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# EVIDENCE OF ASSOCIATED DEPOSITION OF TRAVERTINE AND CALCAREOUS TUFA IN THE QUATERNARY CARBONATES OF VALDELSA BASIN (TUSCANY)

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ABSTRACT: E. Capezzuoli *et al.*, *Evidence of associated deposition of travertine and calcareous tufa in the Quaternary carbonates of Valdelsa Basin (Tuscany).* (IT ISSN 0394-3356, 2008).
The Quaternary continental deposits discontinuously exposed in the southern part of the Valdelsa Basin, represent four orders of terraces corresponding to four Late Pleistocene-Holocene fluvial/palustrine synthems formed as a consequence of the tectonic uplifting of Southern Tuscany. In most of the Elsa River network the terraces are composed of detrital deposits (mixed, siliciclastic-carbonate silty sands with lenticular interbeds of gravels), but locally, along specific segments of the valleys, the detrital sediments are replaced by lenticular bodies of concretionary limestones made of massive, sometimes highly porous, calcareous tufa that, only in the upstream areas, are interbedded with laminated facies with tabular geometry and fabric typical of travertine.
The distribution the different facies can be observed in the upstream part of the Imbotroni Valley in the locality of Bagnoli (SE of San Gimignano - Siena). Their relationships records the development of a complex depositional system controlled by the intermittent outflow of a thermal spring alternated to seasonal/meteoric fresh water input. When the thermal spring was active, the warm waters fed proximal, shallow pools were well laminated travertine facies were deposited while faraway from the spring and/or during the periods of prevailing meteogene, fresh water input, the massive phytoclastic/phytohermal calcareous tufa formed.
A similar depositional evolution appears to have developed at the beginning of all the Quaternary carbonate synthems formed in the Valdelsa Basin, thus explaining the anomalous distribution of the concretionary carbonate deposits, limited only to a segment of the Elsa fluvial network.

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*I depositi continentali quaternari della porzione meridionale del Bacino della Valdelsa registrano una complessa evoluzione paleoambientale segnata da successive fasi deposizionali condizionate dal sollevamento tettonico che ha interessato l'intera Toscana meridionale. Quattro ordini di terrazzi fluviali, rappresentanti altrettanti fasi deposizionali fluvio-palustri del Pleistocene Superiore-Olocene, sono esposti in maniera discontinua lungo la valle del Fiume Elsa e dei suoi tributari (Torrente Foci, Torrente Staggia, Borro degli Imbotroni). Essi corrispondono a quattro sintemi fluvio-palustri composti, nella maggioranza dei casi, da depositi detritici misti (sabbie siltose e calcareo-silicoclastiche con intercalati livelli lenticolari conglomeratici). Localmente, in particolari segmenti del reticolo fluviale, i sedimenti detritici sono sostituiti da corpi lenticolari di calcari incrostanti rappresentati da calcareous tufa massicci, localmente molto porosi. Nella loro porzione più a monte queste stesse facies di calcareous tufa risultano intercalate a facies ben laminate con geometria tabulare e strutture tipiche del travertino. La distribuzione delle differenti facies e i loro rapporti possono essere osservati nella parte superiore del Botro degli Imbotroni, nella località di Bagnoli (SE di San Gimignano - Siena) dove la successione consiste di tre unità deposizionali sovrapposte, separate da superfici erosive. Le tre sequenze, ognuna composta di due intervalli, mostrano un'evoluzione deposizionale laterale e verticale simile. L'intervallo basale delle tre unità è formato da calcari marnosi peloidali con resti fossili (ostracodi e gasteropodi) associati a corpi lenticolari più o meno porosi di calcareous tufa con ciuffi fitoclastici/fitoermali. Solo nella parte basale dell'unità inferiore queste litologie coprono lenti di ciottolami e sabbie siltose silico-carbonatiche. Questi ciottolami giacciono con contatto discordante sul substrato pliocenico. L'associazione di facies può essere interpretata come l'evoluzione da un sistema fluviale (facies detritiche) a condizioni palustri-lacustri (calcareous tufa).*
*L'intervallo superiore delle tre sequenze è caratterizzato da calcari ben stratificati e laminati. Da dettagliate analisi petrografiche e sedimentologiche, questa litofacies risulta essere composta da lamine batteriali/cianobatteriali ("cespugli" micritici e aggregati peloidali). La laminazione tabulare composta esclusivamente da tappeti batteriali, è caratteristica di sedimenti deposti in ambiente termale, in corpi d'acqua stagnante o con poca energia come stagni o laghetti poco profondi. Inoltre, l'assenza di macrofite e di elementi faunistici (ostracodi e gasteropodi) indica caratteristiche chimico-fisiche delle acque (alta temperatura, contenuto in $H_2SO_4$ e bassi livelli di ossigeno) sfavorevoli alla proliferazione di organismi animali e vegetali superiori.*
*La distribuzione delle facies nella sezione di Bagnoli registra quindi, la complessa evoluzione di un sistema deposizionale derivante dall'interazione fra un sistema termale ed uno di acque fredde. Le acque termali scorrevano intorno alla sorgente e alimentavano vasche poco profonde dove si depositavano le facies travertinose laminate, mentre nelle aree più distali e durante l'interruzione dell'apporto termale si aveva la deposizione delle facies massicce fitoclastiche/fitoermali tipiche dei calcareous tufa. A testimonianza di ciò, una piccola sorgente debolmente termale, con limitato potere incrostante è tuttora attiva a Bagnoli.*
*Tale tipo di evoluzione deposizionale sembra aver interessato tutti i sintemi tardo pleistocenici della Valdelsa, spiegando così l'anomala distribuzione dei depositi carbonatici concrezionari limitati a segmenti definiti del reticolo fluviale.*

Key words: Travertine, Calcareous tufa, Quaternary, sedimentology, Valdelsa.

*Parole chiave: Travertino, Calcareous tufa, Quaternario, sedimentologia, Valdelsa.*

## 1. INTRODUCTION

The study of continental carbonates has greatly increased in the last decades, since it has been known that these lithologies are sensible to the environmental conditions and consequently can convey viable palaeoclimatic information.

As a matter of fact many studies have demonstrated that extended and detailed paleoclimatic records can be obtained from the sedimentologic/stratigraphic and geochemical analysis (stable isotopes) of speleothems (Bar-Matthews *et alii*, 1997; Drysdale *et alii*, 2004), calcrete (Dworkin *et alii*, 2005) and lacustrine limestone (McKenzie & Hollander, 1993; Von Grafenstein *et alii*, 2000). Comparable information in type and quality resulted also from the study of some lithofacies of continental carbonates precipitated under open-air conditions by flowing waters in streams, rivers (Garnett *et alii*, 2004; Andrews, 2006) and springs (Frank *et alii*, 2000; Minissale *et alii*, 2005) from calcium-bicarbonate-rich waters. However, the different nomenclature and genetic attributions given by the Authors to the open-air flowstones (Riding, 1991; Koban & Schweigert, 1993; Pentecost, 1995; Ford & Pedley, 1996; Capezzuoli & Gandin, 2004) emphasize the present limited knowledge of the genetic processes of these deposits and the absence of a common point of view (Gandin & Capezzuoli, this volume).

The term Travertine, which for a long time has been used to designate the ornamental/building stone quarried in the thermal deposits of Tivoli, is now generally reserved to calcium carbonate deposits associated to hydrothermal spring systems. This lithology which is relatively enriched in strontium, sulphur (Ford & Pedley, 1996) and $^{13}C$, and as a consequence is characterized by high values (Pentecost, 1995) of total dissolved inorganic carbon (TDIC), appears to be barely dependent upon climate. It is characterized by high depositional rates, regular bedding and fine lamination, a primary, low-porosity crystalline fabric, and by bacteria and cyanophites as the only organic constituents (Gandin & Capezzuoli, this volume).

On the other hand, the term Calcareous tufa, coined in the British literature, refers to calcium carbonate deposits formed under a cool-water regime, around karst spring complexes and/or in a fluvio-palustrine environment. This lithology which is depleted in $^{13}C$ and shows TDIC concentrations more or less in equilibrium with the soil atmosphere (Ford & Pedley, 1996) appears to be highly dependent upon climatic factors. It is characterized by normally low depositional rates, commonly lenticular, highly porous bodies with poor bedding, and abundant remains of micro- and macrophytes, invertebrates as well as bacteria. The distinction between these two groups of lithotypes is not univocal since the cool water calcareous tufa deposits can represent the natural lateral prosecution, away from the thermal-spring complex, of cooled thermal waters. The discrimination of the two types of deposits appears to be crucial in the interpretation of the tectonic, climatic and anthropologic meaning of the fossil continental carbonates. However preliminary, compared analyses of the fabric of travertine and calcareous tufa in formation, show the possibility of using petrologic criteria for their distinction. Here is an example from the Late Pleistocene-Holocene carbonate deposits of the Southern Valdelsa Basin (Southern Tuscany, Italy).

## 2. GEOLOGICAL SETTING

The Valdelsa Basin is one of the larger Neogene-Quaternary basins of Southern Tuscany, bordered to the west and the south by the Middle-Tuscan Ridge and to the east by the Chianti Ridge (Fig. 1). The Tuscan Ridge mainly consists of formations of the Tuscan Domain, comprising metamorphic Triassic siliciclastics (Verrucano facies), Late Triassic/Jurassic carbonates and the "Calcare cavernoso", a carbonate epidiagenetic breccia derived from tectonized Triassic evaporitic deposits (Gandin *et alii*, 2000). The Chianti Ridge is mainly composed of tectonically superposed Units of the Ligurian Domain ranging from Middle-Late Jurassic Ophiolites, Early Cretaceous shales and flinty limestones and Late Cretaceous - Eocene flysch successions of sandstones, limestone and shales.

The Valdelsa Basin developed since the Late Miocene, experienced during the Neogene mixed continental-marine conditions represented by a thick sequence of mainly siliciclastic deposits (about 2000 m; Ghelardoni *et alii*, 1968). In the late Middle Pliocene a general marine regression led the Valdelsa Basin, as well as the greatest part of Southern Tuscany, to emersion (Bossio *et alii*, 1995). This event seems to be related to a major tectonic uplifting that affected Southern Tuscany in successive pulses from Middle Pliocene up to the present (Carmignani *et alii*, 1994; Boccaletti *et alii*, 1999; Bartolini, 2003).

The persistent erosional regime acting on this area since the Neogene, has been episodically interrupted during Quaternary, by recurrent depositional episodes represented by seven synthems locally characterized by terrestrial calcareous deposits (Capezzuoli & Sandrelli, 2004; Capezzuoli *et alii*, 2007). The oldest, Early-Middle Pleistocene deposits (Campiglia dei Foci - CDF; Strove Synthems - STR) consist of lacustrine to palustrine limestones, while the subsequent four, Late Pleistocene-Holocene Synthems (Abbadia - ABB; Calcinaia - CAL; Torrente Foci - FOC; Bellavista - BEL) are locally characterized by calcareous, fluvial-palustrine deposits. The youngest, Holocene Poggibonsi Synthem (POG) is represented by exclusively siliciclastic, fluvial sediments (Fig. 2). All synthems are bounded by basal disconformable contacts and upper subhorizontal aggradational surfaces on which rubefied or brown soils developed (Capezzuoli & Sandrelli, 2004; Capezzuoli *et alii*, 2007).

The Late Pleistocene-Holocene synthems, exposed in a succession of terraces on the slopes of the river valleys, mainly consist of detrital deposits (sands, silts and pebbles) that in some valleys are associated with or replaced by calcareous deposits.

The detrital deposits are usually represented by irregular, fining-upward sequences composed of quartz-sands and silt with gravel lenses associated with clastic calcareous sands. The gravel layers, mainly developed in the basal part of the synthems, are composed of well rounded, poorly sorted (max 20 cm) polygenic clasts of Ligurian and "Calcare cavernoso" provenance, and of a variable amount of sandy matrix. The quartz sand derives from the surrounding Pliocene marine sands while the calcareous sands appear to result from the erosional fragmentation of older calcareous deposits.

In specific segments of the Valdelsa network (Fig.

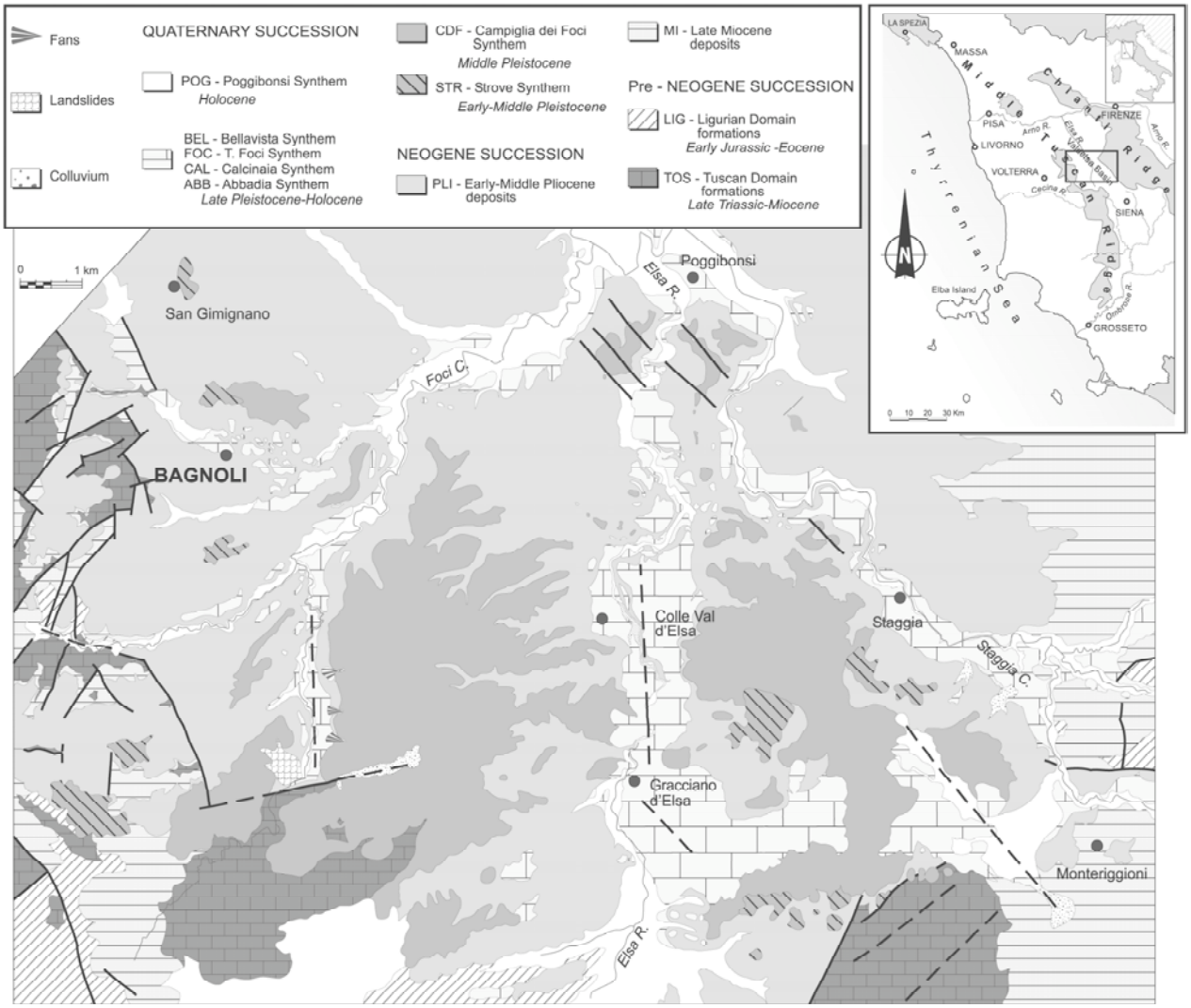


Fig. 1 - Geological scheme of the southern Valdelsa Basin. The ABB, CAL, FOC, BEL Synthems cannot be mapped separately at this scale.

*Schema geologico semplificato della porzione meridionale del Bacino della Valdelsa. I Sintemi ABB, CAL, FOC, BEL non possono essere rappresentati separatamente a questa scala.*

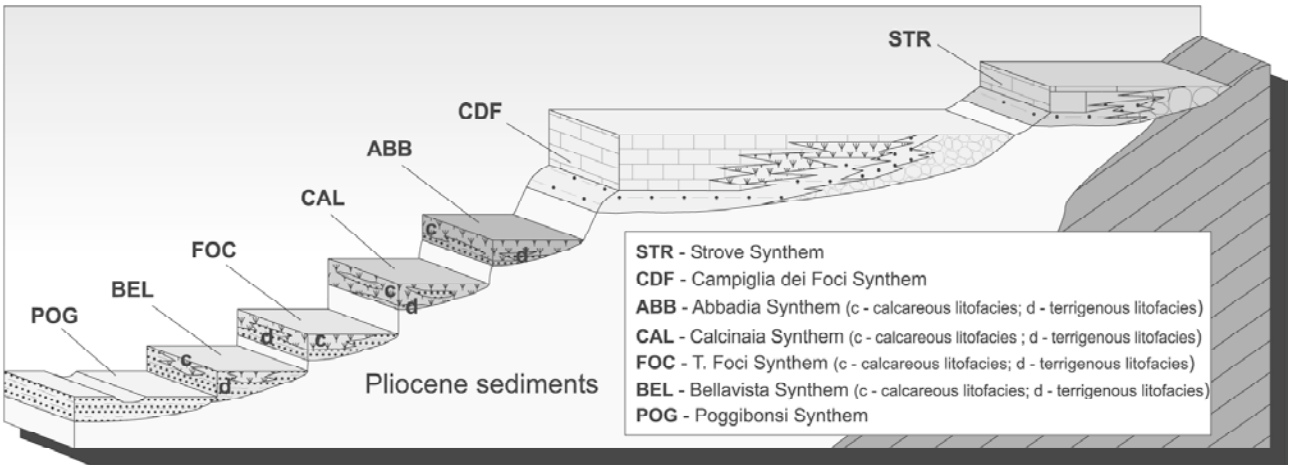


Fig. 2 - Schematic reconstruction of the Quaternary stratigraphic units in southern Valdelsa (not to scale) (after Capezzuoli *et alii*, 2007, modified).

*Ricostruzione schematica delle suddivisioni stratigrafiche adottate per lo studio dei depositi quaternari del settore meridionale della Valdelsa (non in scala) (da Capezzuoli* et alii, *2007, modificato).*

1), namely along the Elsa River (between Gracciano Val d'Elsa to the south and Poggibonsi to the north) and along its tributaries Staggia Creek (between Castellina Scalo and Poggibonsi), Imbotroni Creek and Foci Creek (near San Gimignano and Campiglia dei Foci) the detrital deposits are extensively replaced by poorly stratified, lenticular bodies of encrusting carbonates. The dominant lithofacies include phytoclastic and phytohermal concretionary limestones resulting from the incrustation of macrophytes (rushes, bryophytes and grass stems) associated with calcrete, calcareous sands and occasionally peat clays and/or micritic layers. These facies, characteristic of paludal/fluviatile calcareous tufa (sensu PEDLEY, 1990 and PEDLEY *et alii*, 2003) can be related to relatively high concentrations of Ca-bicarbonate in the flowing waters hence to high water supply and karstic circulation in the carbonate yielding substrate.

The age of the continental carbonates of the Valdelsa basin, previously referred to the Holocene (MERLA & BORTOLOTTI, 1967), has been recently updated. $^{14}C$ radiometric dating of organic clays occurring in the basal part of the intermediate CAL Synthem yielded a Late Pleistocene age of 25.690±180 years B.P. (CAPEZZUOLI & SANDRELLI, 2004).

The thickness of the different carbonate successions is variable, progressively decreasing from the oldest (ABB) to the youngest (BEL) Synthem.

The peculiar distribution of the concretionary carbonates, limited to specific fluvial tracts of the four carbonate synthems, cannot be understood only in terms of karstic activity/climatic depositional conditions. Although the dominant facies represented by poorly bedded/massive chalky limestone can be referred to calcareous tufa, well-bedded, laminated, compact limestone bearing the features of travertine, locally occur at their base in the apical part of the paleovalleys.

Aim of this paper is the detailed analysis and the definition of the origin and relationships of the apical lithofacies of one of these successions (FOC Synthem) exposed at Bagnoli (Fig. 1), a locality SE of San Gimignano, near Siena.

## 3. THE BAGNOLI SUCCESSION

At Bagnoli the carbonate succession located upstream of the Imbotroni Valley in the apical part of the Torrente Foci (FOC) is well exposed in a section about 15 m thick. There, three superposed depositional units separated by erosional surfaces (Fig. 3) can be observed. The three sequences show similar lateral and vertical depositional evolution and comparable calcareous lithofacies.

*3.1 Lithofacies of the Bagnoli section*

- <u>*conglomerates and sands*</u>: (Figs. 4a,$a_1$) The conglomerates are found exclusively at the base of the Lower Depositional Unit (LDU). The subrounded calcareous pebbles mainly derive from the "Calcare cavernoso" and Ligurian lithologies. Subordinate elements made of Neogene sandstones and of boulder-size olistoliths of whitish laminated carbonates (Fig. 4$a_2$) can be locally observed. Most of the grains are enveloped by a thin micritic coating. The abundant matrix is made of mixed siliciclastic-carbonate silty sand that upwards forms decimetric tabular beds with planar lamination and normal grading, containing fossil remains of ostracods and gastropods.
  This lithofacies that upwards grades to chalky carbonates, is interpreted to represent the detrital channel infilling of the paleo-Imbotroni creek.
- <u>*poorly layered, porous/chalky marly calcareous tufa*</u>: composed of irregular, centimetric layers of slightly coherent, porous peloidal mudstone (Figs. 4b,c; 6a) with frequent remains of ostracods (Fig. 6b) and gastropods. Decimetre high phytohermal clusters and tufts (Fig. 4d) built by cyanobacteria, or calcite-encrusted bryophytes and lenticular accumulations of calcified fragments of higher plants are irregularly associated. The phytoclastic facies that locally include abundant dissolution voids (Fig. 6c), is composed of calcified casts of leaves and small branches. This lithotype representing former lime-muds colonized by bacterial/cyanobacterial mats and small mounds deposited in palustrine/lacustrine conditions is considered characteristic of the Phytohermal/Phytoclastic facies of

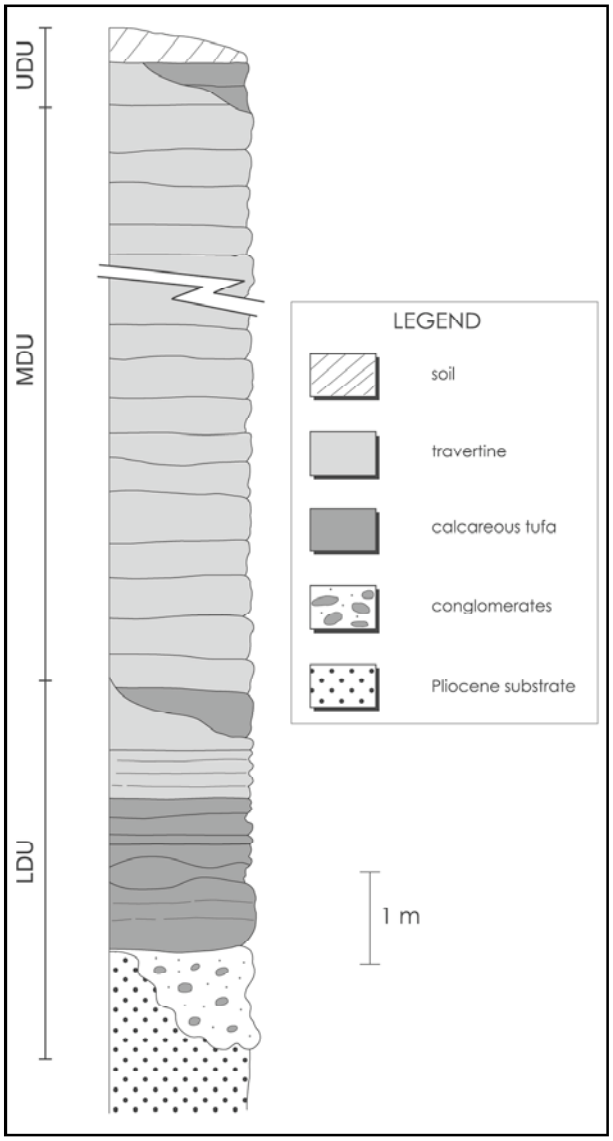


Fig. 3 - Stratigraphic log of the FOC succession at Bagnoli.
*Log stratigrafico del Sintema FOC presso Bagnoli.*

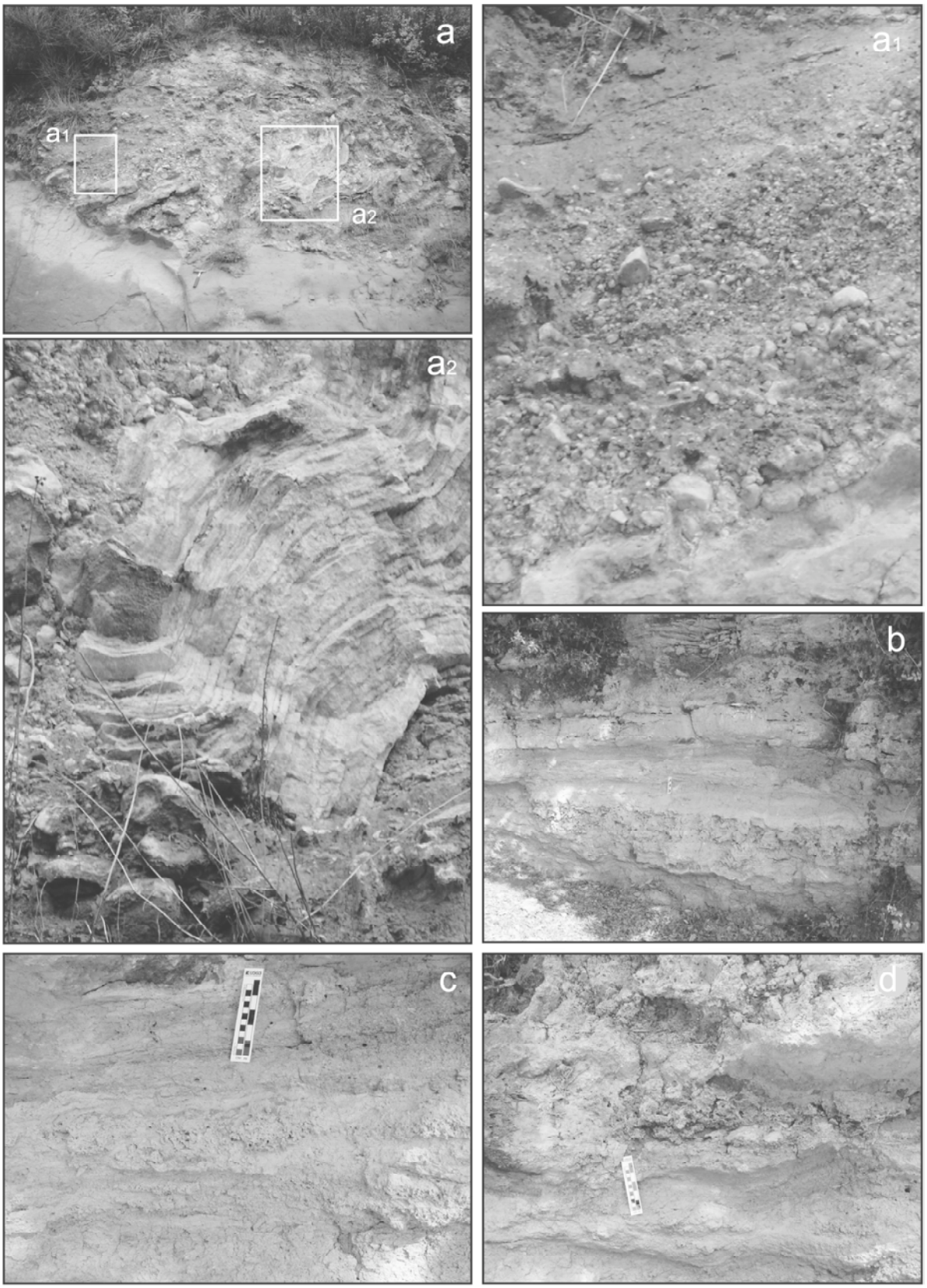


Fig. 4 - a) Basal conglomerates and sands of the LDU; $a_1$) detail of a) showing the FU gradation; $a_2$) detail of a) showing a boulder of travertine with sinuous lamination; b) tabular detrital and calcareous tufa beds in the central portion of the LDU; c) planar laminae of the detrital facies alternated with chalky calcareous tufa with small phytohermal clusters; d) phytohermal clusters and phytoclastic lenses in the calcareous tufa.

*a) Conglomerati e sabbie basali della LDU; $a_1$) particolare della gradazione normale del deposito; $a_2$) particolare dei blocchi di travertino laminato e ondulato; b) livelli tabulari detritici e carbonatici della porzione centrale della LDU; c) lamine piane della frazione detritica e intercalazione calcarea con piccoli cespugli fitoermali; d) cespugli fitoermali e lenti fitoclastiche nella facies calcarea.*

the calcareous tufa (Ford & Pedley, 1996; Pedley *et alii*, 2003).

- *regularly laminated crystalline travertine*: consisting of centimetric laminae formed by dense, white calcite crystals perpendicular to the depositional surface. This lithofacies, distinctive of the laminated blocks enclosed in the basal conglomerate (Fig. 4a$_2$), can be referred to the "Crystalline crust Travertine" which, according to Guo & Riding (1998), is deposited on the slopes and cliffs of thermal systems reflecting rapid precipitation from fast flowing warm waters.
- *regularly laminated bacterial/cyanobacterial travertine*: made of centimetric laminae (Figs. 5a,b,c,d) built by bacterial shrubs and peloidal aggregates (6d,e)

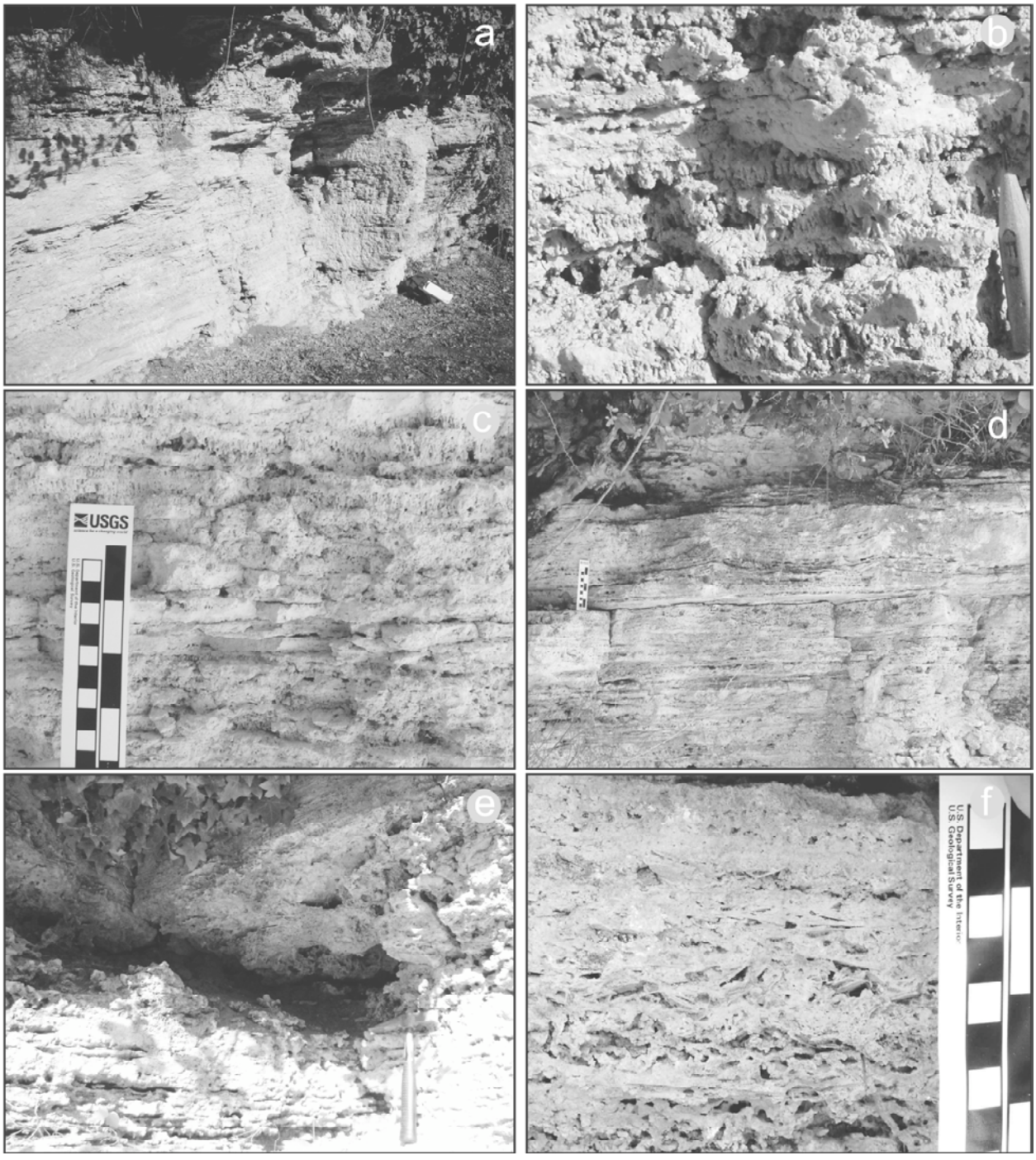


Fig. 5 - a) well bedded, whitish, laminated limestones of the upper part of the LDU; b) detail of the laminated limestone showing centimetric shrubs; c) detail of the laminated limestone showing the alternation between micritic and shrub laminae; d) the travertine laminae are locally cuspidate, probably reflecting a small paleomorphology; e) erosive surface between the LDU and the MDU enhanced by secondary karst dissolution; f) accumulation of fragments of thin crystalline calcite sheets (paper thin rafts).

*a) calcari laminati e ben stratificati della porzione superiore della LDU; b) particolare dei calcari laminati con gli shrub; c) particolare dei calcari laminati con l'alternanza di lamine con shrub ed altre micritiche; d) le lamine travertinose sono localmente cuspidate, probabilmente in corrispondenza di piccole morfologie; e) superfice erosiva fra LDU e MDU evidenziata dal carsismo; f) accumulo di frammenti di lamine di calcite cristallina (paper thin raft).*

lacking any trace of macrophytes or faunal elements (ostracods and gastropods). Fragments of thin, millimetric crystalline calcite sheets corresponding to the Paper-thin raft facies (Figs. 5f; 6f) are locally found in subhorizontal accumulations associated with bacterially induced micritic mudstone. According to GUO & RIDING (1998) and CHAFETZ & FOLK (1984) the brittle crystalline sheets of calcite form at the air/water interface of small pools of hot water and subsequently break and fall down at the bottom. Bacterial/cyanobacterial aggregates, giving rise to the clotted fabric, develop within the micritic mud at the bottom of basins where high temperature, $H_2SO_4$ content, and low levels of oxygen prevent the life of higher vegetal and animal organisms. Tabular laminae exclusively formed by bacterial "bushes" and mats, and the occurrence of paper-thin raft suggest the thermal origin of the laminated facies since "Bacterial shrubs" and "Shrub Travertine" facies are known to form in pools or ponds and generally in stagnant/low energy shallow bodies of warm water (GUO & RIDING 1998; CHAFETZ & GUIDRY 1999).

*3.2 The depositional units*

*Lower Depositional Unit* (LDU) - (about 6 m thick) the base of the sequence, resting unconformably on the clays of the Pliocene substrate, is represented by about 1,5 m of polymodal conglomerates including cobble- to boulder-size pebbles and sands in lenticular layers up to 30 cm thick.

This conglomerate layer is sharply overlain by an alternation, about 2 m thick, of mixed fine sands and chalky marly calcareous tufa, that in turn is sharply overlain by about 2 m of well bedded, regularly laminated whitish, bacterial/cyanobacterial travertine.

The LDU facies association can be interpreted to represent the evolution of an original fluvial system from the eroding stage to a palustrine/lacustrine cool-water environment resulting from the progradation of warm waters in pools fed from a thermal complex. This progression is documented by the basal coarse detrital facies derived from the Neogene and pre-Neogene substrates and the blocks of laminated crystalline travertine removed from more recent continental carbonates, and by the subsequent deposition of calcareous tufa, and of laminated bacterial/cyanobacterial travertine in the upper part of the unit.

*Middle Depositional Unit* (MDU) - (about 9 m thick) it overlies the LDU with an irregular, apparently erosive contact, locally enhanced by local accumulations of residual rusty-red silt (Fig. 5e). This Unit consists of two carbonate intervals similar to those of the LDU. The lower one (max 1 m thick) is represented by well developed Phytohermal/Phytoclastic facies of calcareous

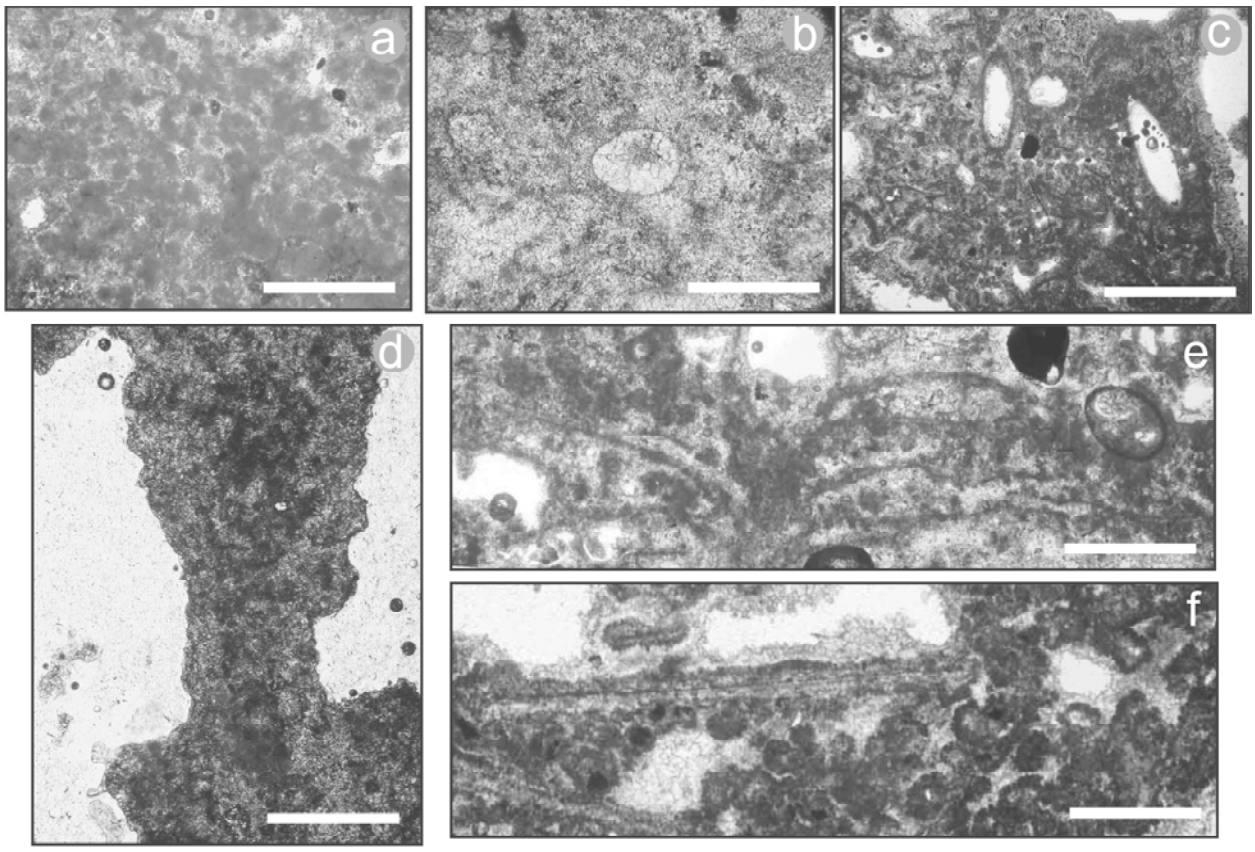


Fig. 6 - a) Thin section of the marly peloidal mudstone (plain light, scale bar of 2 mm); b) section of an ostracod within the marly peloidal limestone of the calcareous tufa (plain light, scale bar of 2 mm ); c) twig-size elliptical sections (plain light scale bar of 2 mm); d) micritic shrub of the laminated limestone (plain light, scale bar of 1 mm); e) bacterial laminae (plain light scale bar of 2 mm); f) paper thin raft of crystalline calcite embedded in a peloidal matrix (plain light, scale bar of 2 mm).

*a) Sezione sottile dei calcari marnosi peloidali (nicol paralleli, barra per scala: 2 mm); b) sezione di un ostracode all'interno dei calcari marnosi peloidali (nicol paralleli, barra per scala: 2 mm); c) cavità ellittiche di sottili steli (nicol paralleli, barra per scala: 2 mm); d) esempio di shrub micritico nei calcari laminati (nicol paralleli, barra per scala: 1 mm); e) lamine batteriali sovrapposte (nicol paralleli, barra per scala: 2 mm); f) sottile lamina cristallina (paper thin raft) immersa in matrice peloidale (nicol paralleli, barra per scala: 2 mm).*

tufa that commonly fill small notches of the erosive basal surface. The transition to the overlying well-bedded travertine interval (about 8 m thick) is rapid. As in the LDU, it is dominantly represented by laminated bacterial/cyanobacterial facies but locally the Paper-thin raft facies is found associated with micritic mudstone layers. The top of the MDU largely coincides with the flat surface of the terrace. It is covered by a rather thick brown soil.

The facies associations, as in the underlying LDU, represent the evolution from the palustine/lacustrine conditions of a fluvial system (Phytohermal/Phytoclastic calcareous tufa) to the stagnant conditions in basins fed by a thermal system (laminated bacterial/cyanobacterial facies and paper-thin rafts).

*Upper Depositional Unit* (UDU) -mainly exposed in the internal front of an abandoned quarry (Fig. 7), it is represented by about 2 m of the poorly layered, porous/chalky marly calcareous tufa alternated with Phytohermal/Phytoclastic facies. This unit, preserved within a small gully cut in the upper part of the MDU, probably attests the beginning of a third cycle of carbonate deposition.

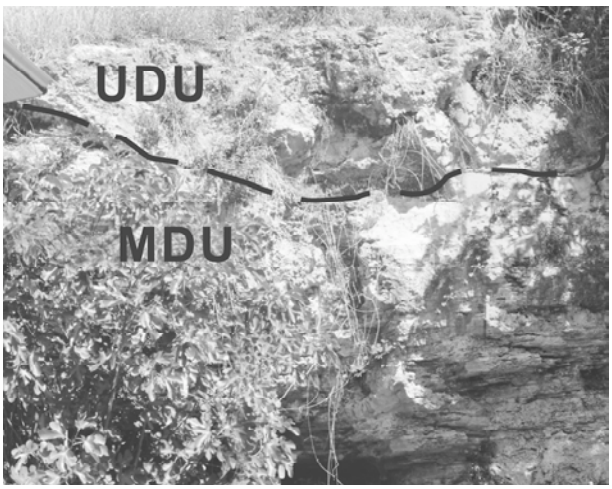


Fig. 7 - Upper part of the FOC succession in the abandoned quarry. Contact between MDU and UDU is enhanced.

*Porzione superiore della successione FOC nella Cava abbandonata. Viene evidenziato il contatto fra la MDU e la UDU.*

## 4. DISCUSSION

The sedimentological and petrographic analysis of the carbonate facies cropping out at Bagnoli in the Imbotroni Valley documents the inception of the carbonate deposition in the FOC Synthem. The succession rests on coarse-grained, high-energy fluviatile alluvial deposits (basal conglomerates) attesting a high-energy erosional event that incised the Pliocene substrate. The occurrence within these conglomerates of carbonate boulders with an evident travertine fabric, support the hypothesis that they derive from the erosion of previous thermal deposits (probably a cone mound) that can be related to the earlier Calcinaia Sythem (CAL) or to an older now eroded, synthem.

The overlying carbonate succession is characterized by two (LDU and MDU), probably three (UDU), depositional cycles consisting of the alternation of poorly bedded chalky calcareous tufa and well bedded crystalline, or dense laminated bacterial travertine. This alternation of calcareous tufa and travertine attests the repeated shifting of the environmental conditions probably caused by the intermittent activity of thermal

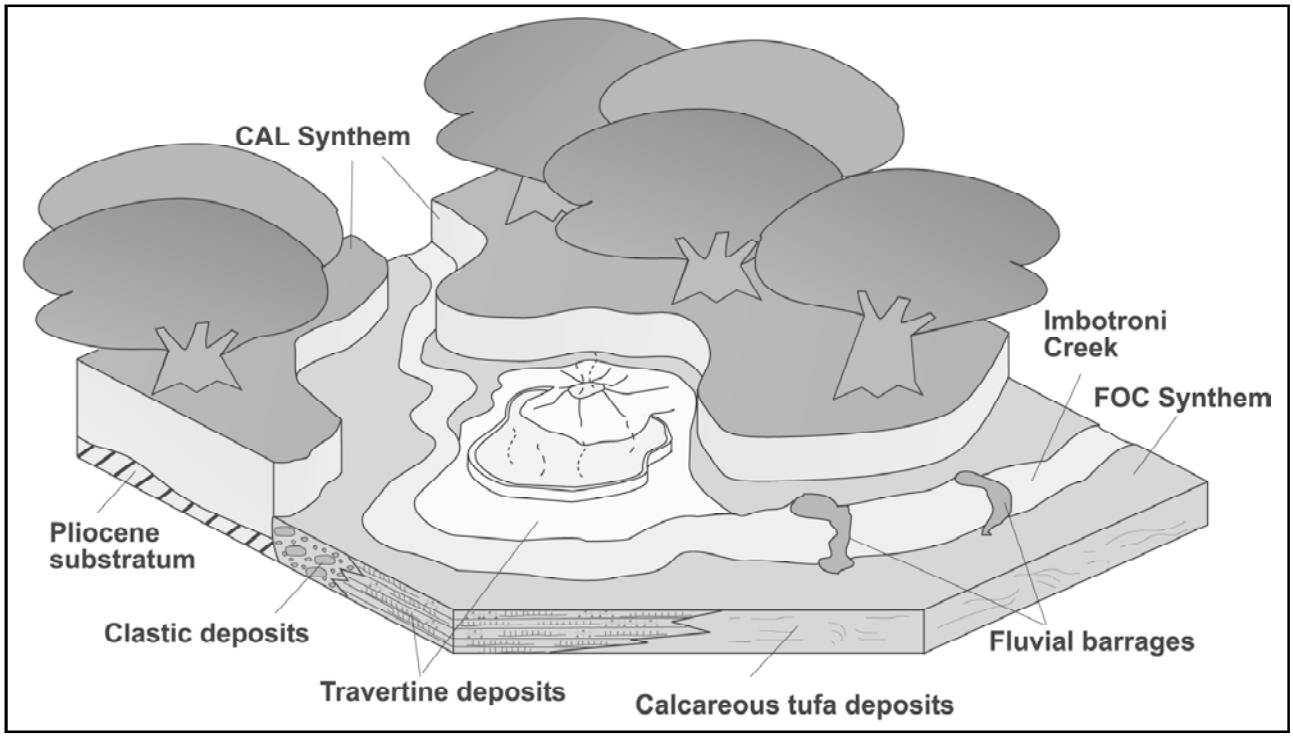


Fig. 8 - Schematic palaeoenvironmental reconstruction of the Bagnoli spring (not in scale).

*Ricostruzione schematica paleoambientale della sorgente di Bagnoli (non in scala).*

spring/s.

The carbonate-rich waters, flowing in the Late Pleistocene Imbotroni valley, were probably mixed waters in part of meteoric/karstic origin, in part cooled waters derived from a thermal source located upstream and now covered by younger deposits.

The thermal spring was building a small travertine depositional system, probably a mound cone (Fig. 8). In the proximal Terrace Slope System (Depression Depositional System; GUO & RIDING 1998) thin bedded crystalline facies, well-bedded shrub facies cyanobacterial laminites and muds with paper-thin raft formed in shallow still-water ponds. These lithologies are indicative of the physico-chemical characteristics of the outflowing thermal water: the high temperature and encrusting capacity, the $H_2SO_4$ content and low levels of oxygen, all adverse to the development of higher vegetal and animal life.

Downstream from the warm water spring/s, calcareous tufa formed in the fluvial valley where a vegetated system with trees, bushes and grass could developed in small cool water ponds and marshes. This system was bounded by shallow barrages colonized by bryophytes and infilled by fine carbonate mud enclosing ostracods, gastropods, in situ small cyanobacterial tufts and/or encrusted fragments of the surrounding vegetation.

The erosional surface between the LDU and the MDU may be related to a temporary dry up of the thermal spring, as a consequence of a fluctuation of the pluvial regime (dry period) and/or the obstruction of the thermal conduit.

The assumption of the activity of thermal springs during the deposition of the calcareous successions of the Quaternary Synthems of southern Valdelsa is supported by the present activity of few low-thermal resurgences in the area. One of them can be observed at Bagnoli near the limestone outcrop described in this paper. The spring is characterized at present by a low water discharge (1 l/s) and temperature of 23°C. Its encrusting capacity is now very reduced, limited to a thin carbonate coating forming only at the spring orifice (CASAGLI *et alii*, 1990).

Other known springs are the Vene di Onci, consisting of several emergences with a mean discharge of 800 l/s and a temperature of 21°C and the Caldane di

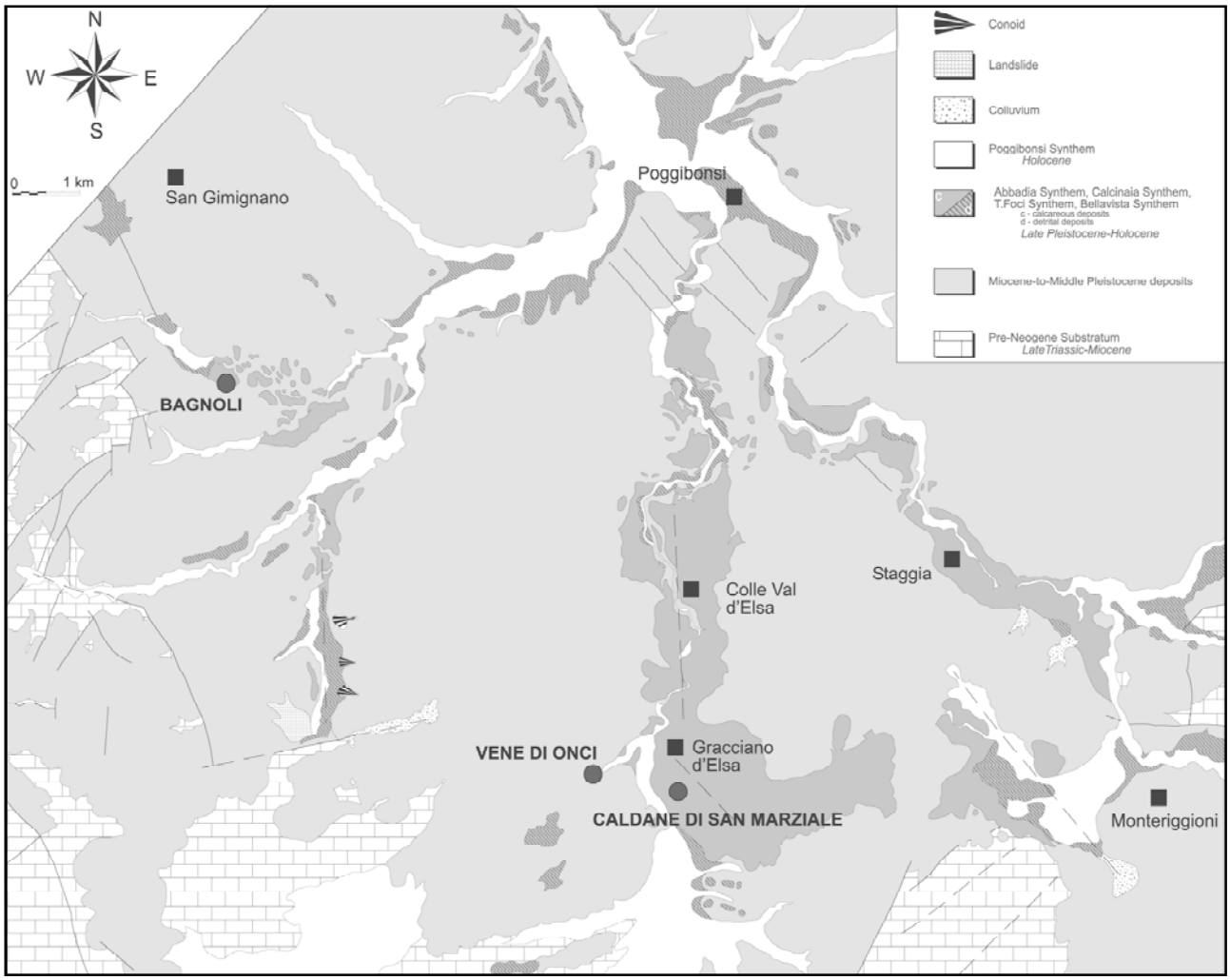


Fig. 9 - Simplified geological scheme of the southern Valdelsa Basin. Distinction between detrital and calcareous deposits of ABB, CAL, FOC, BEL Synthems is evidenced. Location of the active thermal springs (Bagnoli, Vene di Onci, Caldane di San Marziale) supports the assumption that the origin of the calcareous deposits can be related to their presence.

*Schema geologico semplificato della Valdelsa meridionale. La posizione delle sorgenti termali attualmente attive (Bagnoli, Vene di Onci, Caldane di San Marziale) conferma l'ipotesi della loro relazione con i depositi calcarei.*

San Marziale, near Gracciano d'Elsa, consisting of several pools which drain into the Elsa River with a total low-flow of abut 80 l/s and a temperature of 22°C (CASAGLI *et alii*, 1990) (Fig. 9).

The physical and geochemical features of these low thermal springs suggest that the superficial aquifer is fed by waters coming from the "Calcare cavernoso" reservoir (CASAGLI *et alii*, 1990; BARAZZUOLI *et alii*, 2002). The slight thermalism of the springs can be related to the local geothermal gradient, which is about 57 °C/Km (DEL CHICCA *et alii*, 1988).

In all these springs water upwelling seems to be connected to fractures related to the local NE-SW Apennine trending fault system, which connects the deeper circulating network with the upper aquifer (CAPEZZUOLI & SANDRELLI, 2006).

The assumption that the origin of the continental carbonates of southern Valdelsa Basin can be related to the activity over time of these thermal springs appears to be supported by their areal distribution. In fact, as it happens for the small Bagnoli spring, also the Caldane di San Marziale and Vene di Onci springs are located upstream of the segment of the Elsa River Valley where carbonates were deposited. It is possible to presume that all the Pleistocene calcareous deposits occurring in southern Valdelsa Basin were connected with thermal springs that in part are now dried up or concealed/covered by the overlying calcareous tufa.

## 5. CONCLUSION

The results of a detailed analysis of the carbonates exposed at the Bagnoli section provide an interpretation for the genesis and mutual relationships of the different facies and explain the peculiar areal distribution of the calcareous sediments in the Late Quaternary southern Valdelsa Basin. Accordingly, the anomalous distribution of the calcareous sediments of these synthems can be related to the activity of thermal springs that yielded calcium carbonate-enriched water to the local streams thus supporting also the deposition of cool water continental carbonates. Only in the proximity of the spring the physico-chemical proprieties of the water were ideal for the deposition of limestones with the characteristics of travertine. Farther away carbonates with the typical features of calcareous tufa were deposited in the fluvial/palustrine system by mixed, cooled and meteoric waters as long as the carbonate concentration was sufficient for the encrusting process.

Terracing of these Late Quaternary deposits is the main indication that tectonic activity did play an important role in the sedimentation and erosion of the southern Valdelsa Synthems.

This implication, only supposed by CAPEZZUOLI & SANDRELLI (2004; 2006), can be here confirmed owing to the recognition of the hot water-related lithofacies. In fact it is well known that faults and related fracture networks play a major role in channelling and upwelling of hydrothermal fluids (KERRICH, 1986; CUREWITZ & KARSON, 1997). For this reason, travertine bodies are considered good indicators of the activity of thermal springs and also of tensional tectonic activity (ALTUNEL & HANCOCK, 1993a,b; HANCOCK *et alii*, 1999; ATABEY, 2002). Consequently the age of faulting may be constrained by the age of travertine (ALTUNEL, 2005; HANCOCK *et alii*, 1999).

In this case the recognition of the occurrence of travertine lithofacies in the apical part of the calcareous tufa bodies confirms the assumed (CAPEZZUOLI & SANDRELLI, 2006), Late Quaternary-Holocene tensional tectonic activity in the Valdelsa Basin.

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