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TRAVERTINE DEPOSITS OF THE MIDDLE LIRI VALLEY (CENTRAL ITALY): GEOMORPHOLOGICAL, SEDIMENTOLOGICAL AND GEOCHEMICAL STUDY. PALAEOENVIRONMENTAL AND PALAEOCLIMATIC IMPLICATIONS

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ABSTRACT - *The travertine deposits of the middle Liri Valley (Central Italy): geomorphological, sedimentological and geochemical study. Palaeoenvironmental and palaeoclimatic implications.* Il Quaternario, 4(1a), 1991, p. 55-84 - In the middle Liri Valley, between Sora and Fontana Liri, a large plate of travertines outcrops. It has a length of about 10 km, a mean width of 4 km and a thickness from several tens of metres to more than 120 m. The travertine plate, which occupies a palaeovalley carved in a Meso-Cainozoic substratum, has been affected by extension tectonics showing mainly E-W or ENE-WSW trend. Furthermore, it has been eroded and deeply downcut by the Liri river that formed terraced alluvial deposits and/or erosion terraces on its depositional surface or encased in it at different altitudes. The travertine plate is made up of alternating autochthonous and detrital travertine bodies and contains lithofacies associations of different depositional palaeoenvironments, *i.e.*: fluvio-lacustrine, lacustrine, palustrine, of more or less steep slope and waterfall. The study of their floral and malacofaunal content suggests that the deposition of the studied travertines took place during temperate climatic phases characterized by variations of humidity. Travertines are characterized by low-magnesium calcium carbonate content, ranging from 65 to 100%. Content of major and some trace components are also discussed. Oxygen and carbon isotopic composition of travertines suggest that their deposition took place from mother waters with uniform isotopic composition at relatively steady temperatures. In the $\partial^{18}O$ and $\partial^{13}C$ curves an evident specular behaviour of the two parameters has been noted within the plate, especially for the middle and upper parts of the plate, above the altitude of 188 m. Such behaviour could be a reflection of primary isotopic composition of mother waters, conditioned by climatic factors, by mainly ambient temperature and humidity variations (modality and/or quantity of precipitations), that, in turn, influenced the biological activity. A climatic signal in the compared oxygen and carbon isotopic composition curves is pointed out. As regards the origin of carbon dioxide involved in the formation of travertines it is not excluded that a part of it could be of endogenic origin, the studied area being tectonically active and affected by extensional movements. A sedimentation model, considering mainly depositional phases alternating with mainly erosional or non-depositional phases, likely linked with humidity variations, is proposed. The studied travertines have been deposited in the middle Pleistocene, in a period of time comprised between 360 ka BP and the last interglacial stage.

RIASSUNTO - *I travertini della media valle del fiume Liri (Italia centrale): studio geomorfologico, sedimentologico e geochimico. Significato paleoambientale e paleoclimatico.* Il Quaternario, 4(1a), 1991, p. 55-84 - Sono stati studiati i travertini affioranti nella media valle del fiume Liri, tra Sora e Arce, che formano un piastrone della lunghezza di circa 10 km, della larghezza media di 4 km e uno spessore variabile in generale da alcune decine di metri fino a oltre 120 m. Il piastrone, che occupa una paleodepressione nel substrato meso-cenozoico, è stata interessato da tettonica distensiva con direzioni prevalenti E-W o ENE-WSW. Il piastrone è stato inoltre profondamente inciso dal Liri, che, in fasi successive, ha deposto sedimenti alluvionali terrazzati su di esso e incassati in esso. La placca travertinosa è costituita da alternanze di travertini autoctoni e travertini detritici; presenta associazioni di facies che suggeriscono diversi ambienti deposizionali: fluvio-lacustre, lacustre, palustre, di pendio più o meno acclive e di cascata. Lo studio del contenuto floristico e delle malacofaune suggeriscono che la deposizione dei travertini sia avvenuta durante una o più fasi climatiche di tipo temperato caratterizzate da variazioni di umidità. I travertini sono caratterizzati da contenuti di carbonato di calcio, povero in Mg, variabili tra 65 e 100%. Sono discussi anche i contenuti di altri componenti maggiori e in tracce. La composizione isotopica dell'ossigeno e del carbonio dei travertini suggerisce che la loro deposizione sia avvenuta da acque madri con composizione isotopica uniforme ed a temperature relativamente costanti. Le curve dei valori di $\partial^{18}O$ e $\partial^{13}C$ nel piastrone travertinoso mostrano un comportamento speculare, evidente specialmente per le parti media e superiore del piastrone, sopra la quota di 188 m. Detto comportamento potrebbe riflettere la composizione isotopica originaria delle acque madri, condizionata da fattori climatici, in primo luogo dalla temperatura ambiente e dalle variazioni di umidità (modalità e/o quantità delle precipitazioni), che, a loro volta, hanno influenzato l'attività biologica. Sembra quindi evidenziato un segnale climatico nel comportamento di dette curve. Non si esclude, inoltre, che almeno una parte dell'anidride carbonica coinvolta nel processo di formazione dei travertini sia di origine endogena, essendo l'area considerata tettonicamente attiva e soggetta a movimenti tensionali. Viene proposto un modello deposizionale connesso con fasi a prevalente sedimentazione di travertini autoctoni alternate a fasi con prevalente deposizione di travertini detritici. La deposizione è avvenuta nel Pleistocene medio, in un periodo di tempo compreso tra 360 ka BP e l'ultimo interglaciale.

Key-words: Middle Pleistocene, travertines, neotectonics, depositional environments, palaeoclimate, Liri Valley, Central Italy
Parole chiave: Pleistocene medio, travertini, neotettonica, ambienti deposizionali, paleoclima, valle del Liri, Italia centrale

1. GEOLOGICAL AND MORPHOLOGICAL SKETCH AND EVOLUTION SCHEME

1.1 Introduction

The interest in the study of travertine deposits arises from the contribution of knowledge that it brings to the palaeoenvironmental, palaeoclimatic and neotectonic fields. Such knowledge, in turn, forms the base for the understanding of the ongoing evolutionary tendencies of these fields. These are subjects of great social-economic interest and have been widely debated in both national and international spheres.

During the last decades we have witnessed an

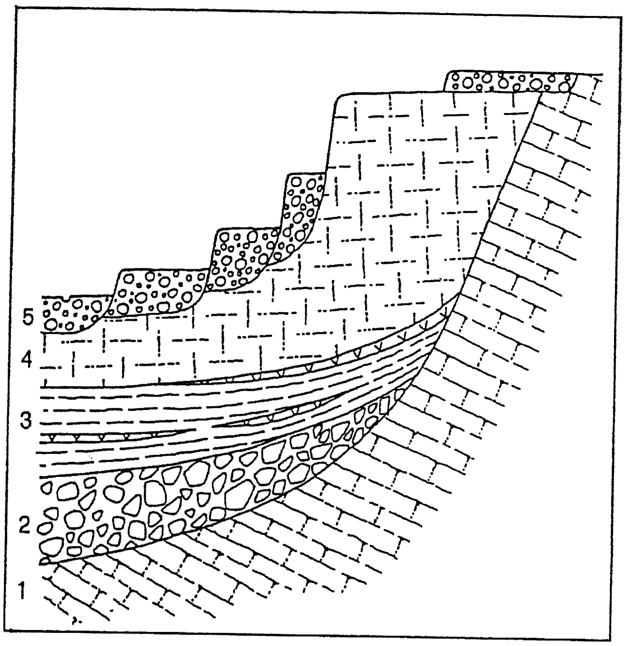

Fig. 1 - Stratigraphic relationships of the formations outcropping within the area. Symbols: 1) Carbonatic Meso-Cainozoic substratum; 2) Alluvial fan deposits; 3) Fluvio-lacustrine deposits with volcanic intercalations; 4) Studied travertines; 5) Terraced alluvial deposits (I-V order).

Rapporti stratigrafici delle formazioni affioranti nell'area. Simboli: 1) Substrato carbonatico Meso-Cenozoico; 2) Depositi di conoide alluvionale; 3) Depositi fluviolacustri con livelli vulcanici; 4) Travertini studiati; 5) Depositi alluvionali terrazzati (I-V ordine).

awakening of interest in the travertines of the central and southern regions of Italy by Italian and foreigner researchers. Their studies used not only classical geological and geochemical methods, but also the ^{230}Th dating method and the determination of oxygen and carbon isotopic composition. These methods are of great interest in evaluating: age of deposition, temperature precipitation and biological activity.

The study of travertines is known to be difficult because of the extreme variability of their sedimentological and textural characters, and the complexity of relationships in space and time of the various parameters, that control the precipitation and post-depositional diagenetic processes (recrystallization, solution and reprecipitation, isotopic exchange with ground waters).

In order to obtain realistic results and verify them independently, a multidisciplinary approach is mandatory.

1.2 Previous work

Bibliographic information on the travertine deposits of the middle Liri Valley, between Isola del Liri and Fontana Liri Inferiore, and in the Amaseno Valley, between Monte San Giovanni Campano and Strangolagalli, are scarce.

Cacciamali (1892), on the basis of original and previous work, describes their location and superimposition on ancient lacustrine sediments. He also describes two main facies of travertines: one of suballuvial and the other of sublacustrine origin. He relates the travertine origin to the carbon dioxide-rich waters coming from the vulcanism which is widespread in the area. He reports also information about interesting findings of bones (*Bos primigenius* and *Cervus elaphus*). The lack of exact topographic and stratigraphic indications, however, does not allow to assign these fossils a chronostratigraphic value.

Alonzi (1965), in a study on clayey-calcareous lacustrine sediments containing travertines lenses, outcropping in the Sora basin and in the Liri Valley, states that all these formations are to be considered of Villafranchian age, without providing more exact and clear explanations.

Accordi *et al.* (1967) claim that, in the upper Liri Valley (Anitrella), yellow-reddish sandy travertines are widespread and their origin is clearly fluviatile and related to the Liri river.

Praturlon (1968) observes that ancient (undifferentiated Pleistocene) lacustrine formations containing yellowish silts outcrop in the Sora plain. In the upper part, these silts, grade laterally and superiorly to travertine and sand layers and to concretionary lithoid travertine (Isola Liri), locally connected with sulphureous springs (Fontana Liri).

Accordi *et al.* (1969) correlate travertines of this area with those that grade heterotopically into the late lacustrine facies of Lake Lirino in the lower Liri Valley (Devoto, 1965). The above-mentioned sediments have been deposited during a cold climatic phase connected with the Rissian glaciation.

Manfra *et al.* (1969), who studied the isotopic composition of Latium travertines, suppose that these sediments have been deposited from mother waters at temperature close to air temperature and with isotopic composition close to that of present-day ground waters. They claim that the detected carbon could derive either from hydrocarbons, widespread in the area, or from biogenic carbon dioxide.

Segre *et al.* (1984), in a longitudinal section through the Sora basin, on the basis of a rich faunal content and of the presence of scarce lithic industry, explain the stratigraphic relationships of the outcropping formations. From that section it can be inferred that the Isola Liri - Fontana Liri travertines, lying on lacustrine sediments with volcanic intercalations, are referable to the Mindel-Riss interglacial, while the travertines outcropping in the Carnello area would have been deposited during the last interglacial.

Giraudi (1990), in a paper describing travertine outcrops near Carnello, a few kilometres NE of Isola del Liri, interprets it as a fossil waterfall of the Fibreno river and refers these deposits to the last interglacial. He reports a ^{230}Th dating of 93 ka BP (+29; -21.2 ka).

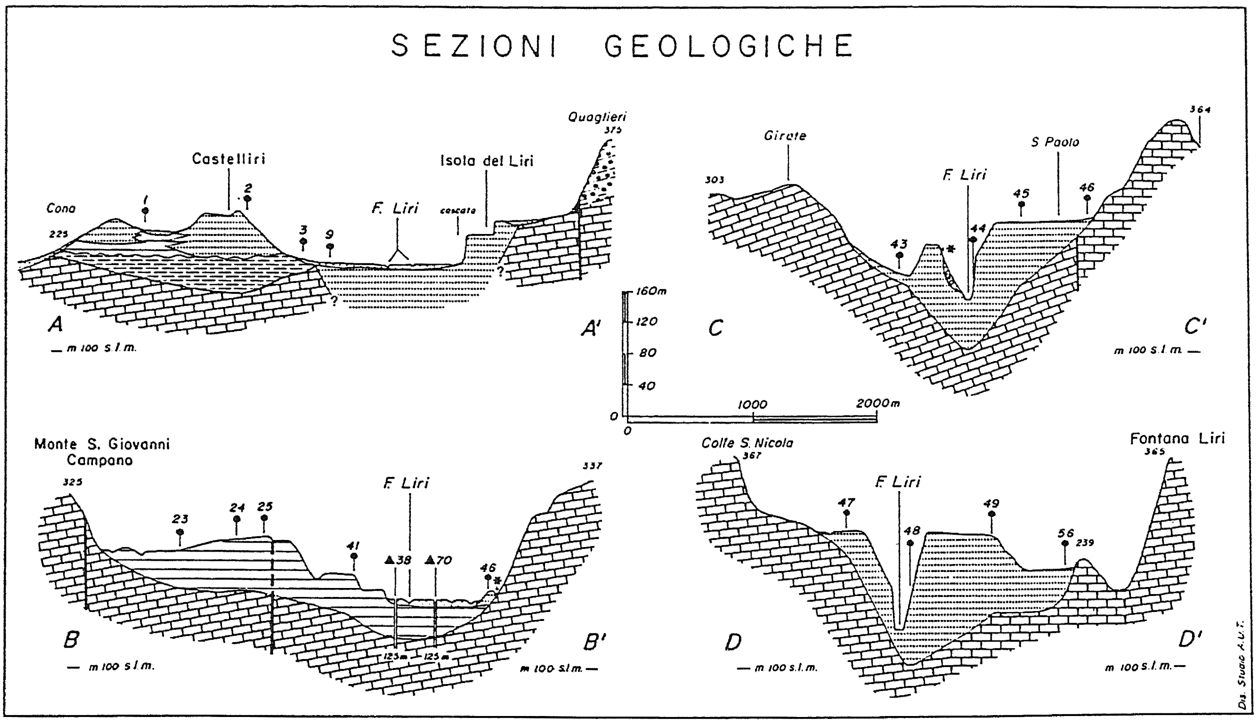

Fig. 2 - Geological sections; symbols as in Plate 1.
Sezioni geologiche; simboli come in Plate 1.

1.3 Lithostratigraphic and geomorphological outline

The studied travertines outcrop in an area roughly surrounded by Isola del Liri, Fontana Liri Inferiore, Strangolagalli and Monte San Giovanni Campano, along the Liri and Amaseno river valleys (Plate 1, Figs. 1 and 2).

The stratigraphic column consists of the following terms, from bottom to top:

- *Substratum*: composed mainly of Meso-Cainozoic limestones and Miocene flysch associated with more or less large outcrops of Tortonian-Messinian sandstones and Mio-Pliocene polygenic conglomerates.
- *Plio-Pleistocene psammitic-ruditic sediments:* of alluvial fan type (Santopadre Formation; Angelucci, 1970).
- *Middle Pleistocene fluvio-lacustrine sediments*: preserved in small outcrops in the Castelliri-Cona and Strangolagalli areas. In the first area they are mainly composed of gray-greenish sands and silts and of organic-matter-rich clays, grading into peaty deposits. They are rich in malacofauna and contain abundant fossil pollen, studied by Follieri *et al.* (1989). This pollen, on the basis of its floristic-vegetational character, suggests a correlation with the zones 3-5 of Valle di Castiglione (Rome), corresponding to the stage 7 of the oxygen isotopic curve. Intercalations of volcanic material occur within the lacustrine sediments.
  In the Strangolagalli area the fluvio-lacustrine sediments are composed of thinly stratified silts and clays containing several intercalations of pyroclastic tuffs related to Pofi vulcanism in Latina Valley (Sevink *et al.*, 1984), dated 400÷430 ka BP (Pasquarè *et al.*, 1979).
  The fluvio-lacustrine deposits of Strangolagalli and Cona areas, outcropping under the travertines, from which are separated by a clear erosion surface, are considered coeval, even if they belong to different basins, as proved by their altitudes. They are correlated with the late lacustrine deposits of Lake Lirino (Sevink *et al.*, 1984), dated 360 ka BP (Devoto, 1965) and 354÷359 ka BP (Bigioggero *et al.*, 1988).
- *Volcanic, mainly pyroclastic deposits*: they overlay either the Meso-Cainozoic substratum or the previously described fluvio-lacustrine silts, or are interposed between the above mentioned deposits and the travertines.
  In the Strangolagalli area, a pyroclastic level outcrops on lacustrine deposits. These pyroclastic materials are dated, by means of K/Ar method on sanidine, 250 ka BP (Arnoldus-Huizendveld *et al.*, 1985). Other layers of volcanic material showing the same mineralogical characteristics occur near Anitrella and along the road going from La Lucca to Panicelli, SE of Monte San Giovanni Campano, interposed between the carbonatic substratum and the examined travertines.
- *Travertines* within the Liri Valley the studied travertines form a plate of about 10 km inlength, a mean width of 4 km and a thickness variable from some tens up to more than 120 m. Within the Amaseno Valley the travertine plate, outcropping between Santa Pudenziana and Biordi, has a

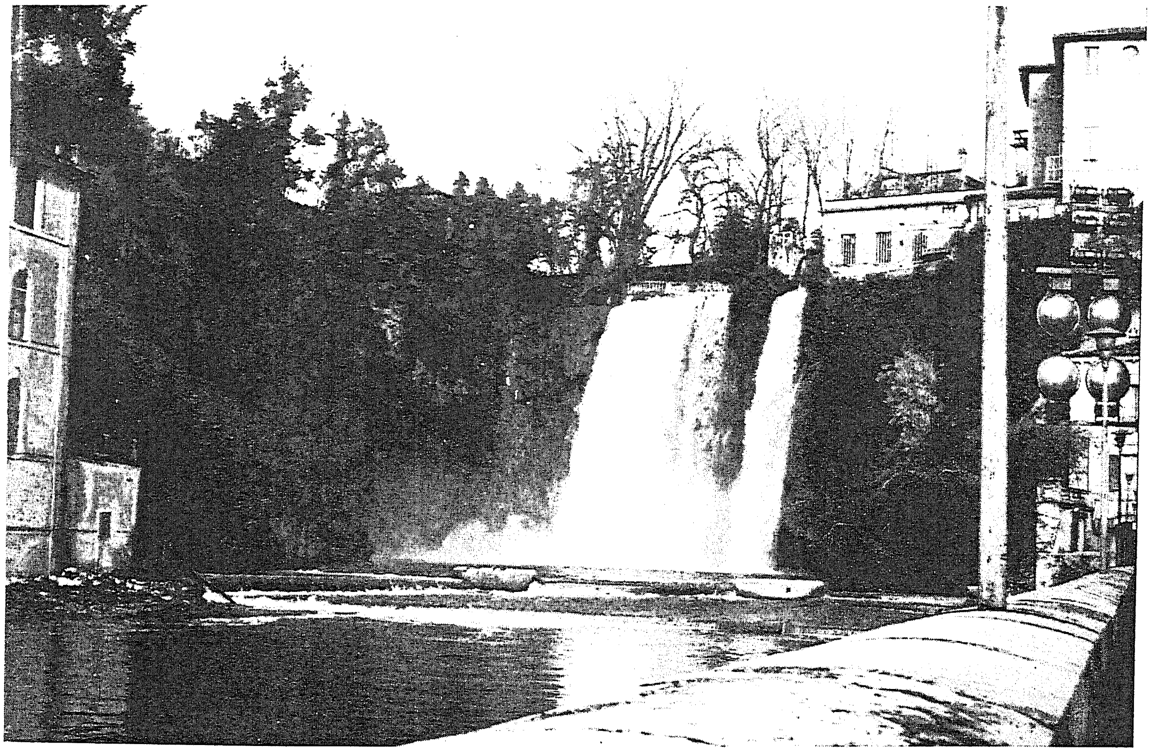

Fig. 3 - Isola del Liri waterfall. Vertical festoons of mainly moss travertine (on the left), covered by mosses and other hygrophilous plants, forming on phytoclastic and phytohermal travertines.

Cascata di Isola del Liri. Drappeggi e festoni verticali di travertino su muschio (a sinistra), coperti da muschio e altre piante igrofile, in accrescimento su travertini fitoclastici e fitoermali (fronte della cascata).

length of about 2 km, a mean width of 1 km and a thickness of some tens of metres. Other smaller outcrops occur southward.

The travertine plate occupies a morphological palaeodepression within the underlying sediments, the axis of which coincides roughly with that of the actual Liri Valley. On the basis of a geophysical survey, such valley seems to be of structural origin. The palaeodepression is characterized by very narrow sectors, with steep slopes and the bottom modelled by a steep and irregular stream, affected by sudden changes of slope (sectors of Anitrella - Fontana Liri Inferiore and Viscogliosi - Isola Liri). Two large sectors are limited by gentle slopes and less steep and more regular bottoms (sectors Anitrella - Monte S. Giovanni Campano - Mt. Sion and Arpino-Morroni - Isola Liri - Castelliri - Porrino).

The uppermost surface of the travertine plate is comprised between the altitudes of 270 m and 280 m. Upstream of Isola del Liri-Viscogliosi the plate continues under the more recent sediments (Holocene-Upper Pleistocene) of the Sora basin, joining probably the travertine deposits encountered there by geological and geophysical borings at the same altitude (Accordi *et al.*, 1969; C.M.P., 1987).

The travertine plate is carved in the very middle by the Liri river that in its southern sector, between Anitrella and Fontana Liri Inferiore, flows at the bottom of a gorge deeper than 120 m, entirely cut in travertine deposits (Figs. 2 C-C' and D-D').

The southern limit of the plate is represented by a very steep scarp rapidly falling from 270 m to 140÷150 m, coinciding roughly with the line joining Fontana Liri Inferiore, Colli and Selva Piana.

Along the Liri river, within the travertine deposits, are found waterfalls from some metres to tens of metres high. The best example is represented by the Isola del Liri waterfall (Fig. 3), where the river, coming from the Sora plain carves its fluvio-lacustrine sediments and forms a fall of about 30 m. Upstream the morphological situation is complex. The river flows at the bottom of an incision whose right side is carved in the alluvial sediments of the Santopadre Formation, while its left side coincides with a longitudinal, nearly vertical scarp, running through the Isola del Liri town for many tens of metres.

This scarp develops from an altitude of 270÷280 m (uppermost surface of the travertine plate) to 215÷220 m. At right angle with the above-mentioned scarp, originates a step, about 30 m high and some tens of metres long, that causes the actual waterfall of the Liri river.

Other smaller waterfalls and rapids can be observed between Isola del Liri and Fontana Liri Inferiore (Fig. 1): one of them, some metres high, 1.25 km N of Manzitti; another one, also some tens of metres high, in Anitrella village and finally another one 1 km upstream from Fontana Liri Inferiore.

- *Alluvial deposits.* They can be subdivided into: a) terraced alluvial deposits on the uppermost surface of the travertine plate; b) locally terraced alluvial deposits encased in the Liri gorge and c) terraced alluvial deposits outcropping downstream from the Liri gorge (Plate. 1 and Fig. 6).
  - a) In the Rapone - Monte Sion area, on the uppermost surface of the travertine plate, outcrop stratified alluvial deposits with horizontal or subhorizontal attitude and a thickness of about 10 m (Plate 1 and Fig. 4, strat. col. 5). These deposits are terraced (lorder), reach an altitude of 290 m and rest either on travertines or, toward NE, on the Cretaceous-Paleocenic limestones of Monte Sion, where the supporting surface of the terrace and the relative scarp are visible. The terraced deposits are composed of conglomerates with scarce gravelly-sandy matrix and calcite cement. The clasts are represented by different carbonatic facies, by Miocene sandstones and by scarce travertine fragments.

    On the eastern slope of Colle Rave Rosse - Colle San Nicola and on the left slope of the Liri Valley, occur erosion terraces carved in the carbonatic substratum, or in other formations at the same altitude of the previously described alluvial deposits;
  - b) Locally terraced alluvial deposits (II order), varying in thickness from few metres to some tens of metres, are encased in the Liri gorge, between Anitrella and Fontana Liri Inferiore (Plate 1 and Fig. 4, strat. cols. 1, 3, 4). These deposits are well stratified and show a subhorizontal attitude, slightly merging downstream. The largest outcrop occurs S of Anitrella, on the right side of the valley, between the altitudes of 170 m and 220 m (Figs. 2 C-C' and 4, strat. col. 3). The clasts are mainly composed of carbonatic facies and scarce pebbles of flysch and travertine rocks.

    Alluvial deposits outcrop also on the left slope of the Liri valley near Strofiano, where they form a terrace reaching the altitude 215÷220 m and extending laterally some tens of metres (Plate 1 and Fig. 4, strat. col. 4).

    The alluvial deposits, at altitudes between 215 and 220 m, can be correlated with small erosion terraces occurring within the Liri Valley and some of its tributaries. Upstream, in the Castelliri area, they reach the altitude of 240 m. They are carved mainly in the travertine plate, but they can be observed also in other formations, such as the Santopadre Formation, the Messinian clays and the Cretaceous-Paleocenic limestones outcropping in the "Vallone di Arpino" or on the eastern slope of Monte Rendola. The described erosion terraces can be recognized also within the profiles of the valleys draining into the Liri river, particularly those on its right side. In fact, the valleys show clear, sudden slope changes at altitudes varying from 220 to 240 m, their upper part being generally well developed and gentle, while the lower part appears short and very steep.

    Other smaller alluvial deposits outcrop along the left side of the Liri Valley between Anitrella and Fontana Liri Inferiore, at altitudes between 165 and 180 m (III order, Plate 1). These deposits are particularly rich in pebbles and cobbles of stromatolite travertines against which they rest. On the right side of the valley another alluvial terrace at an al-

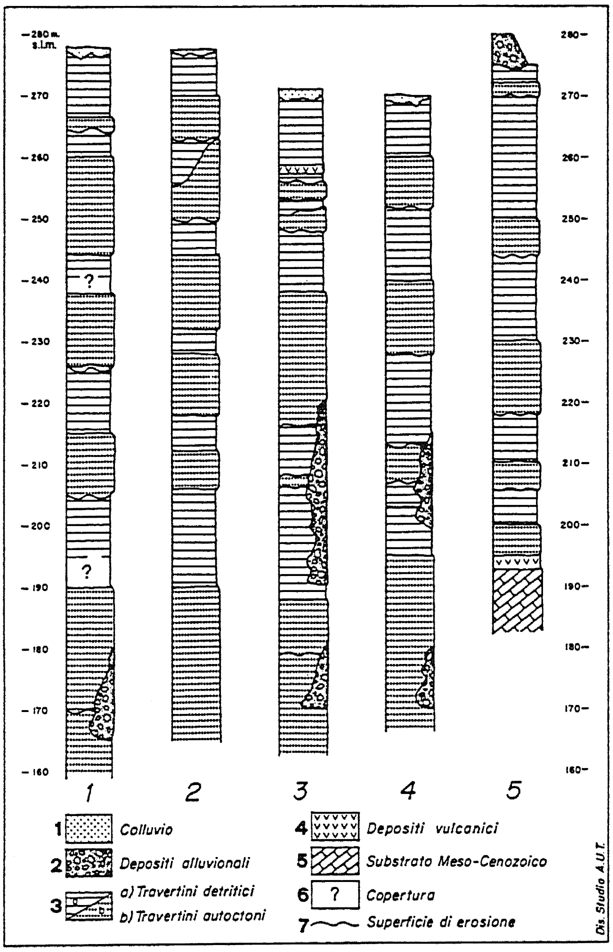

Fig. 4 - Lithostratigraphic columns. Symbols: 1) Colluvium; 2) Alluvial terraced deposits; 3) Travertines: a) detrital, b) autochthonous; 4) Volcanic deposits; 5) Meso-Cainozoic substratum; 6) Vegetation cover; 7) Erosion surface.

Colonne litostratigrafiche. Simboli: 1) Colluvio; 2) Depositi alluvionali terrazzati; 3) Travertini: a) detritici, b) autoctoni; 4) Depositi vulcanici; 5) Substrato meso-cenozoico; 6) Copertura; 7) Superficie d'erosione.

titude of 185 m (III order) occurs;

c) South of the line Fontana Liri Inferiore - Strangolagalli, the southern part of the travertine plate, here particularly eroded, is widely covered by alluvial deposits of the Liri and Amaseno rivers forming three more orders of terraces (III, IV and V).

 The III order terrace reaches the altitude of 185 m. It is composed of several metres of very coarse alluvial deposits containing lenses of sandy and silty gravel. The clasts are represented by carbonatic facies and by flysch and travertine rocks. These alluvial deposits are covered by a well developed soil, 5 YR-7.5 YR in colour, that formed on colluvial-alluvial sediments, containing a large amount of volcanic material.

 The IV order terrace, reaching the altitude 150 m, is composed of some metres of mainly coarse and very coarse sediments containing lenses and layers of sandy and silty gravel. The clasts are mainly made up of limestones and travertine rocks. The terrace is covered by a moderately developed soil, 7.5 YR-10 YR in colour.

 The V order terrace deposits occur along the Liri and Amaseno rivers, just few metres above their beds and are composed of sandy-silty gravel, affected by low-level pedogenesis.

 The alluvial deposits described at point b), outcropping at an altitude of 215÷220 m (II order) in the Liri gorge, downstream from Anitrella and at Strofiano, on the basis of their sedimentological and pedological characteristics and of outcrop altitudes, can be referred to the same alluvial phase. On the contrary, they cannot be directly correlated with those outcropping downstream at lower altitudes (between 165 and 180 m). These deposits seem to be encased in the previous ones and can be correlated probably with the III order alluvial deposits.

- *Carnello travertine and lacustrine deposits*: these sediments are described in detail in the paper by Giraudi (1990) who attributes their deposition to the waters of the Fibreno river during the last Interglacial (5th stage of the oxygen isotopic curve). The direct relationships between the Carnello travertines and the studied travertines are not visible; nevertheless, on the basis of geomorphological observations and ^{230}Th dating, it can be inferred that Carnello travertines are more recent.

1.4 Tectonic outline and geological and morphological evolution

The evolution history of the area, prior to the deposition of the travertines, is quite complex: after a Mio-Pliocene compressive tectonic phase with translational component, the area has been affected by extension tectonic phases, with strike-slip components, trending mainly NW-SE, N-S and E-W. After the deposition of the alluvial deposits of the Villafranchian Santopadre Formation, an extension tectonic phase took place. This phase caused the formation of depressions (Sora, Fibreno, middle Liri Valley) within which Middle Pleistocene fluvio-lacustrine sediments with volcanic intercalations were deposited. Subsequently, an intensive erosional phase, probably connected with tectonic movements, affected the deposits already formed and caused a more or less developed incision, on the bottom of which the travertines sedimented.

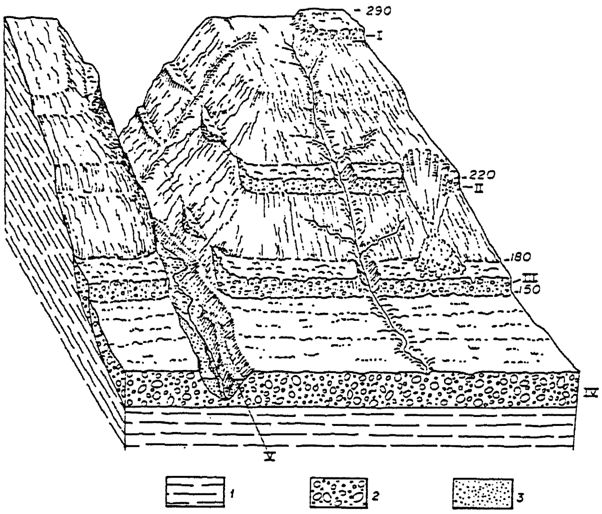

Fig. 5 - Sketch of terraced alluvial deposits and surfaces. Symbols: 1) Travertine plate; 2) I, II, III and IV order alluvial terraces; 3) V order alluvial terrace.

Rappresentazione schematica dei cinque ordini di alluvioni e/o superfici terrazzate. Simboli: 1) Travertini; 2) Depositi alluvionali dei terrazzi di I, II, III e IV ordine; 3) Depositi alluvionali del terrazzo di V ordine.

A geophysical survey based on several geoelectric wells (C.M.P., 1988, Fig. 6) allowed the reconstruction of the surface of the Meso-Cainozoic substratum underlying the travertines, highlighting the main tectonic structures. It can be inferred that the substratum is affected by normal faulting with Apenninic trend (NW-SE). This faulting divides the basement in blocks characterized by differential movements from few tens to several hundreds of metres. The areas of Viscogliosi - Isola del Liri - Morroni, and Porrino - Mt. Sion - Mt. Rendola - Castelluccio, correspond to uplifted blocks, those of Castelliri - Morroni and Monte S. Giovanni Campano - Anitrella - Fontana Liri Inferiore are depressed.

The travertine plate has not been affected by major dislocations. Within it only local extension faulting can be cleared. It is characterized by small displacements (from several centimetres to some decimetres) and fractures. It is worth noticing that the faults and fractures observed by the author or by other researchers (Serafini & Vittori, 1988) show a main E-W trend, while

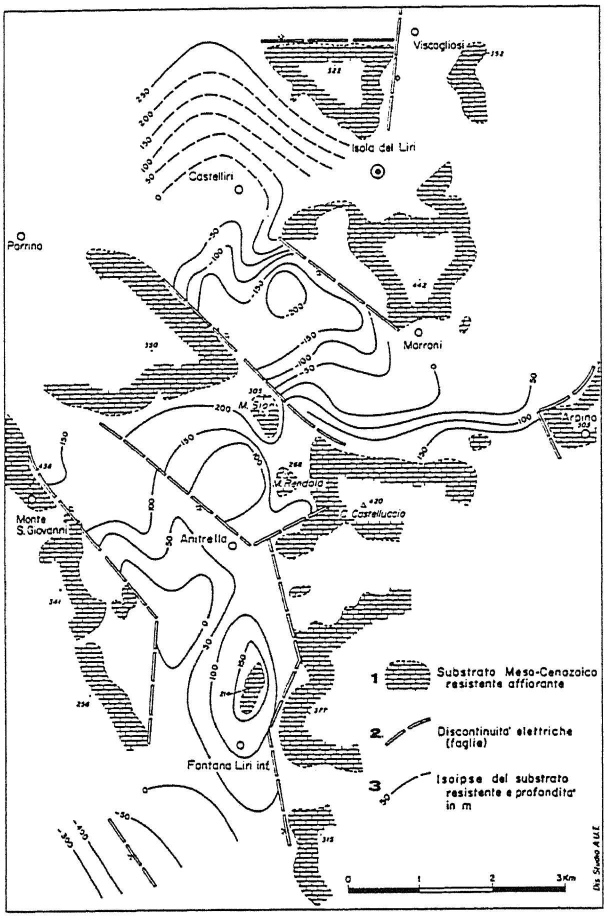

Fig. 6 - Structural sketch of the studied area based on a geoelectric survey. Symbols: 1) Outcropping resistent Meso-Cainozoic substratum; 2) Geoelectric discontinuities (faults); 3) Isohypses of resistent substratum and relative depth in meters.

Schema strutturale dell'area studiata sulla base di una prospezione geoelettrica. Simboli: 1) Substrato meso-cenozoico resistente affiorante; 2) Discontinuità geoelettriche (faglie); 3) Isoipse del substrato resistente e relativa profondità in metri.

pre-Quaternary formations generally follow Apenninic trends.

Aerial photographs and geomorphological analyses have revealed the presence, on the uppermost surface of the travertine plate, of a morphological step, about 20 m high, that develops in a NW-SE direction from S. Stefano - Baccalà to Anitrella and to Fonte Cupa, on the other side of the Liri Valley (Plate 1). The south-western side of the step is higher than the north-eastern one (Fig. 2 B-B'). Coinciding with the step, and within the carbonatic substratum, a geophysical survey has revealed the presence of a normal fault with its southwestern side downthrown: *i.e.* opposite to that of the step. Therefore, the latter could be explained as a fault renewed after the deposition of the travertines.

The uppermost surface of the travertine plate has been modelled by the Liri and Amaseno rivers which have left on it alluvial terraced deposits (I order) in the Rapone area. Locally, ancient meanders and tracts of the two rivers, that likely flowed a hundred metres westward from their present beds, have been preserved. Between San Nicola and Colle Picino occurs a particularly well developed tract of the ancient Liri bed, cut into the travertines and later utilized by the Tepenella stream. The erosion processes due to the rivers are also testified by erosion surfaces and scarps within the Meso-Cainozoic carbonatic formations, outcropping at the periphery of the travertines.

Subsequently, the Liri and Amaseno rivers migrated eastward, reaching roughly their present position and deeply downcut the travertine plate. The results ofthis mainly linear erosion phase differ in different sectors. In the Isola del Liri - Anitrella area, the travertines have been mostly removed. The valleys that formed are large and gentle; in places on their bottom were deposited fluvio-lacustrine sediments with volcanic intercalations. The uppermost surface of the plate has been preserved only in correspondence of outcrops of more compact lithotypes as in Castelliri, Porrino, S. Stefano and Morroni areas.

In the Viscogliosi - Isola del Liri and Anitrella - Fontana Liri Inferiore sectors, the travertines, composed of mainly lithoid lithotypes, have been deeply downcut by the Liri river.In fact, on the left slope of the valley, the river has cut vertically the previously described longitudinal scarp. Such scarp is to be considered, on the basis of travertine lithotypes outcropping within it, a primary fossil depositional structure. On the right side, the river has completely uncovered the conglomerates of the Santopadre Formation.

The previously described transverse scarps, occurring along the river bed, probably have originated in correspondence of preexisting fault-line scarps affecting the substratum and connected with the boundaries of the tectonic blocks, formed in relatively recent times (Lower and Middle Pleistocene). This hypothesis seems to be supported, at least for the Anitrella and Isola del Liri scarps, by their coincidence with tectonic lines and/or block boundaries, revealed by a geophysical survey as well as by the fact that the precipitation of calcareous incrustations along a stream bed is particularly active where waterfalls or rapids occur.

An alternative hypothesis could be the following: on the bottom of the Liri bed cut into travertines, more recent travertine bodies, that could be correlated with the Carnello ones, have grown up thus causing the formation of new waterfalls and rapids.

A deep gorge has formed in the southern sector of the travertine plate (Fig. 2 C-C' and D-D'). The uppermost surface of the plate is much better preserved than in previous sectors. At its southern border the plate ends with a large and high (from altitude of about 250 m to 150 m) scarp that originally represented a depositional pool-gradine structure and was acting as threshold, but was partly eroded and dismantled later on.

During the carving of the travertine plate, erosional and depositional phases alternated and caused the formation of four orders (II to V) of terraces, of which only the second and the third ones have left remnants along the Liri Valley.

It is not easy to establish the causes that originated the erosional or depositional phases. Possibly they could be explained through the study of a larger area. Some evidence, such as the migration of the streams from West to East, the occurrence of faults and fractures grouped within definite trend systems, the alternation of erosional and depositional events and the presence of a certain seismicity (Fig. 7; Postpischl, 1985), seem to represent elements strongly suggestive of neotectonic activity, characterized mainly by a vertical component, which has probably interacted with climatic variations.

2. TEXTURAL, SEDIMENTOLOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE TRAVERTINES

2.1 Lithotypes and lithofacies

Different lithotypes of travertines have been differentiated following the classification suggested by Buccino *et al.* (1978), D'Argenio *et al.* (1983), Brancaccio *et al.* (1986) and particularly by Ferreri (1985) and D'Argenio & Ferreri (1987), whose terminology has been followed here.

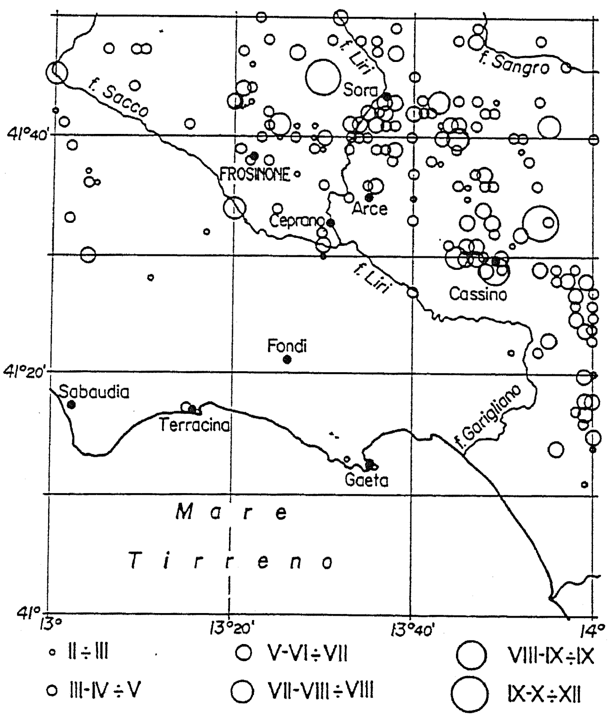

Fig. 7 - Distribution of epicenters of historical earthquakes in the studied area. Intensities in MCS scale.

Distribuzione degli epicentri dei terremoti storici nell'area esaminata. Intensità espresse nella scala MCS.

The lithotypes identified can group to form lithofacies which can be recognized on the basis of their sedimentological, textural and palaeontological characteristics and are essential to determine the environment of deposition (Ferreri, 1985).

Detrital travertines composed of a clastic fraction of incrustations on plant support (phytoclasts), psammitic to ruditic in grainsize and containing variable amounts of finer matrix, are widespread. The most common lithotypes are: calcareous sands and silts, calcarenites and fine to coarse phytoclastic travertines (Fig. 8A), often rich in leaves (bibliolitic travertines). Levels, lenses and irregular bodies, rich in coarse travertine fragments more or less reworked and in mainly inorganic ooids, are associated.

Autochthonous travertines are less widespread. They are composed of "in situ" phytostructures and incrustations; phytohermal and microhermal lithotypes are the most frequent, while stromatolitic lithotypes are less common.

Calcareous sands and silts are generally loose or irregularly lithified in small pockets, bands and lenses. They show regular stratification and massive structure, in places cross-bedded and planar lamination structures occur. Grain size analyses(1) of several samples indicates that they are mainly represented by sandy and clayey silts, silty sands and clays are subordinate (Fig. 9). Poor sorting, skewness tending to null or positive values and mainly negative kurtosis suggest that the sediments are poorly sorted. The lithotypes considered are characterized by high amounts of calcium carbonate(2), on the average from 65 up to 100%; the non-calcareous fraction is made up of clay minerals and variable amounts of quartz, feldspars and heavy minerals. Calcium carbonate, analyzed by means of diffractometer and Energy Dispersive Spectrometer (EDS)(3) resulted to be almost pure calcite, with low content of magnesium, in general less than 1%, rarely from 1 up to 5%.

Under the microscope, sands and silts appear composed of more or less reworked fragments of incrustations (phytoclasts) and subordinate primary concretions. A silicoclastic fraction, reaching in places 10÷15% of the rock and deriving probably from source rocks of flysch type, occurs. Fresh water and terrestrial malacofauna is common. Inorganic and organic coated grains, pellets and grain aggregates, rich in brown, opaque, organic matter also occur. Sedimentological and textural characteristics suggest that these lithotypes have not been much reworked and have been deposited in relatively

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(1) Analyses done by M. Del Gizzo through ENEA laboratories.

(2) Diffractometric analyses have been done by F. Catalano through ENEA laboratories.

(3) Analyses done by S. Forti through ENEA laboratories of Santa Teresa (SP).

calm waters, only in places running and agitated.

Calcarenites generally form tabular massive or roughly stratified bodies that often show cross-bedded and laminated structures. They are composed of phytoclasts scattered in a calcareous matrix groundmass, variable from place to place. Locally the fine matrix is so abundant that the rock grades into mudstone-like limestones. These lithotypes are in general compacted and often contain fresh water or terrestrial malacofauna. In places they are so rich in fossil remains, especially in *Dreissena polymorpha* to form real bioclastic lithotypes. They contain also a non-calcareous detrital fraction similar to that observed in sands and silts.

Travertine phytoclasts, grains of pelmicritic limestones, coated grains, pellets and grain aggregates are observed under the microscope. A silicoclastic fraction composed of crystalline rocks, quartzites, sandstones, chert, quartz, feldspars, micas, epidote, garnet and Fe oxides, occur. Calcarenites often show a banded texture with bands enriched in silicoclastic fraction, ooids and pellets.

Ooids (Fig. 8 C), from some millimetres up to few centimetres (pisoids) in diameter, are represented by different types (Flugel, 1982): the prevailing ones consist of micrite or alternating micrite and sparite in form of dark and clear laminae, showing tangential or radial fabric; ooids with peloid nuclei are common; on the contrary cortoids and oncoids with irregular concentric fabric and algal or bacterial structures are scarce (Folk & Chafetz, 1980; 1983; Chafetz & Meredith, 1983). The observed characteristics suggest that these concretions have formed in calcium carbonate-saturated waters with different levels of turbulence and with concurring biological activities. Among pellets and grain aggregates, microscopic, round or irregularly-shaped structures with filamentous contours can be observed; they could represent calcified bacterial colonies similar to those described by Chafetz and Folk (1984).

The matrix is a dense, massive micrite often containing spots of mosaic recrystallized microsparite or sparite; locally micrite can be completely recrystallized. Vugs and cavities filled with clear euhedral sparry cements with palisade or dog tooth structures occur. Irregular bands and lenses, within which secondary micritization processes developed, have been also observed.

The amount and the dimensions of phytoclasts and the content of matrix vary widely, therefore the described lithotypes often grade vertically and laterally to phytoclastic calcirudites and grain supported travertines, within which phytoclasts can be more or less reworked, graded and sorted. In this type of sedimentary bodies stratification is not well defined and the sedimentary structures are represented by roughly laminated, planar or crossbedded structures, due to a certain degree of orientation of the phytoclasts.

The coarse phytoclasts show in general a complex repetitive concentric texture of clear biologic (cryptalgal) origin (Monty, 1976), with dark, micritic, organic-matter-rich laminae alternating with clear sparry ones; both contain algal remains. Cristalline laminated or massive thrombolitic structures (Monty, 1976), due to complex interferences between algal and bacterial organisms and incrustation processes, occur. When the calcified vegetal support consists of leaves, more or less thin laminites, showing palisade sparry crystals growing perpendicularly to the surface of the leaves, separated by thin micritic films, can form.

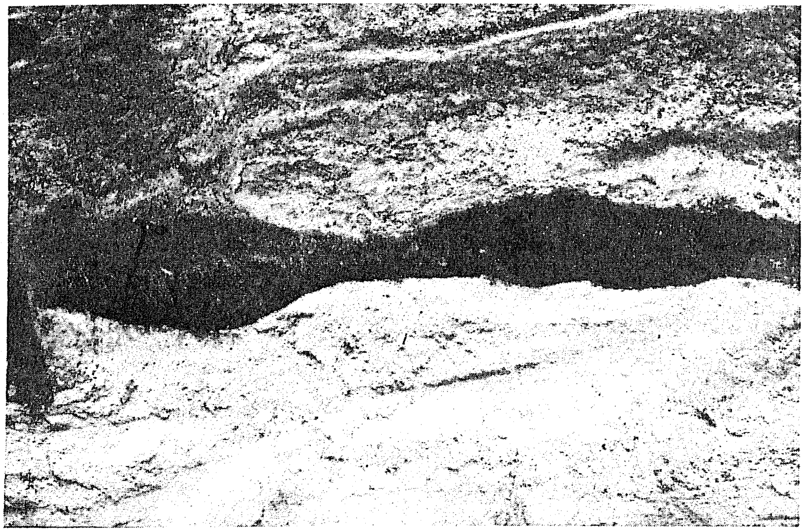
The sedimentological characteristics of calcarenites indicate mainly fluvio-lacustrine and lacustrine depositional environments, with more or less running waters, able to transport clastic material. Lithotypes rich in ooids can be formed in channels or pools with relatively agitated waters.

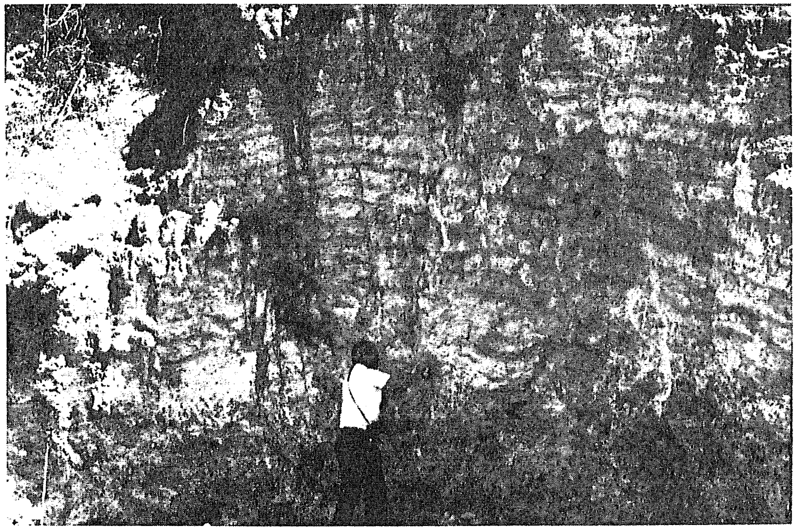
Phytohermal and microhermal travertines make up massive, tabular or lenticular bodies and do not show any clear stratification or other sedimentary structures. Microhermal lithotypes often form thick, superimposed bands, parallel to the slope, characterized by undulate-, dome- or pillow-shaped surfaces. In particular morphological conditions, *i.e.* on waterfall scarps, the attitude of the above mentioned textures can be from very steep to vertical.

Bands, up to some decimetres thick, can superimpose and form very thick sequences of some tens of metres (Fig. 8 B). Within the bands the primary cyclic calcified structure of briophytes (mainly mosses) that represented their support are preserved (Chafetz & Folk, 1984, Fig. 5; Irion & Müller, 1968, Figs. 6 and 9). They are represented by long and thin tubules (with diameter of about 1÷2 mm and length from some centimetres up to some decimetres) with short lateral feathery branches. Tubules are in general isoriented and often show convolute, oscillatory texture. The porosity of the rock is high, cavities and vugs being widespread within and among the tubules.

In detail, on steep slopes or on waterfall scarps, the microhermal laminated textures consist of: a clear basal lamina, 1 to 2 cm thick, quite massive, highly calcified, with irregular not-oriented tubules; a middle yellowish lamina, 8 up to 1÷20 cm thick, in which the calcified tubules, isoriented and provided of stems and leaves, grow perpendicularly to the surfaces of the lamina; an upper dark lamina, 1÷2 cm thick, composed of calcified isoriented stems, not provided of leaves, often growing obliquely and showing a typical prismatic structure; finally, a thin lamina, a few millimetres thick, of friable calcareous material that acts as separation surface between sets of laminae. On gentle slopes microhermal moss travertines produce the same laminated repetitive textures, generally less thick and irregular.

The rhythmic character of the described textures is


(A)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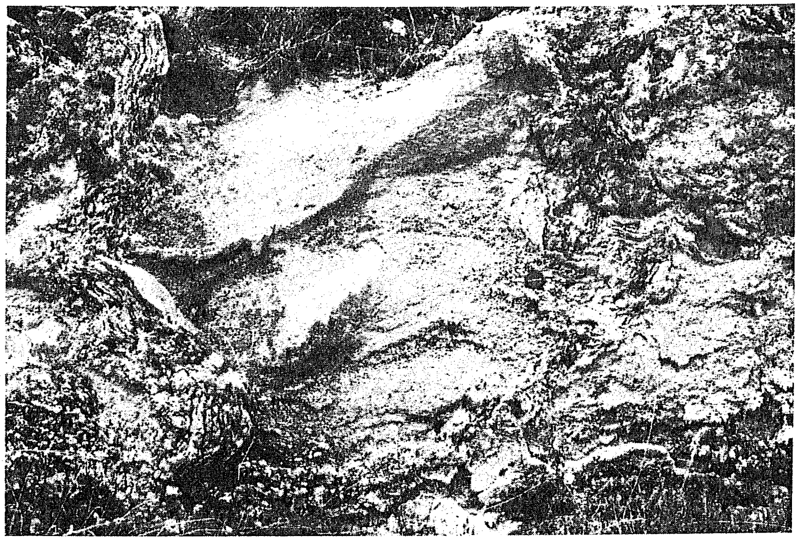
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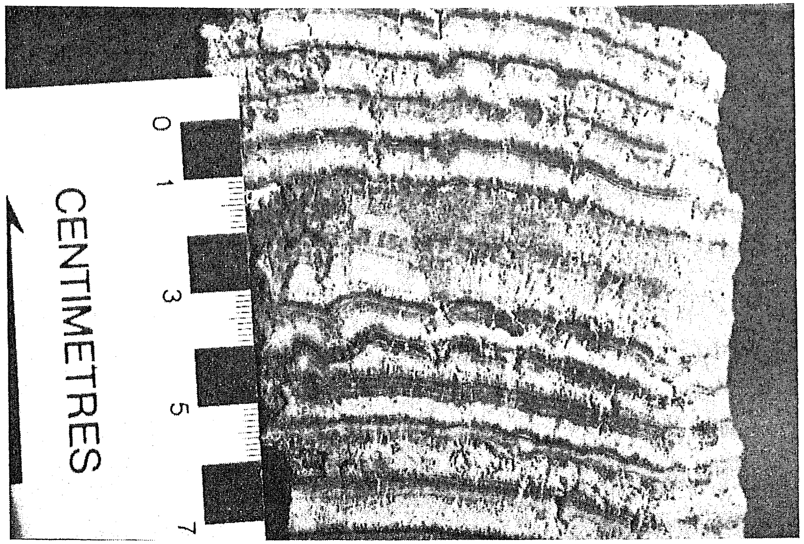


(D)

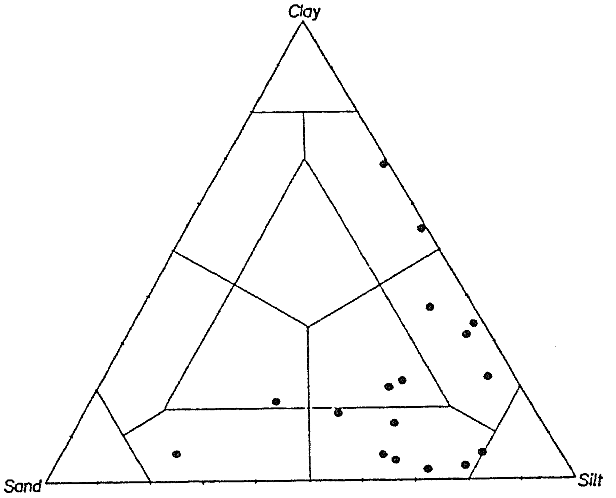


Fig. 9 - Grain size diagram of calcareous sands and silts.
Diagramma granulometrico relativo alle sabbie e limi calcarei.

probably connected with the yearly cycles of growth of calcified plants (mainly mosses). The basal lamina could represent the calcified rhizomatous roots; the middle one could correspond to calcified gametophytes, while the upper lamina could represent calcified sporophytes. Laminae of friable calcareous material can correspond to phases of non-deposition and/or of no plant growth. In Weijemars *et al.* (1986) similar textures within recent and actual travertines, depositing in correspondence of a waterfall, are reported. These authors have also recognized in the species *Cratoneuron commutatum* and *Bryum pseudotriquetrum* the most calcicole and active mosses building the travertine incrustations. Golubic (pers. com.) has recognized in some samples of waterfall microhermal travertines, showed to him by the author, structures of the genus *Cratoneuron*.

The previously described structures and textures are also common within phytohermal travertines which often show the primary vegetal support to incrustation, represented by micro- and macrophytes in growth position. In cross-sections of the tubules, concentric repetitive textures can be observed: a central hole empty or filled with dense opaque micrite or clear equant cement; a more or less thin ring of micrite and microsparite, rich in dark organic matter; another thicker ring of clear radial sparry calcite with euhedral isoriented large crystals up to several millimetres long. The described succession can be repeated several times. Similar textures are reported in Figs. 10 and 11 of the paper by Irion & Müller (1968). Quite often thin continuous films of dark micrite, crossing the radial crystals and forming concentric rings are noted. Within the crystals, algal filaments or arborescent structures are common. In longitudinal sections, calcite crystals grow perpendicular to the tubule walls, forming palisade structures. Tubules are bound by micritic and sparry material in which occur patches and spots, rich in dark, opaque corpuscles, of about 0.04÷0.06 mm in diameter, that could be considered as calcified bacterial structures.

Phytohermal and microhermal lithotypes form mainly in palustrine and fluvio-lacustrine environments rich in hygrophylous plants; moss microhermal travertines can deposit in very shallow waters and under thin films of water flowing on more or less steep slopes, on edges of ponds, pools and waterfalls.

Stromatolitic travertines (Fig. 8 D) are characterized by evident laminar textures showing parallel, planar or undulate laminae, in places plastically deformed, detached and/or dislocated. Clear and dark alternating laminae form sheaths and irregular bands around phytoclasts and phytostructures or give rise to formation of domed and festooned deposits that can reach large dimensions and thickness, with attitude varying from horizontal to vertical.

Laminae are made up of sparry calcite or alternating sparry and micritic material; the former are clear, whitish, porous and thick (on average 7÷8 mm), the latter are darker and thinner (2÷3 mm). Sparite is composed of large and very large, optically isoriented crystals of calcite that occupy the whole thickness of the laminae. These crystals, single or grouped to form fan-shaped rays, grow perpendicular to the laminae and are frequently crossed by continuous, undisturbed, thin, dark micritic films that can produce a further microlamination (Fig. 8 D). Among the laminae, especially among the dark ones, unconformities, erosion surfaces and microchannels can be noted; within the laminae undulations, folds, microfaults and slumping-like structures occur.

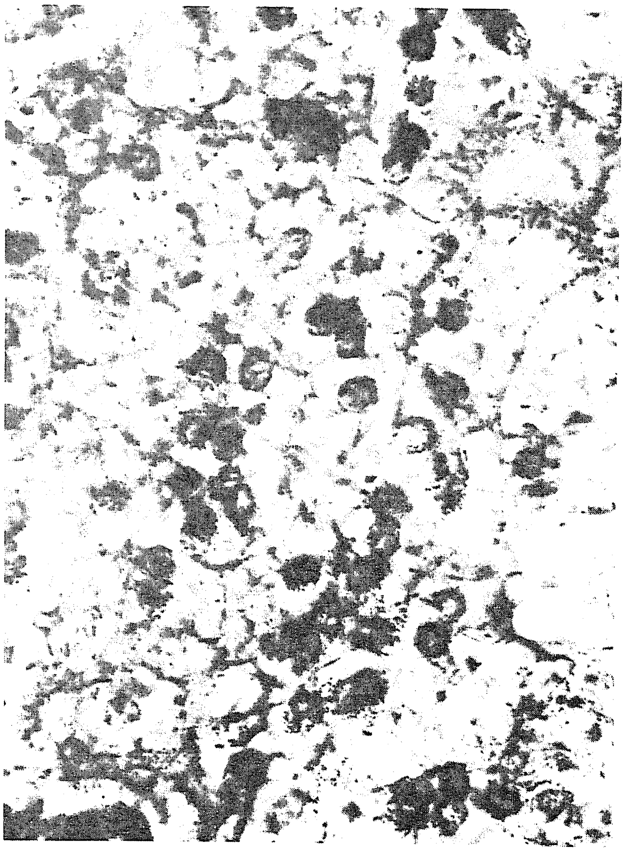
Intra- and interlaminar voids and cavities can be observed. They originated partly through solution processes with subsequent precipitation of clear cements, partly through biological activity of organisms, such as Chironomids (*fenestrae sensu* Monty, 1976) and also through detachment of the lamina from its substratum, caused by desiccation or algal activity.

Within the laminae cryptalgal structures (Figs. 10 A, B and C) are common; calcified, single or composite, fan-

Fig. 8 - A) Irregular lens of soil colluvium lying on an erosion surface within fine- to coarse-grained phytoclastic travertines. B) microhermal moss travertine showing festoon fabric, growing on phytohermal travertine body (bottom right); C) phytoclastic travertines with ooid calcareous sand pool surrounded by stromatolitic fabrics; D) stromatolitic travertine with alternating clear, porous, spathic and dark, dense, micritic laminae showing further microlaminated fabric.

A) Lenti irregolari di colluvio di suolo su superficie erosiva in travertini fitoclastici da minuti a grossolani. B) festoni di travertino microermale su muschio in accrescimento su travertino fitoermale alla base; C) travertini fitoclastici con al centro una vasca di sabbia calcarea ad ooidi e pisoidi, contornata da tessiture stromatolitiche; D) travertino stromatolitico a lamine chiare, porose (spatitiche) e scure, compatte (micritiche) con ulteriore evidente microlaminazione.

(A)



(B)

(C)

(D)

shaped algal filaments can be distinguished. They have a length of some millimetres; in cross-sections they have a diameter of about 0.018 mm and show an opaque round nucleus with a clear outer microcristalline crown. Such structures have been described also by Pentecost (1978).

The interstitial spaces among the rays of crystals are often filled with brown micrite or microsparite with very thin laminar repetitive texture (Fig. 10 D), composed of clear, acicular laminae, 0.01 mm thick and dark, micritic ones, 0.008 mm thick. Such a microtexture has been observed also by Folk *et al.* (1985) that have related it to biological daily cycles. Sparry rays seem to conglobate and replace the microtextures.

Within the stromatolitic lithotypes, with alternating micritic and sparry laminae, (Figs. 8 D and 10 A) the following succession of laminae can be observed: a basal, thin (about 1÷2 mm), dark brown lamina (that can be missing), showing irregular, undulated surface, composed of very fine micritic material, containing in places some detrital grains. This material is thinly laminated because of the occurrence of parallel brownish films which, overlapping each other, can give rise to imbricated and cross-bedded structures. On the basal lamina grow, through a sharp contact, a set of thin, mainly micritic laminae, light brown to yellow-reddish in colour, with dome-shaped and mammillary surfaces. They show a further distinct microlamination already described and contain algal remains. Finally, a set of clearer, whitish, porous and in places friable, sparry laminae, composed of optically isoriented crystals, occur. They often contain filaments and other biological remains, such as brownish arborescent algal structures (Fig. 10 C), growing on the immediately underlying lamina.

The meaning of the described stromatolitic textures has been discussed for long time; most of the authors relate them to yearly biological cycles and/or seasonal physical-ecological rhythms (Irion & Müller, 1968; Monty, 1976; Adolphe, 1981; Casanova, 1981; Fort, 1981; Weisrock, 1981; and so forth). Actually, the dark brown basal laminae composed of very fine micritic material, containing detrital grains, could be connected either with emersion phases or with periods in which a very low amount of physical-chemical incrustations, took place (possibly cold seasons). Micritic and microsparry laminae, light brown to yellow-reddish in colour, within which has been found "spring pollen" (Geurt, 1976), could be correlated to the spring seasons, when the biological activity seems to be more intense. The whitish, porous, sparry laminae, containing "summer-autumn pollen" could have formed subsequently during the mentioned season, when biological activity of various organisms begins to slow down and physical-chemical precipitation processes prevail. The microlamination, occurring within the laminae, could be ascribed to daily biological, mainly bacterial, activity (Folk *et al.*, 1985). Moreover, the thickness of the laminae would depend on the higher or lower amount of humidity during their precipitation, the thickest laminae corresponding to "rainy" years, the thinnest ones to years characterized by a relatively lower amount of rainfall.

2.2 Lithofacies associations

The most widespread lithofacies are:

- *Calcareous sands and silts* with intercalations of calcarenites and phytoclastic travertines. In places grey-greenish clayey sediments, rich in organic material and fresh water mollusks, are associated. The different lithotypes have concordant, only in places heterotopic contacts; but angular unconformities, erosion surfaces and channels, sometimes filled with pedogenized colluvia, can occur.This lithofacies prevails in the upper part of the plate, but it is also widespread in the rest of it. The depositional environment is fluvio-lacustrine and lacustrine.
- *Calcarenites and phytoclastic travertines* with phytohermal bodies. Bibliolithic and in places stromatolitic travertines can occur. The association does not show an evident stratification; sedimentary bodies are mainly lenticular; phytohermal travertines form irregular masses within detrital travertines. Contacts are often erosional. This lithofacies too is widespread, prevailing in the middle and upper part of the plate; the depositional environment seems to be palustrine and fluvio-lacustrine.
- *Microhermal and stromatolitic travertines*, often associated with coarse phytoclastic travertines. Stratifi-

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Fig. 10 - Stromatolitic travertine (photomicrograph). A) sparry and porous clear lamina with algal filaments growing on a dark dense micritic lamina. Plane light, scale 1 cm = 0.10 mm; B) the same as in A, section perpendicular to algal filaments, which appear as round dark structures scattered in equant sparry groundmass. Plane light, scale 1 cm = 62 microns; C) dark and dense micritic lamina showing repetitive arborescent algal fabrics and voids filled with limpid mosaic cements. Plane light, scale 1 cm = 0.2 mm; D) spathic lamina with optically isoriented rays fabric. Among the rays irregular patches of dark, dense, micritic material with evident microlamination occur. Plane light, scale 1 cm = 0.2 mm.

Travertino stromatolitico (microfotografia). A) lamina chiara sparitica con filamenti algali in concrescimento su lamina scura micritica alla base. Nicols paralleli, scala 1 cm = 0,10 mm; B) sezione perpendicolare ai filamenti algali in A che appaiono come strutture tonde scure immerse nella sparite di fondo equidimensionale, Nicols paralleli, scala 1 cm = 62 microns; C) lamina micritica scura e densa con successivi concrescimenti algali arborescenti e vuoti riempiti da cementi limpidi a mosaico. Nicols paralleli, scala 1 cm = 0,2 mm; D) lamina spatitica con struttura a raggi. Tra i raggi di cristalli otticamente isoorientati si notano bande irregolari di materiale micritico denso e scuro con evidente microlaminazione. Nicols paralleli, scala 1 cm = 0,2 mm.

cation is practically missing; sedimentary bodies are lenticular or quite irregular and often show erosional contacts. Microhermal moss and stromatolitic lithotypes form typical dome shaped, festoon and pillow textures with attitude varying from horizontal to moderately dipping. They often contain channels and pools filled with calcareous sands, rich in ooids and coated, more or less reworked, clasts of travertine.This association is especially widespread in the middle and lower parts of the plate; it has likely deposited on more or less steep slope, with local development of pool-gradine mounds.

- *Microhermal and phytohermal travertines* associated with stromatolitic textures and, subordinately, detrital more or less coarse lithotypes. They form massive, lenticular or irregular masses and bodies, with subhorizontal attitude, often reaching considerable dimensions and showing gradational or indefinite contacts. Under favorable conditions of exposure it is possible to observe the inner structures of the bodies, consisting of continuous dome-shaped festoons and bands degrading little by little downstream.The association outcrops mainly in the lower and middle parts of the plate and can be considered as typical of pool gradine facies (step-like terracettes).
- *Mainly microhermal moss and stromatolitic travertines,* forming domes, festoons and drapes with subvertical or vertical attitude, developing on other lithofacies. The association has been observed in general in the lower part of the plate, in correspondence of fossil waterfall structures (Isola del Liri, Anitrella). Within these lithotypes in more or less large cavities, partly primary, partly caused by dissolution processes, speleothem concretions have often been noted. This association is to be considered as waterfall facies. The described drape and festoon structures are still visible on the actual Liri waterfall at Isola del Liri (Fig. 3).

2.3 Concise lithostratigraphic description

Several detailed lithostratigraphic series through the travertine plate have been studied, especially in the Anitrella-Fontana Liri Inferiore area, where the thickness and exposure of travertines are more favorable. The series, reported in Fig. 4, are simplified so that only two associations of main lithofacies have been singled out: 1) mainly detrital lithofacies (sands and silts, calcarenites and fine phytoclastic travertines) and 2) autochthonous, micro-, phytohermal and stromatolitic travertines. In the latter association have been comprised also coarse phytoclastic lithotypes that generally have not undergone a real transport, but only "in situ" collapse and compaction of incrustations.

From Fig. 4 it is evident that the plate consists of alternating autochthonous and detrital associations that cause, due to differential erodibility, the formation of cliffs-and-ledges slopes. Contacts between the two associations are often defined by erosional surfaces, in whose depressions colluvial material can occur.

Lithostratigraphic columns show some degree of correlation; lithofacies associations are quite continuous, even if locally reductions of thickness and dislocations are observed. Within the lower part of the plate, autochthonous lithofacies prevail, while in the upper part detrital ones tend to predominate.

In the lithostratigraphic columns 3 and 5, are reported more or less weathered horizons of volcanics (mainly pyroclastics). These horizons are generally concordant with the attitude of the travertines and are related to Middle Pleistocene Latina Valley volcanic activity.

2.4 Conditions of deposition

The area has been subdivided into four sectors characterized by different morphological and structural conditions that have partly controlled the deposition of the lithofacies (Plate 1).

In the southern sector, between Anitrella and Fontana Liri Inferiore, travertines occupy a narrow incision with steep slopes and irregular bottom, affected by transverse scarps. Here the plate reaches its greatest thickness; its lower part is composed of mainly autochthonous lithofacies, of pool-gradine and waterfall environments; the upper part of detrital, fluvio-lacustrine and lacustrine lithofacies.

The second sector, extending N of Anitrella, in the area of Mastrazza - Monte S. Giovanni Campano - Chiaiamari - Rapone and limited north-eastwards by the ridge of Mt. Sion - Mt. Rendola, is characterized by more gentle slopes and a larger bottom. The substratum underlying the plate appears uplifted; the thickness of the plate reaches 80÷100 m. The most widespread lithofacies are the detrital ones, deposited mainly in fluvio-lacustrine and lacustrine environments.

North of the Mt. Sion - Mt. Rendola ridge is located the third, large sector Manzitti - Arpino - Morroni - Castelliri - Porrino. It is characterized by gentle slopes; the substratum is further uplifted and surficial; therefore the thickness of travertines is reduced to 50÷60 m. The most widespread lithofacies are the same outcropping in the previous sector. The two sectors were probably communicating through the saddles interrupting the Mt. Sion - Mt. Rendola ridge.

In the last sector Isola del Liri - Viscogliosi, the travertines occupy a narrow incision, trending N-S, with very steep slopes. The plate extends towards the North in the subsurface of the Sora basin, where the uppermost travertine surface has been met at altitudes between 270 and 280 m by geoelectrical and geological boreholes (C.M.P., 1988; Accordi *et al.*, 1969). The thickness of travertines is about 50 m. Autochthonous lithofacies prevail on detrital ones and show mostly stromatolitic and micro-phytohermal moss textures, typical of steep slope and waterfall environments.

The formation of the travertine plate took place in the following way: within the steepest tracts of the palaeo-Liri bed and in correspondence of scarps and abrupt slope changes, autochthonous travertine bodies have formed. Growing up little by little they have created real natural dams that could cause upstream more or less large and shallow palustrine-lacustrine pools and basins, in which the relative lithofacies, rich in fresh water and terrestrial mollusks, have been deposited.

At present, those dams are only partly recognizable within the lithostratigraphic sequences through the plate. In fact, they have been subjected to erosional phases that demolished them. Processes of construction and subsequent demolition of the dams could have been repeated several times; the detrital material thus produced could have been transported more or less great distances and deposited to form detrital bodies that locally have buried the autochthonous ones, previously formed.

In the Liri Valley, the main travertine dam, partly dismantled ed eroded, was located in correspondence of the scarp presently outcropping just upstream Fontana Liri Inferiore. In the Amaseno Valley too, south of S. Pudenziana, Ara dei Santi and Panicelli, a depositional scarp acting as threshold is recognizable in places.

The travertine plate, despite its vertical and lateral variability and changes of depositional environments, seems to constitute a sedimentary body "globally" rather uniform. The lithofacies that make it up, in places are heterotopic or are separated by erosional surfaces that could receive colluvial material (Fig. 8 A). Real palaeosoils have never been observed. The deposition of the travertine plate, therefore, in spite of the complex space-time succession of depositional and erosional processes, seems have been continuous and not to have undergone long periods of non-deposition.

The detrital character, the occurrence of: an allogenic component, a small pelitic fraction, coated grains, pellets and colluvial material and the presence of erosional contacts among the different lithofacies, suggest that the erosional and detrital depositional phases corresponded to events, characterized by higher amounts of rainfall, which caused the development of fluvio-lacustrine environments.

On the other hand, it cannot be excluded that the described phenomena are to be related to climatic variations interacting with tectonic movements.

2.5 Fossil flora and fauna

Some sequences collected from calcareous sands and silts have been analyzed for palinological study(4); most of them were barren, with the exception of a short sequence outcropping in the Cona - Castelliri area. The sequence consists of: a) lacustrine calcareous silts with *Dreissena polymorpha*; b) a 10 cm layer of peat containing ostracods and small fresh water bivalves (*cfr. Pisidium*), grading upward to a metre thick layer of dark, silty clays, rich in plant fragments and organic matter; c) fluvio-lacustrine calcareous sands grading to phytoclastic and phytohermal travertines.

Calcareous silts and peat were barren. The silty clays and the lower part of the fluvio-lacustrine sands contain: initially a forest phase with dominant *Abies* and *Pinus*, accompanied by deciduous trees (*Fagus, Quercus, Alnus, Tilia*), sporadic presences of evergreen oaks, followed by a phase with a higher number of taxa, where local plants typical of riparian environment, such as *Alnus* and pteridophytes, are overrepresented. The latter phase contains *Fagus*, deciduous *Quercus, Abies, Carpinus betulus, Carpinus orientalis / Ostrya, Pinus, Ulmus*, evergreen *Quercus, Tilia, Zelkova* (extint in central Italy during the last glacial period; Follieri *et al.*, 1986), *Juniperus*, and Oleaceae.

These floristic features indicate a temperate forest period evolving from a wet to a less wet, and probably warmer phase.

From some bodies of phytohermal and bibliolitic travertines, outcropping in the lower and upper part of the plate, many samples with leaves impressions, often very fragmented, were collected. The preliminary results of the macrofossils analysis pointed out the existence, in the vicinity of the sites, of a forest with angiosperms, both deciduous (*Quercus* sp. and *Acer* sp.) and evergreen (*Hedera helix*, cf. *Smilax*, cf. *Rhamnus*).

These taxa indicate the existence of a mesophilous forest with Mediterranean elements at the time when the travertine bodies were formed.

Malacofaunae contained in different palustrine, lacustrine and fluvio-lacustrine lithotypes have been studied(5). The association occurring within detrital travertines are generally composed of few species of fresh water or terrestrial gastropods (in fragments or complete individuals), of bivalves, ostracods, fish remains and Characeae oogons.

Within the calcareous silts outcropping in the Arpino-Morroni area the following species have been recognized: *Valvata piscinalis* (MÜLLER), *Nematurella subovata* SETTEPASSI, *Belgrandia latina* SETTEPASSI, *Bithynia tentaculata* (LINNAEUS), *Giraylus albus* (MÜLLER), *Armiger crista* (LINNAEUS), *Acroloxus lacustris* (LINNAEUS), *Pomatia elegans* (MÜLLER), *Pisidium* sp. Ostracods are represented by the genera *Candona, Ilyocypris and Erpetocypris* with the species *Candona neglecta-angulata* and *Erpetocypris reptans*.

The association is typical of lacustrine environment

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(4) Analyses done by M. Follieri, D. Magri and L. Sadori through the Dept. of Biologia Vegetale of "La Sapienza" University of Rome.

(5) Study carried out by D. Esu of the Earth Sciences Dept. of "La Sapienza" University of Rome, with the collaboration of R. Casalino.

Table 1 - Growth rates of travertine deposits reported by different authors.
Tassi di crescita dei travertini riportati da diversi autori.

Autori	Controllo biologico	Ambiente	Località	Tasso di crescita
Adolphe (1981)	alghe	continentale	Francia	1 mm/anno
Allen (1934)	"	sorgenti termali calde	Yellowstone	2-56 cm/anno 21,1 cm/anno (medio)
Bargar (1978)	alghe e batteri	" " "	"	20 cm/anno
Casanova (1981)	" "	fluviale	Francia	2-3 mm/anno
Chafetz e Folk (1984)	batteri	sorgenti termali calde	Yellowstone	0,1 mm/giorno
Doemel e Brock (1974)	alghe e batteri	" " "	"	0,1 mm/giorno
Emig (1917)	alghe	" " fredde	Oklaoma	7-13 cm/un'estate
" "	"	" " calde	Italia	15 cm/anno
" "	-	" " -	Sicilia	30 cm/4 mesi
Folk, Chafetz e Tiezzi (1985)	batteri	sorgenti calde prevalenti	Tivoli (Italia)	10-100 cm/anno
Gebelein (1969)	stromatoliti algali	marino	Bermuda	1,1 mm/giorno
Golubic e Focke (1978)	stromatoliti	"	Caraibi	0,6 mm/giorno (medio)
Guerts (1976)	alghe	fluviale	Belgio	2-26 mm/anno
Heimann e Sass (1989)	muschi e alghe	continentale	Israele	0,32 mm/anno
Kitano ((1963)	foglie	sorgenti termali calde	Giappone	20-100 cm/anno
Irion e Müller (1968)	muschi e alghe	" " fredde	Germania	0,6-7 mm/anno
Meredith (1980)	batteri	" "	Idaho	0,3 mm/giorno
Monty (1976)	alghe e batteri	marino	Bahamas	0,2-1 mm/giorno 0,3-0,5 cm/anno 5 mm/4 mesi
Pazdur, Starkel e Szulc (1988)	alghe	continentale	Polonia	parecchi cm/anno
Pentecost (1978)	"	"	Inghilterra e Australia	1,2 mm/anno
Roglic	muschi e altre piante	fluviale	Jugoslavia	1-3 cm/anno
Wallner (1933, 1934)	alghe	continentale	Germania	0,7-1,4 cm/anno
Weijemars, Mulder+Blanken e Wiegers (1986)	muschi	"	Spagna	4-14 cm/anno

characterized by shallow water and rich vegetation. The presence of genus *Belgrandia* indicates spring or running waters. The described malacofauna indicates a temperate climatic phase. From the presence of some species stratigraphically significant, the association is attributed to Middle Pleistocene (*sensu* Richmond, 1982), and it is correlatable with the richer associations contained in the "typical lacustrine facies" of Lake Lirino (Devoto, 1965). In some samples of the same area, *Neritina* cfr. *isseli* CLERICI, known in latial Pleistocene, opercules of *Bithynia* sp. and fragments of *Dreissena polymorpha* (PALLAS) have been recognized. Such species characterize limnic environments with relatively running or stagnant waters with scarce vegetation.

Within the calcareous silts of the Fontana Liri Inferiore-Ceprano area, predominate: *Valvata piscinalis* (MÜLLER), *Bithynia leachi* (SHEPPARD), *Neritina* cfr. *isseli* CLERICI; other species as *Planorbis planorbis* (LINNAEUS), *Armiger crista* (LINNAEUS) and *Viviparus contectus* (MILLET) are subordinated. Bivalves are represented by cfr. *Unio* and *Pisidium* sp. The association, typical of lacustrine environments rich of vegetation, suggests a temperate climatic phase, is attributed to Middle Pleistocene and is correlated with the "typical lacustrine facies" of Lake Lirino.

In the calcareous clayey silts outcropping in the upper part of the plate near Anitrella, the following species have been recognized: *Bithynia tentaculata* (LINNAEUS), *Bithynia leachi* (SHEPPARD), *Valvata cristata* (MÜLLER), *Gyraulus* sp., *Planorbis planorbis* (LINNAEUS), terrestrial gastropods such as *Vertigo* sp. and *Limax* sp.; bivalves belonging to genus *Pisidium* and ostracods. The association indicates limnic environments with stagnant or slightly running waters, but it has no stratigraphic significance.

In phytohermal and microhermal travertines the following species have been recognized: *Bithynia leachi* (SHEPPARD), *Limnea auricolaria* (LINNAEUS), *Planorbis* sp., *Neritina* cfr. *isseli* CLERICI, that indicate limnic, slightly running waters as well as *Dreissena polymorpha* (PALLAS) indicative of running or slightly stagnant waters, with scarce vegetation.

All the information obtained from the study of fossil florae and faunae of the travertines suggests that their deposition likely took place during one or more phases characterized by temperate climate, with warmer and more humid episodes as shown also by some textural and sedimentological characters of the travertines.

2.6 Considerations on the causes of the travertine deposition

The deposition of calcareous concretions in different continental environments from fluvial, lacustrine and spring waters, has been discussed for a long time by several authors who agree that the cause of travertine formation is the concurrence of three main factors:

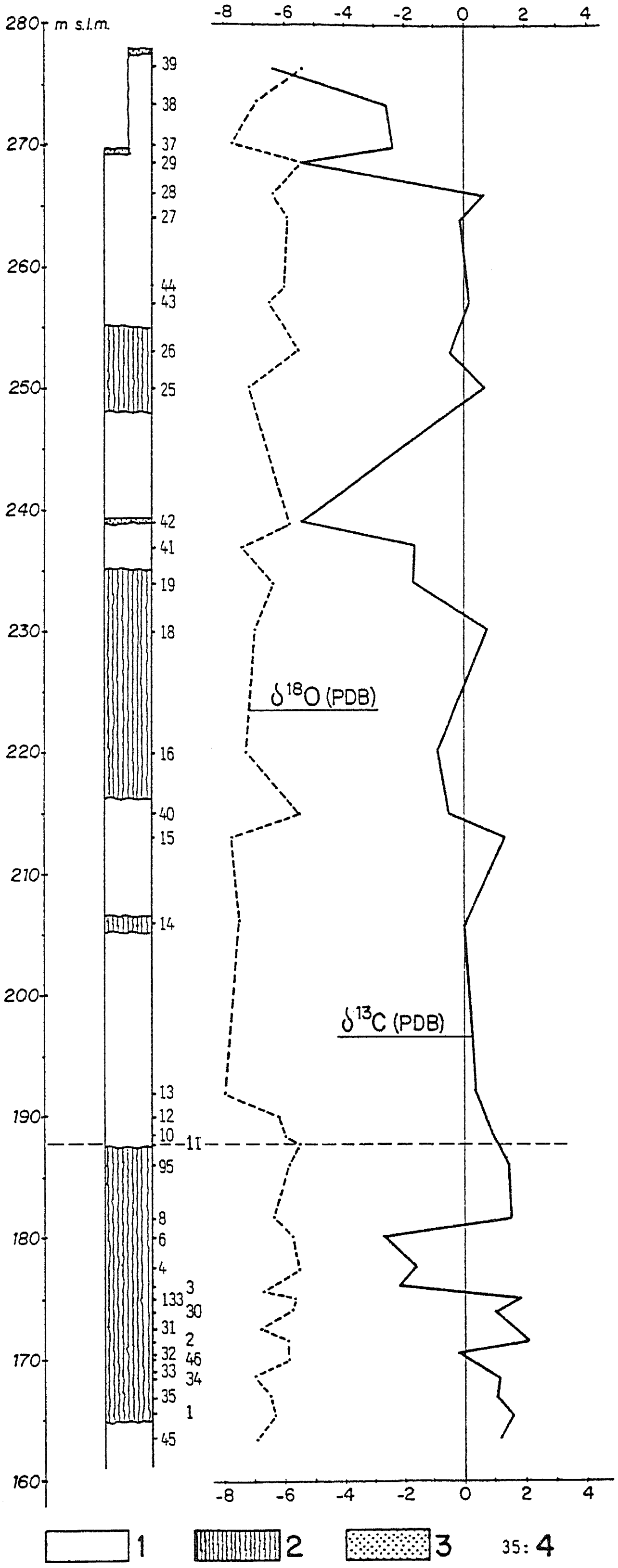

Fig. 11 - Variation of oxygen and carbon isotopic values within studied travertine plate. Symbols: 1) Detrital travertines; 2) Autochthonous travertines; 3) Colluvium; 4) Sample number.

Variazione dei valori isotopici dell'ossigeno e del carbonio nel piastrone travertinoso. Simboli: 1) Travertini detritici; 2) Travertini autoctoni; 3) Colluvio; 4) Numero del campione.

Table 2 - Major components and trace elements of studied travertines. Symbols as in Fig. 13.
Componenti maggiori ed elementi in traccia dei travertini studiati. Simboli come in Fig. 13.

N. campione	Simbolo	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	TiO_2 %	MnO %	P_2O_5 %	LOI %	TOT. %
133	□	0,68	0,13	0,19	54,84	0,39	0,05	<0,02	<0,01	<0,01	<0,02	43,72	100,02
164	□	0,57	0,14	0,23	55,65	0,32	0,05	0,06	<0,01	<0,01	<0,02	43,91	100,85
95C-Ch	△	0,94	0,18	0,62	55,02	0,15	0,04	0,04	<0,01	0,02	<0,02	43,84	100,85
95C-Sc	▲	0,98	0,16	0,29	54,85	0,19	0,04	0,04	<0,01	<0,01	<0,02	44,10	100,63
221-15	●	2,06	0,91	0,52	51,70	0,37	0,06	0,12	0,03	0,04	<0,02	43,22	98,96
221-44	●	1,45	0,49	0,40	54,00	0,31	0,06	0,08	0,02	0,04	<0,02	43,70	100,49

N. campione	Simbolo	Au ppb	As ppm	Br ppm	Co ppm	Cr ppm	Cs ppm	Hf ppm	Hg ppm	Ir ppb	Mo ppm	Rb ppm	Sb ppm	Sc ppm	Se ppm	Ta ppm	Th ppm	U ppm	W ppm	La ppm	Ce ppm	Nd ppm
133	□	<5	<2	11	<1	11	<0,5	<0,5	<1	<5	<5	<20	<0,2	<0,1	<3	<1	<0,5	<0,5	<3	<0,5	<3	<5
164	□	<5	<2	4	<1	7	<0,5	<0,5	<1	<5	<5	<20	<0,2	<0,1	<3	<1	0,6	<0,5	<3	0,5	<3	<5
95C-Ch	△	<5	<2	1	<1	28	<0,5	<0,5	<1	<5	<5	<20	<0,2	0,2	<3	<1	<0,5	<0,5	<3	1,2	<3	<5
95C-Sc	▲	<5	<2	4	<1	33	<0,5	<0,5	<1	<5	<5	<20	<0,2	0,3	<3	<1	<0,5	<0,5	<3	1,2	<3	<5
221-15	●	<5	3	5	1	9	1,4	<0,5	<1	<5	<5	<20	<0,2	0,9	<3	<1	1,7	<0,5	<3	4,4	8	<5
221-44	●	<5	3	4	<1	15	0,9	<0,5	<1	<5	<5	<20	<0,2	0,5	<3	<1	<0,5	<0,5	<3	1,3	<3	<5

N. campione	Simbolo	Ba ppm	Sr ppm	Zr ppm	Y ppm	Li ppm	S %	Be ppm	Cu ppm	Ni ppm	Pb ppm	V ppm	Zn ppm	Ag ppm	Nb ppm	Bi ppm	Sm ppm	Eu ppm	Tb ppm	Yb ppm	Lu ppm	Mass. g
133	□	90	110	<10	2	2	0,01	<1	<5	<10	<50	4	<5	<0,1	<50	<100	0,2	<0,2	<0,5	<0,2	<0,05	0,9184
164	□	50	90	<10	2	9	0,01	<1	<5	20	<50	<2	<5	<0,1	<50	<100	0,1	<0,2	<0,5	<0,2	<0,05	1,042
95C-Ch	△	80	160	<10	4	2	0,03	<1	<5	<10	<50	<2	<5	0,1	<50	<100	0,2	<0,2	<0,5	<0,2	<0,05	0,9906
95C-Sc	▲	50	130	<10	2	7	0,03	<1	<5	10	<50	4	<5	<0,1	<50	<100	0,2	<0,2	<0,5	<0,2	<0,05	0,9184
221-15	●	60	100	<10	4	4	0,03	<1	<5	10	<50	8	5	0,1	<50	<100	0,6	<0,2	<0,5	<0,2	<0,05	0,9979
221-44	●	50	80	<10	4	4	0,03	<1	<5	20	<50	14	<5	0,1	<50	<100	0,2	<0,2	<0,5	<0,2	<0,05	0,9635

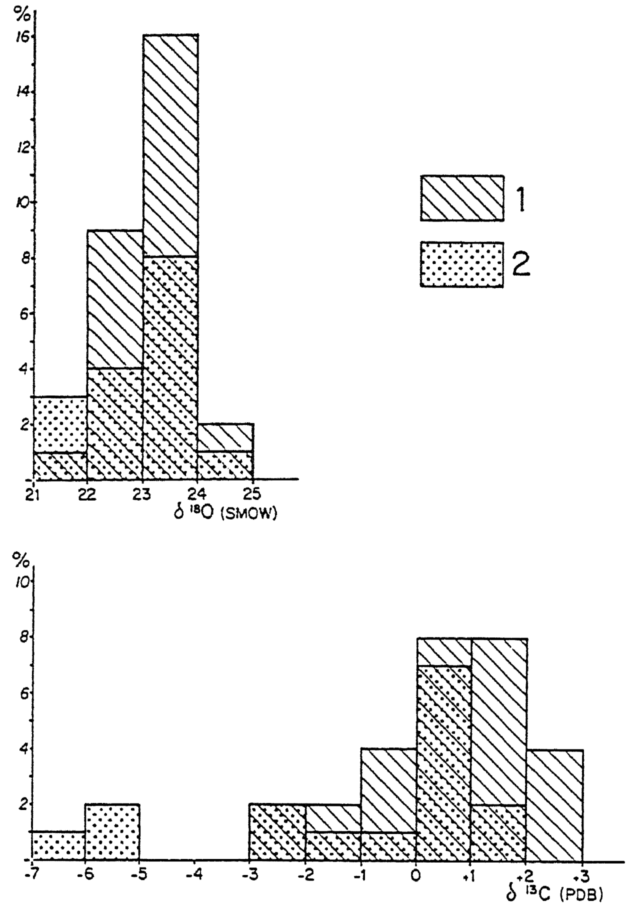

Fig. 12 - Frequency histogram of ∂^{13}C e ∂^{18}O in autochthonous (1) and detrital travertines (2).

Istogramma delle frequenze di ∂^{13}C e ∂^{18}O nei travertini autoctoni (1) e detritici (2).

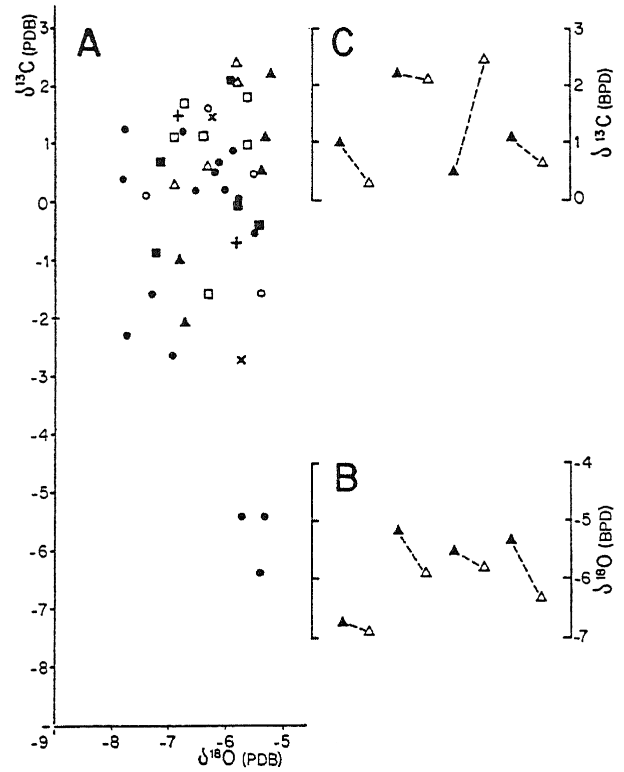

Fig. 13 - A) ∂^{13}C/∂^{18}O values of different travertine lithotypes; B) ∂^{18}O and C) ∂^{13}C values of dark and clear laminae of stromatolitic travertine respectively. Symbols: open squares = microhermal moss travertines; solid squares = phytohermal travertines; open circles = coarse phytoclastic travertines; solid circles = calcareous sands and silts; open triangles = clear laminae of stromatolitic travertines; solid triangles = dark laminae of stromatolitic travertines; x = inorganic ooids; + = sparry cements.

A) Valori del rapporto ∂^{13}C/∂^{18}O nei differenti litotipi; B) valori di ∂18O e C) ∂13C nelle lamine scure e chiare di travertini stromatolitici. Simboli: quadrati vuoti = travertini microermali su muschio; quadrati pieni = travertini fitoermali; cerchi vuoti = travertini fitoclastici grossolani; cerchi pieni = sabbie e silt calcarei; triangoli vuoti = lamine chiare di travertini stromatolitici; triangoli pieni = lamine scure di travertini stromatolitici; x = ooidi; + = cementi sparitici.

chemical-physical, morphological and biological. In many cases one of them prevails on the others (Brancaccio *et al.*, 1986; Chafetz & Folk, 1984; Emeis *et al.*, 1987; Folk *et al.*, 1985; Golubic, 1973; Heimann & Sass, 1989; Kronfeld *et al.*, 1988; Irion & Müller, 1968; Love & Chafetz, 1988; Pentecost, 1978; Stoffers, 1975).

The presence of carbon dioxide-rich waters, saturated or oversaturated with calcium bicarbonates and carbonates, is of primary importance. In fact, calcium carbonate precipitates and forms incrustations for loss of carbon dioxide due to different causes. Physico-chemical control is difficult to evaluate, at least in the short term, as it depends on a certain number of "meteorological" factors, such as environment and water temperatures, carbon dioxide partial pressure, rainfall, drought, water turbulence, etc., that vary in space and time.

On the contrary, its long term influence can be evaluated as climatic variations can occur, which cause depositional and/or erosional phases. In fact, a close relationship between the deposition of calcareous concretions (travertines, speleothems) and interglacial, interstadial or at least warmer periods has been suggested. The reduction and/or interruption of such processes is credited to glacial or at least cooler periods by several authors, including the writer (Blackwell & Schwarcz, 1986; Brancaccio *et al.*, 1988; Geurts, 1976; Glazek *et al.*, 1980; Gordon *et al.*, 1989; Harmon *et al.*, 1978; Hausmann & Brunnacker, 1988; Heimann & Sass, 1989; Hendy, 1971; Hendy & Wilson, 1968; Hennig *et al.*, 1983; Kronfeld *et al.*, 1988; Lao & Benson, 1988; Livnat & Kronfeld, 1985; Pazdur *et al.*, 1988; Radtke *et al.*, 1986; Srdoc *et al.*, 1983; Stuiver, 1970; Taddeucci *et al.*, 1987; Thompson *et al.*, 1976; Weinstein-Evron, 1987, etc.).

The formation of travertine from the Liri, Amaseno and some of their tributaries' waters has been closely connected with the hydrological pattern of the area, being fed not only by abundant surficial waters, but also by many springs, linked with karst hydrology, intensely developed within the Meso-Cainozoic carbonatic formations.

The morphological and biological factors too have played an important role for the deposition of the travertines, as their structures, textures and sedimentological characters suggest. The former has played an important role in the steepest tracts of the streams, where waterfalls, rapids or obstacles of a certain volume, all cause a higher turbulence of water and, therefore, a higher loss of carbon dioxide.

The biological control seems to have been connected mainly with the activity of mosses, algae and bacteria. In palustrine and lacustrine pools and basins, other hygrophytes could have contributed. The partecipation of mosses and algae in calcium carbonate precipitation process could have been either active, connected with their photosynthetic process, or passive, as traps for detrital particles that in turn represented nucleation points for calcium carbonate precipitation as well as support for active bacterial colonies.

The growth rate of travertines can be evaluated on the basis of some stromatolitic and mosses travertines, characterized by laminar repetitive textures. In Table 1 different growth rates are reported; it is evident that they vary widely, depending on different hydrological and morphological conditions of deposition. In fact, daily values are comprised between 0.1 and 1.1 mm, while the yearly ones vary from a minimum of 0.32 mm (Heimann & Saas, 1989) to a maximum of 100 cm (Kitano, 1963; Folk *et al.*, 1985). Most of the authors report mean values varying from some centimetres up to some tens of centimetres per year.

The studied travertines indicate the following mean values: for stromatolitic texture 0.018 mm per day and 8÷9 mm per year (mean values achieved by measuring a hundred couplets of dark and clear laminae); for mosses travertines some centimetres per year on gentle slope; up to 20÷25 cm in waterfall condition.

2.7 Geochemical characters

Several samples of travertines have been analyzed for the determination of organic carbon[6]. The results show that organic carbon content varies widely, between 0 and 5% of total carbon. In detrital travertines such a content show very scattered values: very fine and clayey silts and fine phytoclastic travertines are characterized by the lowest content, with a mean value of about 0.32%, while sandy silts, silty sands and coarse phytoclastic travertines have higher contents, varying from 3% up to 5%. Calcarenites, rich in lacustrine mollusks, show values of about 4%. Autochthonous travertines are characterized by less scattered contents; in phytohermal and microhermal lithotypes, they reach 2%, while in stromatolitic ones they reach 2÷3%.

Analyses of major and trace elements on six samples of different lithotypes have been done; results (Table 2), that are not to be considered statistically representative, suggest that samples are composed almost entirely of calcium carbonate, the content of Mg always being less than 1%. SiO_2 and Al_2O_3, connected with the silicoclastic fraction, are very low (the highest contents occur in calcareous silts); Mg is very low as well as Na and K; they are higher in the silty lithotypes that contain also very scarce amounts of Fe and Mn. The content of Sr seems to be higher in stromatolitic lithotypes and lower in detrital ones, as pointed out also by Buccino *et al.* (1978); D'Argenio *et al.* (1983) and Brancaccio *et al.* (1986), for travertines of Southern Italy. As stromatolitic textures are generally the least affected by diagenetic alterations, the Sr content could reflect the primary composition of mother waters. Cr content seems to follow the same behaviour.

Forty-four samples of different lithotypes occurring within the plate, as shown in Fig. 11, have been analyzed for oxygen and carbon isotopic composition; results are reported in Table 3.

$\partial^{13}C$ values vary from -6.4 up to +2.4; they show a dispersion of some ∂ units and the highest frequency between 0 and +2.0 (Fig. 12). From Table 3 and Fig. 13 one can deduce that stromatolitic lithotypes show $\partial^{13}C$ values on the average higher than those of other lithotypes; in detail, the spring, micritic laminae (light brown to yellow-reddish in colour) resulted slightly enriched in ^{13}C compared to the whitish, sparry, "cooler" ones. Calcareous sands and silts are characterized by the lowest values. This behaviour, pointed out also by Manfra *et al.* (1976) and Buccino *et al.* (1978), is probably connected with the partially detrital origin of the above mentioned sediments.

Samples from the upper part of the plate, underlying pedogenized colluvial material or soils, often affected by secondary micritization processes, show the lowest values of $\partial^{13}C$ (Fig. 11). Such samples could have been likely influenced by the contribution of biogenic carbon dioxide, deriving from soil forming processes, active during or immediately after their deposition.

Moreover, one can also observe that $\partial^{13}C$ values tend to become slightly higher and uniform towards the lower part of the plate. This fact, observed also by Manfra *et al.* (1974; 1976), could be explained assuming that a certain isotopic exchange between travertines and meteoric waters, rich in atmospheric carbon, could have taken place. This phenomenon could be supported by the $\partial^{13}C$ values of two samples of late, sparry cement, filling voids in travertines from the lower part of the plate: these values (-0.7 and +1.5) are very close to those of the host travertines.

It could also be pointed out that a large part of the

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(6) Analyses done by F. Catalano through ENEA laboratories.

examined travertines show ∂^{13}C values that fall into the mean field of dispersion of travertines occurring in the central and southern regions of Italy and in other countries (Fig. 14) (Turi, 1986). Their ∂^{13}C values are also close to those of calcareous lacustrine sediments of the Sora basin, ranging from -3.7 to -1.6, and to those of Lake Lirino, varying from 0 to +5.0 (Manfra *et al.*, 1976).

∂^{18}O values vary from 21.5 up to 24.1; they show a dispersion of few ∂ units and the highest frequency between 23.0 and 24.0 (Fig. 12). Assuming that travertines have been deposited under or nearly equilibrium conditions, the low dispersion of the values could suggest that they reflect the quite uniform and steady isotopic composition of mother waters, which are characterized by temperatures close to ambient ones. The great uniformity of the obtained values, however, could also be a consequence of isotopic re-equilibrium processes with groundwaters, as ∂^{18}O values of late cements (22.5 and 23.5), close to the mean value of travertines (23.0), seem to support.

Considering the mean ∂^{18}O value of travertines equal to 23.0 and a mean ∂^{18}O value of groundwaters in the studied area (Table 4) of -7.0, according to O'Neil *et al.* (1969) equation, a temperature of 16°C is obtained. The mean yearly air temperature in the area, for the period 1926-1955, is of about 13÷14°C (Ministero dei Lavori Pubblici, 1966). At present, some springs in the studied area have mean yearly temperatures of about 14°C, while those of some wells of the Sora basin are close to 13°C (Accordi *et al.*, 1969).

Within the individual lithotypes an evident differentiation of ∂^{18}O values cannot be noted; only calcareous sands and silts show a larger dispersion of values.

Micritic, spring laminae of stromatolitic travertines are generally enriched in ^{18}O. Enrichments in ^{18}O and ^{13}C of micritic laminae for Pisa and Savona (Central and Northern Italy) speleothems have also been reported by Fornaca-Rinaldi *et al.* (1968). The authors ascribe this phenomenon to evaporation and carbon dioxide loss processes, more active during warmer and drier (spring-summer) deposition periods.

Figure 15 shows that oxygen isotopic composition of travertines is very close to the mean value of similar deposits outcropping in central and southern regions of Italy and in other countries (Turi, 1986). Moreover, the obtained values are on the average slightly lower than those relative to lacustrine sediments of the Sora basin (24.9 and 26.7) and Lake Lirino (24.2, 24.7 and 25.1) reported by Manfra, Masi & Turi (1976).

Table 3 - Oxygen and carbon isotopic composition of the studied travertines. Symbols as in Fig. 13.

Composizione isotopica dell'ossigeno e del carbonio nei travertini studiati. Simboli come nella Fig. 13.

N.campione	Litotipo	δ^{13}C(PDB)	δ^{18}O(SMOW)	δ^{18}O(PDB)
221-1	○	+1,6	+23,0	-6,3
221-4		-1,6	+23,9	-5,4
221-11		+0,5	+23,8	-5,5
221-14		+0,1	+21,8	-7,4
221-2	■	+2,1	+23,4	-5,9
221-16		-0,9	+22,1	-7,2
221-25		+0,7	+22,2	-7,1
221-26		-0,4	+23,9	-5,4
221-32		-0,1	+23,5	-5,8
221-19	□	-1,6	+23,0	-6,3
221-30		+1,0	+23,7	-5,6
221-31		+1,7	+22,6	-6,7
221-34		+1,1	+22,4	-6,9
221-35		+1,1	+22,9	-6,4
133		+1,8	+23,7	-5,6
221-3	▲	-2,1	+22,6	-6,7
221-18Sc	▲	+1,0	+22,5	-6,8
221-18Ch	△	+0,3	+22,4	-6,9
95C-Sc1	▲	+2,2	+24,1	-5,2
95C-Ch1	△	+2,1	+23,4	-5,9
95C-Sc2	▲	+0,5	+23,8	-5,5
95C-Ch2	△	+2,4	+23,5	-5,8
95C-Sc3	▲	+1,1	+24,0	-5,3
95C-Ch3	△	+0,6	+23,0	-6,3
221-10	●	+0,9	+23,4	-5,9
221-12		+0,7	+23,2	-6,1
221-13		+0,4	+21,5	-7,8
221-15		+1,3	+21,6	-7,7
221-27		0,0	+23,5	-5,8
221-28		+0,6	+23,0	-6,3
221-29		-5,4	+24,0	-5,3
221-37		-2,3	+21,6	-7,7
221-38		-2,6	+22,4	-6,9
221-39		-6,4	+23,9	-5,4
221-40		-0,5	+23,8	-5,5
221-41		-1,6	+22,0	-7,3
221-42		-5,4	+23,6	-5,7
221-43		+0,2	+22,8	-6,5
221-44		+0,2	+23,3	-6,0
221-45		+1,2	+22,5	-6,8
221-6	×	-2,7	+23,6	-5,7
221-8		+1,5	+23,1	-6,2
221-33	+	+1,5	+22,5	-6,8
221-46		-0,7	+23,5	-5,8

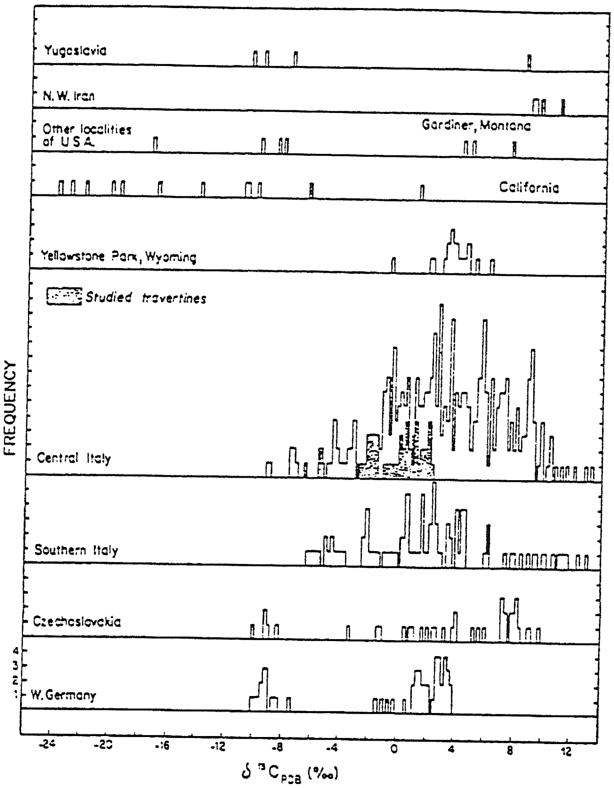

Fig 14 - Carbon isotopic composition of travertines of different localities (from Turi, 1986, modified; data reported in Brancaccio *et al.*, 1986 and D'Argenio *et al.*, 1983, have been added).

Composizione isotopica del carbonio di travertini di differenti località (da Turi, 1986, modificata, con l'aggiunta di dati da Brancaccio et al., *1986 e D'Argenio* et al., *1983).*

If the behaviour of $\partial^{13}C/\partial^{18}O$ for different lithotypes is considered (Fig. 13), it is evident that: a) within stromatolitic travertines such a ratio seems to present a positive relation, noticed also by Fornaca-Rinaldi *et al.* (1968) and Buccino *et al.* (1978). According to Fritz (1965) and Gonfiantini *et al.* (1968), such a behaviour is connected with disequilibrium conditions of travertine deposition, that takes place in general near the spring orifice; b) phyto-, microhermal- and coarse phytoclastic travertines show a vague, though nearly steady relation, while in detrital travertines it is slightly negative. The last two cases would indicate, according to Gonfiantini *et al.* (1968), precipitation conditions close to equilibrium, taking place at a certain distance from spring orifice.

If the $\partial^{18}O$ and $\partial^{13}C$ curves relative to the stratigraphic column reported in Fig. 11, are compared, it can be noted an evident, specular behaviour of the two parameters. Statistical treatment of obtained data, reported in Figs. 16, 17 and 18, quantifies significantly such relation that results very clear for the middle and upper parts of the column (above the altitude of 188 m), while it attenuates considerably in the lower part (under the altitude of 188 m). The rule has only a "global" confidence, owing to a non uniform sampling through the plate.The observed specularity suggests that in the middle and upper parts of the plate, isotopic exchange either could not have taken place or, if it has, it has not been such to conceal the rule.

Bearing in mind the above considerations, and not excluding their influence, the presence of a climatic signal in the specular behaviour of oxygen and carbon isotopic curves can be suggested. Such behaviour could be a reflection of the primary isotopic composition of mother waters, conditioned by climatic factors, mainly by ambient temperature and humidity variations (modality and/or quantity of precipitations), that, in turn, influence the biological activity. Actually, the lowest values of $\partial^{13}C$ correspond to lithotypes deposited during higher pedogenic activity, therefore of higher biological "productivity". To these low values of $\partial^{13}C$ correspond the highest $\partial^{18}O$ values. The latter are connected, in the given depositional environment, with higher temperatures.

The foregoing observation is partly supported by oxygen isotopic behaviour of stromatolitic travertines. In fact, the micritic laminae, deposited during warm seasons, give values generally higher than those of clear, sparry laminae, mainly formed during cooler seasons.

Behaviour of $\partial^{13}C$ values, tending to be higher in " spring" laminae (where, on the contrary, one would expect lower values for the higher biological activity) is likely due to extreme conditions of precipitation of the incrustations. These have been deposited by thin films of running water, subjected to severe loss of carbon dioxide, prevailing on the organic carbon contribution from the biological activity during the warm season.

Table 4 - Oxygen isotopic composition of surface and ground waters of studied area.

Composizione isotopica dell'ossigeno in alcuni campioni di acque superficiali e di falda dell'area esaminata.

Locality	Town	$\partial^{18}O$
Riveri Liri at Isola del Liri	Isola del Liri	-7.5
River Liri at Mad.na di Canneto	Strangolagalli	-7.4
Springs of river Fibreno	Posta Fibreno	-8.0
River Fibreno at Carnello	Isola del Liri	-7.2
Casamari spring	Veroli	-7.4
Castelliri "	Castelliri	-7.1
Strofiano "	Fontana Liri	-6.2
Fameto "	Fontana Liri	-7.2
Pescina "	Arce	-6.4
Well near Fontana Liri Inf. (watertable at -20 m)	Fontana Liri	-6.7

The relative uniformity of $\partial^{18}O$ through the plate could be due to travertine deposition during one or more temperate and relatively uniform phases, as sedimentological and paleontological studies seem to support.

In conclusion, bearing in mind the assumptions previously done, interpreting the data with due care and assigning them a "global" reliability, it seems possible to recognize a climatic signal in the specular behaviour of

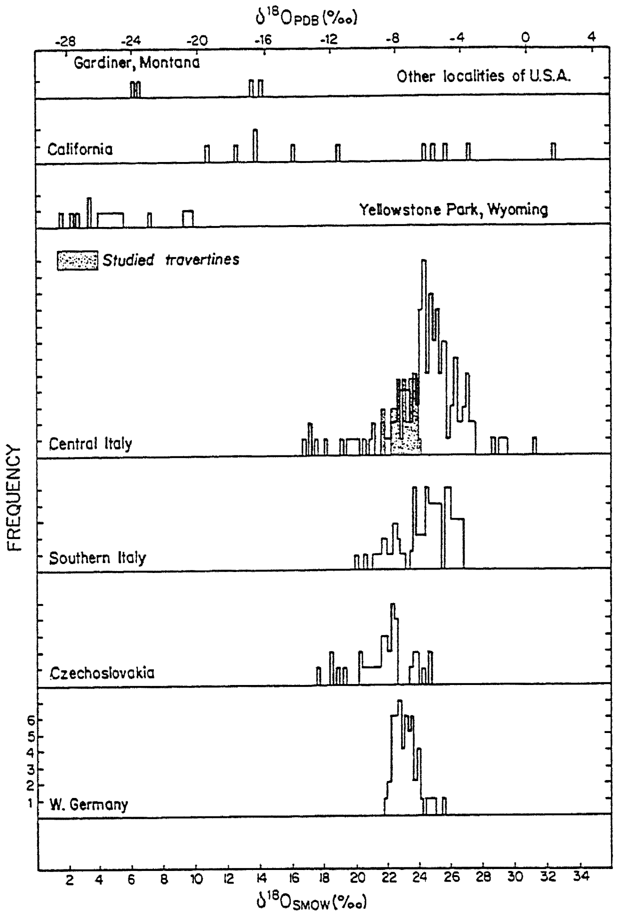

Fig. 15 - Oxygen isotopic composition of travertines of different localities (from Turi, 1986, modified; data reported in Brancaccio *et al.*, 1986 and D'Argenio *et al.*, 1983, have been added).

Composizione isotopica dell'ossigeno in travertini di differenti località (da Turi, 1986, modificata, con l'aggiunta di dati da Brancaccio et al., *1986 e D'Argenio* et al., *1983).*

the $\partial^{13}C$ and $\partial^{18}O$ curves. The relatively steady values of $\partial^{18}O$ would indicate quite uniform temperatures of deposition, while the $\partial^{13}C$ variations would suggest variations of biological productivity, connected also with different conditions of humidity (qualitative and quantitative changes of rainfall).

As regards the origin of carbon dioxide, involved in the formation of travertines, one must not exclude that a part of it could be of endogenic origin, as stated by Bakalowicz (1990) for tectonically active areas affected by extensional movements.

2.8 Chronological scheme

A chronological scheme of travertine deposition can be indirectly obtained, on the basis of their stratigraphic and morphologic relationships with other formations occurring in the area. Travertines, as previously mentioned, lie on fluvio-lacustrine sediments containing volcanic intercalations attributed to Pofi vulcanism (Sevink *et al.*, 1984), dated 400÷430 ka BP (Pasquarè *et al.*, 1979). The fluvio-lacustrine sediments are considered coeval with those outcropping in Lake Lirino (Sevink *et al.*, 1984; Arnoldus-Huizendveld *et al.*, 1985) dated 360 ka BP (Devoto, 1965) and 354÷359 ± 7 ka BP (Bigioggero *et al.*, 1988).

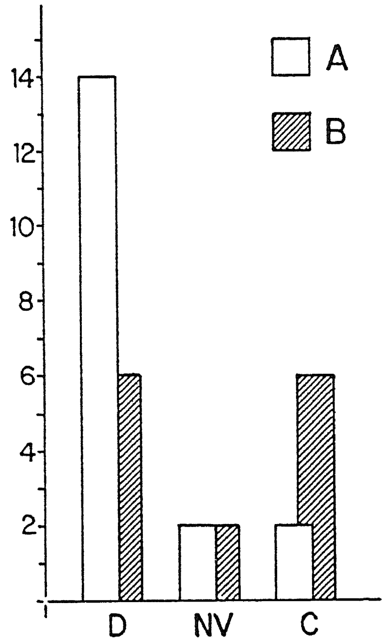

Fig. 16 - Histogram of the number of concordances and discordances of $\partial^{13}C$ and $\partial^{18}O$ increments. A) above m 188; B) below m 188; D) discordances; NV) unmeasurable situations due to no increments; C) concordances.

Istogramma del numero delle concordanze e discordanze degli incrementi di $\partial^{13}C$ e $\partial^{18}O$. A) sopra m 188; B) sotto m 188; D: discordanze; NV) situazioni non valutabili a causa di incrementi nulli; C) concordanze.

Segre (1982), studying a lithostratigraphic sequence occurring in the Anagni area, states that the upper travertines, lying on lacustrine sediments coeval with those of Lake Lirino, are more recent than the Mt. Ernici vulcanism, for which he reports an age of 366 ka BP.

The age of the alluvial terraces of the III and IV orders, resting on the travertine plate and correlated with those formed by the Liri and Melfa rivers (Arnoldus-Huizendveld *et al.*, 1985) in the Latina Valley, have been debated for long time. The III order terrace has been considered pre-last interglacial, and is ascribed to the end of the penultimate glacial. Biddittu & Cassoli (1968) consider it of "Rissian" age; Remmelzwaal (1978) attributes it to stages 7 or 9 of the oxygen isotopic curve, while Segre (1984) relates it to the last interglacial. Devoto (1965) too ascribes the "old terraced alluvium" to the last interglacial.

The IV order terrace, whose deposits are correlated with alluvial sediments in which a tusk of *Elephas antiquus italicus* OSBORN was found, is attributed (Ambrosetti, 1963), also for the occurrence of Middle Paleolithic artifacts, to the last interglacial, while other authors

(Arnoldus-Huizendveld *et al.*, 1985) suggest a more recent age (late Würm).

For the Carnello travertines, encased into the studied ones, a dating of 93 ka BP (+24.9; -21.2) is reported (Giraudi, 1990).

The studied travertines, therefore, could have deposited between 360 ka BP and the last interglacial (125 ka BP).

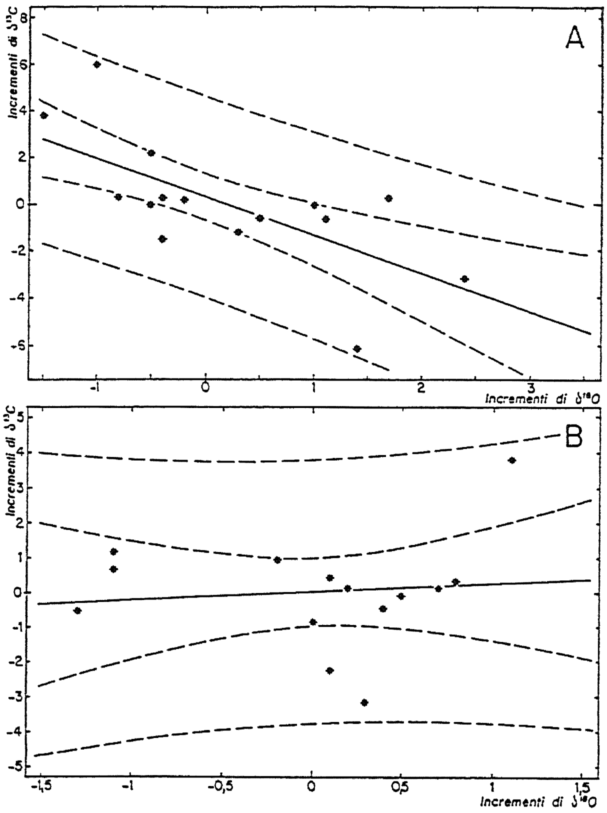

Fig. 17 - Regression curves of $\partial^{13}C$ and $\partial^{18}O$ increments. A) in the middle-upper part of the plate (above altitude 188 m); B) in the lower part (below altitude 188 m).

Curve di regressione degli incrementi di $\partial^{13}C$ e $\partial^{18}O$. A) nella parte medio-superiore del piastrone (sopra la quota 188 m); B) nella parte inferiore (sotto la quota 188 m).

The only datings of the studied travertines available at present, obtained by means of the ^{230}Th method⁽⁷⁾, and relative to a series of twelve samples collected through the whole plate, have given the results reported in Fig. 19. These preliminary datings suggest that the travertine plate has formed during a relatively long span of time, consistent with that obtained on the basis of stratigraphic relationships. They suggest also that the travertine deposition could have had a polyphase character.

Lastly, it is interesting to notice that Hausmann & Brunnacker (1988), dealing with age determination of travertine deposits of both Central Europe and Italy by means of the ^{230}Th method, found out a recurring scansion in the travertine deposition, coinciding with interglacial and interstadial periods. The authors describe a first depositional phase at about 350 ka BP, corresponding to the stage 9 of the oxygen isotopic curve, a second phase at 220 ka BP (stage 7), a third phase at about 125 ka BP (substage 5 e = Eemian of the last interglacial) and a fourth one at 105 ka BP (substage 5 c of the last interglacial).

In the Vulci area (Central Italy) the deposition of travertines, begun before 300 ka BP, has continued also at 200 ka BP (stage 7) and at 105÷115 and 80÷90 ka BP (last interglacial). The considered phases correspond, moreover, to first approximation, to high sea levels.

The data confirm, therefore, that the formation of travertines is controlled by climatic variations and that humidity factors seem to be as important as the temperature ones, and that, in any case, the two together give rise to an increase of biological activity. This process in turn, producing a large amount of carbon dioxide, intensifies the dissolution of calcium minerals and favours the subsequent deposition of incrustations.

In the studied area too, more than one stage of formation of travertine deposits have been observed. In fact, the studied travertines have been deposited during temperate phases from 360 ka BP to, at least, the last interglacial; Carnello travertines have been deposited during the last interglacial, while other travertine deposits occurring in the area or in the adjoining ones (at present in the process of being studied by the author) are recent (Holocene) or are presently being deposited.

3. CONCLUSIVE PALAEOENVIRONMENTAL AND PALAEOCLIMATIC CONSIDERATIONS

The travertine plate was deposited in a palaeo-incision roughly coinciding with the present N-S trending Liri Valley, on a substratum composed of Meso-Cainozoic carbonate formations, in turn covered by Plio-Pleistocene alluvial deposits and Middle Pleistocene lacustrine sediments with volcanic intercalations. Such substratum has been affected by tectonic phases, firstly compressional, afterwards extensional, with strike-slip components, trending mainly NW-SE and E-W, that have been active until Middle Pleistocene. The Liri Valley itself, and the palaeo-incision occupied by travertines, are controlled by tectonic structures characterized by the presence of blocks differentially dislocated. After the deposition, the travertine plate too has been affected by normal faults and fractures, trending mainly E-W and N-S, with displacements varying from a few centimetres to some decimetres.

The uppermost surface of the plate has been remodelled by the Amaseno and Liri rivers that deeply

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(7) Datings done by M. Galletti and G. Paganin through ENEA laboratories.

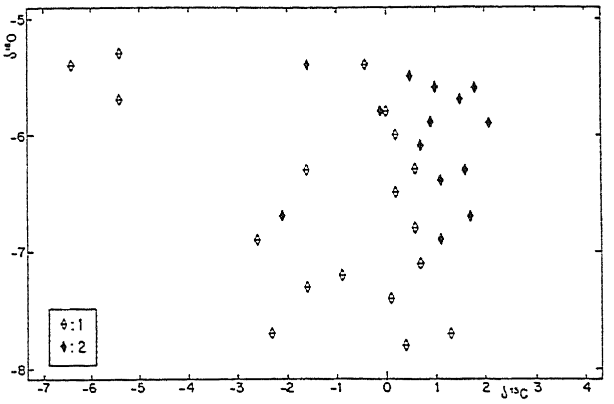

Fig. 18 - Distribution of $\partial^{18}O/\partial^{13}C$ ratio within the travertine plate. Symbols: 1) samples from the middle-upper part of the plate (above altitude 188 m); 2) samples from the lower part (below altitude 188 m).

Distribuzione del rapporto $\partial^{18}O/\partial^{13}C$ nel piastrone travertinoso. Simboli: 1) campioni della parte medio-superiore del piastrone (sopra la quota 188 m); 2) campioni della parte inferiore (sotto quota 188 m).

downcut it, leaving on its surface and in the incised trenches coarse alluvial terraced deposits and/or erosion terraces at different altitudes (I - V order terraces). In the southern part of the plate, the Liri river formed a gorge more than 120 m deep, entirely cut in travertines. Later on, travertines have been affected by karst processes that have caused the formation of several cavities filled with late concretions or pedogenized colluvial material.

The migration of streams from West to East, the occurrence of fault and fracture systems, the alternation of erosional and depositional events and the presence of some seismicity in the area, strongly suggest neotectonic activity, characterized mainly by vertical components, which probably interacted with climatic variations.

Travertines, characterized by high content of low Mg calcium carbonate (65÷100%), are represented by autochthonous lithotypes (in situ incrustations) and detrital lithotypes (non in situ incrustations). Different lithotypes have been recognized and classified according to Ferreri (1985). The most widespread are: calcareous sands and silts, phytoclastic calcarenites and travertines, phytohermal and microhermal travertines.

The following lithofacies associations and their relative depositional environments have been recognized:

a) calcareous sands and silts with intercalations of calcarenites and phytoclastic travertines of fluvio-lacustrine and lacustrine environment (lake-fill deposits);
b) phytoclastic calcarenites and travertines associated with phytohermal and bibliolitic travertines of mainly palustrine environment;
c) phytohermal and microhermal travertines with coarse phytoclastic travertine intercalations deposited mainly on more or less steep slopes;
d) phytohermal, microhermal and stromatolitic travertines deposited in pools and pool-gradine mounds;
e) festoon and dome shaped microhermal and stromatolitic travertine bodies forming overhanging rims on waterfall scarps.

Detailed macro- and microscopic observations allowed to recognize and interpret different structures and textures of travertines and their meaning: physico-chemical and/or biological (moss, algal, bacterial). It has been possible also to determine the daily and yearly growth rate of some laminar stromatolitic textures.

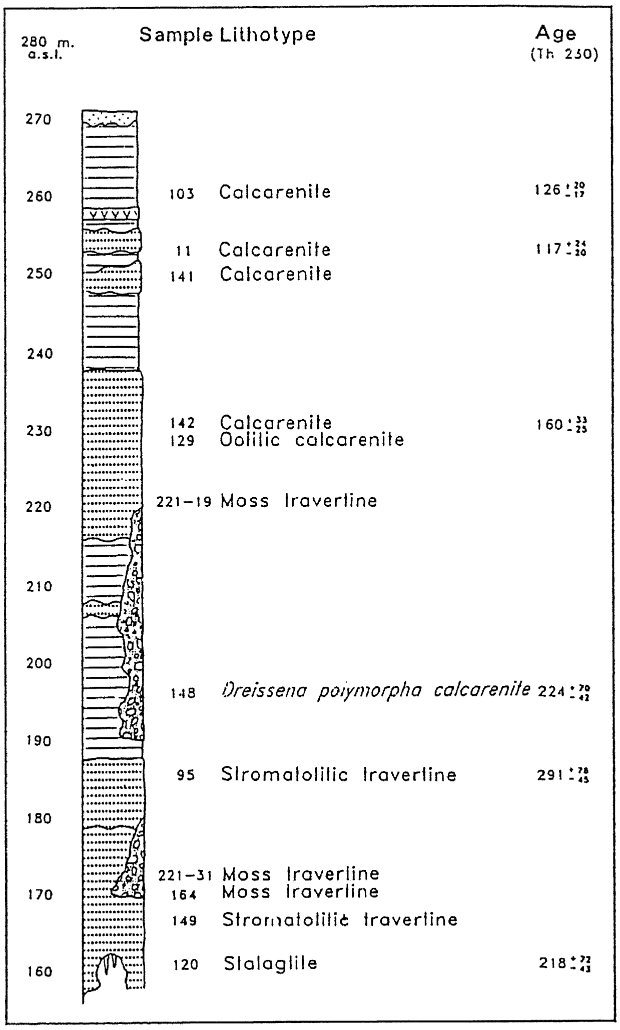

Fig. 19 - Stratigraphic position and age of travertines obtained by means of ^{230}Th method. Symbols as in Fig. 4.

Posizione stratigrafica ed età dei travertini ottenute col metodo ^{230}Th. Simboli come in Fig. 4.

The plate consists of alternating autochthonous and detrital lithofacies associations, that prevail respectively in the lower and upper part of the plate. Relationships between the two associations are often defined by erosional surfaces, in whose depressions colluvial material can occur. The formations of detrital lithofacies is probably connected with erosional (and depositional) episodes corresponding to periods of larger amounts of rainfall that caused the development of fluvio-lacustrine conditions.

The travertine plate, despite its vertical and lateral variability and changes of depositional environments, seems to constitute a sedimentary body "globally" rather uniform. Its deposition could have been continuous and have not undergone long periods of non-deposition. It cannot be excluded that the described evolution of the plate is to be related to climatic variations that have interacted with mainly vertical movements.

The information obtained from the study of fossil flora and fauna of travertines, suggests that their deposition has probably taken place during one or more phases characterized by temperate climate, with warmer and more humid episodes.

Oxygen and carbon isotopic composition of travertines suggest that their deposition took place from mother waters with uniform isotopic composition at relatively steady temperatures. In the $\partial^{18}O$ and $\partial^{13}C$ curves an evident specular behaviour of the two parameters has been noted within the plate, especially for the middle and upper parts of the plate, above the altitude of 188 m. Such behaviour could be a reflection of primary isotopic composition of mother waters, conditioned by climatic factors, by mainly ambient temperature and humidity variations (modality and/or quantity of precipitations), that, in turn, influenced the biological activity. A climatic signal in the compared oxygen and carbon isotopic composition curves has been identified.

As regards the origin of carbon dioxide involved in the formation of travertines, it is not excluded that a part of it could be of endogenic origin, the studied area being tectonically active and affected by extensional movements.

A depositional model of the travertine plate is proposed: along the steepest and irregular tracts of ancient streams (Amaseno and Liri rivers) autochthonous travertine bodies have grown up and formed natural dams. Upstream such dams, lacustrine and palustrine pools and basins were formed in which the relative lithofacies deposited. Inundations, floods and erosional processes, likely connected with climatic variations, have partially destroyed the dams. The detrital material produced from their demolition has been transported to more or less great distances and was deposited to form detrital lithofacies which, locally, have buried the autochthonous bodies. This evolution has caused the complex superimposition of different lithofacies associations observed within the lithostratigraphic columns.

The travertine plate could have deposited between 360 ka BP and the last interglacial (125 ka BP).

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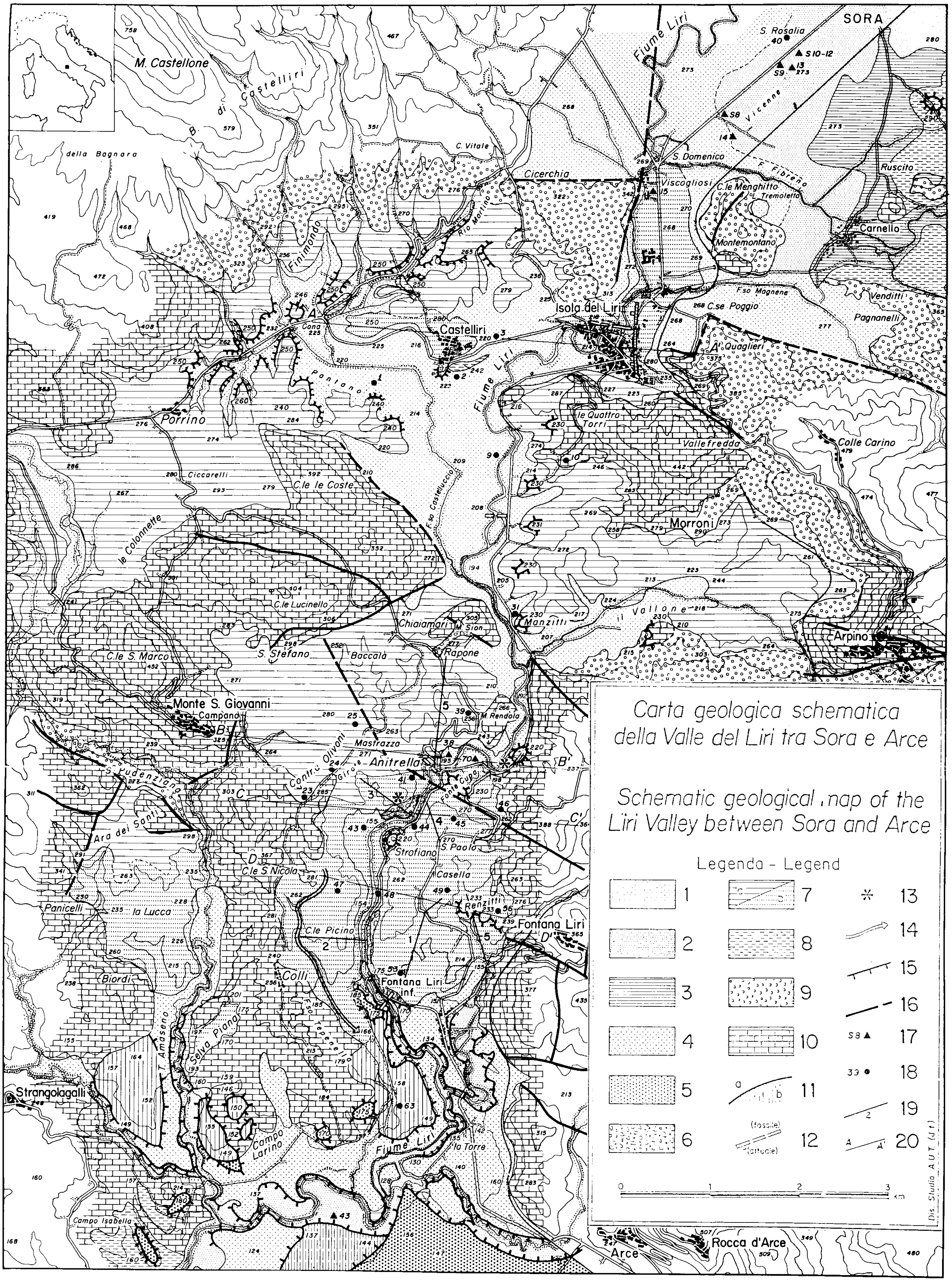

Plate 1 - Schematic geological map of the Liri Valley between Sora and Arce (Frosinone, Central Italy). (The map has been drawn up on the basis of original survey data, of unpublished data by C. Giraudi and data from Sheets N. 152 and 160 of the Geological Map of Italy, scale 1:100,000). Legend: 1) Colluvial and alluvial recent deposits; 2) Alluvial deposits of the V order terrace and Carnello fluviolacustrine deposits (Holocene-Pleistocene); 3) Carnello travertines and lacustrine deposits (upper Pleistocene); 4) Alluvial deposits of the IV order terrace (upper Pleistocene?); 5) Alluvial deposits of the III order terrace (middle Pleistocene); 6) Alluvial deposits and/or erosion surfaces of the II and I order (along the Anitrella gorge and at Rapone respectively) (Middle Pleistocene); 7) Studied travertines (middle Pleistocene): a) mainly detrital, b) mainly autochthonous; 8) fluvio-lacustrine and palustrine deposits with volcanic and peat beds (middle Pleistocene); 9) Alluvial fan deposits of Villafranchian age (Lower Pleistocene-Upper Pliocene) and sandy-clayey colluvial deposits derived from lateritic weathering of polygenic conglomerates (Pliocene?); 10) Meso-Cainozoic limestones; Miocenic deposits (flysch, arenaceous-clay deposits) and Mio-Pliocene polygenic conglomerates; 11) erosion surface on travertines (a) and on other deposits (b)(middle Pleistocene); 12) Waterfalls of Liri, actual and fossil; 13) Volcanic beds within travertines; 14) Liri palaeobed; 15) Terrace scarps; 16) Certain and probable faults; 17) Cores; 18) Geoelectric wells; 19) Lithostratigraphic columns; 20) Geological sections.

Carta geologica schematica della valle del fiume Liri tra Sora e Arce (Frosinone, Italia centrale) (La carta è stata compilata sulla base di rilevamenti originali, di dati inediti di C. Giraudi e di dati presi dai FF. 152 e 160 della Carta Geologica d'Italia, scala 1:100.000). Legenda: 1) Sedimenti colluviali e alluvionali recenti; 2) Alluvioni del terrazzo di V ordine e sedimenti fluvio-lacustri di Carnello (Olocene-Pleistocene); 3) Travertini di Carnello e sedimenti lacustri ad essi collegati (Pleistocene superiore); 4) Depositi alluvionali del terrazzo di IV ordine (Pleistocene superiore?); 5) Depositi alluvionali del terrazzo di III ordine (Pleistocene medio); 6) Depositi alluvionali e/o superfici di erosione del II e I ordine (rispettivamente nella forra di Anitrella e Strofiano e a Rapone) (Pleistocene medio); 7) Travertini in studio: a)prevalentemente detritici, b) prevalentemente autoctoni (Pleistocene medio); 8) Sedimenti fluvio-lacustri e palustri con livelli vulcanici e di torba (Pleistocene medio); 9) Sedimenti di conoide alluvionale villafranchiani (Pleistocene inferiore-Pliocene superiore?) e prodotti sabbioso-argillosi colluviali e di alterazione lateritica di puddinghe poligeniche (Pliocene?); 10) Carbonati meso-cenozoici, sedimenti miocenici (flysch e depositi arenaceo-argillosi) e mio-pliocenici (puddinghe poligeniche); 11) Superficie di erosione sui travertini (a) o su altri depositi (b) (Pleistocene medio); 12) Cascate del Liri: attuali e fossili; 13) Livelli vulcanici nei travertini; 14) Paleoalveo del Liri; 15) Scarpate di terrazzi; 16) Faglia certa e probabile; 17) Perforazioni; 18) Sondaggi elettrici; 19) Colonne stratigrafiche; 20) Sezioni geologiche.