record the transition between pollen zones II and III, seem to be reasonable. As assumed for the Cava Nuova section, swampy coastal facies interval could be dated to about 2.4-2.2 Ma; thus, the base of the composite section (S1-S7 in Figure 5) should be positioned between about 2.95 and 2.8 Ma.

In the Fosso Bianco section, the pollen zone III is associated to deep lacustrine clay deposits enriched in thin mud- or debris-flows deposits, bearing vegetal remains (Pontini & Bertini, 2000; Martinetto et al., 2014), which can be justified as resedimentation deposits from coastal areas enriched in vegetation, as documented in both the Cava Nuova and Fossil Forest areas.

For all the exposed reasons, the time gap between deposits pertaining to the two areas (Cava Nuova and Dunarobba Fossil Forest) and their related sections is reasonably minimum, and an average age comprised between 2.5 and 2.2 Ma for the outcropping portion of Fosso Bianco Unit in the area can be assumed.

5.3. Comparison with former mineralogical and geotechnical data

Considering the distribution in Figure 7, samples collected throughout the Cava Nuova section are comparable with the data of Barbieri et al. (1997): thus, the belonging to the variability of Fosso Bianco Unit sediments is clearly demonstrated. On the other hand, data from Skempton's activity chart does not allow a unique assignment to deep lacustrine (A) and/or swampy coast (C1) facies associations. Moreover, our uppermost samples fall in the area of the graphic, although they are clearly associated to a wave-dominated coast. Contrarily to what supposed by Barbieri et al. (1997) and Bozzano et al. (2000), this parameter does not fully express the facies variability inside the Fosso Bianco Unit. Otherwise, when considered together with numeric grain size distribution, it has a more direct correlation with sedimentological intervals described in the field. Thus, if the sedimentological interpretation is needed, the method can be an additional tool for the analysis of either short sections or wide datasets. On regard to the mineralogical composition of clay fractions, significant bias occur when old and new data are compared, as well as in the comparison between "mineralogical" and "geotechnical" content of clay. Nonetheless, both geotechnical and mineralogical data highlight the uniformity in clay composition, while only the amount of the clay fraction varies throughout the section. This quite homogeneous composition throughout the section confirms the hypothesis of a steady supply from the same source area through time. However, the slight increasing of sandy fraction (consisting mainly in quartz) from bottom to top indicates a modification of sedimentation condition from deep to coastal environments, with intermittent inlets of terrigenous materials highlighted by the occurrence of quartz-rich levels in the middle of the sequence (see for example sample CND15), becoming more frequent and even dominant upwards.

5.4. Insights for the basin evolution

From what discussed in the previous paragraphs, some paleoenvironmental, paleogeographic and geological implication can be proposed.

- Measured sedimentological/geotechnical parameters, such as grain size and Skempton's activity for clay, show a linear trend throughout the section ranging from very high to high (Activity $\simeq$ 0.7), thus indicating a coarsening upward of deposits inside the basin rather than a clear variation of supply. This statement is supported by the overall uniformity in the mineralogy of clays, whose assemblage is due to constant level of illite/smectite, and kaolinite over the sequence.

Assuming a time interval of 150 to 280 kyr (for the deposition of the whole Cava Nuova section), or of 80 to 160 ky for sedimentation of the deep lacustrine clay alone, this homogeneity implies a long-lasting supply of sediments from the same feeding area. Nonetheless, discontinuities in the material supply, suggested by the variability in sand-silt enriched levels, especially in the middle and in the upper part of the section, needs to be explained. This could imply the occurrence of occasionally climatic and/or tectonic events, determining the inlet of quartz-rich sediments. This trend is particularly clear for uppermost section (Fig. 4). As pointed out in § 5.3, a local source for deposits is inferred: in this way, quartz-rich fraction can derive by erosion of Oligocene-Miocene sandstone Units (Fig. 1). This wide paleoenvironmental and compositional homogeneity also lead to exclude a far source of sediments, such as a structured river environment. That is, resediments inside the basin derived from local, contiguous environments, such lake coasts and minor fan-delta.

- The deep lacustrine phase inside the Fosso Bianco Unit (i.e.: the one documented by Facies association A of Basilici, 1997) can be considered as a stable, invariant, and long-lasting environment. Such phase (and the Fosso Bianco Unit as a whole) is characteristic of the South Tiberino Basin, and finds no equivalent in the other sectors of the basin, each one evolving through time in its peculiar way (Ambrosetti et al., 1995a; Coltorti & Pieruccini, 1997; Melelli et al., 2010; Bizzarri et al., 2011, 2018; Pucci et al., 2014; Bucci et al., 2016; Mirabella et al., 2018). On the bases of evidences provided by the ostracofaunas (Medici & Gliozzi, 2008; Spadi, 2018; Spadi et al., 2018a, 2018b), this lake can be properly considered a relic of late Messinian -Zanclean marine to brackish conditions ("Paleo-ancient lake"), a water mass with altered salinity imprisoned into a continental basin, with no input-output dynamics. In fact, no data are available about the beginning of this phase, and maybe only real deep perforations could provide definitive information.

- On the other hand, the clear transition upwards from deep lake to coastal lake conditions, directly described in the Cava Nuova section, is also found in all the sections in the area (Fig. 5). This datum needs to be discussed, and three main questions arise. First, this variation could reflect a climatic trend, as well as it may be driven by tectonics. As a second problem, it is not finally clear where, in the stratigraphic succession of Fosso Bianco Unit, this variation takes place, if in the uppermost part or just at the end of its deposition. The third point is if this regressive trend marks the definitive change in environmental conditions (e.g.: the end of depositional cycle 1 and the transition to depositional cycle 2), or if phases of rise and fall of the lake's level repeated through time. According to what discussed in § 5.2, the Cava Nuova and Dunarobba Fossil Forest areas record the uppermost, but not final, sedimentation inside the Fosso Bianco Unit. As deposits in the whole area can be considered nearly coeval, the outcrop conditions mainly derive from the Late Pleistocene-Holocene evolution of the Tiber Valley. In northern sector (Cava Toppetti area: Fig. 1), deep lacustrine sedimentation extends until about 2.0 Ma. It is possible that the unconformity between the cycles 1 and 2 reasonably cut a sensible part of the lower cycle, particularly in the southern portion of the basin (Ambrosetti et al., 1995a; Basilici, 1997). Inside the >800 kyr lasting sedimentation of Fosso Bianco Unit, study sections (Fig. 5) are relevant but only represent less than the 1/3 of the outcropping Fosso Bianco Unit. They better photograph a single evolution phase, or the transition between two phases, rather than synthesize the whole sedimentological, climatic, stratigraphic variability inside the Unit. Shorter phases (high-order cycles) probably repeated through time, although they seem to be clearly detected only at Fosso Bianco (Pontini & Bertini, 2000; Martinetto et al., 2014). The fossil record from plants (Martinetto et al., 2014, 2017), vertebrates (Abbazzi et al., 1997; Pontini et al., 2002), and ostracofauna (Spadi, 2018; Spadi et al., 2018b), as well as the geological-sedimentological interpretation (Ambrosetti et al., 1995a), suggest a general trend inside the "Fosso Bianco" cycle, from deep lacustrine to coastal facies. Thus, Fosso Bianco Unit (and the related units like Ponte Naja Unit) document at least part of a 3rd order cycle. Regarding what drove the changes, Cava Nuova Section and Dunarobba Fossil Forest somehow insert in the phase of global climatic instability, which characterized the Gelasian stage, but they mainly record local changes. The longer persistence of some floristic species in central Italy after the end of the Piacenzian with respect to the northern part of this country, probably due to the intermediate pattern between climatic changes described for the central Mediterranean littoral and the North Apennine ones (Martinetto et al., 2014, 2017), must be considered. According to Martinetto et al. (2014) the remarkable Fossil Forest at Dunarobba was produced by an ancient swamp vegetation dominated by *Glyptostrobus europaeus*; trees grew in a wetland with high sedimentation rate, bordering the ancient lake, and both disappeared due to the establishment of well-drained paleoenvironmental conditions, testified by a paleosol profile (Basilici, 1997). The successive restoration of wetland conditions was not sufficient for the preservation of *in situ* tree trunks (Basilici, 1997). Coastal facies associations, although different between Cava Nuova and Fossil Forest areas, were probably both related to a lowering phase in the lake's level.

The relative uniformity of the pollen curves (Martinetto et al., 2014) suggests that the extra-local vegetation and climate remained stable for a long time span. All these data fit well with the mineralogical-petrographic homogeneity we record in the Cava Nuova section, so the paleoenvironmental variation was probably better explained by local (or even regional) morphological changes induced by tectonics. Tectonics probably led to a strong activity of faults at the boundary, producing a large sediment supply from the same feeding area, and causing the progradation of coastal lake systems and the fall in the level of the lake, as proposed by Ambrosetti et al. (1995b) and Basilici (1997). The data discussed herein, and their comparison with old and recent papers, lead to suggest this fall represented the main, somehow definitive, phase closing the lower depositional cycle.

Far from a definitive understanding and modelling of timing and evolution for the Tiberino Basin, what discussed in this paper ranks in the wake of the recent literature, which tries to shade new light on such problematic. Furthermore, it is probably time to reconsider and partly revise the general geological, stratigraphic, and paleoenvironmental scheme for the Fosso Bianco Unit.

6. CONCLUSIONS

Inside the Pliocene-Pleistocene evolution of the Tiberino Basin, the vertical and lateral relations of deposits in the "Fosso Bianco" Unit are a key-point and, unfortunately, they are still an open problem. The new collected data, far to dispel all doubts, put new light to better understand the paleoenvironmental features of at least part of the lacustrine phase. Such long-lasting environment, although fairly structured, survived almost invariant for at least 2.1 Ma. Both the Dunarobba Fossil Forest and the Cava Nuova areas record analogous depositional trend, from deep lake to coastal lake, although represented by different facies: this phase, lasting 150 to 280 ky, can find correspondence in the transition between pollen zones II and III documented in the "Fosso Bianco" section by Pontini & Bertini (2000) and correlated with the early Gelasian. Although new evidences are needed, this phase could continue towards the Gelasian-Calabrian boundary, until 2.2-2.0 Ma. During the Gelasian climatic instability, the system seemed to accommodate local variations rather than a global trend, as expected for the global datum of southern Europe. Starting from a section recording a continuous facies transition, this work proposed a multidisciplinary approach to better understand both sedimentological-geotechnical and mineralogical aspects. The analytical procedures reveal useful, and we expect they can be a tool to characterize other clayey soils outcropping in the

Tiberino Basin fluvio-lacustrine context, as well as in other paleolacustrine environments.

ACKNOWLEDGMENTS

We kindly thank dr. F. Posati and dr. F. Famiani for their support on the field, and dr. F. Cavalcante and an anonymous reviewer for their precious comments and suggestions in improving the manuscript.

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Ms. received: August 17, 2018
Final text received: December 1, 2018