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LATE PLEISTOCENE TRAVERTINES AND THEIR ANALOGUES UNDER-DEPOSITION. A COMPARATIVE ANALYSIS

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ABSTRACT: Anzalone E.: *Late Pleistocene Travertines and Their Analogues Under- Deposition. A Comparative Analysis*. (IT ISSN 0394-3356, 2008).
Textures, sedimentary structures and O-isotope data from the late Pleistocene travertines cropping out at Pontecagnano-Faiano (Salerno) are here compared with carbonate incrustations under formation within an adjacent irrigation channel.
Fossil system. A complex paleo-environmental dynamics is documented in the travertine fossil system, spanning in age from 90 ka B.P. (±10ka) at the base, to 55ka B.P. (±10ka) at about 15 m from the summit surface. In this system, aggradational and progradational growth-geometries developed starting from an original gentle slope, that was increasing gradually its inclination while growing downhill. This resulted into a number of rapids and waterfalls at the margins of this system leaving behind flat terrace where swamps and/or shallow lakes developed. The travertine growth was interrupted, at time, by non deposition and/or erosional processes, both documented by discontinuity surfaces. This organization suggests a recurrent dropping of the groundwater level and a decreasing spring-water outflow, considered as due to climatic changes. Moreover, oxygen isotope data have been measured lamina-by-lamina on stromatolitic travertines in which recurrence of the *Chironomid* larvae galleries in the sparitic laminae suggests seasonal variations as also confirmed by the small isotope oscillations (dispersion of about 0,6 ‰ δ units) documented in the laminae of the stromatolitic fabric.
Present-day incrustations. The present-day incrustations derive from waters flowing along an artificial channel fed by springs that has been used as a gentle "slope" depositional analogue of the adjacent fossil deposits. The time-space evolution of the depositing incrustations shows growth geometries well comparable to those occurring at a larger scale in the fossil system. The incrustations develop downhill and from the margins towards the channel axis both through progradational and aggradational geometries. Small barrages and domes (mounds) take form where the carbonate calcium precipitation rate is higher, while micropools tend to spread behind these structures. These depositional structures tend to level themselves to the channel upper surface. The oxygen-isotope data measured in the channel incrustations document small seasonal oscillations (dispersion of about 0,6 ‰ δ units) that do not differ from those recorded in the fossil stromatolitic deposits. Based on the above results a sedimentary model is proposed here, that may bear also on the terraced morphology of other Quaternary ambient-water travertines

RIASSUNTO: Anzalone E.: Travertini del Pleistocene superiore e loro analoghi attuali. Analisi comparativa. (IT ISSN 0394-3356, 2008).
Lo studio comparato dei travertini tardo-pleistocenici e di quelli attualmente in formazione, nell'area di Pontecagnano-Faiano (Salerno, Campania), ha consentito di analizzarne la loro dinamica ambientale e di evidenziare le loro analogie.
Sistema fossile. Le relazioni stratigrafiche tra le differenti associazioni di litofacies e gli originari ambienti sedimentari mostrano nel sistema fossile ricorrenze di tessiture-strutture sedimentarie registrate a scala da decimetrica a metrica e testimoniate da geometrie di crescita sia aggradazionali che progradazionali. Queste, nel complesso, suggeriscono che i processi di incrostazione sono iniziati su un originario pendio poco acclive. La successiva evoluzione ambientale ha portato all'aumento di acclività sul fronte del deposito mentre alla sommità si aveva la formazione di un terrazzo deposizionale con lo sviluppo di facies palustri/lacustri mentre depositi di rapida e/o cascata ne caratterizzavano i margini. Frequenti discontinuità sono registrate a scala da decimetrica a metrica e indicano una generale modalità di crescita per "pulsazioni", legate a ricorrenti fasi di abbassamento del livello di falda, con conseguente diminuzione della portata alla sorgente. Questa ultima è probabilmente collegata a variazioni della piovosità. Il controllo climatico è comunque più chiaramente registrato nei depositi stromatolitici dove le variazioni stagionali sono suggerite sia dalla presenza delle gallerie di Chironomidi nelle lamine spatitiche, sia da piccole e regolari oscillazioni degli isotopi dell'ossigeno (dispersione dei valori di circa 0,6 ‰ unità δ).
Depositi attuali. Queste oscillazioni sono strettamente comparabili con quelle misurate nelle incrostazioni attuali monitorate lungo un canale di irrigazione, che può essere considerato come l'equivalente di un paleo-pendio. Lungo il canale la dinamica ambientale è prevalentemente regolata dai tassi di precipitazione. Laddove questi (a loro volta controllati dalle variazioni dell'idrodinamica e della morfologia del substrato) sono più alti, si osserva lo sviluppo di piccole barre e strutture domiformi. Queste si accrescono sia verso valle che dai margini verso l'asse del canale, sviluppando geometrie di progradazione e di aggradazione. Il processo di crescita porta gradualmente alla diffusione di piccole pozze nelle aree retrostanti le barre fino al riempimento del canale che viene ripulito dalle incrostazioni due volte l' anno.
L'analisi comparata della dinamica ambientale dei travertini tardo- pleistocenici e attuali di Pontecagnano-Faiano suggerisce un modello sedimentario che può spiegare lo sviluppo di morfologie terrazzate osservabile anche in altri sistemi travertinosi fossili.

Keywords: Travertines, Calcium-carbonate incrustations, Sedimentology, Environmental dynamics, Oxygen-isotope, Climatic control.

Parole chiave: Travertini, Incrostazioni carbonatiche, Sedimentologia, Dinamica ambientale, Isotopi dell'ossigeno, Controllo climatico.

1. INTRODUCTION

In the last few years, much scientific interest has been addressed to non marine carbonates and in particular to the late Quaternary travertine deposits, which have been considered in terms of complex depositional systems and used as paleoclimatic proxies. Their geological importance is due to the primary carbonate precipitation that is largely controlled by physico-chemical processes (outgassing of CO_2, pH variation, water temperature, hydrodynamics and so on) and biological activity (mainly microbial and/or algal); both, in turn, are influenced by climate variability (*e.g.* Henning *et al*., 1983; Julia, 1983; Chafetz and Folk, 1984; Matsuoka *et al*., 2001; Soligo *et al*., 2002; Ihnlefield *et al*., 2003; Pentecost, 2004; Anzalone, 2005; Andrews, 2006; Carthew *et al*., 2006; Anzalone *et al*., 2007). Travertines are widespread in central and southern Italy where they deposited in the late Pleistocene-Holocene times, during interglacial warm-wet climatic intervals characterized by increasing volume of the spring waters in the mountain foothills and by forest expansion (*e.g.* Brancaccio *et al*., 1988; Crombie *et al*., 1997; MArtin-Algarra *et al*., 2003).

Although the sedimentary organization of different travertine deposits shows similar gross features, two end-members can be distinguished: ambient-water and hot-water travertines (*e.g*. Golubic *et al*., 1993; Violante *et al*., 1994; D'Argenio, 2001; D'Argenio and Ferreri, 2004). In particular, the lithofacies diversity and the biogenic imprint carried by primary travertine incrustations provide good criteria of distinction between ambient- and hot-water fossil deposits, both at the outcrop and at microscopic scale. In fact, to higher temperature at the spring, lower abundance, size and diversity of the colonizing organisms correspond (*e.g.* Violante *et al*., 1994; D'Argenio, 2001).

In southern Europe, the sites where travertine incrustions are currently forming are rather rare and the deposition rate scarce. Active travertine systems have been analyzed investigating : a) calcium carbonate precipitation processes (*cfr.* Herman and Lorah, 1988); b) parent-water chemistry (Pentecost, 1995) and c) carbon and oxygen isotope composition. Actually from few years, active travertine systems have been considered as "*natural laboratories*" to analyse their growth mode and to compare them to fossil systems, trying to recognize in them a climatic signal.

The present study is mainly based on a comparative analysis between late Pleistocene travertines and present-day incrustations, the latter under deposition along an irrigation channel, seasonally digged[1]. Both deposits are located in the vicinities of Pontecagnano-Faiano village (Salerno, Fig. 1).

The main analogies between the fossil and the active system are discussed, using also new data collected during the last two years (a) to inquire on the large scale control mechanisms by confronting fossil with present-day incrustations; (b) to better delineate the depositional architecture and environmental dynamics of the fossil travertines, allowing their sedimentary model to be delineated and (c) to add new evidence to the climatic significance of the O-isotope signal already measured during the years 2002-2003.

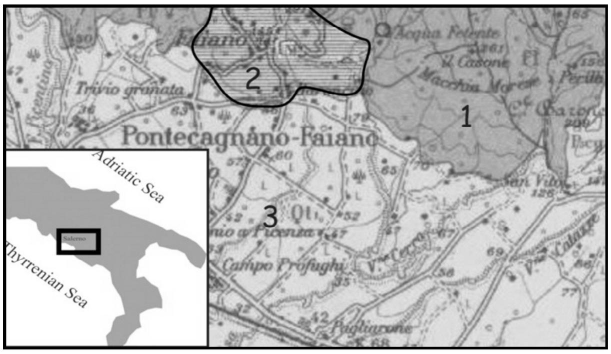

Fig. 1. - Pontecagnano-Faiano travertines (Salerno district, southern Italy). 1. Sedimentary substrate. 2. Pontecagnano-Faiano travertines. 3. Post-travertine alluvial deposits. On the left: location of the studied area.

Travertini di Pontecagnano-Faiano (Salerno, Italia meridionale). 1. Substrato sedimentario. 2. Travertini di Pontecagnano-Faiano. 3. Depositi alluvionali successivi a quelli di travertino. Nel riquadro in basso a sinistra l'area oggetto di questo lavoro.

[1] For further information on the main physico-chemical processes controlling the formation of the present-day deposits see Anzalone *et al*. (2007).

2. SEDIMENTOLOGY

The Pontecagnano-Faiano fossil and present-day travertines crop out at the southern side of the Picentini Mountains (Campania Apennines), whose large-scale tectonic organization consists in a multilayer of structural units mainly made of Mesozoic carbonate rocks and subordinately by Tertiary terrigenous deposits (Fig. 1, see also D'Argenio *et al*., 1987; Casciello *et al*., 2006).

Late Pleistocene travertines

The fossil deposits, cropping out at about 10 km south-east of Salerno, are 90 metres thick, roughly clino-stratified to the south-southwest and range in age from 90 ka (±10ka) B.P. to 55ka (±10ka) B.P. (the last figure refers to a sample collected at about 15 m from the summit surface, *cfr.* Anzalone, 2005; Anzalone *et al*., 2007). Textures and related sedimentary structures have been classified in terms of lithofacies and lithofacies associations (*see* Ferreri, 1985; D'Argenio and Ferreri, 2004 for terminology). In particular, textures made up by *in situ* carbonate incrustations (stromatolitic, microhermal and phytohermal lithofacies) or by incrusted plant fragments (phytoclasts) have been recognised. The *in situ* deposits (stromatolitic and microhermal), associated with phytoclastic travertines, are widespread in the lower-middle part of the travertine body; they are weakly clino-stratified to the south-south west and consist of *gentle to steep slope deposits* (Fig. 2 a, b). Subvertical structures (drapes), formed of phytohermal and microhermal textures, characterise the current travertine margins and indicate *rapid to waterfall deposits* (Fig. 2c). Finally, sub-horizontal deposits, represented by poorly stratified phytoclastic sands with lensoid travertine intercalations, characterise the topmost part of the travertine terrace; they consist of *shallow lake to swamp deposits* (Fig. 2d). The time-space stratigraphic relationships among the above deposits allow to infer that the carbonate precipitation initiated on a gentle slope surface, laterally and downhill evolving into steeper slopes and rapid-waterfall structures. This depositional dynamics is testified by cm- to m-scale growth geometries that suggest, on the whole, a progradation of the fossil system towards south and southwest. Analogously, the upward travertine growth is documented by cm- to m-scale growth geometries resulting in a terraced surface where shallow- lake and swamp deposits are widespread.

These growth geometries imply that the springs originating the Pontecagnano-Faiano fossil deposits were located towards the north. Moreover, several discontinuity surfaces, recurring at dm- to metre- scale intervals, suggest that the travertine growth was often interrupted by not-depositional and/or erosional processes due to recurrent dropping of the groundwater levels and decreasing spring-water outflow (Anzalone *et al*., 2007). In conclusion, the complex interplay between paleoenvironmental and paleohydrological dynamics resulted, on the whole, in a final construction of a terraced morphology.

Sette Bocche channel travertines

In the studied area, several springs are, at the present, precipitating calcium carbonate deposits along irrigation channels. One of these gullies (the easternmost of an E-W gentle arched array of seven springs, named Sette Bocche Channel) is about 2500 m long, 1 m deep and 1,5-2 m wide, with an acclivity of about 5°. It is located at northeast of the town of Pontecagnano-Faiano and from the year 2002 has been used as a natural laboratory. The water temperature is about 17°C; this value does not show significant changes during the sampled period. Moreover, the water-composition is richer in Mg^{2+} and Ca^{2+} rather than in other ions, reflecting the predominant carbonatic nature of the aquifer. At the spring, the concentration gradient of atmospheric CO2 and the dissolved CO_2 in waters emerging from the aquifer produce CO_2 outgassing (*cfr. e.g*. Lu *et al*., 2000; Anzalone *et al*., 2007).

As the concentration moves toward the equilibrium, the water becomes supersaturated with $CaCO_3$, the pH increases (values around 7.5) with carbonate precipitation starting at about 200 m from the spring (Figs. 3 a, b). Calcium carbonates continue to deposit downstream for about 1,2 km and then start rapidly to decrease, until the waters spill into a permanent rivulet, the Asa torrent, where there is not calcium carbonate precipitation at all.

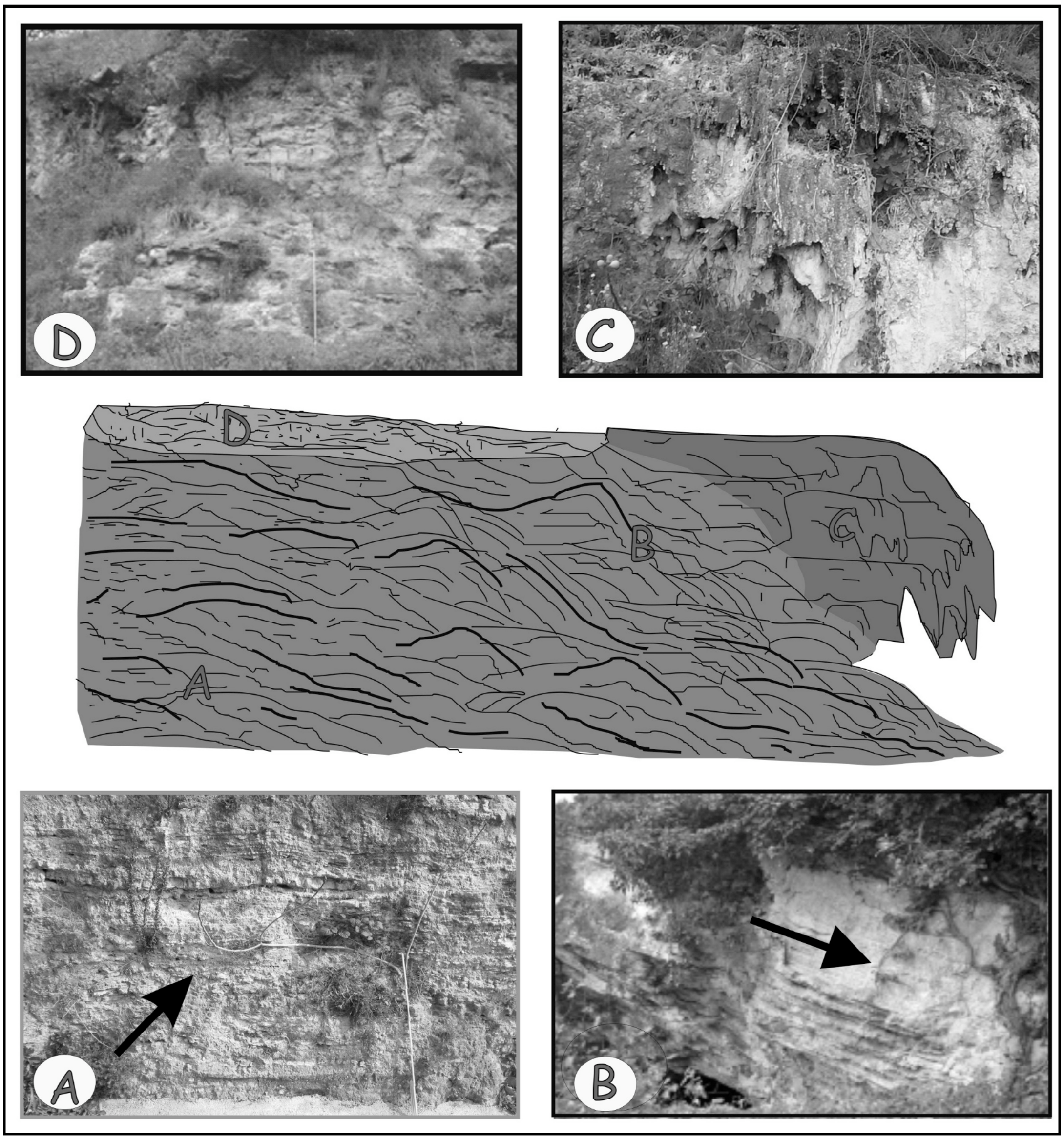

Fig. 2 - Schematic model showing the vertical ("aggradational") and longitudinal ("progradational") growth dynamics of the fossil system. (A) Weakly clinostratified phytoclastic travertines, the arrow shows a lensoid microhermal intercalation: *gentle slope facies.* (B) Clinostratified phytoclastic deposits: *steeper slope facies*, (C) Subvertical "drapes" formed of incrustations on mosses: *waterfall facies*. (D) Poorly stratified phytoclastic sands: *shallow lake facies*.

Modello schematico mostrante la dinamica di crescita verticale (geometrie di aggradazione) e laterale-frontale (geometrie di progradazione) del sistema fossile. (A) Travertini fitoclastici in strati leggermente inclinati; la freccia indica piccola intercalazione lentiforme di travertino microermale: pendio poco acclive. (B) Travertini fitoclastici clinostratificati: pendio acclive. (C) Travertini a muschi in "drappi" subverticali: depositi di cascata. (D) sabbie fitoclastiche a stratificazione indistinta: facies lacustre.

The process of travertine deposition, controlled by hydrodynamics and substrate morphology, is discussed here to show how changes in precipitation and accumulation rates modify the gully morphology. Higher $CaCO_3$ precipitation rates (about 4-6 cm/month) prevailingly occur at small slope-breaks. At these breaks, bar- and dome-geometries ("mounds") develop, with their main axis perpendicular to the direction of the water flow (Figs. 3 c, d). Such mounds are characterized by in situ microhermal incrustations, mostly on *Vaucheria* or mosses, locally associated with phytoclastic travertines. The water velocity strongly influences the growth dynamics and the morphology of these small constructions. Arcuate small barrages, showing frontal steep-slopes and characterized by prevailing progradational geometries, grow under higher hydrodynamics conditions. Conversely, behind these small channel barrages, cm- to dm size microponds gradually take form, where the lower water flux favours development of prevailingly aggradational growth geometries. Moreover, higher $CaCO_3$ precipitation rates also occur at the channel margins, where a series of cm-size "microhermal mounds" (prevailingly made of incrustations on the green alga *Vaucheria*) develop with inward and downhill progradational geometries, gradually occluding the channel lumen (Figs. 3 e, f).

From the above data it is suggested that the present-day travertine incrustations within the channel reach values exceeding 3000 m^3 per year; the $CaCO_3$ precipitates grow through aggradational and progradational geometries, levelling themselves to the water channel upper surface at least twice a year, with an interval of few weeks for digging operations.

3. STABLE ISOTOPE GEOCHEMISTRY

A detailed geochemical analyses of rocks and parent waters has been carried out on numerous samples. Bulk sample stable-isotope analyses have been performed by automated continuous flow carbonate preparation using a GasBenchII device and a ThermoElectron Delta Plus XP mass spectrometer, at the Isotope Geochemistry Laboratory of the IAMC-CNR (Naples). Standard deviations of the oxygen isotope measures were estimated 0.08 per mill on the basis of about 10% repeated samples.

3.1. Late Pleistocene travertines

Oxygen isotope analyses have been made on several lithofacies corresponding to different paleoenvironments, excluding samples affected by diagenetic modifications. The data show that analogous values occur in the phytoclastic as well as in the microhermal and stromatolitic textures suggesting, on the whole, their independence from the primary depositional characteristics. Paleo-temperatures of the parent waters have been investigated. The O-isotope values, spanning from -4.50‰ to - 6.51‰ vs. VPDB with a dispersion of about 2 ‰ δ units, indicate deposition from ambient-temperature waters. In addition, these values are closely comparable to those measured on the channel incrustations (ANZALONE, 2004; ANZALONE *et al*., 2007).

In the last two years new O-isotope data have been collected, lamina-by-lamina, from the stromatolitic intervals that form repeated, 8-10 cm thick, bundles. In these deposits, recurrence of galleries produced by *Chironomid* larvae in the sparitic laminae indicates that such laminae formed during a Spring-Summer season (cfr. *e.g*. IRION and MULLER, 1968). Minor isotope oscillations (about 0.6‰ value dispersion) are here documented that are well comparable with those discussed in ANZALONE *et al*. (2007). Moreover they appear superimposed on centimetre to metre scale trends (dispersion of about 1,6 ‰ δ units) suggesting a hierarchical organization probably linked to external (climatic) control (Fig. 4, see also ANZALONE, 2005).

3.2. Sette Bocche channel deposits

The oxygen isotope study carried out on samples collected during the years 2006-2007 shows that the $\delta^{18}O$ mean values are about -5.93‰ vs. VPDB in Spring-Summer and about -5.54‰ vs. VPDB in Autumn-Winter, with no regard to the primary textures (normally microhermal).

These mean seasonal values almost coincide with those previously measured during the years 2002-2003 (*cfr.* ANZALONE *et al*., 2007) and are in agreement with several authors, reporting analogous results for other active precipitating travertine systems (cfr. CHAFETZ *et al*., 1991; MATSUOKA *et al*., 2001, KANO *et al*., 2003; IHLENFIELD *et al*., 2003). Moreover, it is worth noting that a value dispersion of about 0,6‰ δ units is recorded, closely comparable to that measured in the laminae of the fossil stromatolitic travertines with Chironomid galleries. Here small seasonal variations are clearly documented.

4. DISCUSSION AND CONCLUSIONS

The present study is based on a comparison between the late Pleistocene ambient-water travertines and the present-day carbonate incrustations, both cropping out at Pontecagnano-Faiano (near Salerno, Campania). The active incrustations are here analyzed to better define the environmental dynamics of the fossil system.

The stratigraphic relationships between the different lithofacies associations (and related paleoenvironments) have been studied at cm- to m- scale. They indicate multiscale constructional trends, also testified by aggradational and progradational growth geometries. Moreover they suggest a sedimentary evolution from an original gentle slope to a terraced morphology; here shallow-lakes to swamps and rapids to waterfalls were developing at the top and at the margins, respectively. In addition, more or less evident discontinuity surfaces are documented at decimetre to metre scale intervals, that suggests recurrent gaps in the sedimentary record due to lowering of ground-water levels and consequent decreasing spring-water flow. The climatic control on these features is clearly documented at a seasonal scale by small isotope oscillations (dispersion of about 0,6 per mill δ units) measured on the stromatolitic fossil deposits (see also ANZALONE *et al*., 2007 for further comments).

The present-day travertines have been analyzed at Pontecagnano-Faiano, along an artificial channel fed by spring waters (Sette Bocche Spring), to study chemico-physical processes influencing the travertine deposition. Here hydrodynamic and substrate morpho-

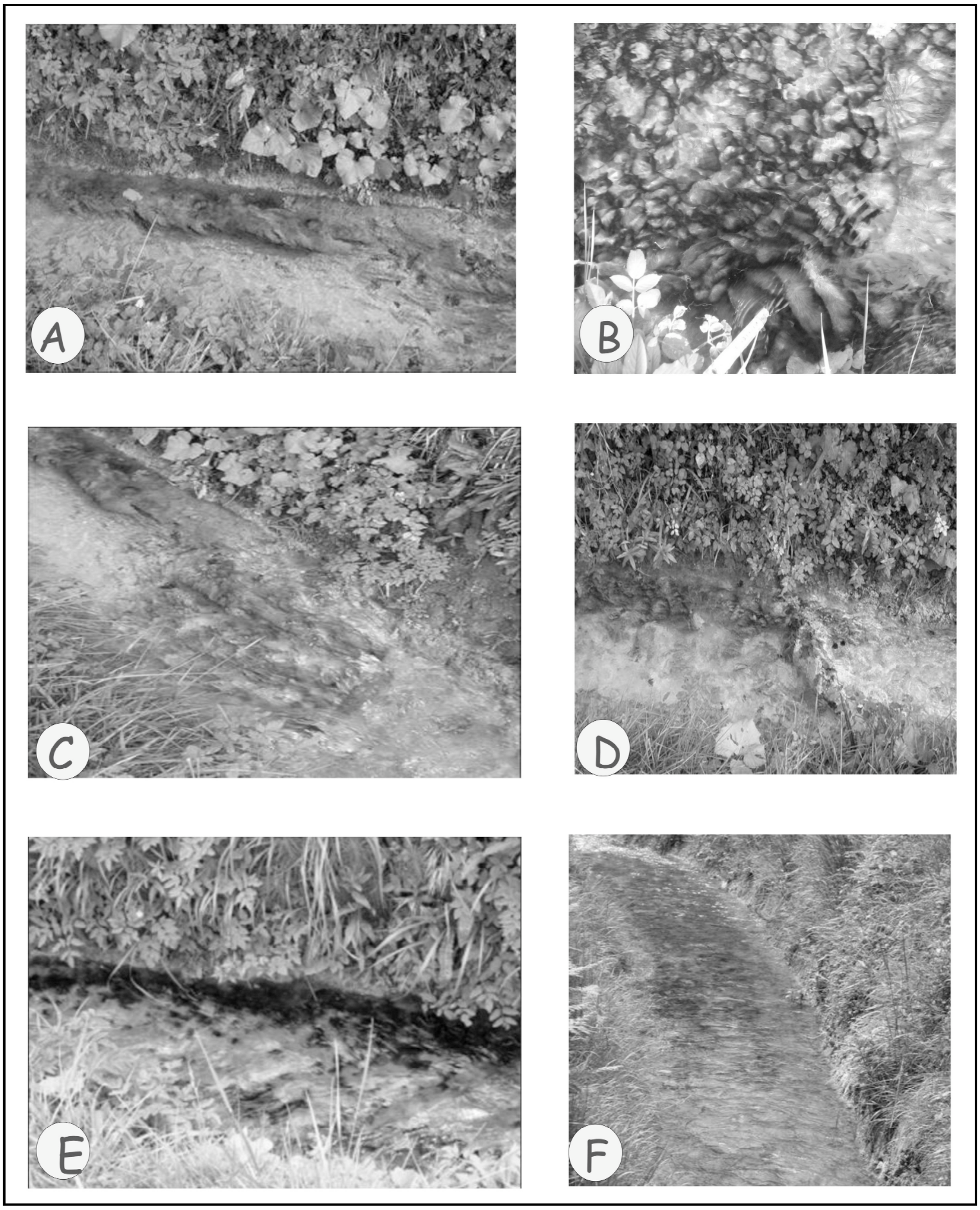

Fig. 3. - Present-day travertine incrustations. (A) Upper part of the Sette Bocche channel (about 200 metre from the spring). (B) Carbonate incrustations on the green alga *Vaucheria* sp.. (C) Small slope-break where a *Vaucheria* "mound" develops, showing a downhill growth. (D) Small slope-break occurring downhill; here a phytoclastic barrage develops. (E) Progressive infilling of the channel, from its margins to its axis. (F) Occlusion of the channel due to the travertine incrustation growth. See the text for further explanation.

Travertino in formazione. (A) Parte alta del canale Sette Bocche a circa 200 metri dalla sorgente. (B) Incrostazioni sull'alga verde Vaucheria sp. (C) Piccola rottura di pendenza in corrispondenza della quale si sviluppa un "mound" a Vaucheria *sp. (D) Piccola rottura di pendenza verso valle; dove si sviluppa una barra di travertino fitoclastico. (E) Progressivo riempimento del canale per crescita delle incrostazioni dai margini verso l'asse. (F) Occlusione del canale dovuta ad incrostazioni. Vedi il testo per ulteriori spiegazioni.*

logy changes, both controlling calcium-carbonate precipitation rates and deriving sediments, have been investigated. The calcium carbonate precipitation starts at about 200 m from the spring and develops for about 1200 m, the higher values occurring at small breaks as well as at the channel margins. This allows aggradational and progradational growth-geometries to be developed that are comparable to those recognized, at a larger scale, in the slope facies of the fossil system (Fig. 2). Moreover, the oxygen-isotope oscillations (dispersion of about 0,6 per mill δ units), measured across the present-day carbonate incrustations, document small seasonal changes. These new collected data are well comparable to those measured on the fossil deposits as well as to those already discussed in ANZALONE *et al.* (2007).

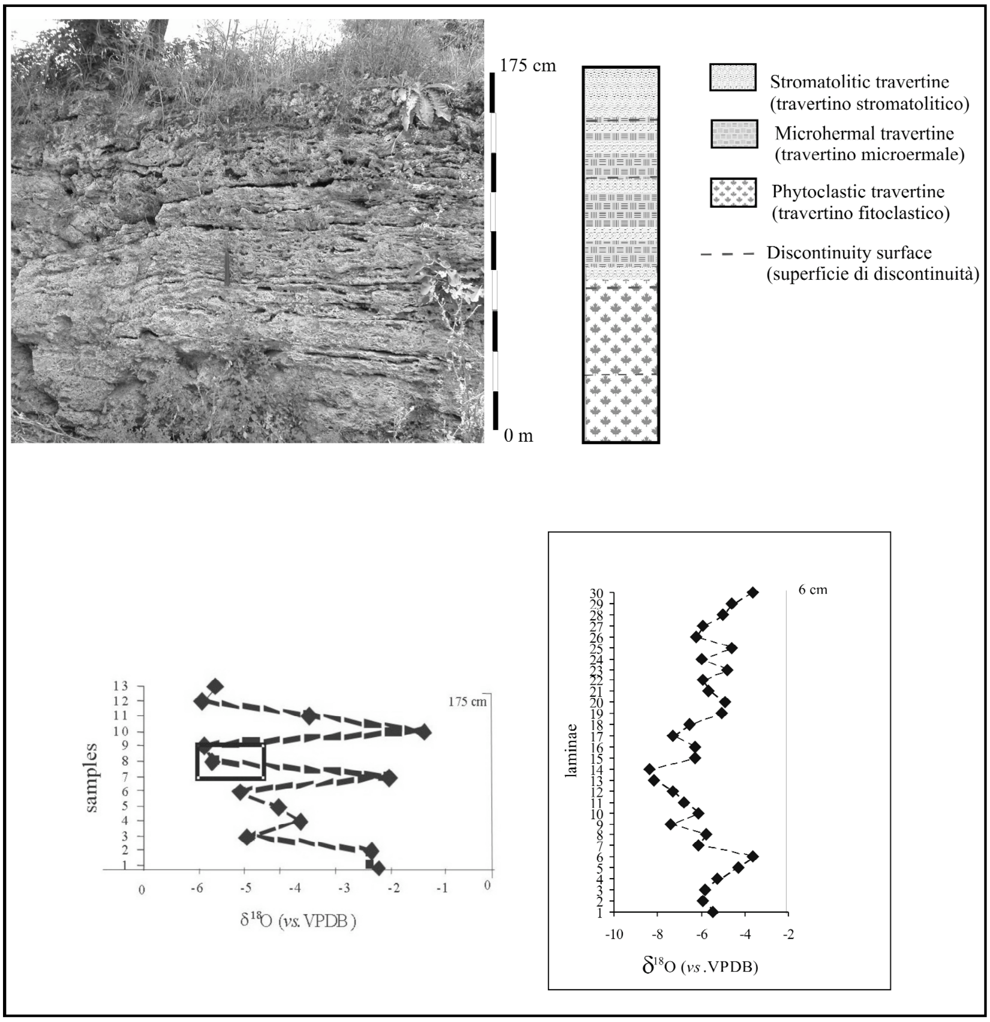

Fig. 4 - Faiano. Late Pleistocene travertines. Upper row: phytoclastic travertine associated with stromatolitic and microhermal travertine (*slope facies*), on the right, the vertical variation of the lithofacies and their thickness. Lower row : Oxygen isotope oscillations measured on 13 samples collected at centimetre scale; the square indicates a stromatolitic interval, about 6 cm thick, measured lamina by lamina. The small oscillations (dispersion of 0,6 ‰ δ units), on the right, record a seasonal signal.

Faiano. Travertini del Pleistocene superiore. Sopra: Affioramento di travertino fitoclastico associato a livelli di travertino microermale e di travertino stromatolitico (ambiente di pendio), a destra colonna litologica mostrante la variazione verticale delle litofacies e del loro spessore.
Sotto: Variazioni degli isotopi dell'ossigeno registrate in 13 campioni raccolti a scala centimetrica; il riquadro indica un intervallo di circa 6 cm di spessore di travertino stromatolitico misurato lamina per lamina. Le piccole oscillazioni ottenute (dispersione di circa 0,6 ‰ unità δ), mostrate a destra, indicano un segnale stagionale.

From the above results, the following conclusions may be briefly delineated:

(a) comparable aggradational and progradational growth geometries may be recognized in the fossil and present-day travertines, suggesting that their depositional dynamics is strongly controlled by changes in the water-flow characteristics, in turn controlled by climate. This may also explain the "pulsating" growth of the fossil travertines, suggested by the frequent discontinuity surfaces, the latter recurring at dm- to m-scale intervals in the stratigraphic record;

(b) the oxygen isotope values indicate that analogous temperatures (about 17° C) may be estimated for both the fossil and the present-day parent-waters; moreover, their hierarchical organization (from cm- to m-scale intervals, Fig. 4), may indicate an external control on fossil travertine formation, probably linked to climatic change. This is also suggested by the seasonal variations, at a mm-scale, recorded in the stromatolitic deposits;

(c) based on the above analogies between fossil and present-day travertines, a sedimentary model is proposed that well explains the terraced morphology of the Pontecagnano-Faiano fossil system; this model may be considered also to interpret the depositional dynamics of other Quaternary ambient-water travertine terraces.

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