Freshwater travertines in Central Apennine (Italy): genesis and climatic and neotectonic significance

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The aim of this study is to present, through the use of new geomorphologic, sedimentological and geochemical data, a synthesis of the knowledge of the genesis of freshwater travertine deposits in the calcareous ridge of the Central Apennines (Italy).
Different areas in the Umbria-Marche and Latio-Abruzzi Ridges have been chosen as very good examples of typical travertine deposition in the central Apennines.
All the areas, even if characterized by different extensions, thicknesses and differences in the hydrochemistry of circulating waters, show similar features (depositional environment, climatic conditions, structural and neotectonic conditioning) significant in the reconstruction of the dynamics of travertine deposition.
The more or less intense deposition of travertine (very different even in the same area, during different phases) is related to the changing of the hydrogeological conditions in time. Valley deepening, consequent to climatic changes (such as glacial-interglacial transition) and/or periods of more intense tectonic uplift, caused the rapid lowering of the piezometric surface inside carbonate aquifers; this fact together with climatic improvement increased the hydrologic regime of the rivers, favouring travertine deposition. Subsequently, the process decreased in time, in the same way as a box, filled with water and with a hole in the bottom of it , progressively empties.
Such phenomenon, together with the above mentioned climatic changes which aim at a new equilibrium, seem to be the most important causes of the progressive decrease (and sometimes interruption) of travertine depositional processes.
In the Acquasanta Terme area also, where the rising up of thermal water along fractures produced the primary condition for travertine formation, deposition occurred in a fluvial environment, along tributary valleys, on the right side of the Tronto river; this is testified by the presence, at the base and inside the deposit, of alluvial gravely material, fluvial facies and typical "fall" structures.
Absolute and relative dating confirmed that travertine formation occurred starting at the end of the Middle Pleistocene and mainly during the transition between glacial and interglacial periods. However, the presence of older deposits (formed in the Early or Middle Pleistocene) in the same areas and that are no longer visible, is not to be excluded

Introduction

Travertine deposits are among the most characteristic continental deposits of central Italy. Their origin in time, sometimes uncertain due to scarcity of chronological elements, should be somewhere within a period that occurs between the Middle Pleistocene and recent times.

Travertine deposition is usually connected to rising waters oversaturated with CO_2. Facies analysis evidences a depositional mechanism characterized by laminar and turbulent flows. The former produces the deposition of stromatolitic crusts, and tough -cross bedded coarse sands and phytoclastic gravels associated with small channels; the latter (mainly in correspondence to morphological steps along the river) formed the typical phytohermal phases (CHAFETS & FOLK, 1984; PEDLEY, 1990; VILES & GOUDIE, 1990; D'ARGENIO & FERRERI, 1992 and *ref. within*; GOLUBIC *et al*., 1993 and *ref. within*; CILLA *et al*., 1994 and *ref. within*; FARABOLLINI, 1995 and *ref. within*; MATERAZZI, 1996 and *ref. within*).

Several classifications have been proposed by different authors. Already in the 1978, BUCCINO *et al*. (1978) evidenced, along the Tanagro river valley (Campania-Italy), the existence of phytoclastic and phytohermal facies and proposes a fluvial dynamics model to explain their genesis.

Afterwards CHAFETS & FOLK (1984), analyzed many travertine deposits in central Italy and in the central-western United States; taking into account the role of the different vegetation species in controlling the deposition process, they identified five main mechanisms. In 1990 PEDLEY classified numerous travertine deposits from all-around the world, on the basis of their depositional angle, water flow typology, microbiological colonisation and environmental temperature. The author distinguished five different categories: "spring", "fall", "fluvial", "swampy" and "lacustrine" travertine, each one characterized by different detritic or bio-built facies associations. A prerequisite is the almost total prevalence of the precipitation due to the vegetable or bacterial organisms, and a small contribution due to the inorganic processes.

GOLUBIC *et al.* (1993), recognized for the Rocchetta al Volturno travertines (central-southern Apennines, Italy), six associations of lithofacies based on their main sedimentological and stratigraphic characteristics and on their fossil content (including vegetable supports).

Recently FARABOLLINI *et al*. (2004) proposed, for travertine deposits of Adriatic Central Italy, a large scale depositional model that, in some cases, includes various morphological situations. They distinguished four different environments: "springs and slopes", "cascades", "riffles and pools", "alluvial plains".

The present work, based on detailed geomorphological surveys and facies analyses and using the classification defined by FARABOLLINI *et al*. (2004), describes some of the most characteristic travertine deposits present in the Umbria-Marches-Abruzzi Apennine area.

Geological and geomorphological setting

The area studied is bound by the Apennine Chain to the west, by the Adriatic coast to the east and by the Esino and Tronto rivers to the north and to the south respectively (Fig. 1). On the basis of physiographic, geomorphological and structural characteristics, it is possible to distinguish two different sectors: the chain area (and in particular its easternmost portion) and the pedemountain belt, near the Adriatic coast.

The chain area is characterized by a series of mountain ridges (with a height of 2000 m and over) aligned from a NW-SE to a N-S direction. They are made up of mainly calcareous, marly-calcareous and marly formations of Jurassic-Cretaceous age. The ridges are interrupted by deep transversal valleys incised by the main rivers (Potenza, Chienti, Tronto, Salinello, Pescara). The structural setting is made up of E and NE verging thrusts which have determined the overlaying of calcareous formations on sandy-pelitic ones (PAROTTO & PRATURLON, 1975; DEIANA & PIALLI, 1992; GHISETTI *et al*., 1994).

Hilly reliefs and gentler slopes characterize the piedemont belt. They are composed of isolated ridges, due to the culmination of meso-cenozoic calcareous terrains, and of reliefs like the *mesa*, *cuesta* and *plateaux*, imposed on terrigenous lithologies essentially arenaceous-pelitic and pelitic-arenaceous, with the intercalation of conglomeratic layers (SERVIZIO GEOLOGICO D'ITALIA, 1969; CANTALAMESSA *et al*., 1986; CENTAMORE *et al*., 1991). The age of these formations ranges from the Late Miocene to the Early Pleistocene, period in which the filling of foredeep and *piggy-back* basins with shallow marine deposits occurred (ORI *et al*., 1991; BIGI *et al*., 1995).

The structuring of the area occured between the Early Pliocene and the Middle Pleistocene (CALAMITA *et al*., 1991 and *ref within* ; BIGI *et al*., 1995; COLTORTI & PIERUCCINI, 2000). In a first phase, compressive tectonics produced the placing of the main thrusts along the

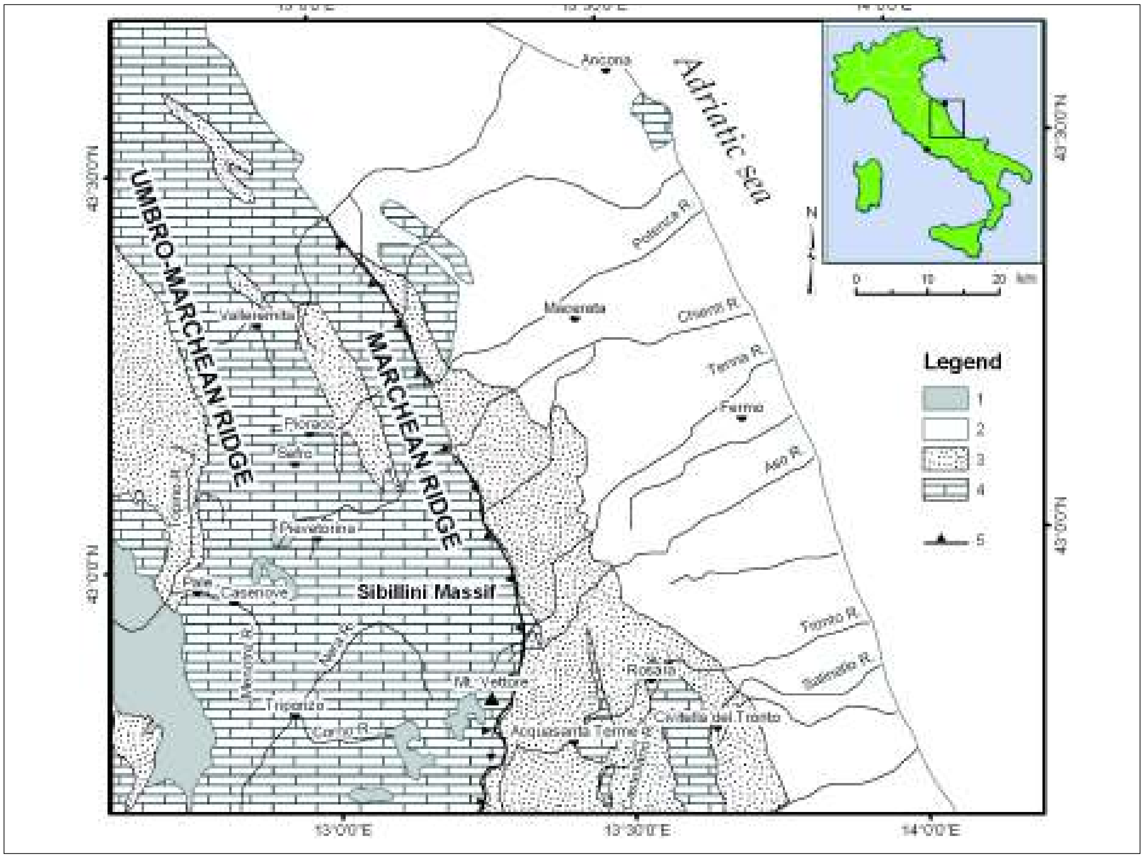

Fig.1. Location of the main travertine deposits in the area studied

mountainous ridges, progressively involving also the easternmost foredeep elements. Afterwards, Quaternary extensional tectonics, accompanied by a generalized tectonic uplifting, took place (DRAMIS, 1992). These tectonic events, mainly starting at the end of the Early Pleistocene (DRAMIS *et al.*, 1992; CENTAMORE *et al.,* 1983; DRAMIS, 1992; COLTORTI & PIERUCCINI, 2000 and *ref within*), caused fragmentation and displacement at different heights of the "summital paleosurface", whose limited remnants are still present on the reliefs tops. At the base of the calcareous chain, a second planation surface, attributed to Villafranchian (DEMANGEOT, 1965) and embanked in the previous one, has been evidenced. This second surface has been observed in the whole area and, moving toward the sea, within the Miocene-Pliocene-Pleistocene deposits. It is well preserved, as wide limbs, on the watersheds of the main rivers and shows altitude variations comparable to the summital paleosurface and to the deposits of the Crotonian-Sicilian trasgressive regressive cycle (DRAMIS, 1992; FARABOLLINI, 1995).

Important fault systems, NW-SE and NS oriented and with high displacement, developed along the chain and caused the formation of wide intramountain basins. At the same time in the pedemountain area, dip-slip fault, also with a N-S direction but characterized by modest displacement, was being created . Intense uplift and consequent tectonic displacements, strongly conditioned the morphogenesis of the Marches-Abruzzi area and, in particular, the lay out and evolution of the hydrographic network and the mass movement typology (DRAMIS, 1992; GENTILI & PAMBIANCHI, 1994; DRAMIS *et al.*, 1995).

Gravitational morphogenesis, by means of the action of phenomena on different scales, played an important role in modelling calcareous landscape; tectonic-gravitational movements, deep seated slope deformations

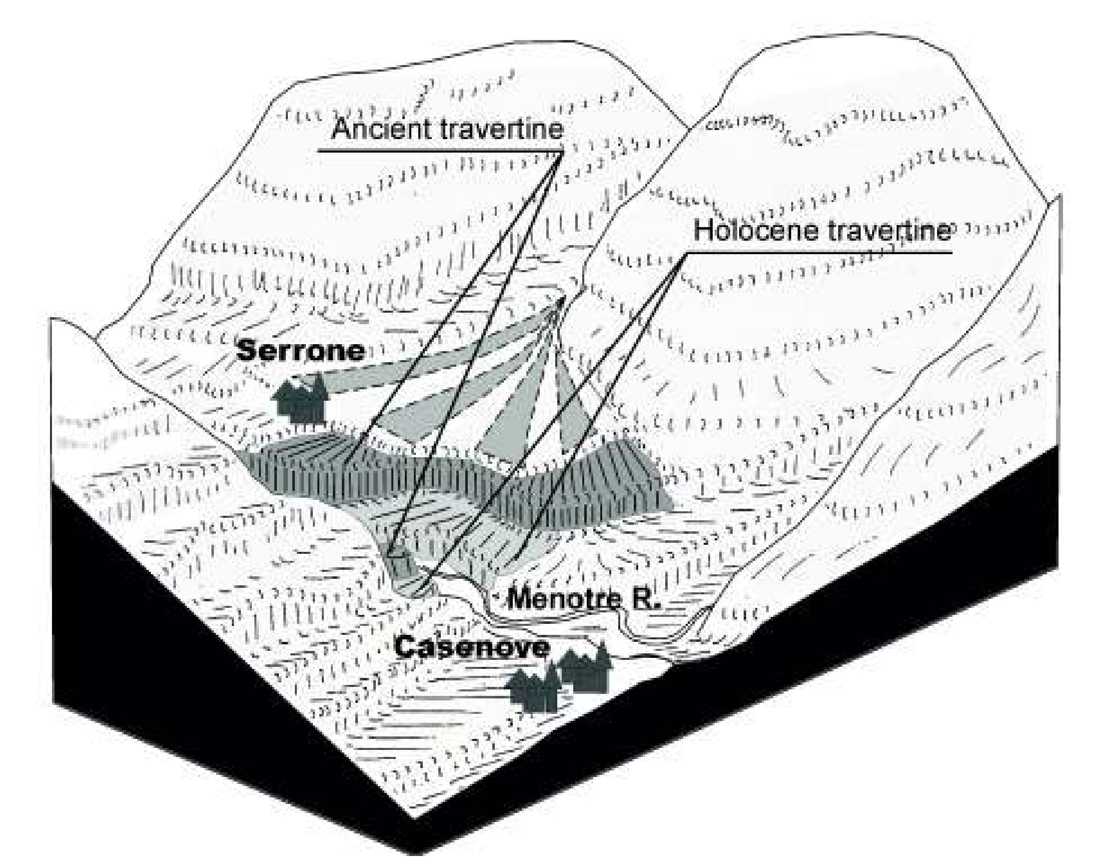

Fig. 2. Block diagram showing travertine deposits located in the Casenove and Serrone area.

and large landslides were the main typologies. The latter in particular, during the Middle Pleistocene-Holocene interval, caused a lot of damming phenomena along the river valleys (GENTILI & PAMBIANCHI, 1994; ARINGOLI *et al.*, 1998); some of these left evident steps, still visible, where, sometimes, travertine deposits are present.

The chain sector shows a somewhat articulated morphology, influenced, during the Quaternary, by alternating climatic phases contemporary with the above mentioned generalized uplift. These conditions left very evident traces made of regularised slopes and stratified deposits, the latter were produced by crioclastism on the slopes without vegetation and deposited by rill processes and surficial mass movements. The most spectacular phenomena are observed on the eastern flanks of the chain, where it is possible to recognize numerous landslide bodies (falls prevalently); mountainwards fissures, steps, trenches, undulations and an intense fracturing of bedrock have been produced (DRAMIS *et al.*, 1982; GENTILI & PAMBIANCHI, 1994; DRAMIS *et al.,* 1995).

In the vast piedmont area, gravity driven morphogenetic processes are responsible for the widespread and intense landsliding. Processes connected to surface waters modelled a well developed hydrographic network and wide fluvial valleys with a SW-NE direction and low gradient. These valleys, occupied by the main rivers, form broad alluvial plains and little beaches in correspondence with the mouths (COLTORTI, 1981; DRAMIS *et al.*, 1982; COLTORTI *et al.*, 1991; FARABOLLINI, 1995).

Geomorphological evolution caused the formation of thick Quaternary continental deposits within the chain area and inside the main intramountain basins; these deposits are made up of slope, alluvial and lacustrine deposits and of wide travertine bodies. On the contrary in the piedmont area, along the main rivers, four orders of alluvial terraces and two different generations of travertines are present; fluvial deposits in particular are located at different heights on the thalweg and are connected either to cold Pleistocene climatic conditions or, in recent times, to human activity (Coltorti, 1981; Coltorti *et al.*, 1991; Farabollini, 1995).

The travertines

The deposits of Casenove – Serrone (Menotre river). The Menotre river (Fig.1) initially flows in a N-S direction along a sinclinalic valley where marly-calcareous terrains ("*Scaglia rosata*" and "*Scaglia cinerea*" formations) outcrop. Along its middle-final portion, up to the confluence with the Topino river, it runs roughly E-W, crossing the anticlines made by the calcareous formations ("*Maiolica*" and "*Calcare massiccio*"). With respect to other zones of the ridge, the valley floor is wider and flattened because of the presence of a structural step near the locality of Pale that strongly reduces linear erosion mountainward.

The sketch in Fig. 2, synthetically shows the situation in the Casenove and Serrone area, two villages located a few hundreds meters apart, where wide travertine deposits, up to 20–25m thick, are present. The thickness is related to two different depositional phases: the former, older one, is visible at Serrone, on the hydrographic left of the Menotre river, at an elevation of about 20m with respect to the valley floor; the latter, younger one, outcrops next to Casenove, along the present river.

The existence of two different depositional events, was hypothesized on the basis of geomorphologic and stratigraphic considerations. First of all, there is a substantial difference in the nature of the deposits: the higher and older one of Serrone is very tough and resistant and it is made up of the thick phytohermal facies of a "pools and riffles" environment (Farabollini *et al.*, 2004b); the younger one of Casenove, presents a higher phytoclastic component, even if it is still associated with the same environment.

The presence of an older deposit is confirmed by a large alluvial fan, attributed to the Late Pleistocene, *Materazzi, 1996) that partially covers the Serrone deposit. That of Casenove, on the basis of its location with respect to the recent alluvial deposits along the valley floor, has been attributed to the Holocene.

A similar situation is visible at Rasiglia (Fig.1), where travertine was deposited in two different phases, in a slightly terraced position above the thalweg. Analogies concerning facies typologies and elevation on the thalweg, allow us to correlate these deposits with those of Casenove and Serrone, similarly hypothesizing a "riffles and pools" environment. The origin of these deposits seems to be essentially connected to the particular morphology of the Menotre river, characterized by a steep gradient, rapids and small waterfalls; this situation was ideal for the formation of travertine. At Rasiglia a further favourable condition was the presence of a short and narrow valley segment that produced a consequent increase of the water velocity and turbulence.

The deposits of Triponzo (Nera and Corno rivers). The village of Triponzo was built on a very tough travertine bank, present on both valley sides, at the confluence of the Nera and Corno rivers within the Umbria-Marches Ridge (Fig.1).

Geomorphological survey in the area allowed us to confirm that travertine is present in two distinct phases: the former is older and located higher with respect to the village; the latter, Holocene in time, was deposited near the actual valley floor (Fig. 3).

The oldest deposit reaches a maximum thickness of about 60 m on the left side of the valley, while on the right one it is a little less thick. The presence, inside and on top, of colluvial fersiallitic paleosoils and stratigraphic correlations with alluvial deposits allow us to attribute this phase of deposition to the last interglacial period. These travertines are mainly made up of phytohermal facies of "cascade" environment, characterized by very

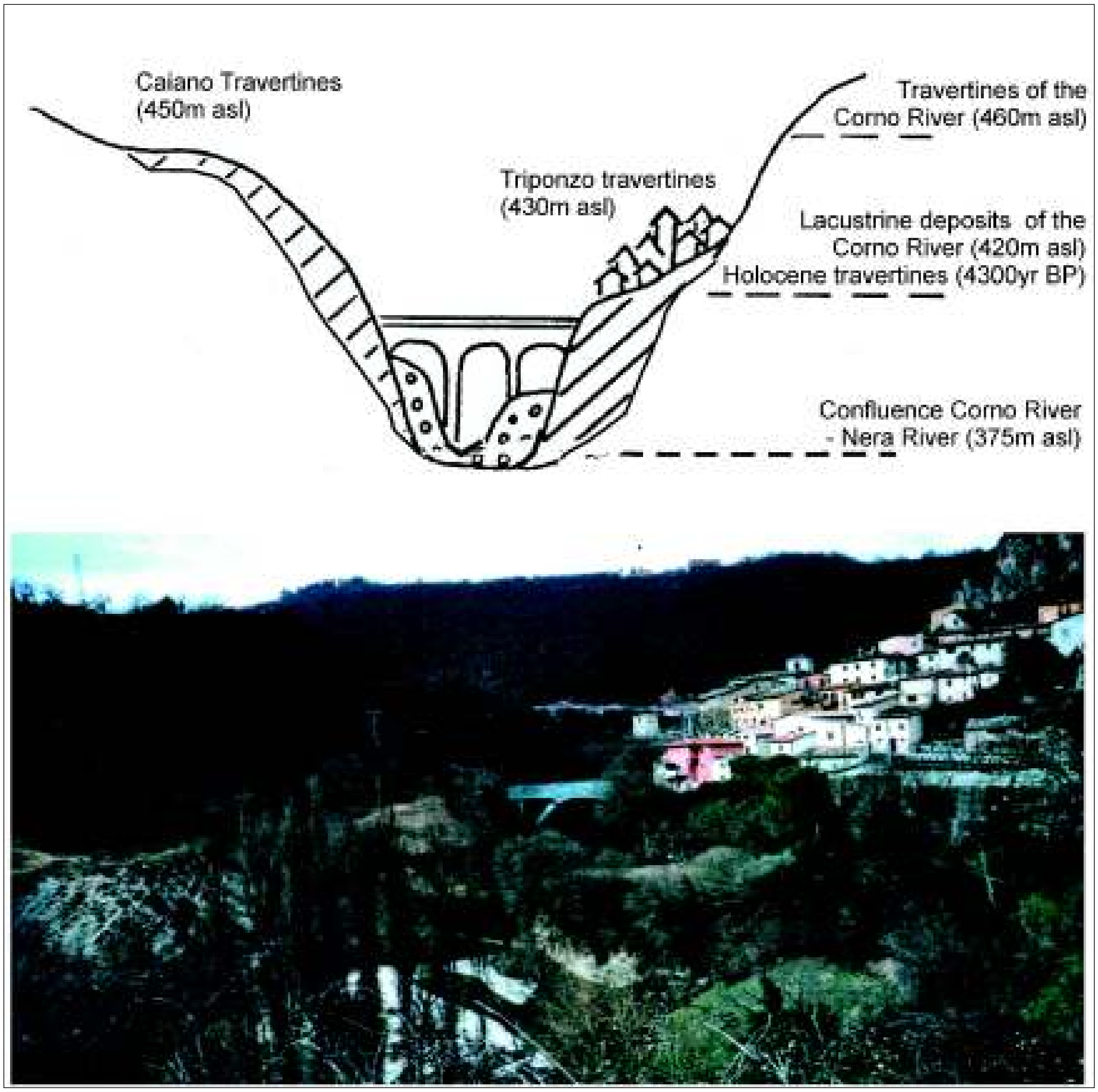

Fig. 3. The travertine deposit of Triponzo; Photo and transversal schematic cross section (above).

low porosity and a strong presence of calcite due to the secondary circulation of water. Similar facies, stratigraphically correlated with the previous ones even if of minor thickness, are visible also in some deposits along the Corno river.

A younger phase is present near Triponzo along the valley floor and is composedof two small terraces located on both sides and about 30 m thick. These deposits have a greater phytoclastic component with respect to the older ones and are made up of prevalently calcareous sands and gravels alternated with banks of phytohermal travertine a few meters thick.

The presence, a little mountainward along the Corno river, of a thick peaty-clayey deposit about 40 m thick, allows us to hypothesise that in the past the forming travertine constituted a natural dam on the river; as a consequence a long lacustrine event occurred. The age of the younger phase of travertine is therefore associated with that of the lacustrine deposit; VINKEN (1968), on the basis of absolute dating, gave ages between 8800 and 4300 yr B.P.

Also the deposit of “Colle il Tonno”, about 1 km valleyward of Triponzo, is Holocene in time and can be related to the others described above. Hanging about 40 m over the thalweg, it is made up of alternating phytohermal and phytoclastic facies, a few meters thick, forming the typical "pools and riffles" system. The greater thickness of the phytoclastic facies within the Holocene travertine (as compared to the older generation), is connected to a gentler gradient and a more regular morphology of the Nera and Corno river beds in this period.

The deposits of Pale (Menotre river). The village of Pale is placed about 3 km mountainward of the confluence between the Menotre and Topino rivers (Fig. 1). It is built up over a thick and wide bank of phytohermal travertine, deposited in correspondence to a very abrupt morphological step (almost 200 m in a few hundred meters) along the Menotre river (Fig. 4).

This travertine, actually inactive, shows a clear "cascade" morphology: compacted, almost without phytoclastic facies, it is more intact in the upper portion (in proximity of the village) while it is dissected and strongly eroded in the lower one, where, too, large blocks which falled from above are visible.

The origin of the deposit is probably connected to the structural setting of the area: the above mentioned structural threshold is located on the western flank of the Mt. Serrone anticline, where the older "Calcare massiccio" formation, in the core, passes to the less resistant terrain above. In this context, a progressive deepening of the Topino river inside marly formations occurred, while Menotre, strongly conditioned by its structural binds, maintained a steeper profile and formed a real fall near the present village of Pale. This morphological setting favoured, probably during the warm and humid phase at the end of the Middle Pleistocene, an intense travertine deposition; today the deposit is separated into three different steps (Fig. 4) due to the regressive erosion of the structural threshold.

The deposits of Sefro (Potenza river). It is located along the Scarsito stream, a right tributary of the Potenza river (Fig. 1) that flows about SW-NE entirely incised in the "calcareous formations ("Calcare massiccio" and "Scaglia rosata"). The longitudinal profile is gentle and the valley floor is wide (about 150 m) and flattened due to the presence valley ward, of a structural threshold at the confluence between the Scarsito and Potenza rivers; at this point, where today the village of Pioraco is located, a huge travertine deposit of "cascade" environment is present.

At Sefro in particular, a travertine bank of limited thickness (3-5 m), more or less continuous for about 80 m, is visible on both valley sides. It shows a typical "pool and riffle" morphology (MATERAZZI, 1996; FARABOLLINI *et al.*, 2004b), even though phytohermal facies are more developed. The presence along the actual valley floor and its relationship with fluvial and lacustrine deposits that date to the Holocene (MATERAZZI, 1996), allow us to attribute the deposition of travertine to the warm and humid initial phase of this period. In addition, a little valley ward on the hydrographic left, another travertine bank is present. It is deposited over the remnants of an alluvial terrace of the end of the Middle Pleistocene, made up of fairly well cemented gravels; on the top, the Upper Pleistocene stratified slope deposits cover the travertine, allowing us to attribute the depositional phase to the last interglacial period. A reddish paleosoil, partially, and attributed to the final warm and humid phase of Middle Pleistocene interglacial periods (COLTORTI *et al.,* 1991), is visible where fluvial gravels and travertine come into contact.

The deposits of Pievetorina (Chienti river). Near the village of Pievetorina, along a left tributary of the Chienti river (Fig. 1) two different travertine generations are present. Both generations are visible on the right side of the valley: the older one is deposited several tens of meters above the thalweg while the younger one is present a few meters above the valley floor. This latter is the most significant one because of its longitudinal extension that reaches several hundreds of meters, even if it is present only on the right side.

The oldest deposits, less extended and generally buried by a widespread detritic cover,

Fig. 4. Aerial photo of the travertine deposit at Pale; (1, 2 and 3 represent different steps within the deposit).

form a small terrace, a few meters thick and about 20 – 30 m long, partially hidden by the vegetation.

On the contrary, the younger ones are composed of a thick sequence (of up to 10 m) of travertine facies and are well recognizable because of the recent fluvial incision. They are made up of travertine gravels, sands and silt (typical phytoclastic facies) alternated with phytohermal and stromatolithic travertine. On the top, an alluvial brown paleosoil, containing pebbles of phytohermal traver-

Fig. 5. Panoramic view of alluvial deposits at the base of travertine deposits in the Acquasanta Terme area

tine up to 10 cm in thickness, close the sequence.

The deposit of Valleremita (Giano river). It is located at the confluence of the Valleremita stream and the Giano river within the Umbria-Marches ridge (Fig. 1), and is characterized by a length of about 1 km, a width of about 200 m and an average thickness of 15 – 20 m or more . The travertine has the shape of a large alluvial fan deposited over an alluvial deposit of the Upper Pleistocene (CALDERONI *et al*., 1996). The base of the deposit (8-10 m) is composed of an almost continuous bank of phytohermal and stromatolithic travertine, very compact and with rare thin levels of phytoclastic sands intercalated. Upward, several channels filled by a thin layer of stromatolithic travertine and calcareous gravels and sands, up to a fewmeters in width, are present. The sequence goes on with several meters (5-10 m) of sandy phytoclastic travertine, characterized, in the lower portion, by three different brown paleosoils (10-15cm thick), laterally continuous for the whole width of the deposit (MATERAZZI, 1996).

On the sequence top, radiometric dating carried out on a charcoal fragment found inside a paleosoil level gave an age of 4535±80yr BP (CALDERONI *et al*., 1996).

The deposit of Acquasanta Terme (Tronto river). The travertine deposit of Acquasanta Terme, well known as "Acquasanta Terme marbles" for their manufactural and their ornamental properties, shows elevated thickness (even several hundreds of meters) and an area of several square kilometres in extension (BONI & COLACICCHI, 1966a and b). It is composed of three different levels located at as many different heights on the thalweg; the younger level is present a few meters above the valley floor while the oldest is about 250m above it.

Travertine deposition in the area has been so far associated to thermal water (still present) oversatured with calcium carbonate which rises up along deep fractures (BONI & COLACICCHI, 1966a) or is connected with a buried regional tectonic structure that would conditioned travertine deposition also in other localities of central Italy (Triponzo, Cotilia, MINISSALE *et al*., 2003).

Further studies, based on the relationship between travertine and the alluvial deposits of the Tronto river and its tributaries (FARABOLLINI *et al*., 2003 and 2004a), evidenced that travertine formed during interglacial periods, along the tributary valleys of the Tronto river, when climatic improvement produced the development of vegetation and the consequent increase of CO_2 in the circulating waters (DRAMIS *et al*., 1999); these waters, besides, mixed with the thermal ones described above (MATERAZZI, 2003).

Geomorphological survey and facies analysis confirmed that travertine deposition, characterized by "cascade" and secondary dome-shaped structures (i.e. Castel di Luco), occurred in a typical fluvial environment. This fact is testified to by a characteristic fluvial architecture (grading and stratification) and by the presence, at the base of each level of travertine, of alluvial deposits associated with fan systems inside the tributary valleys

Fig. 6. Stratified alluvial sands and gravels underlying travertine deposit at Civitella del Tronto.

(Fig. 5). The remnants of an older alluvial fan without travertine on top, located higher up and attributed to the Middle Pleistocene, confirms the hypothesis that alluvial fan systems govern travertine formation and the start of deposition after the Middle Pleistocene.

The deposits of Civitella del Tronto (Salinello river). At Civitella del Tronto (Fig. 1), travertines are composed of three main plates (Monte Santo, Civitella del Tronto and Colle San Nicola) wedge-shaped toward the south and with a thickness ranging from 15 to 50 m. All together, they look like a lens whose greatest thickness is at the Civitella del Tronto deposit oriented in the same direction as the Salinello river.

Travertines are generally deposited over coarse alluvial deposits and show the typical “pool and riffle” environment (PREITE MARTINEZ *et al*., 1990; FARABOLLINI, 1999; FARABOLLINI *et al*., 2004b) (Fig. 6): phytoclastic facies are prevalent in the lower portion while phytohermal and microhermal ones (PREITE MARTINEZ *et al*., 1990) increase upward. The thickness of phytohermal facies and the presence of channels filled with fluvial gravels and pisolithes 2-3 cm in diameter, suggest a steep longitudinal profile locally interrupted by high morphologic steps (falls) (FARABOLLINI, 1999; FARABOLLINI et al., 2004b).

Pollen analyses (DE SANCTIS & FREGONESE, 1981), gave evidence that deposition occurred in a typical interglacial environment. On the other hand, the relationship between all travertine plates and a limb of alluvial terrace located about 50 m down valley and attributed to the end of the Middle Pleistocene (DRAMIS *et al*., 1982) and the presence, at the base of the travertine (Fig. 6), of another alluvial deposit associated to an older valley floor (FARABOLLINI, 1999), confirmed that travertine deposition is strictly connected to the Salinello river dynamics and occurred during an interglacial phase olderthan the end of the Middle Pleistocene.

Depositional mechanisms, paleo-environmental significance and chronology

Travertine deposition in the Umbria-Marches-Abruzzi area is a very important process because it can be used to reconstruct the Quaternary paleo-environmental context. In particular, different depositional phases can be related to well defined climatic and/or historical periods.

Travertine deposition along river beds during the Quaternary, is a generalized phenomenon, more or less contemporary in temperate or sub-tropical countries (HENNING *et al.*, 1983; FORD & PEDLEY, 1996 and *ref. within*; MATERAZZI, 1996; FARABOLLINI et al., 2004 a and b). In absence of particular phenomena (i.e. the presence of thermal waters), climatic conditions are fundamental to explain the genesis and development of these deposits. In particular, deposition may occur where a high gradient or irregularities of the river longitudinal profile are present. If the gradient is very steep or a real fall exists a "Cascade" environment (FARABOLLINI *et al*., 2004b), characterized by a dominance of phytohermal facies, may form. If the gradient is a little gentler, or small steps are present, a "riffles and pools" environment (FARABOLLINI *et al*., 2004) develops: in this case deposit is formed of alternating layers of phytoclastic and phytohermal facies. In both cases the associated water turbulence and the presence of aquatic vegetation (moss and algae) are fundamental factors: in particular the latter, using dissolved CO_2 for their metabolism, are encrusted with calcium carbonate and constitute a "skeleton" for travertine built up.

Sometimes, where travertine deposition creates a real dam, lacustrine episodes or overflooding phenomena may happen along the river (as observed at Triponzo and Pale).

As evidenced by several authors (GULLENTOPS & MULLENDERS, 1972; NICOD, 1986; GOLUBIC *et al*., 1993), the great amount of calcium carbonate in solution, responsible for travertine formation, is due to a strong presence of CO_2 in waters circulating inside calcareous bedrock; this fact was in turn connected to vegetation development and the consequent presence of very high thicknesses of soils during interglacial periods. A considerable vegetable cover also favoured the regularisation of the hydrologic regime: the soil's capacity to hold infiltrating waters, which came back in the thalweg much later, allowed a greater enrichment of carbon dioxide.

More recently DRAMIS *et al.* (1999) also evidenced the role played by groundwater temperature changes in controlling the calcium carbonate dissolution equilibrium. In particular, differences between the lower temperature of groundwaters (influenced by deep penetration into calcareous aquifers of glacial period surface temperatures) and higher external temperatures at the springs may have caused, for a more or less long time depending on the thermal capacity of the aquifers, a greater loss of CO_2 and consequent strong travertine deposition. The process may have been continued until the thermal disturbance in the ground was exhausted and a normal heat flux towards the surface was re-established.

The combined effects of climate and Pleistocene tectonics, also allow us to explain the different development (thickness and extension) of the oldest travertine deposits with respect to the Holocene ones. First of all, the longer duration of the glacial and interglacial periods of the Lower and Middle Pleistocene may justify the higher deposition. On the other hand, strong Pleistocene tectonic uplift (DRAMIS, 1992), which favoured river downcutting mainly during interglacial periods, caused a rapid lowering of the piezometric levels inside carbonate aquifers and a consequent increase of fluvial discharge (FARABOLLINI *et al.*, 2003). This effect gradually decreased as a result of the new base level (Fig.7).

The climatic factor, together with Pleistocene tectonic events, also allow us to explain differences in the development of ancient travertine deposits (as far as their area and their thickness are concerned), usually greater with respect to those of the Holocene. On one hand, in fact, the greater length of the cold phase in the interglacial periods of the lower and middle Pleistocene could justify a greater development of travertine precisely because of longer lasting favourable condi-

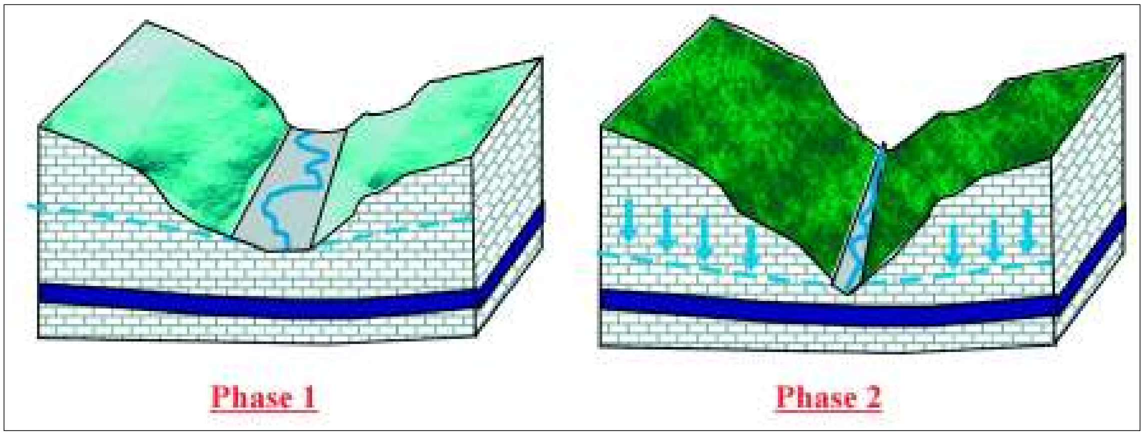

Fig. 7. Schematic representation of neotectonic and hydrogeological variations (phase 1: initial condition; phase 2: together with tectonic uplift increasing during the Late Quaternary).

tions of deposition. On the other hand, strong Pleistocenic tectonic uplifting (DRAMIS, 1992) also favoured, especially in the interglacial periods characterised by an increase in linear erosion, the deepening of the river valleys, with the resultant rapid lowering of the piezometric surface and the increase of the hydrologic regime of the water courses (FARABOLLINI *et al.,* 2003) . This effect, initially more intense, gradually diminished as a new equilibrium was established with the new basic piezometric level (Fig. 7)

Chronological data are in perfect agreement with previous indications. As far as the oldest travertines, (Civitella del Tronto, Sefro, Pale, Acquasanta Terme), for which absolute dating is not available, relationships with other geomorphological elements (alluvial deposits, alluvial fans, slope waste deposits, palaeosoils, etc.) allowed us to attribute travertine deposition to the warm-humid phases of the interglacial periods older than the Late Pleistocene

The younger deposits (Pievetorina, Sefro, Valleremita) instead, on the basis of radiometric dating, can be attributed to the Early Holocene, as well as those observed in other localities of the central Apennines (CILLA *et al.*, 1994; CALDERONI *et al.*, 1996; MATERAZZI, 1996).

Conclusions

The study carried out on several deposits in the Umbria-Marches-Abruzzi area allowed us to verify the existence of three fundamental conditions governing travertine deposition:

1- a high energy depositional environment: all deposits developed along fluvial systems which were more or less developed, characterised by steep profiles, morphological steps or structural thresholds. Their belonging to a fluvial environment is also testified to by the location (symmetric and parallel to the river axis), by the presence of typical fluvial facies and by their relationship to alluvial deposits;

2- favourable climatic conditions: climatic changes occurring between glacial and interglacial periods (such as during the Middle Pleistocene, the Late Pleistocene and the Holocene) strongly influenced the genesis and development of travertine in the areas. Also in the Acquasanta Terme this effect contributed to deposition in a system highly regulated by thermalism;

3- neotectonics and hydrogeological conditions changing in time: valley deepening, consequent to climatic changes (such as glacial-interglacial transition) and/or periods of more intense tectonic uplift, caused rapid lowering of the piezometric level inside carbonate aquifers. This fact increased the hydrologic discharge of the rivers and, together with climatic improvement, favoured travertine deposition, in correspondence to the above mentioned morphological steps.

Also at the Acquasanta Terme, a change of the hydrogeological regime, could have played a very important role in travertine deposition together with the action of thermal waters. In this case too, deposition of travertine occurred in a fluvial environment, along tributary valleys, where mixing of thermal water and freshwater was present. Progressive lowering of piezometric levels, together with the above mentioned climatic changes, which aim at a new equilibrium, seem to be the most important causes of the progressive decreasing (and sometimes interruption) of travertine depositional processes.

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