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CALCAREOUS TUFA DEPOSITS OF THE ANIENE VALLEY BETWEEN VALLEPIETRA AND MANDELA-VICOVARO (LATIUM, CENTRAL ITALY)

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ABSTRACT: Carrara et al. – *The calcareous tufa deposits of the Aniene Valley between Vallepietra and Mandela-Vicovaro (Latium, Central Italy)*. (IT ISSN 0394-3356, 2006).
Calcareous tufa deposits occurring in the Aniene and Simbrivio Valleys (Latium, Central Italy) between Vallepietra and Mandela-Vicovaro areas have been studied by means of morpho-geological mapping, mineralogical and facies analysis, malacofauna investigation, geo-archeological research and U/Th dating. The deposits of Subiaco and Mandela-Vicovaro have been studied in detail, because their formation has modified not only the geomorphic features of the two areas, but has strongly controlled and directed the human activity. A 15 m thick calcareous tufa body occurring in a bore drilled near Marano Equo, intercalated in a Paleoaniene alluvial deposits, has also been studied.
After having examined the geological and structural pattern of the valley, controlled by apenninic (NW-SE) and antiapenninic (NE-SW) faults and by a complex hydrological system, that makes it one of the richest valleys in spring-waters of Latium (most of Roman aqueducts came from the Aniene Valley), the deposits of the different sectors are described. Calcareous tufa deposits, occurring in the Simbrivio Valley, connected to several cool springs issuing from the right, steep slope are described. The tufa deposits, prograding vertically and towards the valley bottom, interdigitate and often form highly vegetated terraces, on the front of which still active waterfalls, covered by moss and algae already partially calcified, occur. In the Aniene Valley, upstream of Subiaco very interesting examples of still active tufa deposits, forming fan-shaped bodies, prograding towards the river bed, occur. They are made mainly of phyto-microhermal and stromatolitic laminites, rich in leaf moulds, covered by a thick mat of algae, mosses, liverworts and other hygrophytes. Small barrage tufa deposits can also be observed. In the Subiaco area a tufa deposit, covering an area of about 1 km^2, 70-80 m thick, occurs; it represents a barrage deposit, formed in the gorge at the outlet of the Subiaco basin, probably built up in correspondence to a morphological step of tectonic origin. Its basal portion is mainly made of palustrine, thinly laminated facies, rich in leaf moulds and vegetal frustules, grading upward to massive or grossly stratified, phyto- microhermal framework, containing well-developed large pools, filled with sandy-silty phytoclastic sediments of fluvio-lacustrine environment. The outer part of the deposit is partially covered by vertical hanging festoons and drapes of moss cascade lithofacies. The deposit has been terraced in three orders of terraces by the river, at present flowing in a narrow gorge in the Miocene substratum. The Ist order terrace surface is covered by a thick, pedogenized soil colluvium, rich in volcanic minerals, while the terraces of the IInd and IIIrd orders are covered by reddish-brown or brown soils, poor or devoid of volcanic minerals. In the Mandela-Vicovaro area a continuous calcareous tufa terrace extends along the Aniene gorge for about 3 km, up to 60-70 m thick. It formed as a barrage deposit near Vicovaro, where the emplacement of Middle Pleistocene volcanics, superimposed by younger, coarse alluvial sediments has produced a discontinuity in the river bed. As in the Subiaco deposit, the lower portion of the Mandela-Vicovaro one is composed of thinly stratified, laminitic and microhermal lithofacies, rich in leaf molds and vegetal frustules, of palustrine environment. They grade upward to massive phyto- microhermal litofacies, associated with large sandy-silty pools, rich in malacofauna. The surface of the terrace is covered by brown, calcareous soil. The terrace has been cut deeply as far as the Miocene substratum by the Aniene river and Licenza stream, its main right tributary. The sections of the terrace along the river are partially covered by waterfall moss lithofacies, forming vertical hanging drapes. The study of malacofauna contained in pool filling sands and silts referred the sediments to shallow freshwater, well vegetated environment, under temperate climate. Several Marano Equo, Subiaco and Mandela-Vicovaro samples have been dated by means of U/Th method which allowed the reconstruction of the chronostratigraphic evolution of the three calcareous bodies, referring the first to Late Pleistocene, the second to Upper Pleistocene-Early Holocene and the third to Late Glacial-Middle Holocene. Finally, on the basis of direct and bibliographic researches, the presence of Roman dams built up in the Subiaco area, forming upstream lacustrine basins, at present no longer existent, are discussed.

RIASSUNTO: Carrara et al. - I travertini della valle dell'Aniene tra Vallepietra e Mandela-Vicovaro (Lazio, Italia centrale). *(IT ISSN 0394-3356, 2006).*
Nel presente lavoro sono stati studiati i depositi di travertino presenti nella valle dell'Aniene e del Simbrivio, tra Vallepietra e Vicovaro, alcuni dei quali ancora in via di formazione. Con particolare dettaglio sono stati studiati i vasti depositi di Subiaco e di Mandela-Vicovaro, che con la loro formazione hanno naturalmente modificato la struttura morfologica delle due aree, controllandone anche l'attività antropica. E' stato studiato anche un corpo travertinoso di circa 15 m di spessore attraversato da un sondaggio effettuato presso Marano Equo, compreso in sedimenti alluvionali del Paleoaniene e legato a sorgenti allora attive nell'area.
Dopo un esame geologico-strutturale della valle, profondamente controllata nel suo andamento da faglie appenniniche ed antiappenniniche e dalle condizioni idrogeologiche, che ne fanno una della valli del Lazio più ricche di sorgenti, connesse con circuiti carsici molto sviluppati, si descrivono i lineamenti geo-morfologici dei depositi di travertino dei vari settori considerati.
Nel settore della valle del Simbrivio si osservano modesti corpi interdigitati, connessi con una serie di sorgenti fredde emergenti sul ripido versante di destra della valle. Detti corpi progradano verso il fiume, lungo il quale formano dei terrazzi di accumulo molto vegetati, in parte ancora attivi, con formazione di facies di cascata con muschi e alghe. Nel settore della valle dell'Aniene a monte di Subiaco, si osservano begli esempi di corpi travertinosi di sbarramento fluviale e di corpi conoidiformi progradanti dal versante verso il fondovalle, ancora in via di deposizione, costituiti principalmente da facies fito-microermali e stromatolitiche, su ricca vegetazione di batteri, alghe, muschi, epatiche e altre igrofite. Nel settore di Subiaco è presente un grande deposito di travertino, ricoprente una superficie di circa 1 kmq, dello spessore di 70-80 m, creatosi per sbarramento della forra del fiume allo sbocco nel bacino di Subiaco, sbarramento impostatosi probabilmente in corrispondenza di un gradino morfologico di controllo tettonico. La porzione basale è caratterizzata da facies di ambiente palustre, mentre la porzione medio-alta è costituita principalmente da facies fito-microermali massive o grossolanamente stratificate con sviluppo di vasche riempite da facies sabbioso-limose fitoclastiche. La scarpata del deposito è parzialmente coperta da grandi festoni e drappeggi verticali di facies fitoermali su muschio. Il deposito, costituito da tre terrazzi deposizionali, è stato

inciso dal fiume, che attualmente scorre in una stretta forra con pareti di travertino, sul fondo della quale affiora il substrato miocenico. Il terrazzo del I ordine è coperto da un colluvio di suolo fortemente evoluto, ricco di frammenti di rocce e minerali vulcanici; mentre sui terrazzi del II e III ordine si sviluppano un suolo rosso-bruno e bruno rispettivamente, poco sviluppati, privi o quasi di materiale vulcanico. Nel settore di Mandela-Vicovaro, lungo la forra, si estende per circa 3 km un terrazzo di accumulo di travertino, con uno spessore che raggiunge 60-70 m, formatosi per sbarramento dell'Aniene in corrispondenza di una discontinuità nel letto del fiume, causata dalla presenza di vulcaniti medio-pleistoceniche, sormontate da depositi alluvionali più recenti. Come quello di Subiaco, il corpo del terrazzo è costituito alla base da facie laminitiche e fito-microermali, sottilmente stratificate, ricche di foglie e frustoli vegetali, di ambiente palustre molto vegetato, passanti verso l'alto a facies massive microermali con sviluppo di ampie vasche a sedimentazione sabbioso-limosa, più o meno fitoclastica, ricca di malacofauna, di ambiente fluvio-lacustre. Sulla superficie del terrazzo si sviluppa un suolo bruno, calcareo, mediamente sviluppato. Anche qui il terrazzo è stato inciso fino al substrato miocenico dall'Aniene e da alcuni tributari di destra. La scarpata del terrazzo lungo la valle è localmente coperta da spesse cortine verticali di travertino in facies fitoermale su muschio. Lo studio della malacofauna contenuta nei limi di Mandela ha permesso di riferirli a un ambiente temperato di acque basse, pozze d'acqua, piccoli laghi, ricchi di vegetazione.

Le numerose datazioni col metodo U/Th di campioni di travertino dei depositi di Marano Equo, Subiaco e Mandela-Vicovaro hanno permesso di ricostruire l'evoluzione dei depositi studiati, che cadono il primo nel Pleistocene superiore, il secondo nel Pleistocene superiore-Olocene inferiore, il terzo nel Tardo Glaciale-Olocene medio. Infine, sulla base di ricerche dirette e bibliografiche, viene discussa la presenza di dighe di epoca romana, che sbarravano l'Aniene presso Subiaco, formando vasti laghi a monte.

Keywords: calcareous tufas, facies analysis, malacofauna, U/Th dating, Pleistocene, Holocene, Simbrivio-Aniene, Latium, Italy.

Parole chiave: travertini, malacofauna, analisi di facies, datazioni U/Th, Pleistocene, Olocene, Simbrivio-Aniene, Lazio, Italia.

1. INTRODUCTION

The calcareous tufa deposits[1] occurring in the Simbrivio and Aniene Valleys between Vallepietra and Mandela-Vicovaro area have not yet been studied in detail. In the present work the mentioned deposits have been examined by means of detailed geo-morphological, sedimentological and facies analysis; mineralogical and petrographical composition, malacological content and U/Th dating have also been determined. The research allowed not only the definition of their main geological features, but also their paleoenvironmental and paleoclimatic significance and evolution. The study has been carried out within the Quaternary and Paleoclimate Research Program of CNR-IGAG.

2. GEOLOGICAL AND MORPHOLOGICAL REGIONAL SETTING (C. Carrara, V. Verrubbi)

The studied stretch of the Aniene Valley (fig. 1) has been deeply cut in geological formations attributed to different palaeogeographic units. East of the study area lithologies related to carbonate platform facies, from Upper Triassic to Upper Cretaceous in age, are widespread in the Simbruini Mountains. West of the Aniene Valley mainly transition and basinal facies occur. Between these two palaeogeographic-structural units, Upper-Middle Miocene siliciclastic deposits outcrop (Damiani, 1992). The studied chain sector began to be involved with Neogenic-Quaternary geodynamic evolution from Messinian times and underwent a polyphase tectonics resulting in imbricate NE vergency thrusts (Bally *et al.*, 1986), followed by NW-SE extentional tectonics (Salvini & Storti, 1992; Cavinato *et al.*, 1992).

During the Lower Pliocene last compressive tectonic phase, important E vergency thrusts occurred. Sabina units, already structured in Apenninic trend by preceding compressive phases, have been pushed toward East to pile up on the carbonate complex of Latium-Abruzzi platform. The tectonic line, along which the thrust of the basin units on the platform ones occurs, is known as Olevano-Antrodoco line.

The later extensional tectonics that caused the dislocation of the thrust pile, dividing it into more or less extended, often tilted blocks and giving rise to horst and graben structures, is still active and is responsible for the seismicity observed in the upper Aniene basin. The extensional tectonics has also determined the thinning of the crust along the Tyrrhenian coast, favouring the upwelling, from Middle Pleistocene, of the magma that has generated the Alban Hill district, immediately west of the studied area, and other volcanic centres within the Apennine Chain.

After the complete emersion that took place in the Upper Miocene, the area underwent strong subaerial land shaping, mainly caused by the erosion due to meteoric water activity.

It acted differently on calcareous and dolomitic sediments and on turbidites, depending on the degree of chemical and physical weathering of rocks, on their geometric setting, as well as on the microclimate of the exposed area and the climatic variations undergone.

In carbonate sediments, outcropping generally in the highest parts, valleys show V cross profiles, more or less open according to their evolution stage. Furthermore, they are often asymmetric because of different structural attitude.

In the turbidite rocks the modelling gave rise to more open valleys with less steep slopes than the preceding ones. The cross sections have a higher degree of symmetry and generally the slopes are more regular.

In some parts of the studied area a strong fluvio-denudation process has been active. It has mainly affected dolomitic lithologies in the Fiumata and Vallepietra localities, where dolomites have been reduced to loose rocks with little aggregation of crystals, due to strong tectonic activity and secondary crystallization (Damiani & Pannuzi, 1981).

Infact, the slopes, cut into the dolomites, appear strongly incised and show several small valleys separated by short and sharp crests. In other carbonate

[1] "Calcareous tufa" is a term widely used in the most recent international literature, as reported by Capezzuoli & Gandin, 2004, to define continental "calcium carbonate deposits formed under cool water regime".

lithotypes too, examples of strong linear erosion can be observed, as in the orographic right of some stretches of the Aniene Valley between Jenne and Subiaco.

The accumulation deposits resulting from fluvio-denudation occur mainly as recent valley floor deposits, forming flat areas along the river; talus and landslide bodies *sensu lato* caused by strong erosion processes are also present (as for example south of Santuario della Trinità and under Monastero di San Benedetto).

Karstic modelling too is widespread on carbonate rocks. Dolinas, poljes, sinkholes etc. among epigeal phenomena, caves among hypogean ones are well known.

During the Quaternary the considered area has been subjected to deposition of continental successions, particularly extended in the Subiaco basin. Herein, between Cappuccini locality and Agosta, on the right side of the Aniene River, and near Madonna del Rapello, on the left side, deposits of stratified, horizontal, heterometric conglomerates, several tens of metres thick, composed of generally well reworked, grossly sorted and imbricated, mainly limestone pebbles, occur. They correspond to the "Antiche Alluvioni Terrazzate" of the old Authors (De Angelis D'Ossat, 1897; Viola, 1903; Beneo, 1934 and 1943). Within the described deposits, intercalations of lacustrine episodes, composed of fine grained sediments, showing in places calcareous tufa characteristics, are described (Damiani *et al*., 1998). They have been interpreted as deposited in the interchannel zones of the described alluvials, even if the Authors do not esclude that they may represent a fandelta in a large lacustrine basin. In these deposits lignite levels as well as vertebrate remains (*Elephas antiquus* Falk.; *Rinoceros merkii* Kaup and Jag.; *Bos taurus primigenii* Bos.; *Cervus euriceros* Aldr.) have been found that refer them to the Pleistocene (Ponzi, 1862, 1878; De Angelis D'Ossat, 1897,1924; Damiani *et al*., 1998). Similar deposits, in places showing clear breccia characteristics, related to ancient alluvial fans, and talus deposits are widespread in the Vallepietra area.

In the tract of valley between Subiaco and Vicovaro, small, *in situ* exsposures of Intrapenninic Middle Pleistocene volcanics, widespread in the adjacent map sheets, represented by leucititic pyroclastic and lithoid flows, occur. Weathered and often anthropically derived volcanoclastic ashes are also widespread (Ponzi, 1852; Damiani *et al.*, 1998).

It is important to note that strongly evolved, thick, soil colluvia, rich in small volcanic rock fragments and minerals, can be observed. They occur not only in the depressions and on the stable zones of siliciclastic and carbonate substratum, but also on the surfaces of the described terraced alluvials, as well as on the surface of the Subiaco I[st] order calcareous tufa terrace (see 5.3).

Moreover, along the Aniene River, downstream

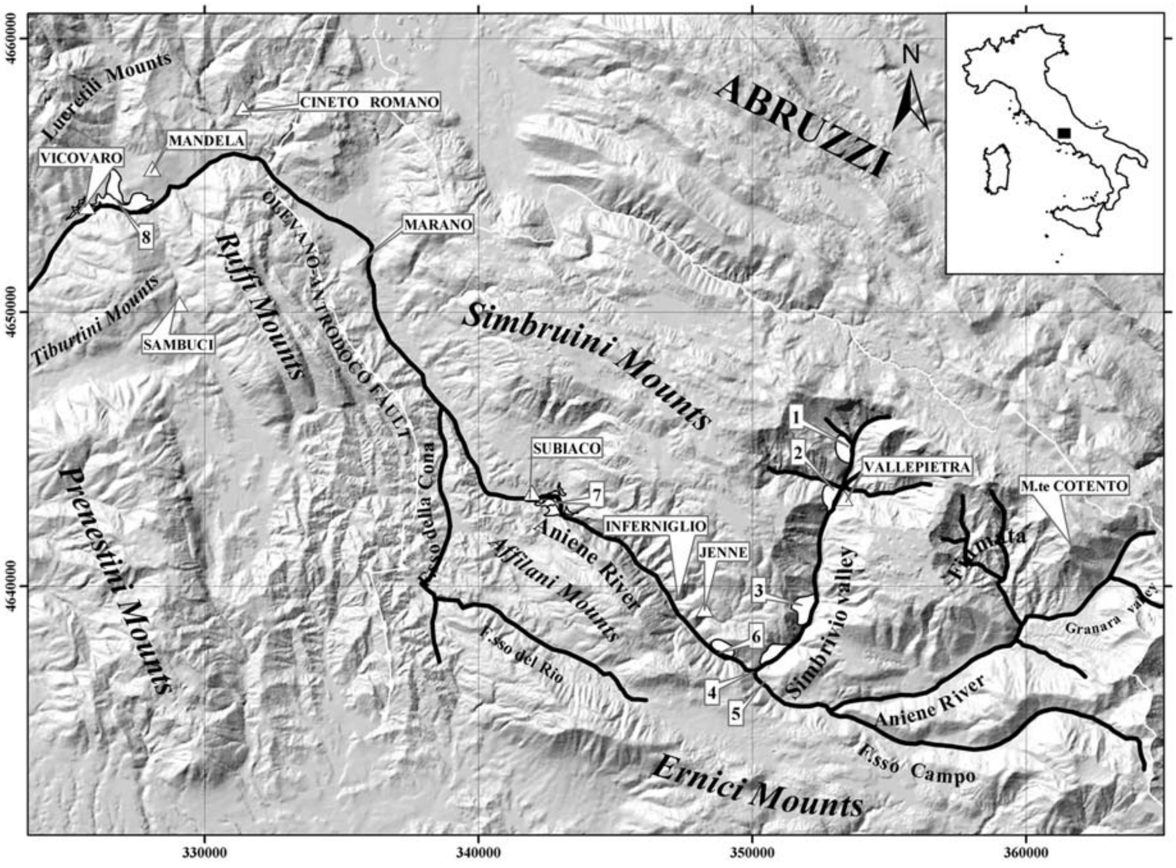

Fig. 1 - Localization of the tufa deposits in the study area: 1. Fonte Acqua delle Donne; 2. Ponte del Tartaro; 3. Case Reali; 4. Brutto Colatore; 5. Comunacque; 6. Acqua dei Cardellini; 7. Subiaco; 8. Mandela-Vicovaro.

Localizzazione dei depositi di travertino nell'area studiata: 1. Fonte Acqua delle Donne; 2. Ponte del Tartaro; 3. Case Reali; 4. Brutto Colatore; 5. Comunacque; 6. Acqua dei Cardellini; 7. Subiaco; 8. Mandela-Vicovaro.

Subiaco, local, lacustrine episodes and terraced deposits, referred to Holocene, are present.

3. HYDROGEOLOGICAL LINEAMENTS (C.Carrara, V. Verrubbi)

The studied area (fig. 1) belongs to the II[nd] order basin of the Aniene River, tributary of the Tiber River and is part of the Mt. Simbruini-Ernici karstic hydrostructure, whose geometry follows the boundary marked by the Upper Miocene terrigenous sediments that surround the carbonate ridge (PERCOPO, 1992).

The river, that upstream Subiaco and in the Mandela-Vicovaro area, shows the morphology of a very incised and narrow gorge, rises in Granara Valley at an elevation of 1619 m. From here as far as Ponte delle Tartare, where it receives the Fosso Campo, the river flows in NE-SW direction; at Ponte delle Tartare it changes direction and flows as far as Cineto Romano in SE-NW direction; from here to Vicovaro it takes again the former direction. These changes of direction are the result of the regional tectonic structure of the considered area; the NW-SE trend is reported to be the more ancient, while that from NE to SW seems to be due to more recent tectonic structures (DAMIANI & PANNUZI, 1981; DAMIANI, 1990A e 1990B). The tributaries of the Aniene River generally pour into the river at right angle.

Not far upstream Ponte Comunacque the Aniene River receives, on hydrographic right, the Simbrivio stream that drains the Vallepietra gorge and is fed by several cool springs issuing at an elevation of about 1000 m. Other cool springs occur particularly upstream Subiaco; among the most important ones: the Inferniglio, Pertuso, Sorgenti di Jenne, Ponte del Tartaro, Acqua dei Cardellini and Comunacque can be mentioned.

The abundance of spring waters of the Aniene Valley was well known by the Romans; among the aqueducts bringing water to Rome, at least four (Anio Vetus, Anio Novus, Acqua Marcia e Claudia) came from the Aniene Valley (CAROSI, 1956).

The waters of the mentioned springs are generally characterized by a carbonate-calcic, locally magnesic, composition, being connected mainly to calcareous and/or calcareous-dolomitic rocks. The Ca/Mg ratio allows the discrimination of the waters circulating in calcareous environment (higher values), from those belonging to dolomitic one (lower values) (BRONDI, 1995-96).

Almost in all the mentioned springs, either in their inner, karstic course or along the outer flow, more or less developed concretionary deposits, speleothems, calcareous pool infilling muds or other calcareous tufa deposits still depositing (Simbrivio Valley, Ponte del Tartaro, see 5.1) or prograding fan-shaped bodies (Sorgente dell'Acqua dei Cardellini, see 5.2), occur.

From Subiaco to Mandela-Vicovaro area, along the Aniene Valley, small calcareous tufa bodies, related to cold springs, characterized by carbonate-calcic, magnesic, locally ferrugineous or sulphureous composition (VENTRIGLIA, 1990), occur.

In the Mandela-Vicovaro area, on the contrary, between the Aniene River on the Southern side and the Licenza stream on the Northern side, an extended calcareous tufa deposit, described in detail in chap. 8, occurs. The formation of this deposit is related to several cool, mainly carbonate-calcic, magnesic springs (VENTRIGLIA,1990), linked to the hydrological circuits of the Simbruini and Lucretili Mounts, draining partly towards the Aniene River (BONI, BONO & CAPELLI, 1988A e B).

On the basis of geochemical and isotopic data of Quaternary fossil and present travertines and the relative spring waters in the region north of Rome, MINISSALE *et al*. (2002) show that there are important differences in their composition between the springs and deposits placed west and east of the Tiber Valley. The western deposits show typical thermogenic (high temperature) characteristics, while the eastern ones (including the springs and travertine deposits described in the present work) show meteogenic (low temperature) characteristics. "The travertine-precipitating waters east of the Tiber Valley have shallower flow paths than those to the west", therefore they are cooler and "have CO_2 isotopic signatures, indicating a significant biogenic contribution acquired from soils in the recharge area and limited deeply derived CO_2".

4. PREVIOUS AUTHORS (C. Carrara)

Geological information about travertine deposits of the considered stretch of Aniene Valley are scarse and short. Among the first the geological observations on travertine deposits of the Roman Country can be mentioned that of PELLATI (1882), where the Author cites travertine quarries of the Subiaco area, some of which give high quality material, while others produce only light and vacuolar travertine.

An interesting, geological-geographic work on the upper Aniene Valley is that published by DE ANGELIS D'OSSAT (1897). In this work, besides the orographic, hydrographic and geological description of the area, the deposits of "Lower Post-Pliocene age (*sic*)", comprising the terraced conglomerates of Subiaco containing mammal rests and several more or less consolidated volcanic *in situ* products are described in detail. The deposits of "Upper and Recent Post-Pliocene (*sic*)" comprise mainly travertine sediments and weathered loose volcanic materials mixed with colluvial detritus. The author asserts that travertine deposits are widespread in the Subiaco area, where they seem to form "three different surfaces (sic)" likely terraced by the river that deeply cut them, and in Mandela-S. Cosimato area. They are rich in moulds of leaves, present flora and snails. Moreover, the author states that in the deposit of the Sambuci stream he found a frontal portion of a deer skull cut by man, while near Jenne and Mandela a big harts-horn and a fragment of an ox shoulder, both clearly recent, have been found respectively.

The loose volcanic materials mixed with colluvial detritus, composed mainly of augite, black mica, feldspar and leucite grains, occur in several parts of the valley not only on ancient formations, but also on the most recent ones, such as the Subiaco conglomerates, the travertines and the recent alluvial deposits of the Aniene River.

VIOLA (1903) breifly describes the Ancient

Quaternary of the Aniene Valley, which comprises several deposits of terraced conglomerates, occurring near Subiaco and in other parts of the valley, and travertine deposits of Subiaco and Mandela-Vicovaro areas. The Subiaco travertine deposit, according to the author, forms a terraced body of a thickness not less than 100 m, spread on a surface of about 1 km^2. This body, as well as that of Mandela-Vicovaro area, has been cut by the river that reached the Tertiary substratum below. BENEO (1934) mentions the ancient terraced conglomerates of Subiaco, showing a thickness of about 50 m, and the volcanic tuffs widespread in the study area, which, being intercalated in the recent alluvial deposits of the Aniene River, can be considered more recent than the Subiaco fluvial terraces.

DEVOTO (1967) too mentions the Pleistocene travertine and lacustrine calcareous tufa deposits filling the incised and extended valleys of the Simbrivio and Aniene Rivers, observing that in the travertine deposits thin calcareous clayey layers are often intercalated, which have been deposited in small lacustrine mountain basins, as proved by their malacofaunal content, represented by *Bulimus B. tentaculatus* Limn., *Bulimus B. leachi* (Sheppard) and ostracofaunal content, consisting of *Potamocypris fulva* (Brady), *Ilyocipris brady* Sars, *Candona neglecta* Sars, *Candona (Pseudocandona) lobipes* Hartwic, *Cypridopsis subterranea* (Wolf), *Ilyodromus fontinalis* (Wolf), *Ilyodromus olivaceus* (Br. And Norm.), Candona cf. *acuminata* (Fisch.), Candona cf. *procera* Straub, *Candona rostrata* (Br. And Norm.).

DAMIANI *et al*. (1998) describe briefly the Quaternary deposits occurring in the Subiaco area, composed mainly of terraced conglomerates with intercalations of lacustrine episodes, containing remains of plants and mammals, generically attributed to Pleistocene, as well as Holocene-Pleistocene highly weathered volcanic ashes, resting on more ancient volcanoclastic and continental units, including the travertine deposits occurring in several parts of the Simbrivio and Aniene Valleys.

5. MORPHOLOGICAL AND GEOLOGICAL FEATURES OF THE CALCAREOUS TUFA DEPOSITS (Carrara, Verrubbi)

5.1 The Simbrivio Valley

In the Simbrivio Valley, a right tributary of the Aniene River, several small bodies of calcareous tufas occur (DAMIANI *et al.*, 1998). The main ones occur north of Vallepietra near Fonte Acqua delle Donne at 830 m a.s.l. and at Ponte del Tartaro at 785 m, while south of Vallepietra other two bodies can be recognized at 20th km of state road SP 45 at Case Reali locality at 623 m and at Brutto Colatore locality, 1 km from the convergence to the Aniene River at 590 m (Fig. 1).

The mentioned calcareous tufa deposits are similar for morfological and lithological characteristics. They form depositional coalescing fan-shaped bodies that from the western right steep slope have prograded towards the valley floor, forming a tabular sheet-like terrace that reached the river, encased of a few metres in its overflowing terrace. The progradation of the terrace towards the river, in places, seems to have determined its shifting to east. The surfaces of the terrace is flat and slightly dipping towards the river; the vertical escarpments, 5-6 m high, are visible continuously over distances ranging from some tens of metres to 200-300 m. The depositional terrace consist of superimposed, horizontal or subhorizontal irregularly stratified bodies, composed in the lower part of mainly microhermal lithofacies interfingered with phytoclastic sands and silts and lensoid phytohermal growths. Upward they grade to an association of stromatolitic and microhermal lithofacies with intercalations of phytoclastic lithofacies; a few centimetres thick layers, very rich in moulds of leaves (bibliolitic lithofacies) are often associated. From the upper margin of the terrace scarps, thick, lobate, moss phytohermal drapes often hang; in places they can cover the whole scarp wall (Fig. 2).

The formation of the studied terrace is related to the activity of cool springs issuing on the right steep slopes of the valley; the springs, owing to the deposition of calcareous tufa sediments, have undergone frequent

Fig. 2 - A: The scarp of the calcareous tufa terrace of Ponte del Tartaro. The deposition of calcareous tufas is still active, the scarp being flowed through by streams of incrusting waters and covered by vertically hanging drapes and festoons of hygrophites, partially calcified.

Scarpata del terrazzo di travertino di Ponte del Tartaro. La deposizione di travertino è ancora attiva; la scarpata è, infatti, corsa da ruscelli di acqua incrostante ed è coperta da festoni e drappeggi verticali di vegetazione igrofita parzialmente calcificata.

diversions and shiftings of their course, giving place to the formation firstly of braided stream like deposits, then toward the valley bottom of more uniform sheet-like interfingered bodies as reported in other calcareous tufa deposition areas (perched springline model of PEDLEY, 1990; VIOLANTE *et al.*, 1994; Pedley et al., 2003). In the terraces of Fonte Acqua delle Donne and Ponte del Tartaro the activity of cool springs and the deposition of calcareous tufas still continue.

5.2 The Aniene Valley upstream of Subiaco.

In the upper Aniene Valley, SE of Subiaco, several small calcareous tufa deposits occur; the main ones crop out at about 1 km upstream from the Ponte di Comunacque at 550 m and at Acqua dei Cardellini at 558 m (DAMIANI *et al.*, 1998) (Fig. 1).

The Ponte di Comunacque deposit represents a typical fluvial barrage (PEDLEY, 1990) composed of a micro- phytohermal, massive, some metres high framework, extended from one bank to the other of the river. The downstream wall of the barrage shows a gradine structure, where moss phytohermal vertical drapes associated with laminated, often wavy encrustations occur. The upstream part of the barrage forms a body extending some tens of metres, composed of coarse phytoclastic sands and silts. Its inner structure is not visible, owing to the thick vegetational cover, but in some local incisions, which indicate outcrops of microhermal and stromatolitic textures. The calcareous

Fig. 3 - Still active fan-shaped calcareous tufa body (Acqua dei Cardellini), prograding and aggrading from the slope to the riverbed, covered by mosses, algae and other hygrophytes.

Corpo conoidiforme di travertino (Acqua dei Cardellini) ancora attivo, progradante e aggradante dal pendio al letto del fiume, coperto da muschi, alghe ed altre igrofite.

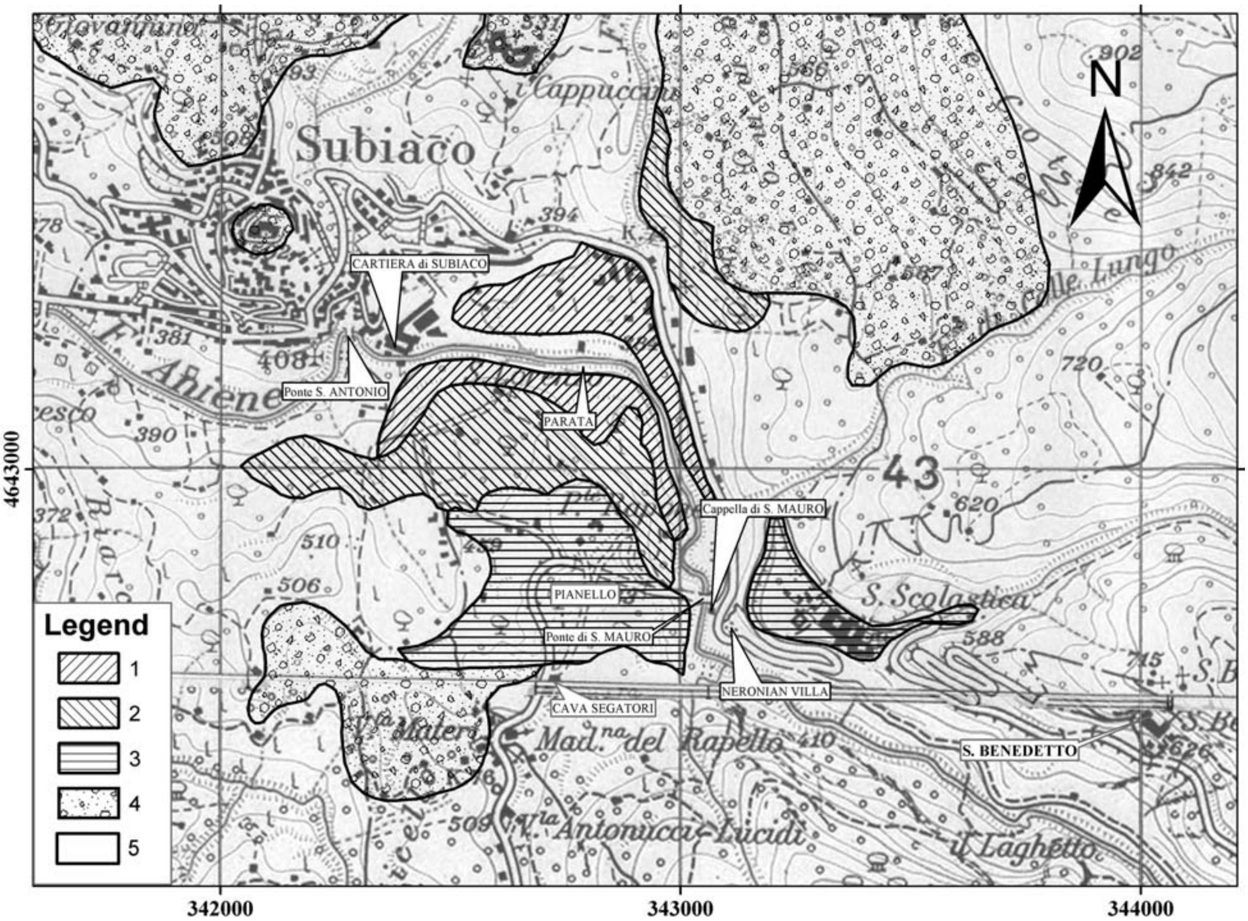

Fig. 4 - Simplified geological scheme of the Subiaco area. Legend of symbols: 1. IIIrd order terrace (Holocene), 2. IInd order terrace (Early Holocene), 3. Ist order terrace (Upper Pleistocene), 4. Alluvial deposits (Lower Pleistocene), 5. Miocene substratum.

Schema geologico semplificato dell'area di Subiaco: 1. Terrazzo del III ordine (Olocene); 2. Terrazzo del II ordine (Olocene inferiore); 3. Terrazzo del I ordine (Pleistocene superiore); 4. Depositi alluvionali (Pleistocene inferiore); 5. Substrato miocenico.

tufa barrage has undergone at least from the III-IV century b.C. water diversion and catchment, as well as the cutting of deep and narrow channels for water penstock needed to turn mills. At present the deposit and the ruins of the mentioned works are only partially visible, because of the thick vegetation cover, comprising not only trees and bushes, but also a widespread mat of moss cushions and algae, already partially calcified by the river encrusting waters, herein forming cascades, rapids and whirlpools.

The Acqua dei Cardellini deposit (cardellino is the name given in this region to the surficial, weathered, highly porous and vacuolar part of micro-phytohermal deposits) represents the typical example of a lobate, gradine, fan-shaped calcareous tufa body, genetically linked to an encrusting spring (Fig. 3), prograding downslope (VIOLANTE *et al.*, 1994). Its base is about some tens of metres width and several metres thick. It is presently precipitating and prograding, being run by several divergent streams of water and covered almost intirely by a luxuriant vegetation of mosses, algae and other hygrophyte plants.

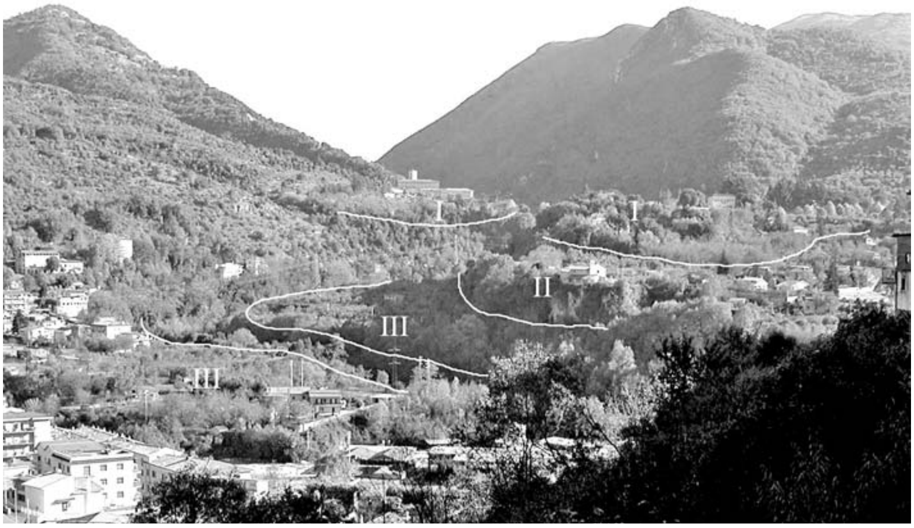

Fig. 5 - View of the Subiaco calcareous tufa deposit and the relative three orders of depositional terraces.

Veduta del deposito di travertino di Subiaco con i relativi 3 ordini di terrazzi di deposizione.

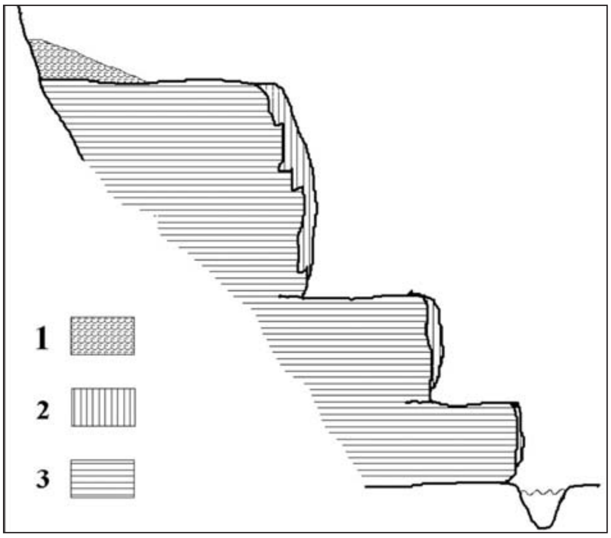

Fig. 6 - Profile sketch (not to scale) of the three depositional terraces of Fig. 5. Legend of symbols: 1 Pedogenized soil colluvium rich in volcanic minerals; 2 Cascade moss phytohermal lithofacies; 3 Mainly microhermal and phytohermal lithofacies framework.

Profilo schematico non in scala del deposito di Subiaco con i relativi tre terrazzi deposizionali mostrati in Fig. 5. Legenda: 1 Colluvio di suolo pedogenizzato ricco di minerali vulcanici; 2 Litofacies fitoermali su muschio di cascata; 3 Struttura di sbarramento costituita prevalentemente da litofacies micro e fitoermali grossolanamente stratificate.

5.3 The Subiaco area

In the stretch of the Aniene Valley comprised of between Subiaco and the Monastero di S. Scolastica, a calcareous tufa deposit exposed on a surface of about 1 km^2 and composed of three depositional terraces, occurs (DE ANGELIS D'OSSAT, 1897; DAMIANI *et al.*, 1998) (Figg. 4, 5, 6). The Ist order terrace consists of two segments occurring respectively on the left and right banks of the river, at the outlet in the Subiaco basin. They rest uncomformably as wedge-shaped bodies on the Miocene limestone bedrock.

The segment on the right bank, on which the monastery is located, shows a vertical scarp of about 70 m (from 510 to 440 m), and a regular, flat surface. Other portions of minor dimensions occurr along the road to Comunacque, where in places are affected by evident landslide phenomena due to undercutting by the Aniene River that, after having cut the entire deposit, at present flows in the limestones of the bedrock.

The segment on the left side, wider than the right one, lies partly on the Miocene substratum, partly on alluvial deposits related to Lower Pleistocene (DAMIANI *et al.*, 1998); it shows an even scarp, comprised of between 500 and 440 m in the river gorge and a flat surface in places cut by secondary minor scarps.

The most complete section of the deposit is visible along the road rising to Monastero di S. Scolastica and in the Cava Segatori locality, where the uncomformable, abrupt contact of calcareous tufas on bedrock is often observable.

From a lithological point of view two longitudinal parts of the deposit can be recognized: an inner one, mainly composed of autochthonous lithofacies associations, grading upwards to mainly phytoclastic lithofacies and an outer one, downstream, almost wholly composed of cascade lithofacies.

The reconstructed section representative of the inner part of the deposit, is here described (Fig. 7). At the base generally horizontal or gently dipping downstream layers of thinly laminated microhermal and stromatolitic lithofacies, from some centimetres to few decimetres thick, resting on a reddish-brown paleosol, outcrop. They can contain many molds of leaves, frustules and other parts of plants. In places, however, lenticular bodies of micro- phytohermal lithofacies showing high vacuolar texture, occur. Phytohermal lithofacies on mosses and macrophytes prevail upwards, in the middle part of the section, where they form massive or coarsly stratified subhorizontal framework.

To this phytohermal lithofacies lenticular intercalations of pool infilling phytoclastic calcareous sands and silts[2], ranging from some decimetres to several metres in size, are associated. These phytoclastic lithofacies can be organized in massive or thinly laminated layers, showing in places planar cross-bedding structures, slightly dipping towards SW and containing small lenticular or rounded phytohermal cushions. The edges and the bottom of the pools are often coated by thinly laminated lithofacies, often showing microterraced structures.

In the upper part of the section grossly stratified sandy and silty phytoclastic lithofacies prevail. They often contain lithified microhermal layers.

On the surface of the deposit (I^{st} terrace) a reddish-brown (5YR÷7.5YR), well-developed soil, some metres thick, containing a great quantity of volcanic minerals and highly weathered volcanic rock fragments[3], occurs.

The outer part of the deposit consists of moss phytohermal lithofacies, that form discontinuous, lobate, vertical curtains and drapes strongly tied to the external walls of the inner part. They have a variable thickness ranging from few decimetres to several metres. They often form landslide accumulations at the foot of the wall (Fig. 6).

The II^{nd} order terrace also occurs on both banks of the river; its surface, dipping gently towards the river, develops at an elevation of about 450 m a.s.l. The scarp of the terrace outcrops only in some sections along the river, at Parata under Chiesa di S. Lorenzo.

Here, on the right bank of the river, the lower part of the deposit consists of a body, about 20 m thick, characterized by a chaotic structure, composed of phytoclastic, sandy matrix supported calcareous tufa boulders, varying from several cubic centimetres to more than a cubic metre, showing a different orientation (Fig. 8). The boulders are mainly made of phytohermal and microhermal lithofacies; laminitic lithofacies are less widespread.

The upper surface of this chaotic body is strongly eroded and is cut by deep, large channels and pools, filled with stratified, calcareous phytoclastic sands, in places associated with thin laminitic concretions and small phyto-microhermal lenses. These sediments lie uncomformably on the chaotic body at the base. The described lithofacies association grades in the uppermost 2-3 metres to laminated silts, containing thin, brown-blackish clayey layers. The chaotic body could represent an intraformational landslide or a local accu-

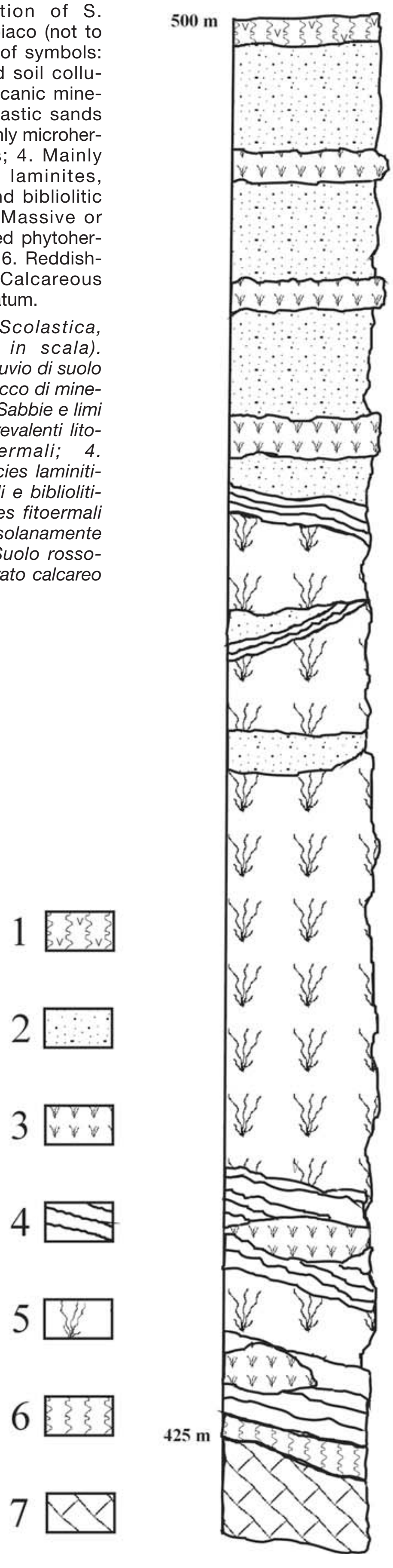

Fig. 7 - Section of S. Scolastica, Subiaco (not to scale). Legend of symbols: 1. Pedogenized soil colluvium rich in volcanic minerals; 2. Phytoclastic sands and silts; 3: Mainly microhermal lithofacies; 4. Mainly stromatolitic laminites, microhermal and bibliolitic lithofacies; 5. Massive or coarsely stratified phytohermal lithofacies; 6. Reddish-brown soil; 7. Calcareous Miocene substratum.

Sezione di S. Scolastica, Subiaco (non in scala). Legenda: 1. Colluvio di suolo pedogenizzato ricco di minerali vulcanici; 2. Sabbie e limi fitoclastici; 3. Prevalenti litofacies microermali; 4. Prevalenti litofacies laminitiche, microermali e bibliolitiche; 5. Litofacies fitoermali massive o grossolanamente stratificate; 6. Suolo rosso-bruno; 7. Substrato calcareo miocenico.

[2] They are mainly composed of fragments of microcrystalline calcite and micritic fitoclasts, few fragments of mollusc and ostracods and rare volcanic minerals.

[3] Well developed, acalcareous, reddish-brown soil, showing prismatic structure and containing clayey cutans and Fe-Mn striations; the skeleton is composed of angular fragments of limestone and dense tufa. The volcanic content ranges up to 40% and more of the rock and is represented in decreasing order by prismatic blackish pyroxene, large biotite plates, prismatic sanidine and rare leucitic grains.

mulation of heterometric blocks of a preceding dismantled deposit. It does not occur on the left scarp of the terrace.

It is worth noting that the II[nd] order terrace surface is covered by a reddish-brown (5YR÷7.5YR) pedogenized silty-clayey colluvium, 1-2 m thick, lacking volcanic material, or containing a very poor fraction of such material, not comparable to that contained in the soil developed on the I[st] order terrace body.

The III[rd] order terrace, whose discontinuous scarp is comprised of between 400 and 385 m, consists of a larger part, occurring on the right side of the river, at present completely covered by the recent buildings of Subiaco, and of a narrow strip along the left side of the river under the S. Lorenzo II[nd] order terrace scarp.

The III[rd] order terrace is poorly exposed; only discontinuous and small outcrops can be seen on its scarp along the river. Vacuolar, micro- and phytohermal lithofacies, associated with thinly laminated bands, rich in moulds of leaves and small frustules, can be observed; they are associated with irregularly distributed stromatolitic lithofacies and pool infilling phytoclastic sands and silts; in places they are covered by small moss cascade curtains.

On the III[rd] order terrace surface a brown (7.5YR), calcareous soil, devoid of volcanic material, occurs.

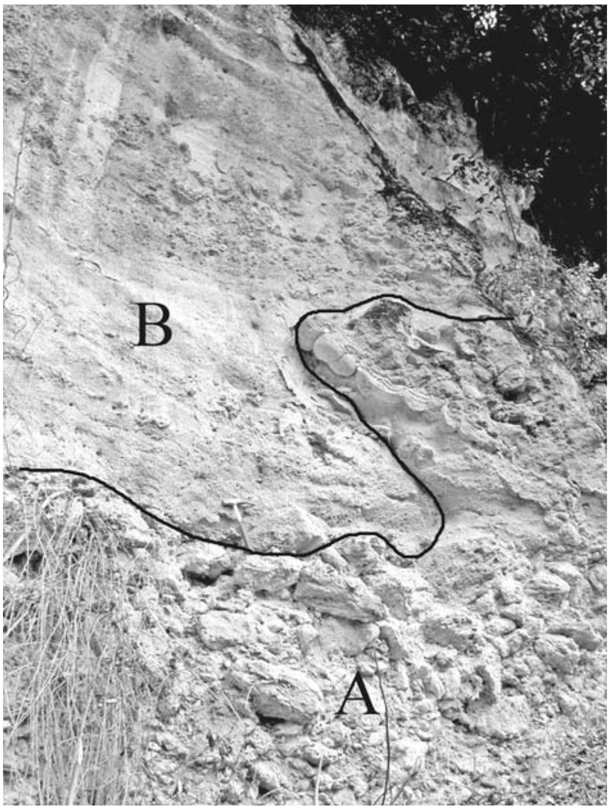

Fig. 8 - Scarp of the II[nd] order terrace at Parata. In the lower and right side of the picture landslide body made mainly of phytohermal and microhermal boulders (A); in the middle-upper part pools filling phytoclastic sands and silts (B); laminar textures bound an erosional surface (solid line).

Località Parata: scarpata del terrazzo del II ordine. Nella foto in basso corpo di frana ad elementi di travertino (A); nella parte medio-alta vasche di limi calcarei fitoclastici (B) con tessiture laminitiche che limitano una superficie di erosione (linea continua).

The morphological and structural features of the described terraces suggest their depositional origin. The deposit has been deeply cut and dissected by the river, during non depositional and/or strong erosional phases.

Moreover, the calcareous tufa deposit of Subiaco has been particularly affected by strong karstic processes, that developed mainly along fracture systems and the cavities left by decayed organic matter of plants. Therefore, a very complicated and variable set of channels, cavities and caves formed; in general they are coated by laminar concretions of sparry, alabastrine calcite and by speleothems of variable sizes. On the bottom of some cavities thinly laminated, gray-greenish silty-clayey sediments, containing fragments of terrestrial gastropods, occur.

The framework and the distribution of the associations of lithofacies described suggest a depositional model typical of fluvial barrage (Buccino *et al*., 1978; Pedley, 1990; Carrara *et al*., 1995). At the outlet of Subiaco basin, where the Aniene Valley was deepest and narrowest, the river met a morphological structure, tectonically controlled (the presence of transverse faults is reported in Damiani & Pannuzi, 1981; Damiani *et al*., 1998), that caused a variation of the river flow and of the water turbulence. The obstacle triggered, therefore, the precipitation of calcium carbonate and the formation of the calcareous tufa barrage. This process was associated with the activity of many different macro- and microorganisms that contributed to tufa deposition, as reported by several authors (Carrara, 1991, Golubic *et al*., 1993; Farabollini *et al*., 1994; Pedley, 2000; Pedley *et al.*, 2003).

Upstream the barrage, a well vegetated, palustrine to shallow fluvio-lacustrine environment formed, characterised by the deposition of laminated and micro- phytohermal and phytoclastic bodies, rich in moulds of leaves and parts of plants. Afterwards a massive, phytohermal framework, with complex intercalations of pool infilling phytoclastic lithofacies, grew up. At the same time, on the barrage front cascade lithofacies deposited vertical curtains and drapes.

5.4 Marano Equo Deposit (Branca, Voltaggio)

The morphological depression of Marano Equo formed in early Pleistocene as the result of the extensional tectonics which affected the Late Miocene-Early Pliocene units in the Central Appennines thrust belt.

Lithostratigraphical, compositional and paleontological analyses on sediment cores, from 8 continous boreholes 62.5 to 155 m deep drilled on behalf of the ACEA firm, suggested (Branca *et al*., 1995) that the sedimentary sequence accumulated in notably different depositional environments rather than under uniform conditions. The coarse lithofacies, represented by conglomerate intervals and breccia episodes are related to a paleo-Aniene River transport and erosion of rimming reliefs, respectively. Sandy and clayey muds, along with humified and peaty levels record fluvial braided-plain events. Lithoid tufas and calcareous sands point to the occurrence of formerly active springs issuing bicarbonate-enriched waters. In a core, 145 m deep, containing alternating sands and clayey muds, a calcareous tufa horizon 15 meter thick has been crossed. It extends from -64 m to – 50 m; two samples were collected from -59 level (SU4-51) and -52 level (SU4-52)(see chap. 7 and Tab. 1).

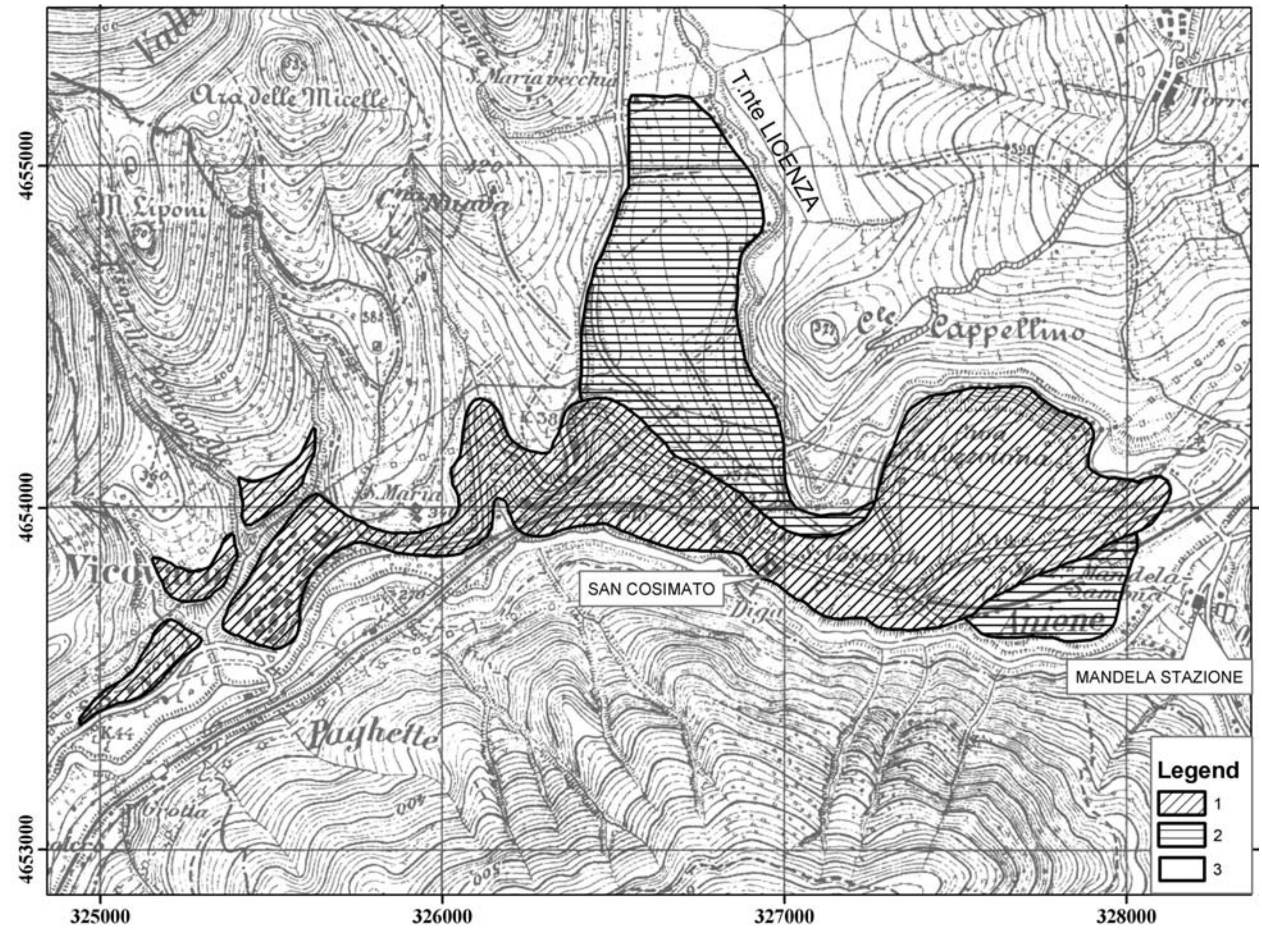

Fig. 9 - Simplified geological scheme of the Mandela-Vicovaro area: 1. Outcropping calcareous tufas (Late Glacial-Holocene); 2. Calcareous tufas covered by colluvials; 3. Miocene substratum.

Schema geologico semplificato dell'area di Mandela-Vicovaro: 1. Travertino in affioramento (Tardoglaciale-Holocene); 2. Travertino coperto da colluvi vari; 3. Substrato miocenico.

5.5 The Mandela-Vicovaro area

In the Mandela-Vicovaro area, a uniform, continuous, depositional, calcareous tufa deposit occurs, extending for about 3 km, from Stazione di Mandela to Monastero di S. Cosimato, as far as some hundreds of metres downstream Vicovaro (figg. 9, 10). The deposit is bounded on the Southern side by the Aniene River, where its scarp follows closely the morphology of the valley, widening out as far as 450-500 m near S. Cosimato and getting narrower where the valley forms a very incised gorge. On the Northern side the deposit is limited by the Licenza stream, right tributary of the Aniene river. The stream has deviated its lower course from north-south direction to east, flowing counterslope into the Aniene River at about 2 km eastward, due to emplacement of volcanics (Bieler Chatelain, 1929) and alluvial deposits near Vicovaro, followed by the growth of the Mandela-Vicovaro calcareous tufa deposit.

The two streams have deeply cut the terraced deposit, reaching the Miocene calcarenitic substrate and exposing the inner structure of the deposit in several vertical sections, varying in thickness from a few tens of metres to 60-65 m.

The surface of the deposit, at a mean elevation of 350 m, is flat and regular, in spite of the dissection by several tributaries on the right side of the Aniene River and of the human activity.

One of the more complete sections of the tufa deposit occurs at Monastero di S. Cosimato (Fig. 11). The section goes down from 340 m to the river, at 275 m, near the ACEA artificial dam at 275 m, where it is possible to observe the abrupt contact of the tufas on

Fig. 10 - Partial view of the Mandela-Vicovaro terrace.

Veduta parziale del terrazzo di Mandela-Vicovaro.

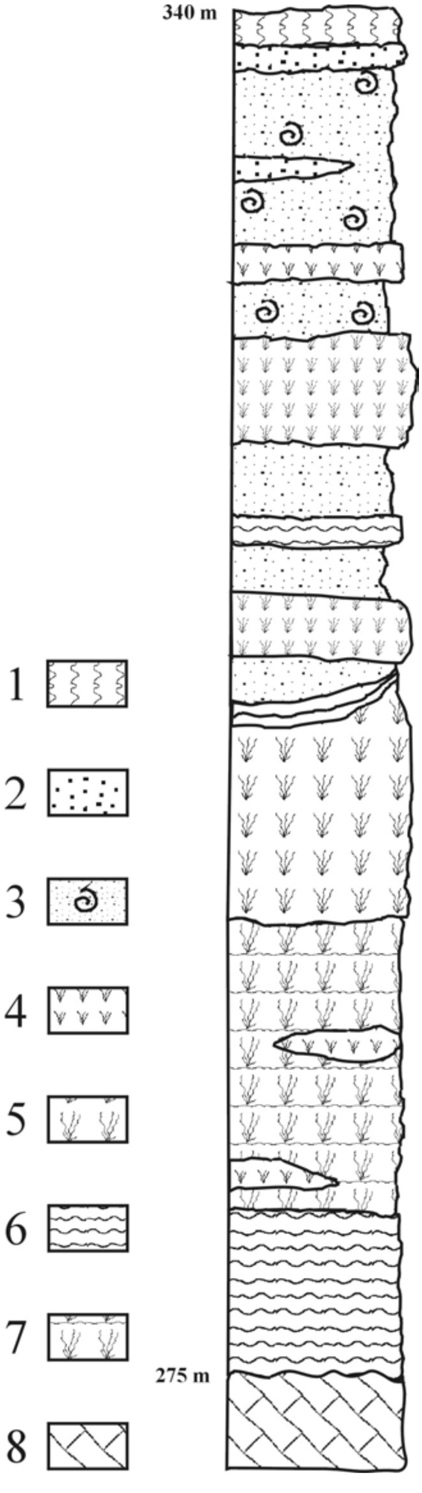

Fig. 11 - Section of S. Cosimato (not to scale). Legend of symbols: 1. Reddish-brown soil; 2. Strongly diagenized silts; 3. Phytoclastic sands and silts rich in molluscs; 4: Mainly microhermal lithofacies; 5. Unbedded mainly phytohermal lithofacies; 6. Stromatolitic laminites and microhermal and bibliolitic lithofacies; 7. Coarsely stratified microhermal and phytohermal lithofacies; 8. Calcareous Miocene substratum.

Sezione di S. Cosimato (non in scala). Legenda: 1. Suolo rosso-bruno; 2. Limi fortemente cementati; 3. Sabbie e limi fitoclastici ricchi di molluschi; 4. Prevalenti litofacies microermali; 5. Prevalenti litofacies fitoermali non stratificate; 6. Laminiti stromatolitiche e litofacies microermali e bibliolitiche; 7. Litofacies microermali e fitoermali massive o grossolanamente stratificate; 8. Substrato calcareo miocenico.

the bedrock and to recognize two distinct depositional lithofacies associations.

The first one represents the whole thickness of the calcareous tufa deposit and shows a planar, coarsely stratified structure; the second lithofacies association forms a thick, vertical or subvertical complex closely draped to the walls of the scarp along the river.

The basal portion of the first association is mainly composed of microhermal laminar lithofacies that form thin, wavy layers, often separating small, lensoid phytomicrohermal cushions. Pool infilling phytoclastic sands and silts, in places ruditic, as well as rich bibliolitic lithofacies can be found as irregular, lenticular intercalations.

The described associations grade upwards to mainly phytohermal, massive or poorly stratified framework, often interfingered with pool filling phytoclastic sands and silts, ranging from a few to dozen metres in extention and a few metres in thickness. These phytoclastic lithofacies contain several brown (7.5YR) clayey, levels, which often show a subhorizontal wavy lamination, planar cross-bedding structures and internal erosional surfaces (Fig. 12). Silty lithofacies are rich in fresh-water fauna, particularly in the area of Stazione di Mandela (see 5.5).

The second depositional association of the calcareous tufa deposit is composed of moss phytohermal

Fig. 12 - Thinly laminated calcareous sands and silts, filling a large pool and containing brown colluvial levels, showing erosional surfaces.

Sabbie e limi calcarei sottilmente laminati di riempimento di vasca, contenenti livelli bruni colluviati, interessati da superfici di erosione.

lithofacies, forming lobate curtains and drapes, ranging from a few metres to some tens of metres in thickness, that hang vertically from the scarp of the deposit and in places cover a great part of it (Fig. 13). This cascade lithofacies is particularly widespread in the steepest and deeply incised sector of the river valley, extending from Monastero di S. Cosimato and some hundred metres downstream from ACEA dam.

Another interesting section of the deposit can be observed just south of Vicovaro, where the terrace has been cut deeply by the right tributaries of the Aniene River. The section has a thickness of about 30 m and is mostly composed of a massive phytohermal lithofacies, covered in the upper part by laminated stromatolitic lithofacies, forming wavy layers, gently dipping towards the river. The basal portion of the section, a few metres in thickness, shows planar micro-phytohermal lithofacies, separated by laminated microhermal intercalations, a few centimetres thick. At the base of the section, stratified alluvial deposits, composed of well reworked, carbonate pebbles, several metres thick, occur.

In the basal portion of the Mandela-Vicovaro deposit the lithofacies associations are indicative of a paludal depositional environment, characterized by still or slightly running waters. In the middle-upper portion of the section the observed lithofacies associations seem to reflect a fluvial barrage model (D'ARGENIO & FERRERI, 1986; PEDLEY, 1990, CARRARA *et al*., 1995), grading upstream to a well vegetated fluvio-lacustrine environment, composed of large pools, filled with phytoclastic lithofacies, containing a very rich fresh-water fauna.

The second depositional phase is composed of typical cascade lithofacies associations, that were deposited on the threshold of the scarp, as the deepening river cut it down.

In the Mandela-Vicovaro area the calcium carbonate precipitation process was probably triggered by a morphotectonic structure, located just south of Vicovaro, where a fluvial barrage body has been recognized. It could have formed near Vicovaro, where the emplacement of Middle Pleistocene volcanics, superimposed by younger, coarse alluvial sediments produced a morphologic discontinuity in the river bed.

Later on, during non depositional and/or strong erosional phases, the deposit has been deeply cut and dissected by the Aniene River and its right tributaries.

Moreover, during the cutting down process, the river left several niches of alluvial deposits encased in the calcareous tufas, at different altitudes on the present thalweg, well visible along the Tiburtina Road in the Vicovaro area. They generally consist of horizontally stratified gravels and conglomerates, a few metres in thickness, composed of phytohermal tufa fragments and well reworked, in places graded and imbricated, siliciclastic matrix supported limestone pebbles.

The Mandela-Vicovaro deposit also underwent intensive karstic processes, that caused the formation of cavities and caves, coated by laminated sparry calcite incrustations and speleothems, of remarkable dimensions. Some of them, particularly in Monastero di S. Cosimato area, were inhabited by hermits in Medieval times.

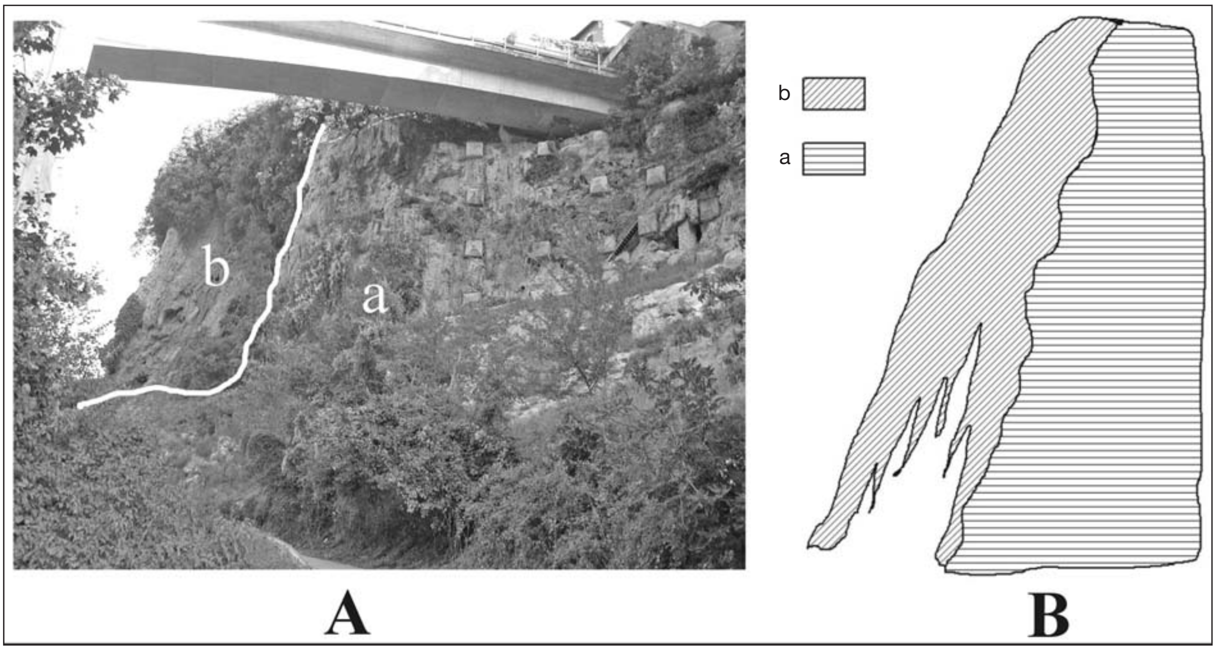

Fig.13 - A: Mandela-Vicovaro scarp terrace under the A24 motorway. a: horizontally grossly stratified, phytohermal and microhermal lithofacies; b: cascade lithofacies, subvertically hanging from the edge of the terrace scarp (solid line).
B: Profile sketch (not to scale) of the Mandela-Vicovaro deposit of Fig. 13A.

A: La scarpata della placca di travertino di Mandela-Vicovaro sotto l'autostrada A24. a: banchi orizzontali, grossolanamente stratificati, di associazioni fitoermali e microermali; b: associazioni di cascata, subverticali, appese alla scarpata del terrazzo (linea continua).
B: Profilo schematico non in scala della placca di travertino di Mandela-Vicovaro di Fig. 13A.

6. Faunal assemblages and palaeoecological considerations (E. Pisegna Cerone)

The study of the faunal content of the calcareous sands and silts cropping out near Mandela Railway Station allowed the identification of the following mollusc species:

Class **Gastropoda**
Subclass **Prosobranchia**
Pomatias elegans (Müller, 1774)
Bithynia leachi (Sheppard, 1823)
Subclass **Heterobranchia**
Valvata cristata Müller,1774
Valvata piscinalis (Müller,1774)
Subclass **Pulmonata**
Carychium minimum Müller,1774
Carychium tridentatum (Risso, 1826)
Lymnaea palustris (Müller, 1774)
Planorbis planorbis (Linneo, 1758)
Gyraulus laevis (Alder, 1838)
Hippeutis complanatus (Linneo, 1758)
Oxyloma elegans (Risso, 1826)
Punctum pygmaeum (Draparnaud, 1801)
Discus rotundatus (Müller, 1774)
Oxychilus draparnaudi (Beck, 1837)
Oxychilus cellarius (Müller,1774)
Macrogastra plicatula (Draparnaud, 1801)
Clausilia dubia Draparnaud, 1805
Hygromia cinctella (Draparnaud, 1801)
Class **Bivalvia**
Subclass **Heterodonta**
Pisidium amnicum (Müller, 1774)

The palaeoecological analysis of the species has been carried out according to the method elaborated by Ložek in 1964 for the study of the Quaternary non-marine molluscs of Czechoslovakia.

Thanks to this methodology every considered species is part of an ecological class indicated by marks formed by the number of the ecological group and the abbrevation of the belonging biotope. The marks used in this work are:

Wood species

1W: species linked exclusively to wooded places;
2W(M): species living mainly in woods, but which can also live in mesophylous areas in mean moist localities and moist or dry biotopes.

Species living in wood as well as in open lands with different needs of moisture

7M: mesophylous species mainly distributed in mean dry places, but which can live in moist as well as dry biotopes;
8H: species fond of moisture, but not linked to clearly wet biotopes;
7Wf: species living in woods or on mean moist rocks.

Terrestrial marsh species and aquatic species

9P: species living in marshes, in wet grasses, in highly moist to particularly wet biotopes, mainly near water;
10P: aquatic species living in shallow water, marshes rich in vegetation;
10S: aquatic species living in still water, from small pools and bogs to ponds and lakes;
10SF: species living in still or running water;
10F: aquatic species living in running water, from streams to rivers.

The following symbols have been associated to ecological marks:
!: species indicative of warm-moist intervals;
!!: species characteristic of warm-moist intervals;
(+): species occurring locally in loess.

Index of species and their habitat

Gastropoda
Pomatias elegans (Müller, 1774)
Habitat:
It is a mesophylous, almost exclusively calcicole species; it rarely occurs on calcareous substratum. It lives on dry slopes, between shallow bushes, dead leaves, along fences, seldom on stream banks, at the borders of woods (Ehrmann, 1956; Settepassi & Verdel, 1965; Kerney & Cameron, 1979).
Ecological marks according to Ložek (1964): **2W(M)!!**

Bithynia leachi (Sheppard, 1823)
Habitat:
It lives in still or slightly running waters, in lakes, ponds, marshes; it is not particularly demanding. It occurs in mesohaline waters with salinity up to 6‰ (Girod *et al*., 1980).
Ecological marks according to Ložek (1964): 1**0P**

Valvata cristata Müller,1774
Habitat:
It lives in still, shallow, clear and clean waters, rich in vegetation, on leaves and stalks of aquatic plants (Settepassi & Verdel, 1965), also in marshes and ditches (Ložek, 1964), in slowly flowing water (Ehrmann, 1956) or in lakes, on pebbly bottoms with plenty of mud (Girod *et al*., 1980). It occurs in mesohaline waters with salinity up to 12‰ (Girod *et al*., 1980). It reaches a depth of 20 m and an elevation of more than 100 m (Settepassi & Verdel,1965).
Ecological marks according to Ložek (1964): **10P**

Valvata piscinalis (Müller,1774)
Habitat:
It lives in still or slightly running waters: lakes, ponds, springs, channels and marshes (Girod *et al*., 1980). It can live up to 50 m in depth, but generally it can be observed within the first 20 m (Girod *et al.*, 1980); in lakes it reaches -80 m (Ehrmann, 1956). It can be found up to 1000 m elevation (Girod *et al*., 1980) and tolerates a maximum salinity of 4‰ (Ehrmann, 1956).
Ecological marks according to Ložek (1964): **10SF**

Carychium minimum Müller,1774
Habitat:
It lives in moist areas such as marshes, woods, grasses, especially in plains and low mountainous places (Kerney & Cameron, 1979).
Ecological marks according to Ložek (1964): **9P**

Carychium tridentatum (Risso, 1826)
Habitat:

It is a less hygrophilous species than *Carychium minimum*. It does not live in marshes, but it occurs in moist grasses, in woods, in bushes, under dead leaves, in well sheltered places. It also lives in hilly and mountainous areas (SETTEPASSI & VERDEL, 1965; KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **8H**

Lymnaea palusris (MÜLLER, 1774)
Habitat:
It lives in shallow waters such as ponds, marshes, bogs, streams, ditches, rarely in rivers; it occurs also on the shores of some lakes (GIROD *et al*., 1980).
Ecological marks according to LOŽEK (1964): **10P(+)**

Planorbis planorbis (LINNEO, 1758)
Habitat:
It lives in calm or slightly flowing waters within acquatic vegetation, on muddy bottoms (GIROD *et al*., 1980).
Ecological marks according to LOŽEK (1964): **10P(+)**

Gyraulus laevis (ALDER, 1838)
Habitat:
It lives in ponds, ricefields, streams and channels (GIROD *et al*., 1980).
Ecological marks according to LOŽEK (1964): **10S**

Hippeutis complanatus (LINNEO, 1758)
Habitat:
It lives in lakes, along the coast in places with sandy and muddy bottoms, sheltered from floods, in ponds and marshes (GIROD *et al*., 1980).
Ecological marks according to LOŽEK (1964): **10S**

Oxyloma elegans (RISSO, 1826)
Habitat:
It lives along the banks of rivers, ditches, lakes, ponds and marshes (SETTEPASSI & VERDEL, 1965; KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **9P**

Punctum pygmaeum (DRAPARNAUD, 1801)
Habitat:
It prefers mean moist localities. It occurs generally under leaves and wood, but also in open regions, on rocks, in moist grasses, in shady and fresh places (ESU, 1978).
Ecological marks according to LOŽEK (1964): **7M(+)**

Discus rotundatus (MÜLLER, 1774)
Habitat:
It lives in moist places, in woods, at the bottom of trees, among dead leaves, in wet grass, under stones, in the fissures of walls (SETTEPASSI & VERDEL, 1965; KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **2W(M)**

Oxychilus draparnaudi (BECK, 1837)
Habitat:
It lives in woods and among rocks (KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **7M!**

Oxychilus cellarius (MÜLLER,1774)
Habitat:
It lives in underbrush environments among rocks (KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **7M!**

Macrogastra plicatula (DRAPARNAUD, 1801)
Habitat:
It lives in litter or among decaying beechwoods (GIUSTI *et al*., 1985), rocks, generally in moist and shady places; it can reach 2000 m elevation on Swiss Alps (KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **1W!**

Clausilia dubia DRAPARNAUD, 1805.
Habitat:
It lives on rocks or walls, rarely in woods (KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **7Wf(+)**

Hygromia cinctella (DRAPARNAUD, 1801).
Habitat:
It lives in woods, hedgerows, in moist environments (banks of brooks) on slopes with fresh vegetation (KERNEY & CAMERON, 1979).
Ecological marks according to LOŽEK (1964): **2W(M)**

Bivalvia
Pisidium amnicum (MÜLLER, 1774)
Habitat:
It lives in rivers, channels, brooks, ponds and lakes, up to 40 m in depth, in waters mildly rich in calcium carbonate, on muddy or fine sandy bottoms. It occurs in water with salinity comprised between 0,5 and 3‰ (CASTAGNOLO *et al*., 1980).
Ecological marks according to LOŽEK (1964): **10 F**

DATA ANALYSIS

PALAEOECOLOGICAL CONSIDERATIONS

The analyzed sediments contain a very rich mollusc assemblage composed of aquatic species of fluviolacustrine environment and of terrestrial gastropods for a total of 19 species. Moreover some ostracods and vegetal remains also occur. Among gastropods many species belonging to Prosobranchs, Heterobranchs and Pulmonates have been recorded; one species of Bivalve also occurs in the assemblage (Fig. 14).

The mollusc fauna is composed mainly by fresh water species, such as *Bithynia leachi*, *Valvata cristata*, *Valvata piscinalis*, *Lymnaea palustris*, *Planorbis planorbis*, *Gyraulus laevis*, *Hippeutis complanatus* and *Pisidium amnicum*.

Among them the dominance of *Valvata piscinalis*, characteristic of slightly flowing waters, has been observed. This species reaches 55.93% representing the most widespread species in the examined sample. The abundance of several species living in ponds and lakes shows variable percentages ranging from 11.19% (*Valvata cristata*), to 10.51% (*Planorbis planorbis*), 5.15% (*Bithynia leachi*) and finally 0.67% (*Lymnaea palustris*). The species *Hippeutis complanatus* and *Gyraulus laevis* also prefer to live in ponds and lakes and show, respectively, the following percentages: 0.67% and 1.34%.

The bivalve *Pisidium amnicum*, reaching 0.89% in abundance, prefers channels and rivers, actually resulting to be a good indicator of running waters.

Moreover, species of moist and open environments, such as the strongly hygrophilous *Oxyloma elegans* reaching 0.67%, *Carychium tridentatum* and *Carychium minimum*, both reaching 0.22%, have been recorded.

The species *Punctum pygmaeum*, *Oxychilus draparnaudi* and *Oxychilus cellarius*, occurring in relatively low percentages, respectively 3.36%, 0.22% and 2.01%, prefer underbrush environments, but can live also in open lands.

Among the wood species *Macrogastra plicatula* has been noted. It is associated esclusively to woody places and occurs in the low percentage of 0.67%. Other species such as *Pomatias elegans* (3.58%), *Discus rotundatus* (2.24%), *Hygromia cinctella* and *Clausilia dubia* (both reaching 0.22%), prefer the border areas of woods.

The study of the recovered malacological assemblage, characterized by the dominance of proper aquatic species, as well as by highly hygrophilous species and by terrestrial ones loving woody environments, allows the reconstruction of a palaeoenviroment typical of moist wood, open in places, in the presence of a shallow water-body, rich in vegetation, such as pond and small lake. It is possible, moreover, to suppose, on the basis of the richness of the mollusc assemblage, of the occurrence of some species indicative of temperate-warm climatic phases and of the above described palaeoecological observations related to the species, that the climate was temperate.

It is not possible to infer any chronostratigraphic consideration, as all the recorded species are still living and occur in Italy at least from the beginning of the Pleistocene.

7. Chronostratigraphy and paleoclimatic outlines (M. Branca, C. Carrara, M. Voltaggio)

Nine samples from the Subiaco deposit, four samples from the Vicovaro-Mandela one and two samples of a core from the Marano Equo buried body were chosen for chronological determinations by the $^{230}Th/^{234}U$ method. Elementary and isotopic composition of uranium and thorium was determined by a-spectrometry following the method of Gascoyne *et al*. (1978). Seven samples showing a high content of detritic not-radiogenic thorium were analyzed also for the non carbonate fraction and corrected ages were computed using the correction method of Ku and Liang (1985) (Tab. 1).

Mandela	Ecological class	No specim.	% specim.	% ecological classes	
Macrogastra plicatula	1W!	3	0,67	1W	0,67
Hygromia cinctella	2W(M)	1	0,22	2W(M)	6,04
Discus rotundatus	2W(M)	10	2,24	7Wf	0,22
Pomatias elegans	2W(M)!!	16	3,58	7M	5,59
Clausilia dubia	7Wf(+)	1	0,22	8H	0,22
Punctum pygmaeum	7M(+)	15	3,36	9P	0,89
Oxychilus draparnaudi	7M!	1	0,22	10P	27,52
Oxychilus cellarius	7M!	9	2,01	10S	2,01
Carychium tridentatum	8H	1	0,22	10SF	55,93
Carychium minimum	9P	1	0,22	10F	0,89
Oxyloma elegans	9P	3	0,67		
Bithynia leachi	10P	23	5,15		
Valvata cristata	10P	50	11,19		
Lymnaea palustris	10P(+)	3	0,67		
Planorbis planorbis	10P(+)	47	10,51		
Gyraulus laevis	10S	6	1,34		
Hippeutis complanatus	10S	3	0,67		
Valvata piscinalis	10SF	250	55,93		
Pisidium amnicum	10F	4	0,89		
		447			

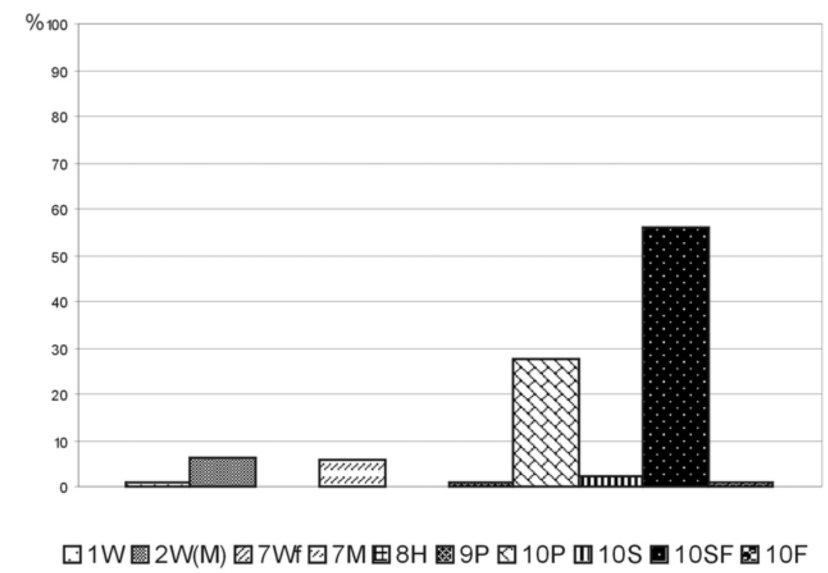

Fig. 14 - Palaeoecological diagram of the malacological association of Mandela Station.
Spettro paleoecologico dell'associazione malacologica della Stazione di Mandela.

Tab. 1 - U/Th dating of Marano Equo, Subiaco and Mandela-Vicovaro tufa deposits.
Datazioni U/Th di campioni dei depositi di travertino di Marano Equo, Subiaco e Mandela-Vicovaro.

Sample	U_{ppm}	Th_{ppm}	$^{230}Th/^{232}Th$	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	Age(ka)
*SU3	0.26±0.006	0.026±0.008	8.74±0.59	1.06±0.026	0.277±0.008	35.2±1.2
SU12$_l$	0.13±0.003	0.06±0.003	2.50±0.15			
				1.028±0.051^c	0.152±0.008^c	17.9±1
*SU12$_r$	5.29±0.159	32.98	0,345833333			
*SU12C$_l$	0.48±0.010	0.089±0.003	1.44±0.06			
				1.084±0.054^c	0.038±0.002^c	4.2±0.2
SU12C$_r$	5.98±0.179	1,009722222	0,54375			
*SU19	0.24±0.008	0.020±0.002	6.42±0.73	1.100±0.042	0.163±0.008	19.3±1.0
*SU20A$_l$	0.26±0.007	0.192±0.004	2.26±0.06			
				1.059±0.053^c	0.451±0.023^c	64.8±4.5
SU20A$_r$	4.94±0.148	34.36.00	0,310416667			
*SU34	0.23±0.008	0.022±0.003	9.10±1.32	1.037±0.044	0.271±0.015	34.3±2.2
*SU35$_l$	0.23±0.006	0.044±0.002	4.38±0.26			
				1.086±0.054^c	0.193±0.010^c	23.2±1.3
SU35$_r$	3.32±0.099	0,482638889	1.22			
*SU41$_l$	0.22±0.004	0.032±0.003	2.44±0.27			
				1.098±0.005^c	0.064±0.003^c	7.2±0.3
SU41r	1.77±0.053	10.55	1.038			
*SU43$_l$	0.24±0.006	0.025±0.004	3.08±0.57			
				1.021±0.051^c	0.083±0.004^c	9.4±0.5
SU43$_r$	1.50±0.045	0,275694444	0,431944444			
°SU21$_l$	0.17±0.004	0.037±0.003	2.09±0.19			
				1.082±0.054^c	0.101±0.005^c	11.6±0.6
SU21$_r$	1.19±0.004	5.53	0,464583333			
°SU21A	0.16±0.005	0.005±0.001	10.32±1.93	1.12±0.046	0.090±0.006	10.2±0.7
°SU22	0.16±0.004	0.007±0.002	10.24±2.32	1.066±0.034	0.135±0.010	15.7±1.3
°SU23	0.17±0.003	0.0008±0.0003	37±13	1.078±0.021	0.049±0.003	5.5±0.3
^ S4-51	0.54±0.005	0.053	21	1.042±0.005	0.648±0.025	112±7
^ S4-52	0.48±0.004	0.16	6.01	1.042±0.005	0.636±0.001	109±0.3

* Subiaco
° Mandela-Vicovaro
ˆ Marano Equo

r = residuo - *residue*
l = liscivato - *leachate*
c = valori corretti - *correct values*

The samples from the Marano Equo core sampled at -52 (SU 51) and -59 metres (SU52) were analyzed by TIMS mass spectrometry using a Finnigan Mat 62 + RPQ mass spectrometer and this accounts for the minor errors associated with their measurements. The two samples gave ages of 112 ±7 and 109±3 kyr.

The samples of the I[st] order terrace of Subiaco (SU3, SU12, SU12C, SU19, SU20A, SU34, SU35) were picked up from different sections that, due to the great variability of tufas, the very irregular pattern of the substratum and the lack of marker beds, cannot be correlated, nor on the basis of precise altitude.

Dated samples were chosen from phyto- and microhermal lithofacies or from stromatolitic laminites, generally lacking of late diagenetic cements or clear recrystallized portions. The samples of the I[st] order Subiaco terrace, collected from the lower and middle parts of the body, gave the following ages: 64.8 ± 4.5, 35.2 ± 2.2, 23.2 ± 1.3, 19.3 ± 1.0, and 17.9 ±1.0 kyr. A sample of a crystalline calcareous crust collected near S. Scolastica Monastery within the silts near the surface of the terrace gave 4.2 ± 0.2 kyr. This age could represent the age of a late deposit, linked to local, ephemeral circulation of encrusting waters still visible at present.

The mean deposition rate for the I[st] order Subiaco terrace body, considering an average apparent density equal to 1.74 ±0.2, is of 0.19 g mm^{-2} a^{-1}, a value comparable with other Quaternary Italian calcareous tufa plates (Fig. 15).

From the body of the II[nd] order terrace two samples of stromatolitic laminites have been dated: 9.4±0.5 e 7.2±0.3 kyr.

No samples of the III[rd] order terrace have been dated, because the lacking of favorable facies to dating.

The Subiaco calcareous tufa deposit can be related, therefore, to Upper Pleistocene-Holocene. In detail, the I[st] order terrace could have been formed during the Upper Pleistocene, while the II[nd] order terra-

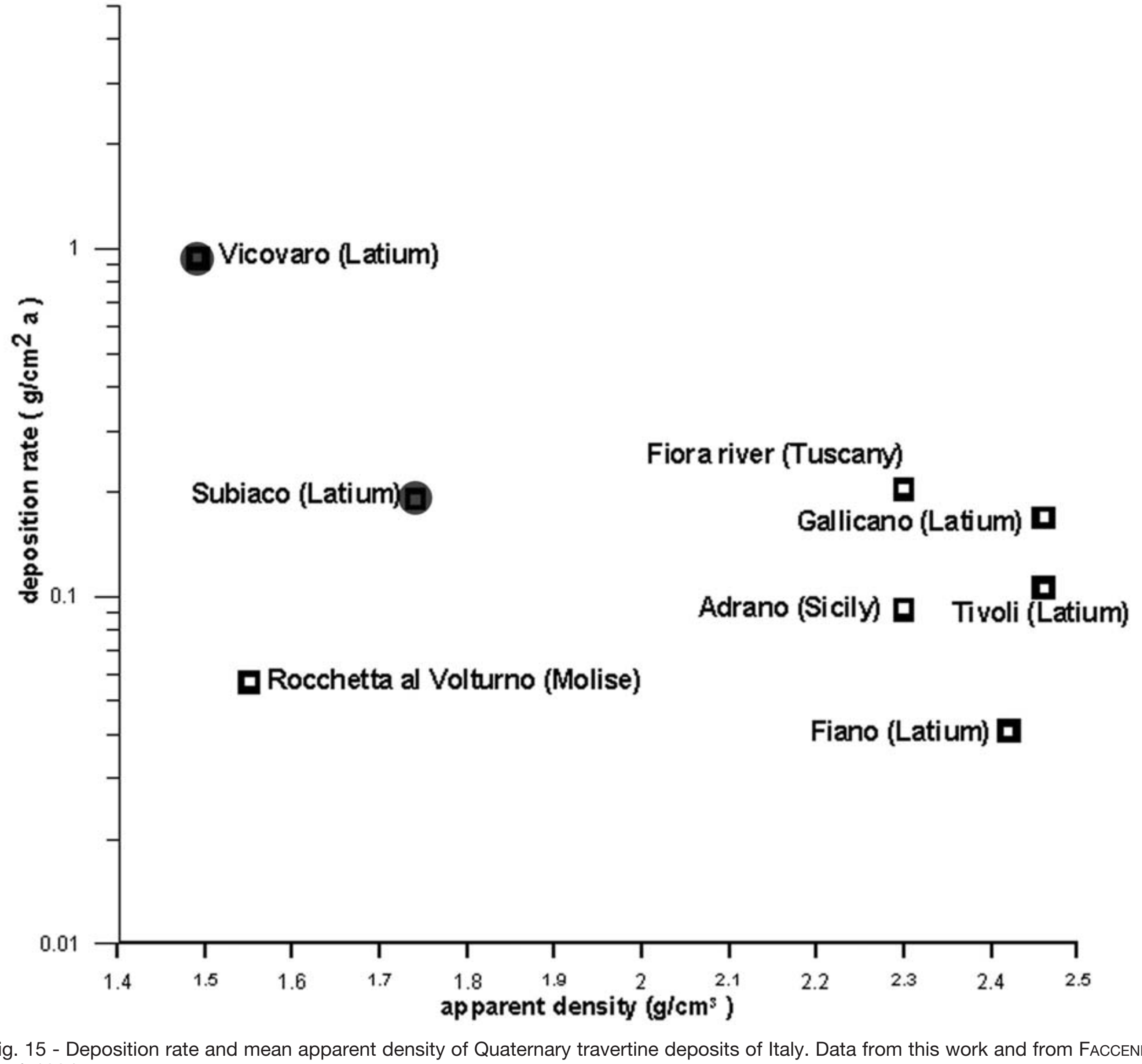

Fig. 15 - Deposition rate and mean apparent density of Quaternary travertine deposits of Italy. Data from this work and from Faccenna *et al*.,1994.

Tasso di deposizione e densità media apparente dei depositi di travertino quaternari in Italia. Dati di questo lavoro e da Faccenna et al., *1994.*

ce seems to have an Upper Holocene age.

From S. Cosimato Monastery in the Mandela-Vicovaro deposit four samples (SU 21, SU21A, SU22, SU23) were collected and dated, their ages being : 15.8±1.3, 11.6±0.6, 10.2±0.7, and 5.5±0.3 kyr. The beginning of the deposition of this deposit have started, therefore, from Late Glacial to Middle Holocene.

Its mean deposition rate, considering an average apparent density of 1.49, is of 0.94 g mm^{-2} a^{-1}, the highest value among Quaternary Italian travertine deposits (fig. 15) but comparable to other Holocenic calcareous tufas of the world (PAZDUR *et al*., 2002; KANO *et al*., 2004). The fast erosion of the Vicovaro Gorge during the last 5 kyr was likely accelerated by the acidity of many springs that in the sector between Marano Equo and Mandela are at present enriched in H_2S (i.e. Campo Oreella). Also the occurrence of at present still active CO_2 degassing zone at 12 km from Vicovaro along the Aniene River (between Roviano and Marano Equo) probably contributed in the past to lower the calcium carbonate oversaturation of the depositing waters. The variation of the CO_2 and H_2S degassing rates also explain the discontinuity over space and time of the deposition of calcareous tufa in the Marano Equo site. Presently in the Subiaco-Vicovaro fluvial segment the eventual erosion is only of a physical nature because in this segment the Aniene waters are oversaturated in calcium carbonate even if the calcium carbonate oversaturation factor Ω decreases notably from Subiaco to Vicovaro (Tolomeo L. pers. communication).

From chronostratigraphic data reported previously, the following evolution phases of the Subiaco tufa deposit can be recognized:

<u>Ist depositional phase</u>:

Growth of the tufa barrier; formation of the Ist order terrace, as far as the elevation of 500-510 m; ages comprised of between 64.8±4.5 and at least 17.9±1.0 kyr.

Emplacement of soil colluvium rich in volcanic minerals on the surface of the terrace.

<u>Erosional phase</u>:

Cut down of the Ist order terrace as deep as 450 m, comprised between 17.90 ± 1 and 9.4 ± 0.5 kyr.

<u>IInd depositional phase</u>:

Formation of the IInd order terrace body with surface at 450 m; ages comprised of between 9.4 ± 0.5 and at least 7.2 ± 0.3 kyr.

<u>Erosional phase</u>:

Cut down of the IInd order terrace as deep as 400 m, more recent than 7.2 ± 0.3 kyr.

<u>IIIrd depositional phase</u>:

Formation of the IIIrd order terrace body with surface at 400 m a.s.l.; age undetermined.

<u>Erosional phase</u>:

Cut down of the IIIrd order terrace as far as the present river bed, still in progress.

From this evolution scheme it follows that the deposition of calcareous tufa in the area of Marano Equo preceeds the formation of the Ist order Subiaco terrace, whereas the Mandela-Vicovaro tufa deposit seems to be more or less contemporary of the formation of the IInd order Subiaco terrace body, beginning in the Late Glacial (15.8 ± 1.3) and continuing during the Early-Middle Holocene (11.6± 0.6, 10.2±0.7, 5.5±0.3).

Comparing the ages of the studied tufas with the isotopic curves (RAVAZZI, 2003), cautiously keeping in mind the method error, it is possible to draw some paleoclimatic considerations. The formation of the buried plate of Marano Equo (112 ±7, 109± 0.3) took place during the MIS 5d, a substage of the Last Interglacial (Fig. 16) characterized by a climate deterio-

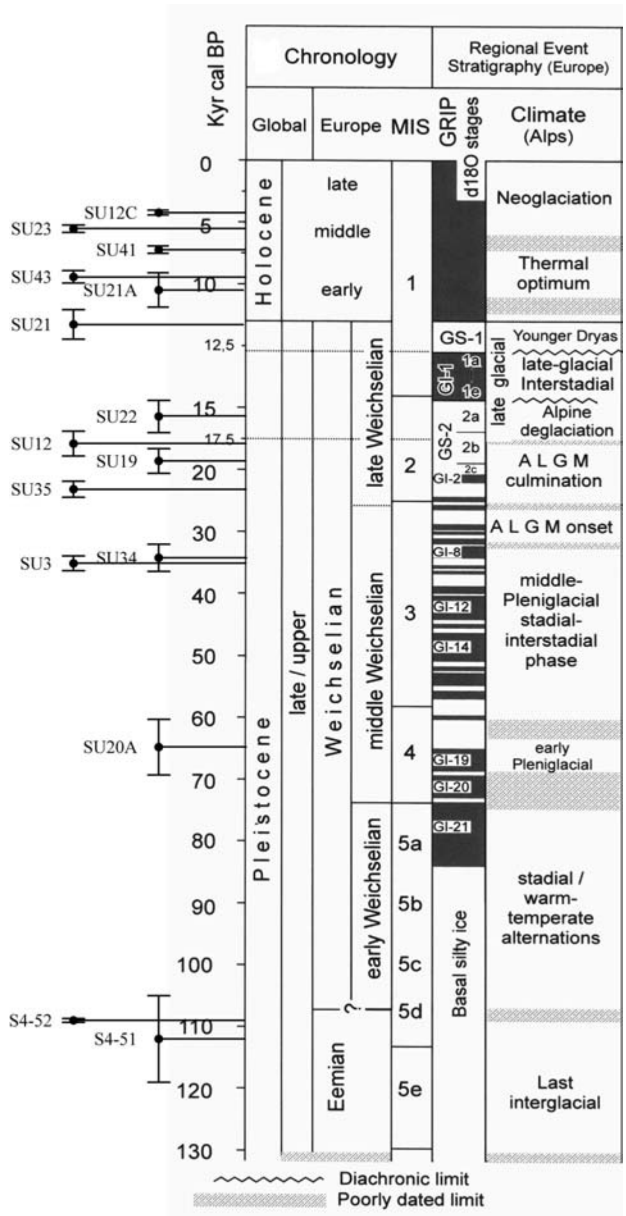

Fig. 16 - Dated samples of Marano Equo, Subiaco and Mandela-Vicovaro calcareous tufa deposits inserted in the framework of Late Pleistocene chronologic and climatostratigraphic reference units used in Europe (from RAVAZZI, 2003, modified).

Campioni datati dei depositi di Marano Equo, Subiaco e Mandela-Vicovaro inseriti nello schema cronologico e climatostratigrafico delle unità di riferimento europee (da RAVAZZI, 2003, modificato).

ration. The formation of the lower part of the Subiaco deposit took place during MIS 4 (64.8±4.5), in correspondence to the gap between Greenland Interstadial 18 and 19, characterized by a deterioration of climate if compared to the Last Interglacial. The middle part of the deposit falls into the MIS 3 (35.2 ±1.2, 34.3±2.2), between the Greenland Interstadials 8 and 9, while the middle-upper part is comprised in the MIS 2 (23.2±1.3, 19.3±1.0, 17.9±1.0), the two stages being characterized by great climatic variability.

The depositional phase of the IInd order terrace body (9.4±0.5 and 7.2±0.3) occurred in the MIS1, in the Early Holocene, characterized by a decise climatic amelioration (Thermal Optimum).

The Mandela-Vicovaro deposit begins to form during MIS2, in the Late Glacial (15.8±1.3) in correspondence to the Greenland Stadial 2, characterized by the beginning of Alpine deglaciation, then continuing in the Early and Middle Holocene (11.6±0.6 ,10.2±0.7, 5.5±0.3), during Thermal Optimum.

The deposition of calcareous tufas in the studied area seems to have been active in spans of time characterized by opposing climatic variations: not only during warm and wet stages (interglacials or interstadials), generally more favorable to calcium carbonate deposition, as already pointed out by a very wide literature (see for example GORDON *et al.*, 1989), but also during temperate and wet stages, as already mentioned in other works (CARRARA 1994, 1998, CARRARA *et al.*, 1998) and proved by malacological content of sandy-silty sediments.

The age frequency histogram for 64 samples of Central Italy travertines deposited in the last 150 kyr (62 dated by ^{230}Th/^{234}U method in the U-Th Geochronology laboratory of IGAG-CNR during the 1988-2005 period) (fig. 17) shows clearly that the growth frequency is indipendent of the temperature. Conversely, considering the temporal evolution of the accretion rate of coeval speleothems (calculated on about 70 samples from the Frasassi cave), a parameter which is directly proportional to the pluvial regime, we can note how the growth frequency of calcareous tufas is correlated with it. It is therefore probable that, at our mid latitudes and altitudes, the calcium carbonate precipitation process from continental waters is influenced more by the "degree of humidity" of that moment in that area, rather than by variations of temperature and that the deposition of calcareous tufas stops fully only during the cool and /or warm but dry intervals, while it undergoes a decrease or an increase during the intermediate ones.

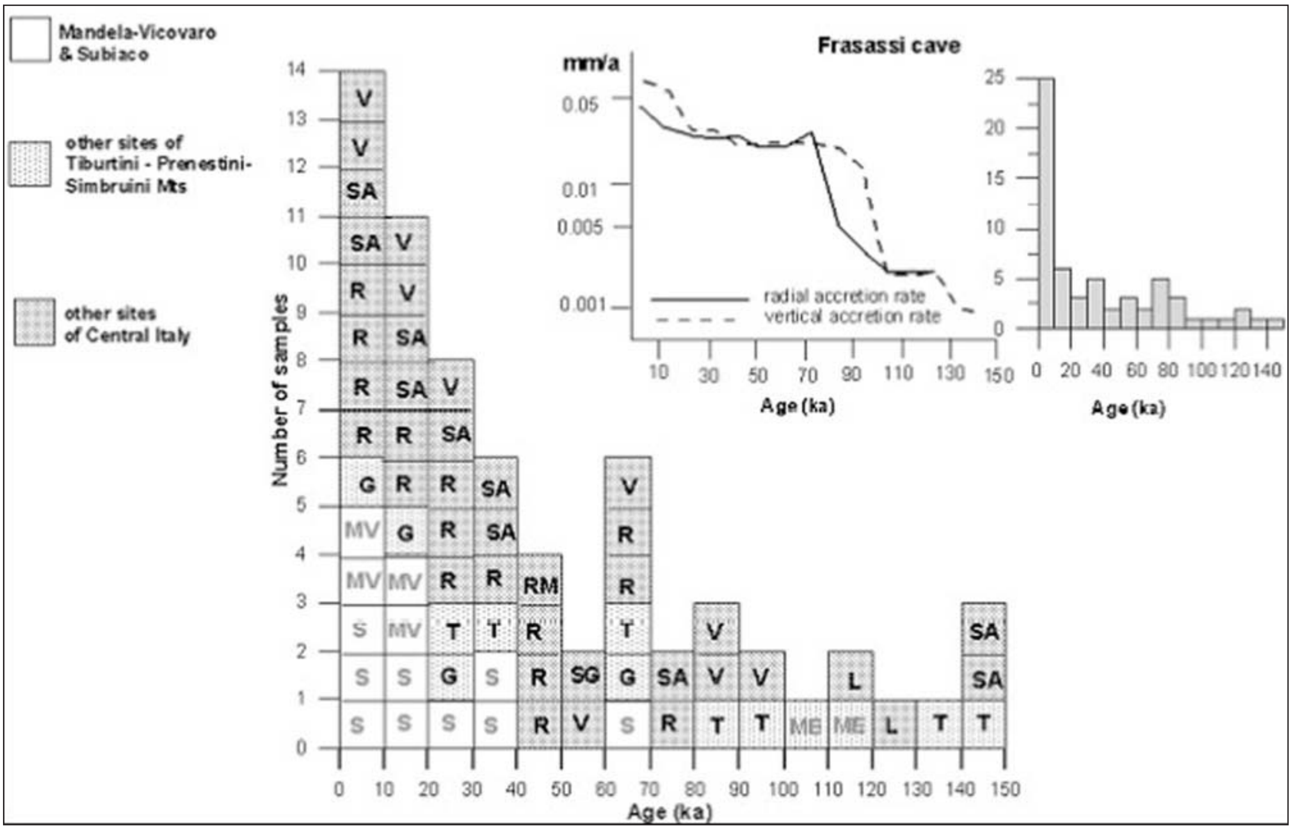

Fig. 17 - Age frequency histogram of Central Italy travertines: V samples = Vulsini (TADDEUCCI & VOLTAGGIO, 1987); T samples = Tivoli (FACCENNA *et al*., 1994); R samples = Rocchetta al Volturno (BRANCACCIO *et al*., 1988); G samples = Gallicano (FUNICIELLO *et al.*, 1992); L = Liri (CARRARA, 1991); MV samples = Mandela-Vicovaro (this work); S samples = Subiaco (this work), ME samples = Marano Equo (this work); SA samples = Sabatini and RM = Roccamonfina (CNR-IGAG, U/Th Laboratory), unpublished. Frasassi data are from TADDEUCCI *et al*., 1992.

Istogramma di frequenza delle età dei travertini dell'Italia centrale: V campioni = Vulsini (TADDEUCCI & VOLTAGGIO, 1987); T = Tivoli (FACCENNA et al.*, 1993); R = Rocchetta al Volturno (BRANCACCIO* et al.*, 1988); G = Gallicano (FUNICIELLO* et al.*, 1992); L = Liri (CARRARA, 1991); MV = Mandela-Vicovaro (questo lavoro); S = Subiaco (questo lavoro), ME = Marano Equo (questo lavoro); SA = Sabatini and RM = Roccamonfina (CNR-IGAG, U/Th Laboratorio, non pubblicati. I dati di Frasassi sono da TADDEUCCI* et al.*, 1992.*

Discussing about paleoclimate problems, OROMBELLI & RAVAZZI (1996) write: "The variations in the hydrologic balance, particularly in the areas that are presently arid and hyperarid, had a much greater role in the environmental changes during the Holocene, compared to the role played by temperature variations". As regards to the deposition of calcareous tufas we think that the same phenomenon also counts for less dry areas and other Quaternary periods.

Comparing the chronology of the studied deposits and the pre-protostoric peopling of the middle Aniene Valley that took place between the Middle Paleolith and the final Bronze Age, in places near the river and concentrated in the widest areas of the valley (FESTUCCIA & ZABOTTI, 1992), a close relationship between the two events seems to be recognized. The occurrence of springs and the relative calcareous tufa deposits could have favoured the mentioned peopling. Such a relationship, moreover, has been observed in other Italian archeological sites, in areas rich in spring waters depositing calcareous tufas, exploited by man for agricultural, domestic and cult purposes (CARRARA, 2002).

Field observations on considered deposits have not allowed the recognition of sure evidence of postdepositional neotectonics. The bedding attitude of the calcareous tufa bodies in the basal and proximal parts generally follows the substratum palaeomorphology, while they get horizontal or subhorizontal in the middle and distal parts. Several open fractures and normal faults with displacements up to a few centimetres have been observed. Nevertheless, such structures seem to be interpreted as mainly due to slope instability and the high vertical faces cut in the deposits. This is also suggested by the presence of frequent and great synsedimentary and postdepositional landslides (see 5.3). Landslide events, probably cosismic, that affected the studied areas were recognized during excavations carried out by Soprintendenza Archeologica del Lazio between 1994 and 1996 in the portion of the Neronian Villa where S. Clemente Monastery was located (FIORE CAVALIERE & MARI, 1996). Other slope instability phenomena in the calcareous tufa bodies, where S. Scolastica Monastery is located, have been reported by MOLIN *et al.* (2002).

The Quaternary morphotectonic evolution of the area has certainly conditioned the location and the deposition of studied calcareous tufas (see chap. 2); during and after their deposition the deposits have undergone strong erosion and quick incision events (see chap. 7), due to complex interactions between the uplifting of the area and the variations of the base level in their turn connected to climatic variations.

To better understand such interactions, detailed studies on the Quaternary geologic and geodinamic evolution of the whole Aniene Valley and adjacent areas would be necessary.

8. Geoarcheological considerations (C. Carrara, V. Verrubbi)

The name of Subiaco derives from Latin *Sublaqueum*, term used by some Latin writers to indicate the area where a great villa was built up by Nero in the first years of his rein (54-68 a.D.) and some artificial lakes close to it ("*lacus treis, amoenitatem nobiles, qui nomen dedere Sublaqueum*" Pliny the Elder; "*ex lacu qui est super villam neronianam Sublaquensem*" Frontinus; "*in villa cui Sublaqueum nomen est*" Tacitus (from CAROSI, 1956). The mentioned villa was localized in part on the right side of the Aniene river, where at present there is the Monastero di S. Scolastica, in part on the left side at Pianello locality. Both these places are at 500-510 m and occur on the surface of the I[st] order terrace; they were connected by a road going from the right side of the river to Pianello on the left side, then descending towards Chiesa di S. Lorenzo on the surface of the IInd order terrace.

Near the villa and in the Subiaco area one or more lakes (at least three according to Pliny the Elder) existed; their number, width and position have been long discussed by many archeologists. Among them CAROSI (1956), ORLANDI (1984-88, 2002) and QUILICI (1996) have carried out a detailed, critical examination of ancient sources as well as of extant archeological ruins description and topographical localization. CAROSI (1956) suggests that the lakes were three, supported by three different artificial dams built up by Nero. He is certain that a dam was "where at present the Ponte S. Mauro occurs, slightly to the west"; this dam, according to his estimate, was about 60 m high and at most about 20 m large, the altitude of the lake level could be around 459 m. The author suggests, moreover, that the other two dams, were next to the present Ponte Rapone at an elevation of about 450 m a.s.l. and the other next to the Ponte S. Antonio, at 400 m.

ORLANDI (1984-1988) also debates in detail the Neronian constructions and the existence of the three lakes, of which the highest, localised under the Speco di S. Benedetto, at Ponte S. Mauro, was certainly "the more extensive in lentgh and surface"; the lake level could not be less than 60 m over the river bed. Some important remains of the dam, still *in situ* on both sides of the Ponte S. Mauro, and large ruins along the bottom of the river, are described.

The author also reports the description of another Neronian lake contained in "a letter written during the stay at Subiaco of Pope Innocenzo the III[rd], in 1202, by a member of the papal court". He writes that the described lake must not be confused with the highest one and "must be searched far down, near the present Subiaco". The dam was probably localized near the Cartiera di Subiaco, at Ponte S. Antonio, and the depth of the lake has been estimated of about 27 m. This lake was probably separated by the highest one (Ponte S. Mauro) by a third lake whose dam could be sited in an area known as Parata, where the Author could observe recent lacustrine deposits.

QUILICI (1996) sums up and subjects to a rigorous examination the works of the numerous preceding authors about the occurrence and the localization of the three Roman dams, which ruins he describes in detail. They are still visible in the three above-mentioned sites along the river. He has no doubt on the occurrence of the highest and most spectacular dam at Ponte S. Mauro, where the river flows through a gorge between 6 to 20 m large and at least 50 m high; the lake level could have been placed at about 450 m. A second dam, from 10 to not more than 20 m high, could have occurred at Parata, forming a lower lake reaching the base of the S. Mauro dam. On the contrary he doubts of the existence of the Ponte Rapone dam; according to him the Ponte Rapone hillock overlooked the lower lake. Finally, the dam at Cartiera di Subiaco, near the Ponte S. Antonio, is not to be considered of Roman age, but it is dated to the XV century.

Almost all the authors agree that in 1305 a catastrophic flood caused the collapse of the highest dam, the emptying of the relative lake and heavy damage downstream along the valley.

From archeological research, therefore, it can be inferred that in the Subiaco area the lakes, still active until 1305, were two (presumably three). They were substained by artificial dams or bridge-dams localised as follows: near the present Ponte S. Mauro, the highest and more extended lake with a surface at an altitude of 460 (fig. 18), near Parata a supposed middle lake with a surface at 440-450 m and at Cartiera di Subiaco near Ponte S. Antonio, the third one, dated to the XV century (QUILICI, 1996) at 400 m.

On the basis of data coming from the archeological ruins, described by archeologists, and of the results of morphological and geological detailed research, carried out in this research in the tract of Aniene River between the mentioned bridges, it is worth noting that near Ponte S. Mauro and in the Parata locality the ruins, related to Roman dams, also observed by CAROSI (1956), ORLANDI (1984-1988, 2002) and QUILICI (1996), are still visible. Actually, on the left side of the Ponte S. Mauro, wall ruins of great thickness (some metres) occur. They are linked to the Northern vertical scarp of the I[st] order terrace, in which the Cava Segatori has been cut. The quarry, on the other hand, has been excavated for a long time and it cannot be excluded that it was used for the extraction of calcareous tufa materials for the construction of the dam. On the right side of the bridge, under Cappella di S. Mauro, the same walls were connected to the vertical scarp of the I[st] order terrace that also shows signs of quarrying. Moreover, ruins of the dam have been observed by archeologists on the river bed under the bridge.

It is worthy noting that along the Aniene Valley, upstream of Subiaco, well preserved terraces, whose surfaces are at about 460-465 m, occur. The most developed one (Fig. 19) extends some hundreds of metres and shows a scarp up to 10 m on the riverbed, where a section composed of fluvio-lacustrine, yellow-reddish, fine-grained sands and silts, containing in the upper part brown, organic layers, can be observed. DAMIANI *et al*. (1998) have already assumed that these terraces could be referred to the highest Neronian lake. During the present research from the above-mentioned organic layers several samples for ^{14}C dating have been collected, but until now results are not available.

Also at the locality of Parata, where, according to several archeologists the second dam occurred, on the left side of the river, another thick, heavily dismantled wall can be observed. It is linked to the vertical tufa scarp of the II[nd] order terrace body, here 30-40 m high. On the river bed, here flowing in a gorge not larger than some tens of metres, remains of a great ancient walls, related to Roman age, under the gravel cement bulkheads built in more recent times, crops out (Fig. 20).

As regards the dam at Ponte S. Antonio, presumably built up in XV century to raise the river waters in order to feed the Cartiera di Subiaco, at present no ruins occur. Probably this dam joined the river banks at the same elevation of the III[rd] order terrace surface.

The morphological and geological features of the areas where the three dams were built up (Fig. 21) and the information obtained from archeological data demonstrate that the three depositional calcareous tufa

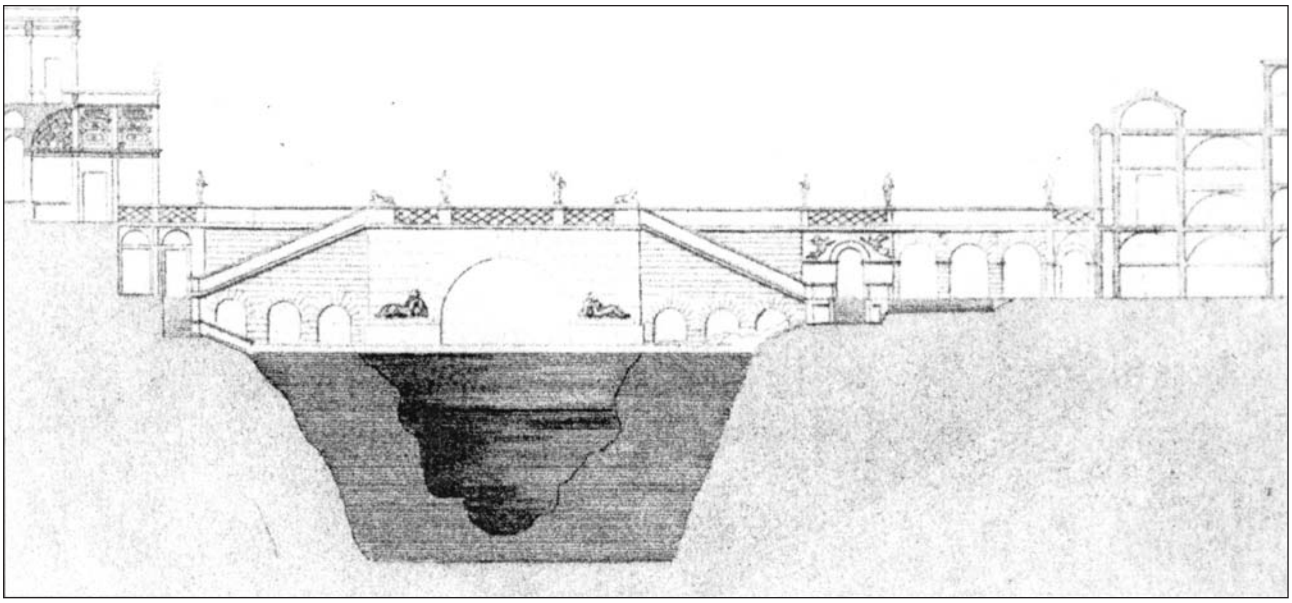

Fig. 18 - Reconstruction of Neronian villa and dam at Ponte S. Mauro at Subiaco by L. Canina (from ORLANDI, 2002).
Ricostruzione della villa e della diga di Nerone al ponte di S. Mauro a Subiaco di L. Canina (da M. ORLANDI, 2002).

terraces previously described were fundamental in choosing the dam sites. Infact, they were localized where the thick, vertical scarps of calcareos tufa terraces formed very narrow gorges. The sites, therefore, were most favourable for the construction of such works. Hence, it can be inferred, if there is still need, that in the studied area the deposition of calcareous tufas and the formation of the relative terraces, in spite of the following erosion and remodelling phases, has considerably modified the former geomorfic framework of the valley and has been decisive in conditioning the human activity and its works.

9. Conclusions

In the Aniene Valley several calcareous tufa deposits occur; some of them are still active and are connected to mainly carbonate-calcic cool springs, linked to karstic paths of the Simbruini-Ernici and Lucretili Mounts. The Marano Equo, Subiaco and Mandela-Vicovaro deposits have been studied in greater detail. The first one, 15 m thick, has been found underground in a borehole that crossed alluvial sediments related to the paleo-Aniene River, at a depth comprised of between –50 and –64 m. The Subiaco deposit, about 70 metres thick, is composed of three depositional terraces, the formation of which alternated with extensive erosional phases. Its lithofacies associations indicate that the deposition evolved from a palustrine to a higher energy, fluvio-lacustrine environment, due to fluvial barrage of a calcareous tufa system grown in correspondence to a morphological step of tectonic origin.

The Mandela-Vicovaro deposit also, forming a wide terrace with a thickness of 60-70 m, extending about 3 km along the Aniene Valley, evolved from a palustrine to a fluvio-lacustrine environment. It was developed because of a fluvial barrage grown in the Vicovaro area, where the emplacement of Middle Pleistocene volcanics covered by more recent alluvial sediments, caused the formation of a morphological high.

The malacological content of calcareous sands and silts occurring in the upper part of the deposit indicates the presence of a depositional environment characterized by highly vegetated small shallow lakes, pools and ponds in a temperate climate.

U/Th datings of Marano Equo, Subiaco and Mandela-Vicovaro deposits suggest the attribution of the first deposit to Upper Pleistocene, while the second and the third are related to Upper Pleistocene-Lower Holocene and Lateglacial-Middle Holocene ages.

The deposition of calcareous tufas in the studied area has been active in spans of time characterized by opposing climatic variations: not only during warm and wet stages (interglacials or interstadials), but also during fresher, temperate and wet stages, as proved by the malacological content of sandy-silty sediments and by datings. It is therefore probable that, at our mid latitudes and altitudes, the calcium carbonate precipitation from fresh waters is more influenced by the “degree of humidity” of that moment in that area, than by variations of temperature and that the deposition of calcareous tufas stops during the cool and /or warm but dry intervals, while it undergoes a decrease or an increase during the intermediate ones.

On the basis of detailed bibliographic and field archeological and geological reserches, some considerations about the occurrence of artificial dams built up by Nero in the Subiaco area, which dammed the Aniene River and caused upstream the formation of extended lakes, whose hypothetical reconstruction is drawn in fig. 18, have been discussed. At least two dams, at Ponte S. Mauro and at Parata, have been built during Nero’s reign; they were destroyed by a cathastrophic flood in 1305. A third dam, built near the Cartiera di Subiaco, can be attributed to the XV century.

In the studied area the deposition of calcareous tufas and the formation of the relative terraces, in spite

Fig. 19 - Lacustrine terrace occurring about 3,3 km upstream of Subiaco, probably related to the Neronian dam at Ponte S. Mauro and the relative lake, ruined in 1305 because of an alluvial flood.

Terrazzo lacustre affiorante a monte di Subiaco, probabilmente connesso con la diga neroniana di Ponte S. Mauro e il relativo lago, distrutta nel 1305 da un’alluvione.

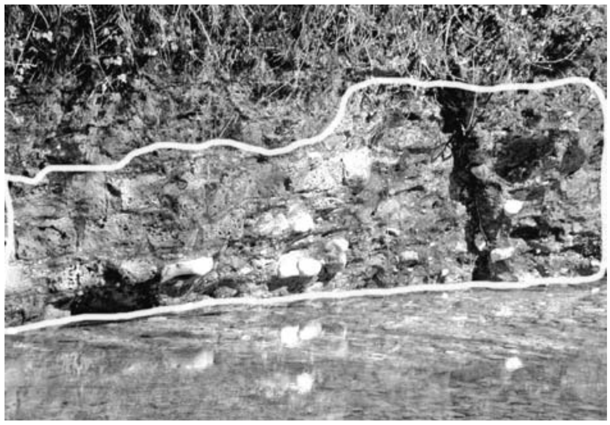

Fig. 20 - Ruins of a Roman wall, occurring under more recent cement dam in the locality of Parata, probably related to the Neronian Parata dam.

Resti del muro romano affioranti sotto una diga in cemento più recente, probabilmente connesso con la diga neroniana di Parata.

of the following erosion and remodelling phases, has considerably modified the former geomorphic framework of the valley and has been decisive in conditioning the human activity and its works.

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Fig. 21 - Hypothetical reconstruction of the lakes in the Subiaco area, formed by the Neronian dams at Ponte S. Mauro (1) and Parata (2) and by the dam of XV century at Cartiera di Subiaco (3).

Ricostruzione ipotetica dei laghi presenti nell'area di Subiaco, dovuti alle due dighe neroniane di Ponte S. Mauro (1) e Parata (2) e a quella del XV secolo della Cartiera di Subiaco (3).

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