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The geology of the Camerano area through the reconstruction of sedimentary sequences of the urban caves

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ABSTRACT

The historical town of Camerano (Ancona, central Italy), built on a hill just west of the Mt. Conero promontory, is laced with a broad underground system of remarkable man-made caves. Thanks to the caves, we can view and describe a composite sedimentological and stratigraphic section of Early Pleistocene (Calabrian) marine deposits, which lack subaerial outcrops. This study is aimed at a better definition of the sedimentological and palaeoenvironmental context of the Camerano area, and at improving the knowledge of the Camerano caves. Sediments are mainly couplets of massive- to- laminated, yellow-brown, bioclastic calcareous sand and massive, grey-green clay, of variable thickness. Each couplet shows an erosive basal surface and normal gradation, from sand to clay. Plane-parallel lamination, marked by recurring variations in grain size, is attributed to traction carpets and the sand horizons to resedimentation by sediment-gravity flows, with an eastern source (Mt. Conero). Conversely, clay reflects both western distal river-delta supply and a local contribution from marine productivity. Beds of matrix-supported gravel made of heterometric clay fragments dispersed in a bioclastic sand matrix also occur within the sedimentary section. These interpretations differ partially from earlier geological schemes and offer new insights into the palaeoenvironmental reconstruction of the Camerano area. The reconstruction involves a tectonically active Early Pleistocene basin, mainly dominated by clay sedimentation, but periodically reached by storm- and seismic-induced carbonate gravity flows. The matrix-supported conglomerate of large clay fragments was probably derived from remobilization of partially lithified deposits along the basin's eastern flank.

Keywords: Sedimentology, Periadriatic Basin, Early Pleistocene, Marches, Central Italy

1. INTRODUCTION

Around the Mt. Conero promontory of the Marches region (central Italy, Fig. 1), several hill towns, including Sirolo, Loreto, Castelfidardo, Osimo and Camerano, have man-made cave systems, originally intended for various uses e.g., water supply, housing, defence, granaries, escape routes, gatherings and rituals (RECANATINI, 1997, 2000). The extensive Camerano "underground town" is composed of more than twenty complexes, formerly all connected. A local popular saying attests that *"...there is more of Camerano underground than above ground"*. The entire cave system is localized under the historical centre, in the area of the first Piceno settlement of VII-VI century B.C. (as testified by the necropolis at the western side of the hill), subsequently occupied by the nucleus of the medieval fortress (Castelvecchio, 800 A.D.). Starting in pre-Roman times, the caverns were excavated in weakly cemented marine sands and clays. The original purpose of such wide and pervasive excavation is still unknown. The interpretation of sandstone quarries seems unsatisfactory, due to the richness of architectural motifs and ornaments testifying to a continuous human use through the centuries. Furthermore, the underground town has been utilized from the XI century A.D. to recent years for several different uses, often denoting a parallel evolution with the growth of the external town (RECANATINI, 1990, 1997). Thanks to the interest and competence of the Camerano Municipality and to the contribution of local amateurs, the historical and artistic features of the cave system have been well studied and the underground town is now largely accessible. Nevertheless, its geological features are still largely unknown.

The recent building development superimposed on the medieval remains has totally obliterated the geological features and the outcrops all around the hill. Thus the exceptional underground town is the only avenue to reconstructing a composite sedimentological and stratigraphic section of the Early Pleistocene marine deposits (LUCCIONI, 2007), a component of the composite evolution of the Periadriatic Basin (a sector of the Plio-Pleistocene Adriatic foredeep *sensu lato*). In the whole Marches area (Fig. 1A), the surface structural configuration of the foredeep sediments, essentially referable to as a gentle, easterly dipping growth monocline, largely obscures the complexity of the basin's evolution. A series of buried deep-seated active thrusts and transverse faults, strongly affected the basin physiography and guided the clastic fill patterns, imposing major control during much of the Plio–Pleistocene and dividing the basin into sectors with unique features and evolution (ORI & FRIEND, 1984; BIGI et al., 1997; CENTAMORE & NISIO, 2003; CANTALAMESSA & DI CELMA, 2004). The basin is mainly filled by a Plio-Pleistocene clay-rich succession, and a general regressive trend is usually recognized, but the occurrence of several coarse clastic bodies, commonly underlain by major unconformities and intercalated at various stratigraphic levels, testifies to a complex sedimentary evolution (CANTALAMESSA et al., 2002; CANTALAMESSA & DI CELMA, 2004). Recent studies indicated the occurrence of submarine canyons in the southwestern area, further complicating the sedimentological and palaeoenvironmental scenery (DI CELMA et al., 2010; DI CELMA, 2011; DI CELMA & CANTALAMESSA, 2012). This work provides description and interpretation of sedimentary features never previously described in the Ancona sector. In spite of their position in the uppermost part of the Plio-Pleistocene sedimentary sequence, within the general shallowing-upward trend, the studied deposits record outer-shelf resedimentation rather than beach and subaerial environments. The composite underground section of Camerano puts a new light on sedimentary environments and processes and gives some insight into the evolution of the eastern margin of the basin, at least to the west of the Conero Mountain 'island.'

2. GEOLOGICAL SETTING

Camerano is located 15 km SW of Ancona, in a hilly territory on the western flank of Mt. Conero, and was built on top of a hill at about 231 m above s.l. (Fig. 1). Mt. Conero

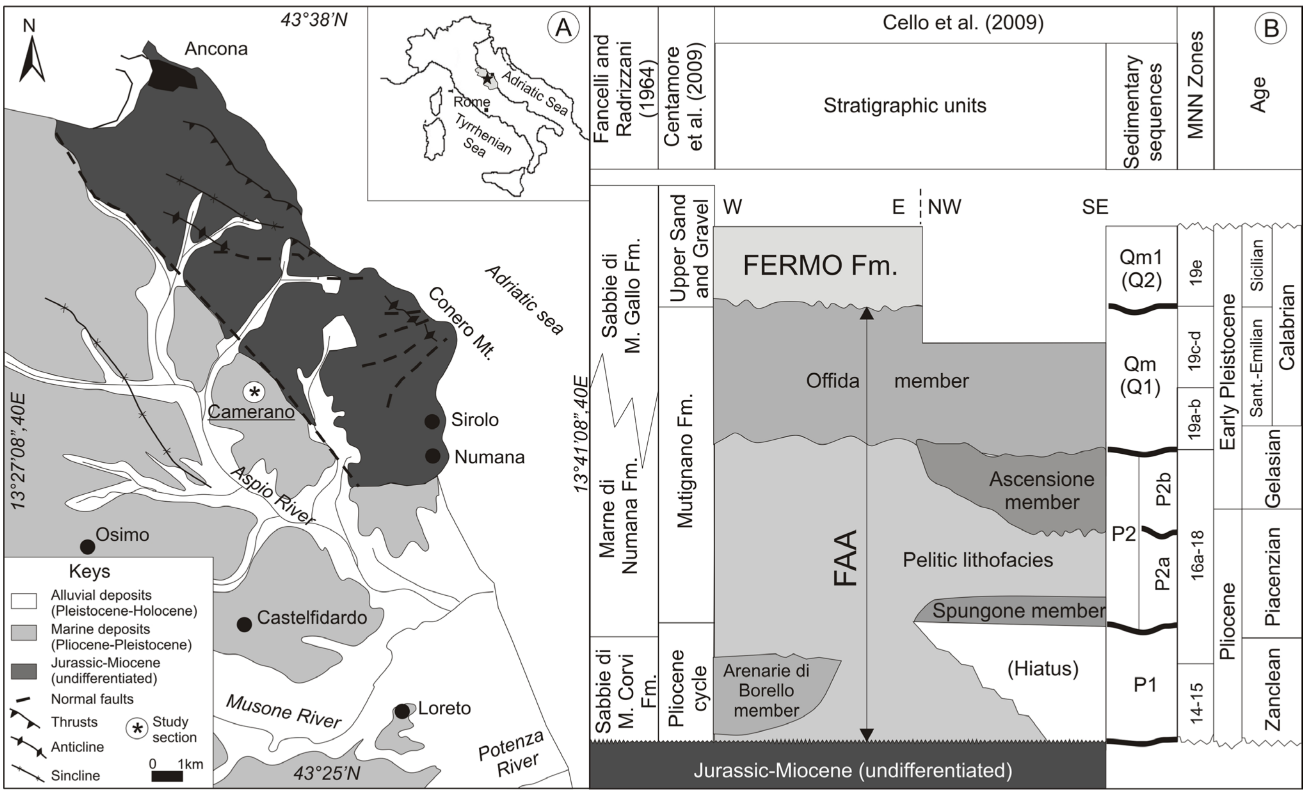

Figure 1: A) Geological sketch of the Ancona sector. The Marches area is also underlined (light gray in the insert). B) Comparison between lithostratigraphic schemes proposed for the Pliocene-Pleistocene of the Periadriatic Basin. MNN=Mediterranean Neogene Nannofossil (according to RIO et al., 1990).

is an anticline of Umbria-Marches Meso-Cenozoic lithostratigraphic units. The hilly area west of Mt. Conero is cut by the present-day Aspio and Musone river valleys, both part of the wider Chienti Basin. It belongs geologically to the Neogene-Quaternary Periadriatic Basin that developed during the late phases of the Apennine orogeny as the foredeep and foreland migrated eastward (BOCCALETTI et al., 1986, 1991; RICCI LUCCHI, 1986; CALAMITA et al., 1991; CENTAMORE et al., 1991; ORI et al., 1991; CENTAMORE & NISIO, 2003).

The main structure of the Periadritic Basin is the result of at least three different tectonic phases, that took place from the Miocene to recent times (CALAMITA et al., 1991; ORI et al., 1991; CELLO et al., 2009). On the basis of different tectono-sedimentary evolution, the Periadriatic Basin can be divided in the Ancona, Fermo, Teramo, and Chieti sectors (CANTALAMESSA et al., 1986; CENTAMORE & NISIO, 2003; CENTAMORE et al., 2009). Several authors interpreted the Ancona sector (Fig. 1A), (which includes the Camerano territory), as a Pleistocene syn-tectonic basin (wedge-top basin: CENTAMORE et al., 1991; open piggy-back basin *sensu* ORI et al., 1991), related to evolution of the Marches foredeep basin. The Ancona sector is bordered to the north and south by NE-SW oriented structural highs (faulted uplifts), while to the east and west it is bounded by compressional structures (anticlines, which are partially buried: CENTAMORE et al., 2009).

The entire Periadriatic Basin was submarine during most of the Pliocene and Pleistocene. The sedimentary deposits record the composite effects of tectonics and sea-level changes. Several transgressive-regressive sedimentation cycles, delimited by major unconformities, are recognizable (Fig. 1B: COLALONGO et al., 1979; CANTALAMESSA et al., 1986; NANNI et al., 1986; CENTAMORE et al., 1991, 2009; ORI et al., 1991; CANTALAMESSA & DI CELMA, 2004; CELLO et al., 2009; MICARELLI et al., in press). Vertical and lateral facies variations suggest an intra-basin palaeoenvironmental differentiation, induced by local tectonics and sea-level fluctuations (CANTALAMESSA & DI CELMA, 2004; CELLO et al., 2009; DI CELMA et al., 2010; DI CELMA, 2011; DI CELMA & CANTALAMESSA, 2012). The Pliocene - Pleistocene marine succession (Fig. 1B) shows an overall transgressive-regressive trend, characterized, from base to top, by neritic- to- littoral sandstone and conglomerate deposits (Pliocene cycle), by pelitic deposits with interlayered gravely sand/sandstone and sandy clay horizons (Mutignano Formation), and finally by neritic- to- littoral and/or continental sand and gravel (Fermo Formation) (cf. CANTALAMESSA et al., 1986; CENTAMORE & MICARELLI, 1991; CENTAMORE et al., 1991, 2009; CENTAMORE & NISIO, 2003). Recent geological mapping led to a partial stratigraphic revision (CELLO et al., 2009; SARTI et al., in press): deposits from both the Pliocene cycle and the Mutignano Formation are now grouped in the "Argille Azzurre" Formation (FAA - Formazione delle Argille Azzurre: Early Pliocene - Early Pleistocene: Fig. 1B). The FAA is mainly pelitic and is subdivided into a Pliocene marly pelite with minor sandstones and a Pleistocene dominantly pelitic portion, characterized by four intercalated lithofacies: gravely sand/sandstone, sand/sandstone, clayey sand and sandy clay. Based on the sand/clay ratio and the distribution of lithofacies, several local members are also recognizable in the FAA (CANTALAMESSA et al., 2002; CANTALAMESSA & DI CELMA, 2004; CELLO et al., 2009).

This study deals only with the Pleistocene section. The Camerano sedimentary sequence is characterized by a lower part of mainly pelitic composition and by an upper part dominated by sand/sandstone intermingled with clay, formerly referred to as the Marne di Numana and Sabbie di Monte Gallo Formations, respectively, and as the Mutignano Formation (Fig. 1B: FANCELLI & RADRIZZANI, 1964; CENTAMORE et al., 1991; CENTAMORE & MICARELLI, 1991; CANTALAMESSA & DI CELMA, 2004). On the new geological maps (SARTI et al., in press), the Camerano sed-

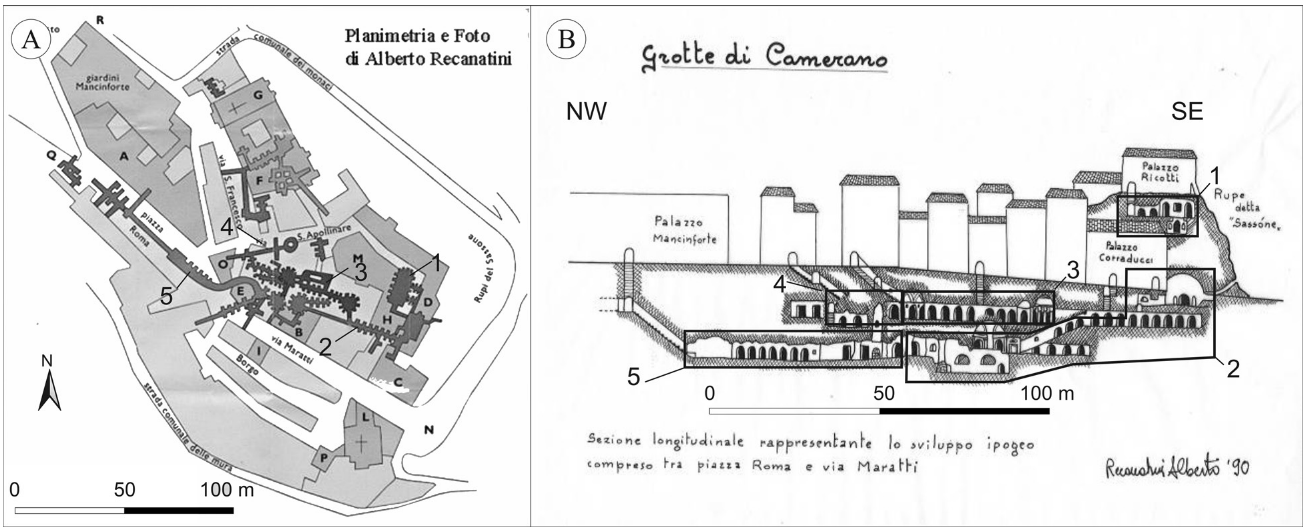

Figure 2: Map of the Camerano underground system (modified after RECANATINI, 1990): A) Planar view; B) Section view (same horizontal and vertical scale). 1=Grotta Ricotti; 2=Grotta Corraducci; 3=Grotta Gasparri-Trionfi; 4=Grotte del Torrone; 5=Grotta Mancinforte.

iments are entirely attributed to the FAA (Fig. 1B), in particular to the pelitic lithofacies (lowermost part) and to the arenitic/pelitic and pelitic/arenitic lithofacies (uppermost part). The stratigraphic position and sedimentary features of the upper deposits place them in the Offida Member (Q1 phase *sensu* CELLO et al., 2009).

3. THE SUBTERRANEAN CAMERANO SECTION

3.1. Materials and methods

Sedimentological and lithostratigraphic description has been carried out along and across the underground levels (Figs. 2, 3 and 4), and a composite sedimentological section has

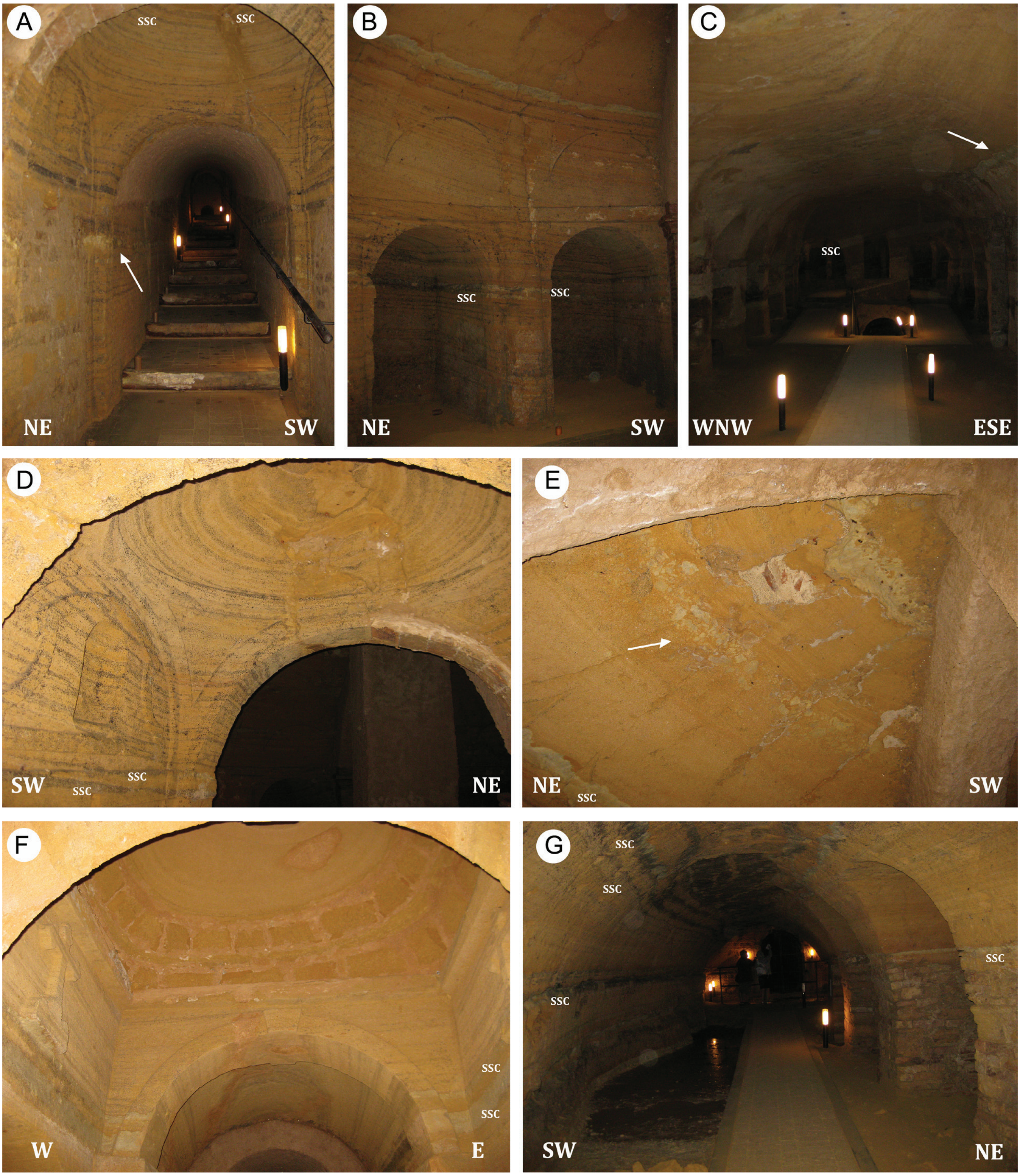

Figure 3: Views of the Camerano cave system: A, B, D, E) Grotta Corraducci: A) and B) show entirely the "Stairs" and "Trionfi room" sections of Figure 4, respectively; C) Grotta Ricotti; F) Grotta Gasparri-Trionfi; G) Grotta Mancinforte. Horizontal beds (A, D-G) and 5° westward inclined beds (B, C) are visible, as well as sand-clay couplets (SSC) and matrix-supported clay-clast conglomerate (arrows).

been reconstructed. In both the Grotta Mancinforte and Grotta Ricotti sections, close sampling (about 10 cm-spacing) for each sand-clay couplet (see below) was carried out, and 1 cm^2 of washed residue has been counted to provide a quantitative analysis of foraminifers (Tab. 1). These samples also provide a semi-quantitative grain-size analysis. With the same criteria, some clay fragments have been sampled and analysed (Fig. 4). Finally, nannoplankton biostratigraphy was carried out on all Grotta Mancinforte and Grotta Ricotti clay samples (Fig. 4).

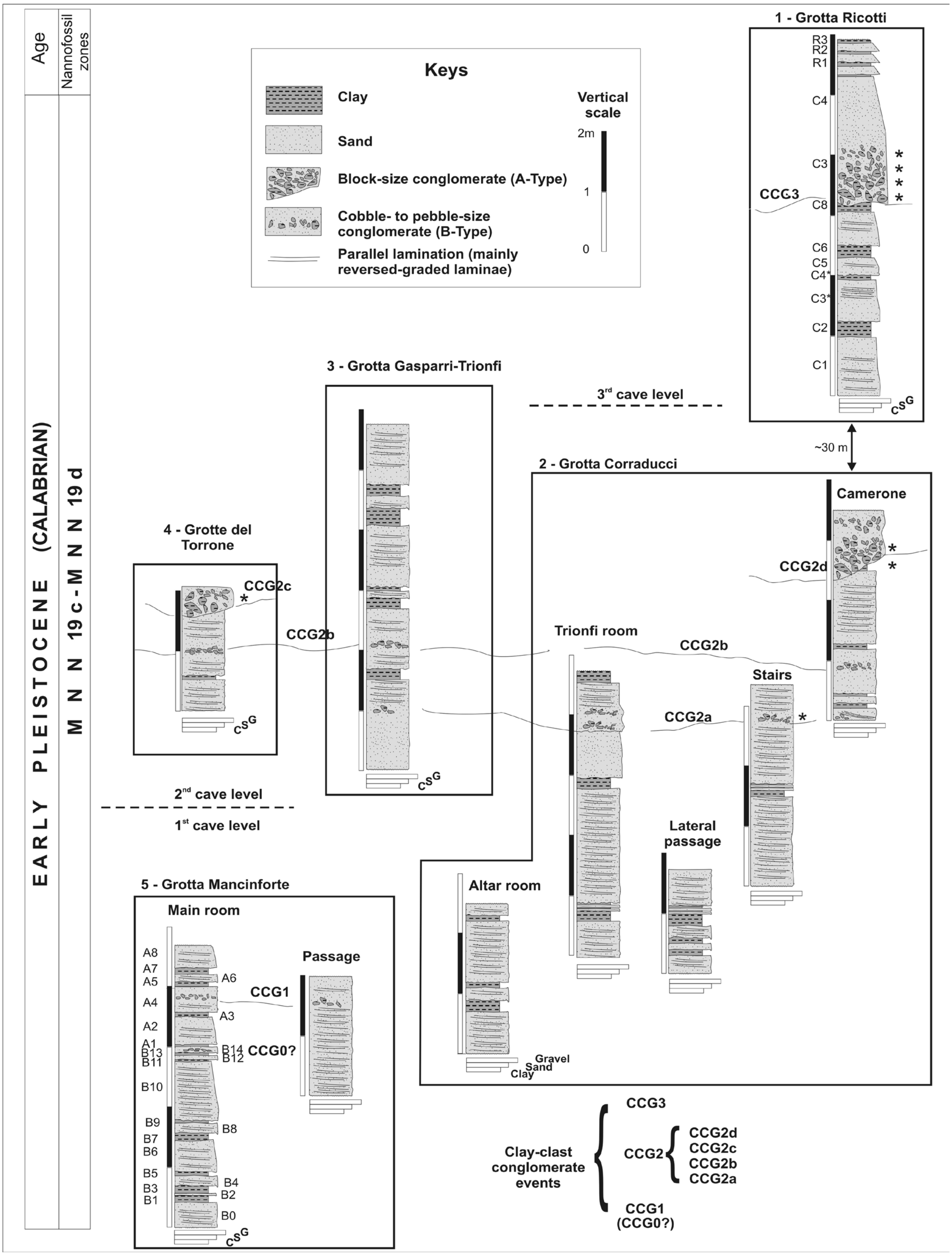

Figure 4: Sedimentological and stratigraphic logs, drawn throughout the rooms, from west (left) to east (right), and along the three main cave levels. Horizontal distances are not to scale. Micropalaeontological and biostratigraphic samples (letters) and clay fragments samples (asterisks) are indicated. Nannofossil zones refer to RIO et al. (1990).

Table 1: Foraminifera assemblages in the lowermost (Grotta Mancinforte) and uppermost (Grotta Ricotti) Camerano section (modified after LUCCIONI, 2007). Percentage for each taxon is calculated on the total of benthic and planktonic foraminifera, respectively. S=sand level; C=clay level.

									Benthic foraminifera																	Planktonic foraminifera										
									Infaunal						Infaunal/ Epifaunal		Epifaunal																		
	Samples	Lithology	Benthic foraminifera (n)	Planktonic foraminifera (n)	Total specimens/cm2	P/B ratio	Planktonic foraminifera (%)	Species Diversity	*Ammonia* group %	*Bulimina* group %	*Cassidulina* sp. %	*Melonis* sp. %	*Pullenia* sp. %	*Uvigerina* group %	*Bolivina* group %	*Elphidium* group %	*Gyroidina altiformis* %	*Hyalinea balthica* %	*Lenticulina* sp. %	*Lobatula lobatula* %	*Patellina corrugata* %	*Planulina ariminensis* %	*Quinqueloculina* sp. %	other *benthic foraminifera* %	*Globigerina bulloides* %	*Globigerina quinqueloba* %	*Globigerinoides ruber* %	*Globigerinoides sacculifer* %	*Globigerinoides trilobus* %	*Globorotalia crassaformis* %	*Globorotalia inflata* %	*Globorotalia* cfr. gr. *menardii* %	*Hastigerina siphonifera* %	*Neogloboquadrina spp.* %	*Orbulina universa* %
Grotta Ricotti	R3	C	120	522	642	4	81	14	17	13	0	0	0	0	1	27	0	3	2	9	28	0	0	0	20	0	13	0	7	0	20	0	0	16	23
	R2	C	42	336	378	8	89	12	5	0	0	0	0	0	0	24	0	5	0	36	24	0	0	7	18	0	27	0	0	0	33	0	0	0	23
	R1	C	70	237	307	3	77	13	1	30	0	0	0	0	31	1	0	1	1	14	19	0	0	0	34	0	22	0	23	0	0	0	0	0	21
	C4	S	129	119	248	1	48	25	6	7	0	2	0	3	0	8	2	2	8	5	32	0	8	19	24	0	11	0	38	0	18	0	7	0	3
	C3	S	132	362	494	3	73	25	9	8	0	1	3	2	3	6	12	1	18	6	24	0	0	7	43	0	11	0	24	0	13	0	6	0	3
	C8	C	187	607	794	3	76	25	10	5	0	3	3	4	4	3	17	1	25	1	13	2	0	10	22	0	14	0	34	0	15	0	12	1	2
	C6	C	8	756	764	95	99	11	0	13	0	0	0	0	0	0	0	13	13	50	13	0	0	0	19	0	16	0	16	0	15	0	0	16	17
	C5	S	15	17	32	1	53	10	20	20	0	0	0	0	0	13	7	0	0	0	20	0	7	13	0	0	41	0	29	0	0	0	0	0	29
	C4*	C	111	247	358	2	69	25	20	5	0	5	0	3	1	5	3	2	19	2	25	1	5	6	19	0	13	0	38	0	17	0	10	0	2
	C3*	S	77	304	381	4	80	18	6	6	0	0	6	1	0	4	10	0	5	4	55	1	0	0	20	0	19	0	33	1	21	0	1	1	4
	C2	C	97	384	481	4	80	20	10	9	0	0	0	6	7	7	29	1	4	1	18	0	0	7	23	0	9	0	30	2	22	2	11	0	2
	C1	S	58	51	109	1	47	19	10	7	0	3	0	2	2	17	9	2	7	7	28	7	0	0	14	0	12	0	24	0	35	0	6	0	10
Grotta Mancinforte	A8	S	57	39	96	1	41	16	4	16	0	0	0	0	0	7	2	4	12	2	9	0	42	4	5	0	3	0	54	0	3	0	8	0	28
	A7	C	267	515	782	2	66	35	3	11	2	1	0	4	1	8	14	1	6	7	27	0	0	13	23	0	22	0	30	0	12	0	6	2	4
	A6	S	71	73	144	1	51	23	6	4	0	1	0	4	1	13	1	1	21	1	24	0	0	21	23	0	15	0	55	0	0	0	3	4	0
	A5	C	81	74	155	1	48	20	7	5	0	1	0	0	0	26	4	2	0	20	27	0	0	7	20	0	3	0	18	0	9	0	0	9	41
	A4	S	72	32	104	0	31	20	13	10	0	0	0	0	0	11	6	0	17	3	21	1	10	10	3	0	9	0	38	0	6	0	0	3	41
	A3	C	188	322	510	2	63	29	1	16	9	0	1	1	4	1	14	0	15	4	15	1	0	17	33	0	14	0	17	0	20	0	10	3	3
	A2	S	46	61	107	1	57	19	2	13	4	0	0	2	0	11	4	0	24	2	13	0	13	11	11	0	13	0	52	0	11	0	2	0	10
	A1	C	179	247	426	1	58	38	8	7	4	2	0	2	5	6	14	2	6	7	17	0	3	16	32	0	17	0	19	0	17	2	7	2	4
	B14	S	37	264	301	7	88	11	0	0	0	0	0	0	0	30	3	0	0	0	54	0	11	3	23	0	23	0	23	0	27	0	0	0	5
	B13	C	165	165	330	1	50	15	6	12	0	0	0	0	0	18	12	1	0	12	27	0	6	5	21	0	24	0	24	0	0	0	0	0	30
	B12	S	9	-	9	-	0	3	0	0	0	0	0	0	0	44	0	0	0	0	0	11	44	0	0	0	0	0	0	0	0	0	0	0	0
	B11	C	52	146	198	3	74	14	40	0	0	0	0	0	0	2	8	2	0	6	37	2	0	4	34	0	0	0	55	0	3	0	0	1	7
	B10	S	99	54	153	1	35	23	10	7	4	1	0	2	0	3	10	1	18	3	26	2	3	9	20	0	19	0	37	0	11	4	0	0	9
	B9	C	199	255	454	1	56	32	1	9	2	0	2	3	5	2	16	2	15	4	22	2	0	17	27	0	22	0	25	0	11	2	8	2	2
	B8	S	54	52	106	1	49	22	26	6	0	0	0	2	2	0	6	4	7	0	26	4	4	15	10	0	19	0	46	0	4	0	2	0	19
	B7	C	229	327	556	1	59	33	12	9	0	1	1	3	1	8	10	0	9	8	21	2	1	12	24	0	16	0	22	0	13	1	17	2	4
	B6	S	38	80	118	2	68	22	11	5	0	3	0	0	0	0	5	0	21	3	16	8	8	21	18	0	16	0	38	3	11	1	4	3	8
	B5	C	128	191	319	2	60	37	2	4	1	4	0	4	2	8	4	2	4	10	32	6	1	16	25	0	11	2	26	2	8	3	10	4	10
	B4	S	42	40	82	1	49	21	12	5	0	0	0	5	0	36	7	0	0	2	14	2	5	12	18	0	8	0	20	0	15	0	5	18	18
	B3	C	105	81	186	1	44	29	6	7	1	0	0	4	0	20	0	4	0	1	42	0	5	11	31	0	11	1	19	1	11	4	5	5	12
	B2	S	65	95	160	2	59	26	2	14	0	0	0	0	0	20	0	0	2	8	34	8	2	12	23	2	5	4	32	0	11	2	5	1	15
	B1	C	158	86	244	1	35	33	0	6	4	1	1	4	2	15	1	1	1	18	29	3	2	13	0	1	8	5	19	0	14	1	0	6	47
	B0	S	66	42	108	1	39	31	5	3	0	2	0	5	2	12	6	0	2	3	15	9	6	32	17	0	10	7	24	0	10	2	2	2	26

The superposition of three main accessible cave levels (Figs. 2, 3: RECANATINI, 1990, 1997), with their pattern of tunnels, allows one to describe a section about 30 m thick of Early Pleistocene marine deposits (Fig. 4), and provides a three-dimensional view of depositional geometries. The recent opening of the touristic route across the caves allows completion of the stratigraphic succession, and a one-metre-spaced sampling was carried out. A refinement of the preliminary micropalaeontological analyses (cf. LUCCIONI, 2007) is also provided.

Sedimentary deposits are mainly lightly cemented, yellow-brown sand and grey-green clay couplets, with variable thickness and sand/clay ratios. Sedimentary beds alternatively show a sub-horizontal attitude or an average 5° westward inclination (Fig. 3): this feature is extremely variable along the section, and also for the same beds throughout the rooms, while interposition of tectonic disturbances has not been documented. Although it may reflect the regional tectonics (main gentle south-westward dip of FAA in the Ancona sector), this local variability is considered here as a primary depositional feature reflecting the original gentle inclination and the irregularities of the slope. Unfortunately, the interposition of erosional scars and/or unconformity surfaces has not yet been documented, and the 3D geometries of depositional bodies are hard to reconstruct. The uppermost (Grotta Ricotti) and intermediate cave levels are separated by about 30 m of deposits (Figs. 2b, 4), only partly visible through some ventilation pits, indicating that the sand-clay alternation is continuous throughout the section. In the uppermost Grotta Ricotti (n. 1 in Fig. 2) and in the middle- level cave system (Grotta Corraducci, Grotte del Torrone: ns. 2 and 4 in Fig. 2, respectively), two main matrix-supported gravel horizons occur, made of claystone fragments of various sizes (from 2–3 cm to 50–60 cm), dispersed in a bioclastic sandy matrix (hereafter: clay-clast conglomerate). Minor clay-clast horizons are locally visible in the Corraducci-Trionfi-Torrone complex (ns. 2, 3 and 4 in Fig. 2) as well as in the lowermost Grotta Mancinforte (n. 5 in Fig. 2).

3.2. Sedimentological analysis

Sand-clay couplets - Sand-clay couplets are the main depositional feature visible in the caves. Each couplet is marked at the base by an erosional surface, locally with load casts. Most couplets are normally graded, from plane-paral-

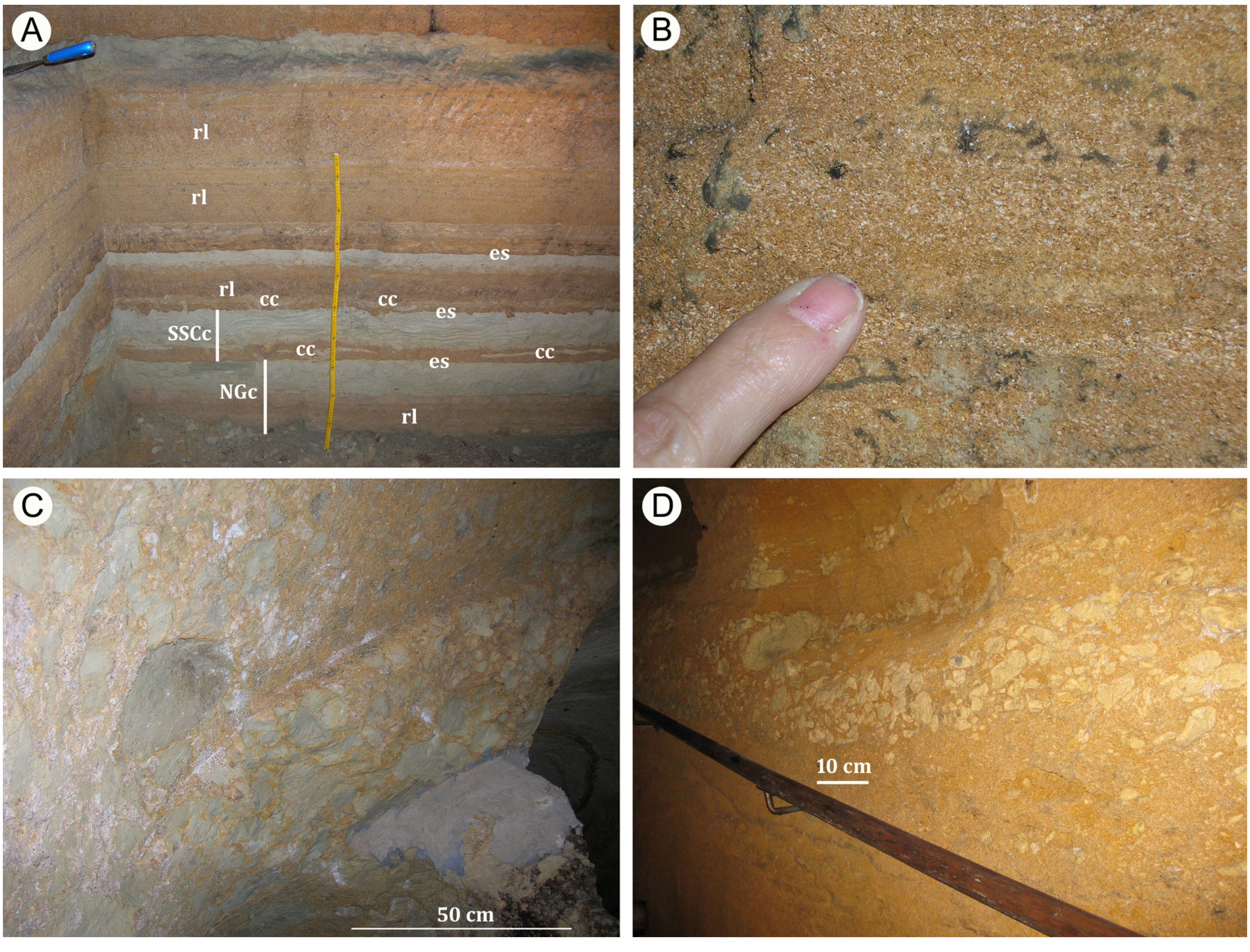

Figure 5: Main facies occurring in the studied deposits. A) Sand-clay couplets: alternation of plane-parallel laminated sand and massive clay horizons (Grotta Corraducci). NGc=normally graded couplet; SSCc= couplet with sharp sand-clay contact; rl=reverse-graded laminae; es=erosion surface; cc=clay chips. B) Detail of reverse-graded laminae in sand (Grotta Mancinforte). C, D) Matrix-supported conglomerate of clay clasts dispersed in yellow sand matrix: *A*-type (C, Grotta Ricotti) and *B*-type (D, Grotta Corraducci) clay-clast conglomerates are shown.

lel laminated sand to massive clay, or more rarely the sand-clay transition is sharp (Fig. 5A). However, the sand intervals are typically reverse graded at the base.

A single couplet can vary from 10 cm to 1.5 m in thickness, and the sand/clay ratio is also variable: thickness varies from 5 cm to 1 m for sandy horizons, and from 5 to 50 cm, for clay beds. Average values are about 40–50 cm and 20 cm for sand and clay horizons, respectively. The sand/clay ratio approximately varies from 1:1 to 4:1. Sand lithology is dominated by bioclastic fragments, with subordinate limestone clasts and rare quartz and chert clasts. Sand grains, varying from fine to coarse sand, are 50–90% bioclasts (mainly shell fragments and benthic foraminifera), 10–50% monogenic carbonate lithoclasts, with less than 5% other lithoclasts. Clay chips occur at the base of some sand horizons (Fig. 5A). In their lowermost portion, most sand horizons are characterized by reverse-graded, plane-parallel laminae (Figs. 5A, 5B); only rarely, do sands appear massive. Patchy pseudospar cement occurs, whereas a pelitic matrix is totally absent ("washed" look). Some sand horizons also show parallel cross-lamination (H ~5 cm) and/or symmetric ripple lamination in the uppermost part, but they are very rare along the section (less than 10% of the couplets). Grain size gradually decreases upward, passing to silt and clay, and it is still generally marked by a parallel lamination; sharp sand/clay contacts are also documented (Fig. 5A). The rare cross- to ripple laminated layers are confined to some of these sand beds with sharp tops. Among the mud fraction, clay largely dominates. Massive clay beds are characterized by high plasticity and by a fossil content of foraminifera and other very small bioclasts.

Oxidation zones are present at the erosional base of many couplets, or marking sharp sand-clay transitions. Oxidation partially extends into the overlying deposits, and thus appears to represent a post-depositional (diagenetic) feature.

Clay-clast conglomerate – Matrix-supported conglomerates are represented by claystone fragments, partially lithified and dispersed into a bioclastic sandy matrix. Clay fragments are highly variable in size (from few centimetres up to 50 cm in diameter) and shape, sub-angular to sub-rounded. The claystone chips appear identical in colour, plasticity, and grain size to the interlayered clay horizons, and they are also comparable to the clay beds in terms of fossil content. The sandy matrix has the same grain size, composition, cementation as the sand beds, and comparable microfossil assemblages. Two different types of conglomerate are recognizable (Fig. 5):

A – Type: block-size conglomerate, with erosion base surface, probably channelled (Figs. 3C, 5C). The size of clay clasts decreases upward, and a sort of normal gradation is documented; nonetheless, the contact with overlying sands is sharp.

B – Type: cobble- to pebble-size conglomerate layers, localized within sand layers (Figs. 3E, 5D), with no recognizable erosion base surface. Clay clasts are interposed between very coarse grained, massive sand and medium to fine grained, plane-parallel laminated sand.

3.3. Palaeontological record and stratigraphic data

Malacofauna – The first naturalist studies of the Camerano caves (PROCACCINI RICCI, 1841; DE BOSIS, 1860) noted the abundance of fossil remains, mainly represented by marine molluscs. The major fossil horizons are observable along the cave vaults. A rich fossil collection has been gathered between 1970 and 1980, and is on display at the Camerano Town Hall (Collezione A. Ruzziconi). The fossil record includes *Pecten jacobaeus* (LINNAEUS), *Callista (Callista) chione* (LINNAEUS), *Glossus humanus* (LINNAEUS), *Venus* spp., *Chlamys (Aequipecten) opercularis* (LINNAEUS), *Chlamys (Flexopecten) inaequicostalis* (LAMARCK), *Ostrea lamellosa* BROCCHI, scaphopods and serpulids. Although the fossil assemblage has no stratigraphic relevance, it is roughly homogeneous throughout the section and comparable to the one described by FANCELLI & RADRIZZANI (1964) for the "Sabbie di Monte Gallo" Unit.

Foraminifera - Both sand and clay beds are rich in benthic and planktonic foraminifera. Preliminary stratigraphic and micropalaeontological data for Grotta Mancinforte and Grotta Ricotti deposits are reported by LUCCIONI (2007).

The occurrence, from the base of the section, of frequent *Globorotalia inflata* and rare *Globorotalia crassaformis* constrains the whole section to the Gelasian-Calabrian interval. An Early Pleistocene age is also indicated by the common occurrence throughout the section of *Hyalinea balthica* (BALDANZA et al., 2011).

Calcareous nannofossils - The Calcareous nannofossil analysis has been carried out in clay deposits, as they are totally missing in sand horizons. The nannoflora, locally very abundant and in a good state of preservation, is dominated by small *Gephyrocapsa*, medium *Gephyrocapsa*, large *Gephyrocapsa* (*sensu* RAFFI, 2002), *Coccolithus pelagicus, Helicosphaera sellii* and *Helicosphaera carteri*, and could be referred to MNN 19c and MNN19d Nannofossil Subzones (RIO et al., 1990).

Nannofossil analyses constrain the Camerano section to the Calabrian, thus better defining the age as Q_m phase, as described in CENTAMORE et al. (1991) and CENTAMORE & MICARELLI (1991), or the Q_1 phase (CELLO et al., 2009). These data also agree with the age proposed for the top of FAA in the recent CARG Project (SARTI et al., in press).

4. DISCUSSION

4.1. Palaeoecological inferences

The whole malacofauna is indicative of clayey or sandy floor palaeoenvironments (PERES & PICARD, 1964); the occurrence of the genera *Glossus*, *Callista* and *Chlamys* probably reflects a minimum depth of about 40 m. Furthermore, *Glossus* indicates cool conditions at the sea floor. We suppose the lack of gastropods in the assemblage is probably due to the instability of the sea-floor.

The benthic and planktonic foraminifera assemblages (Tab. 1) show no remarkable differences between sand and clay horizons in the Camerano sedimentary sequence, except for specimen abundances and species diversity, which are both higher in clay beds (LUCCIONI, 2007). The micropalaeontological content (Tab. 1) shows evidence of mixed planktonic foraminifera, shallow-water (20-50 m depth) (*Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp.) and deeper water (50-100 m) benthic foraminifera (*Bolivina* spp., *Bulimina* spp., *Cassidulina* spp., *Hyalinea balthica, Uvigerina* spp., *Gyroidina* spp.). Percentages of shallow water specimens on total benthic foraminifera (Tab. 1) vary from 21% to 55% in sandy beds and from 6% to 64% in clay horizons. As expected, the P/B ratio is significantly higher for clay beds: nevertheless, in 60% of the sand beds, the P/B ratio is ≥1, evidencing an anomalous enrichment in the planktonic component for sandy deposits (Tab. 1). Thus, sand-clay couplets reasonably document resedimentation/remobilization events, followed by the re-establishment of low-energy conditions, while clay horizons document resedimentation, distal river supply and water-column productivity of biota. As a result of remobilization, a gradual transition is expected in clay beds, from a reworked microfauna assemblage at the base, to an assemblage at the top dominated by water-column productivity. Unfortunately, the available data do not allow documentation of this variation; more detailed analyses are needed.

Benthic foraminifera assemblages (average values of about 33% of shallow-water taxa and about 25% of deeper water taxa), as well as plankton/benthos ratios (Tab. 1), indicate a shallow-water sandy sea floor, distally connected to a deeper (up to 100 m) clayey floor (circa-littoral to upper bathyal zones). Cold-water planktonic foraminifera, such as *Globorotalia inflata*, *Globigerina bulloides* and *Neogloboquadrina* spp., consistently occur in the assemblage with temperate to warm water specimens (*Globigerinoides* spp., *Orbulina universa*) (Tab. 1). Through the deeper benthic foraminifer assemblages, the abundance of *Bolivina* spp., *Bulimina* spp., *Cassidulina* spp., *Hyalinea balthica* and *Lenticulina* spp. also indicates that the basin-floor environment underwent low-oxygenated, cool-water conditions (BALDANZA et al., 2011). This situation is probably related to water-mass stratification and thermal isolation of the basin floor.

4.2. Sedimentological interpretation

According to fossil content and sedimentary features, deposits are referred to an open marine environment, mainly below and only occasionally across the storm wave base, as testified by the extreme rarity of wave-induced structures; nonetheless, some clay should be discussed. Clay beds reflect a suspension-dominated offshore marine environment. On the other hand, considering the micropaleontological assemblages, sandy beds clearly show evidence of mixing of proximal (both epifaunal and infaunal) and distal benthic taxa. The clay source is distal river sedimentation and/or intrabasinal remobilization rather than ancient Conero "Island" beach systems. Except for the argillaceous Oligocene Schlier Fm., the limestone/marly limestone units outcropping in the present-day M. Conero anticline, could not produce the large amount of clay in Pliocene to Pleistocene marine deposits. Moreover, in the Camerano deposits, Cretaceous to Miocene reworked microfossils are very rare.

Sands are mainly reverse-graded, plane-parallel laminated. Plane-parallel lamination in sandy deposits may be indicative of various sedimentary environments; nevertheless, reverse grading more commonly occurs in sediment gravity flow deposits than in current/wave deposits. Sandy storm deposits may be parallel-laminated in the basal portion (plane beds). As a storm subsides a decrease of energy, from erosive capacity to critical and subcritical flow, to the final recovering of fair-weather conditions, should produce a suite of sedimentary structures, from HCS to swaley-laminations, to wave ripples. Except for the rare occurrence of small scale cross-lamination and/or wave ripples, these structures are not documented through the Camerano section. The hypothesis that sand-clay couplets are shelf storm deposits seems unsatisfactory.

Plane-parallel laminated, reverse-graded sands can be identified as facies F7 (MUTTI, 1992) or S1 (LOWE, 1982), both described from siliciclastic turbidites, and are comparable to the "traction carpets" described in sandstones (DZULYNSKI & SANDERS, 1962; MIDDLETON, 1970, 1993; HISCOTT & MIDDLETON, 1979; LOWE, 1982; TODD, 1989; SOHN, 1997). On the other hand, the sands are largely bioclastic. A study on the hydraulic equivalence between bioclasts and lithoclasts of different lithology is beyond the scope of this work; nevertheless, bioclastic and lithoclastic sands should behave similarly during the formation of "traction carpets". Both facies S1 (LOWE, 1982) and F7 (MUTTI, 1992) in siliciclastic deposits are attributed to "High Density Turbidity Currents". Sandy beds presumably represent basinal resedimentation of nearshore bioclastic sands, promoted by storm-induced turbidity currents.

The lack of clay matrix in the sandy beds is probably due to the flow conditions during the event, and to a negligible original amount of clay in nearshore remobilized deposits, according to a mechanism resembling the one proposed for 'carbonate turbidites' (COLACICCHI & BALDANZA, 1986). Thus, the gradual to sharp transition to clay mainly represents the more or less gradual or rapid re-establishment of low-energy conditions. The physical characters (colour, plasticity, textural features) and the microfossil content (see below) are unvarying across clay beds, as well as in clay chips at the base of couplets. In each couplet, a clay content reasonably derives from erosion of clay-floor sediments, entrapment of clay chips and resedimentation of fines during the turbiditic event (ENOS, 1969). Nevertheless, this "turbidite" clay fraction is indistinguishable from the true hemipelagite (Fig. 6A). This interpretation looks reasonable; however, some issues are to be considered. The carbonate turbidites are typically fed by a carbonate platform system, which provides the biogenic component. The question is, if a submerged beach, in a siliciclastic context, may export basin-ward carbonate sand with a relevant amount of bioclasts. The origin of sand is presumably local, and the most reasonable explanation is that M. Conero island and its Pliocene to Pleistocene calcarenitic beaches were the main source area for sandy deposits (Fig. 6). In fact, bioclastic calcarenitic beaches are documented in the area, at least during the Early Pliocene ("Trave horizon": e.g. CANTALAMESSA et al., 1986; CENTAMORE & MICARELLI, 1991; SARTI et al., in press).

The lack of clay matrix in the sandy beds is a critical point in interpreting sand-clay couplets as turbidites. In fact, the suspended silt/clay fraction (or micrite in carbonate turbidites: COLACICCHI & BALDANZA, 1986) plays a significant role in the turbulent flow movement. The occurrence of beds showing gradation from sand to clay (NGc in Fig. 5A) seems to demonstrate that clay was initially present in the suspension together with sand. The sand/clay separation may derive from flow partition between a lower laminar layer (i.e., flowing grain layer) and an upper turbulent layer (i.e., turbidity current). In this case, sand layers may be better defined as grain flow deposits, while only the upper, very fine sand to clayey part of graded couplets can be considered a true turbidite (SANDERS, 1965; POSTMA et al., 1988; SANDERS & FRIEDMAN, 1997; MULDER & ALEXANDER, 2001; SHANMUGAM, 2002). The occurrence of both graded and sharp sand-clay transition indicates that the original sediment gravity flow may or may not reach the conditions for internal stratification. Thus, not all the flows evolve as turbidity currents, and the sharp transition could represent the successive settlement of suspended clay above a grain flow deposit.

B-type clay-clast conglomerates seem to be integral parts of the sand layers. Sedimentary features resemble those in the experiments of POSTMA et al. (1988) on high-density turbulent flows, except for the larger scale of clay clasts in Camerano deposits. According to that model, deposition originates in consequence of density stratification of the flow. B-type conglomerate might result from storm-induced, high-density turbidity currents.

A-type clay-clast conglomerates are identifiable as debrites (*sensu* STOW, 1985), deriving from remobilization of semi-lithified clay beds and unlithified sands. Thus, they are interpreted as debris-flow deposits. Slope failure can produce debris flows directly, if internal cohesion is lost, even on gentle slopes (DOTT, 1963; RODINE & JOHNSON, 1976), or debris flows may derive from distal evolution of other mass-movements (LOWE, 1982; NEMEC & STEEL, 1984; STOW, 1985; MUTTI, 1992; MULDER & ALEXANDER, 2001; DASGUPTA, 2003). The original clay amount is probably a leading factor in debris flows (HAMPTON, 1975). However, clay in the conglomerates of the Camerano section is confined to large clay clasts, and none is present within the sandy matrix. The lack of cohesion in unlithified sand beds should facilitate initiation of flows.

Finally, some considerations about the relationship between clay-clast conglomerates and sand-clay couplets are proposed. Grain flows/turbidites may be induced in sands both by down-current evolution of debris flows (HAMPTON, 1972; MUTTI, 1992; ILSTAD et al., 2004a; ELVERHØI et al., 2010) or promoted by storm events (WALKER, 1984). The amount of clay in the initial mixture is critical for debris-flow movement along a low-inclination slope (less than 2% of clay to maintain a fine-sand debris flow, up to 19% for coarse-sand debris flow, according to HAMPTON, 1975), as well as for the features of evolving flow caused by water intrusion (HAMPTON, 1972, 1975; POSTMA et al., 1988; ILSTAD et al., 2004a; ELVERHØI et al., 2010). Thus, the clay-clast conglomerates may result from disturbance and mass failures of semi-lithified beds by overloading or earthquakes rather than storm-induced hydraulic pressures.

In this scenario, sand-clay couplets and clay-clast conglomerates result from different processes acting on a gentle, but unstable, slope (Fig. 6A).

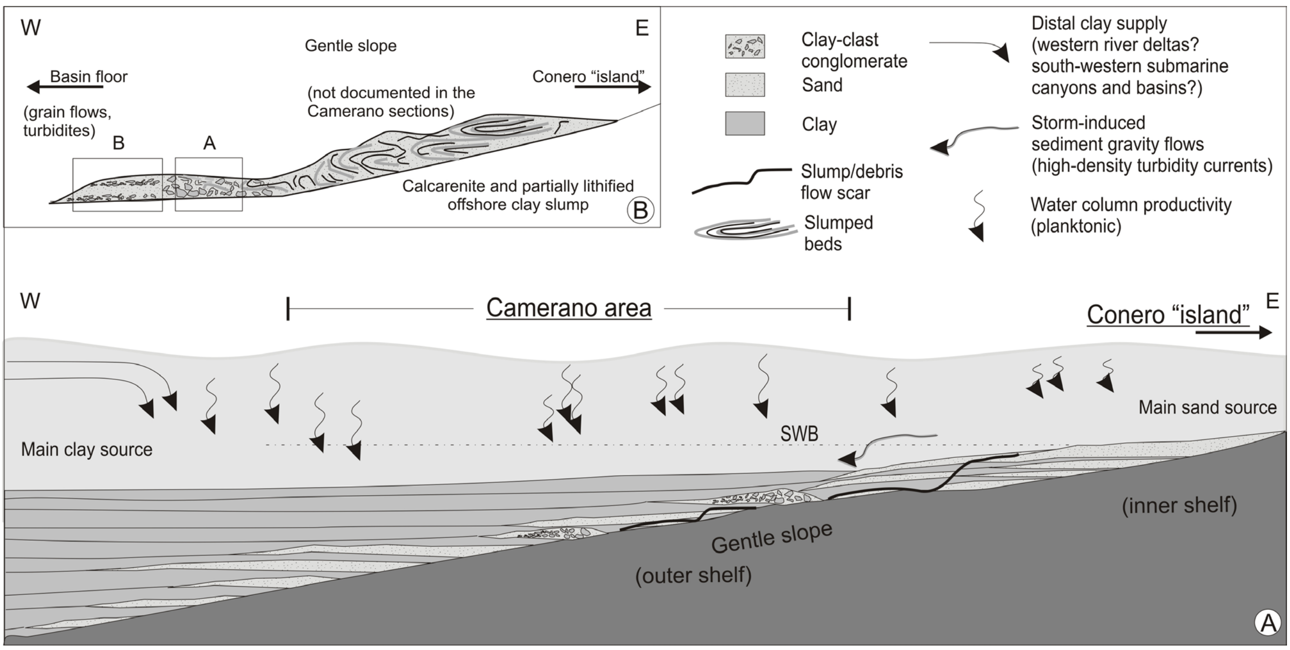

Figure 6: Basin and palaeoenvironmental reconstruction, according to the alternative proposed sedimentation models (see text). A) Gentle sloped outer shelf, with alternate sediment gravity flows deposits (sands) and offshore clay deposits, and occurrence of seismic-induced debrites (conglomerates). B) Alternative interpretative model for A-type and B-type clay gravel. Seismic-induced slumps (not documented in the Camerano section) remobilizing bioclastic sand and cohesive clay horizons, evolving basin-ward to matrix-supported gravel. SWB = Storm wave base.

In an alternative interpretation, both A- and B-type conglomerates, as well as sand-clay couplets, may originate from the distal modification of slumps (Fig. 6B). Slump deposits have not yet been found in the Camerano section or in the neighbouring areas, however. The two gravel types could be interpreted as more proximal (*A*) and distal (*B*) slump deposits, respectively (Fig. 6B). Slumps were most likely induced by seismic activity, and clay beds acted as detachment levels along a gentle slope. Nevertheless, clay does not occur within the matrix, which is solely bioclastic sand. The seismic shock probably mobilized semi-lithified sand-clay couplets, which started moving as a unique body. Low-permeability clay layers are responsible for the increase in fluid pressure as pore water is expelled from underlying sand beds under shear stress (STURM, 1971; HAMPTON, 1972; MALTMAN, 1994; HAMPTON et al., 1996; STRACHAN, 2002; ILSTAD et al., 2004b; SULTAN et al., 2004). Pore-water pressure causes slumps on very low slopes (FIELD et al., 1982; MCADOO et al., 2000; STRACHAN, 2002; GARCIA-TORTOSA et al., 2011; ALSOP & MARCO, in press). Slumps distally evolved to non-cohesive debris flows (*sensu* LOWE, 1982 and NEMEC & STEEL, 1984), mainly supported by buoyancy and dispersive pressure mechanisms, rather than by cohesion. Large clay clasts were preserved during the motion, a very short transport. This slump model (Fig. 6B) is comparable to the one proposed by COLACICCHI & MONACO (1994) for the Cretaceous-Palaeogene Scaglia Basin. If the debris flow continues incorporating water, the dilution may promote a high-density turbidity current, with flow density stratification (SANDERS, 1965; HAMPTON, 1972, 1975; POSTMA et al., 1988; SANDERS & FRIEDMAN, 1997; SHANMUGAM, 2002; ILSTAD et al., 2004a; ELVERHØI et al., 2010). During this evolution, the sand-clay couplets are probably sedimented, as turbidity currents and/or grain flows are succeeded by settlement of suspended clay.

4.3. Facies interpretation

The alternating sand/clay beds, characteristic of the uppermost deposits of the Camerano hill sedimentary succession, observable only in the subterranean outcrops, are very similar to the arenitic/pelitic or pelitic/arenitic lithofacies belonging to the FAA (SARTI et al., in press). There are, however, some important differences between the Camerano and typical FAA lithofacies. Compared to the FAA, massive sand beds in the Camerano sedimentary sequence are rare, large-scale cross-lamination and hummocky geometries are totally lacking, sand is dominantly plane-parallel laminated and reverse graded, and clay beds are massive rather than thin-laminated. On the other hand, the sand/clay ratio is the sedimentological feature most comparable with the ones exhibited by arenitic/pelitic lithofacies in deposits cropping out west of Camerano and by the Offida Member (CELLO et al., 2009; SARTI et al., in press). Sand lithology is dominated by bioclastic fragments, with subordinate lithics, indicating that sediments were locally derived. Deposits referable to slump evolution were formerly reported in deposits from the western flank of the Periadriatic Basin (CANTALAMESSA et al., 1986; DI CELMA et al., 2010; DI CELMA, 2011), but were never documented before in the eastern area and in Early Pleistocene deposits. Finally, according to our interpretation, both *Sand-clay couplets* and *Clay-clast conglomerate*, cannot be related to the shoreface and/or offshore transition deposits recognized by SARTI et al. (in press) in the Camerano area, and are most likely resedimented in a deeper basin environment (outer shelf).

4.4. Palaeoenvironmental reconstruction

Sedimentological evidence indicates that the Camerano sedimentary sequence was deposited in a shallow outer shelf (Fig. 6A), positioned in close proximity to a partially emergent structural high, an island, today partially identifiable with Mt. Conero. This sandy shoreface to inner shelf environment represented the source of the carbonate sand. Deposits were moved offshore by storm waves, and resedimented to the outer shelf by storm-induced turbidity currents, debris flows and grain flows. Due to their carbonate composition and the richness in bioclasts, a local origin for sandy deposits is presumed. The outer shelf/basin was characterized by deposition of clay, presumably supplied by distant western river deltas, mixed with primary productivity within the water column. In addition, an integrated submarine-canyon and basin system is documented in the southwestern Periadriatic basin, during the Early Pleistocene at least (DI CELMA et al., 2010; DI CELMA, 2011). A local contribution to clay from this source cannot be excluded.

The close variability of sub-horizontal and 5° westward inclination for sedimentary beds could reflect an original gently inclined, irregular slope. Irregularities may be the consequence of 3D geometries of larger sediment gravity flow deposits (debrites). The outer shelf periodically received shallow-water carbonate near-shore sediments, remobilized from the eastern inner shelf by storm events and resedimented as carbonate turbidites of high density and/or grain flow deposits. These sediment gravity flows also partially eroded clay beds, and clay was involved in the resedimentation events. From Miocene times onward the Marches area underwent a tectonic compressive regime and seismic activity; the occurrence of seismic-induced debris flow deposits and/or slump deposits, recorded as conglomerates in the Camerano succession (Fig. 6), documents sedimentation in a tectonically active context, continuing throughout the Early Pleistocene.

5. CONCLUSIONS

Thanks to the exceptional underground town of Camerano it is possible to describe a composite sedimentological and stratigraphic section of Early Pleistocene marine deposits (MNN 19c and 19d Nannofossil subzones), that are lacking suitable subaerial outcrops. Additionally, superposition of different cave levels and the complex pattern of tunnels provide a unique three-dimensional view of depositional geometries, facies heterogeneity, and succession. Relative to the usual FAA features, facies described through the Camerano section show some peculiarities; moreover, some contradictory characteristics have been described, and not all of them can be easily interpreted. Deposits are clearly marine, and they are not referable to the alternation of foreshore/backshore deposits and brackish deposits, recognized in the area by SARTI et al. (in press). Due to the dominance of planktonic foraminifera, deposition on a nearshore environment has been excluded, and an outer shelf environment is more probable. The lack of typical storm-related structures, such as HCS, swaley cross-lamination, etc., indicate the sand-clay couplets are not tempestites. Thus, deposits are interpreted herein as sediment gravity-flow deposits, mainly initiated by storm events, above storm-wave base.

On the basis of facies analysis and sedimentological inferences, we constructed a sedimentation model and hypothesized the palaeoenvironmental context for the deposition of the Camerano sedimentary sequence (Fig. 6). Sand-clay couplets are described as storm-induced carbonate turbidites of high density and/or grain flow deposits, and matrix-supported conglomerate of clay clasts are interpreted as debrites. If they were produced by debris flows or distal evolution of slumps, the conglomerates, particularly the A-type, suggest that sedimentation occurred in an unstable, probably tectonically active, outer-shelf environment.

Palaeoecological data indicate a depth range from 40 to about 100 m, supporting the hypothesis of a shallow outer-shelf environment. Clay horizons were apparently supplied from distal river deltas to the west, enriched by planktonic pelagic sedimentation. Storm-induced carbonate turbidites periodically carried proximal bioclastic material from the western coast of Mt. Conero "island" (Fig. 6). Large clay fragments from matrix-supported conglomerates, probably derived from seismic remobilization of partially lithified deposits along the inner shelf, although their provenance is not clearly determinable. The microfossil record is consistent with the inferred palaeoenvironmental reconstruction. Nevertheless, some uncertainty remains about some apparently conflicting aspects (relatively shallow depth, low slope, lack of clay matrix in "turbidites", source area, rare occurrence of symmetrical cross-lamination), and other studies are needed.

Overall, the data presented in this study greatly improve the geological knowledge of the Camerano caves and surrounding territory.

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