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Travertines as self regulating carbonate systems. Evolutionary trends and classification

A travertínók mint önszabályozó karbonátrendszerek – fejlődési irányok és osztályozás

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(2 tables)

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Tárgyszavak: meleg és a környezetükkel azonos hőmérsékletű vízből keletkező travertínók, kvarter vége, Közép- és Dél-Olaszország, lerakódási rendszer

Összefoglalás

A késő-negyedidőszaki travertínók Közép- és Dél-Olaszországban általános elterjedésűek, s ezek vagy meleg vízből vagy a környezetükkel egyező hőmérsékletű vízből váltak ki. A néhány négyzetkilométer kiterjedésű, lencse alakú kőzettestek, vastagsága néhány méter lehet. Lényegében vegetáció által táplált karbonátos bekérgezések és a tengeri karbonátos kőzetekhez hasonló szöveti és szerkezeti bélyegekkel jellemezhetőek. Ezek alapján különböző litofáciesekbe és litofácies együttesekbe sorolhatók, s az utóbbiak pedig komplex üledékképződési rendszereket képviselő különleges üledékképződési környezeteknek felelnek meg. A travertínó kőzettestek fejlődési törvényszerűségei sok tekintetben analógok a karbonát platformok rendszerével.

Abstract

Travertines are widespread in Central and Southern Italy, where they formed mostly during late Quaternary times, either from ambient or from hot waters, and now crop out as lensoid bodies up to some square kilometres in extent and several metres in thickness. These deposits, at present-day exceptionally forming, result essentially from calcareous incrustations on plant templates and can be described in terms of textures and sedimentary structures, like marine carbonate rocks. On these bases several lithofacies and lithofacies associations can be identified, the latter corresponding to specific sedimentary environments, grouped into complex depositional systems. The evolutionary trends recorded in the travertine bodies show many analogies with carbonate platform systems.

Introduction

Non marine carbonate deposits form very frequently in a variety of environmental conditions, at ambient temperature (springs, caves, waterfalls, lakes, rivers) as well as at thermal springs and in their vicinities. Such deposits are small in size (from a few 102 m^3 to several 106 m^3, seldom up to 107 m^3) and largely of biogenic origin or primarily accumulated on biotic templates. Two main categories of such deposits are known: lacustrine deposits (BRADLEY 1929; KEMPE et al. 1991; ARP 1995; ARP et al. 1999, 2001) and spring-river deposits referred to as

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travertines (BUCCINO et al. 1978; PENTECOST 1978, 1990; BRANCACCIO et al. 1986, 1992; GOLUBIC et al. 1993; D'ARGENIO 2001). We discuss here the latter category.

Textural and diagenetic features

Travertines are widespread in Central and Southern Italy, mostly deposited during the last uplift stages of the Apenninic chain (middle to late Pleistocene) and quite exceptionally formig today. They derived from ambient and hot waters. Moreover, travertine lithologies are most commonly made up of low Mg calcite, sometimes in excess of 95% (e.g. BUCCINO et al. 1978; D'ARGENIO et al. 1983; FOLK & CHAFETZ 1983; CHAFETZ & FOLK 1984; BRANCACCIO et al. 1986, 1992; D'ARGENIO & FERRERI 1987, 1992).

Textural classification. Several travertine classifications have been proposed by different authors on sedimentological, botanic, chemical and morphological bases (IRION & MÜLLER 1968; CHAFETZ & FOLK 1984; FERRERI 1985; D'ARGENIO & FERRERI 1987; PENTECOST 1995; FORD & PEDLEY 1996). In particular, the sedimentological classification by FERRERI (1985) is based on textural characteristics of the primary carbonate incrustations and inspired by EMBRY & KLOVAN (1971) marine-carbonates classification.

FERRERI (1985) considers two main groups of incrustation textures: autochthonous and detritic (*Table 1*). On this basis several lithofacies and lithofacies associations can be identified. Their analysis and interpretation, together with that of microstructures and sedimentary features (stratification, lamination, erosional surfaces and so on) allows: (1) fossil travertines to be mapped, (2) palaeoenvironmental reconstructions to be inferred and (3) genetic models to be proposed (FERRERI 1985; BRANCACCIO et al. 1986, 1992; VIOLANTE et al. 1994; D'ARGENIO 2001).

Lithofacies associations

At the present stage of our studies (BUCCINO et al. 1978, D'ARGENIO et al. 1983; FERRERI 1985; BRANCACCIO et al. 1986, 1992; D'ARGENIO & FERRERI 1987, 1992; GOLUBIC et al. 1993; VIOLANTE et al. 1994, 1996; D'ARGENIO 2001) the following lithofacies associations have been distinguished (Table 2):

1. Calcarenite with travertine intercalations (shallow lake facies)
2. Phytohermal travertine associated with poorly sorted phytoclastic travertine (swamp facies)
3. Microhermal and stromatolitic travertine associated with grain supported phytoclastic travertine (gentle to steep slope facies)
4. Micro-phytohermal and stromatolitic travertine (pool-gradin facies)
5. Phytohermal and microhermal travertine (waterfall facies)

1. Calcarenite with travertine intercalations (shallow lake facies).

Calcareous sands are made up of calcareous grains among which phytoclasts can be recognized. These are mainly represented by fragments of charophyta (oogonia and "stems"), molluscs and ostracods. The travertine lithotypes are prevailingly formed of phytoclastic wackestone associated with phytohermal and stromatolitic travertine. This lithofacies association characterizes stratified tabular bodies of relatively large horizontal extent deposited in very shallow lakes.

2. Phytohermal travertine associated with poorly sorted phytoclastic travertine (swamp facies).

The most common lithotypes are represented by phytohermal-phytoclastic textures, in which the phytohermal travertine appears "floating" in a poorly sorted phytoclastic matrix. Incrusted leaves are very abundant ("bibliolitic travertine"), but their orientation is random; pulmonate gastropods are generally

Table 1 Textural classification of the travertines of Central and Southern Italy, inspired to EMBRY & KLOVAN (1971)

1 táblázat. Közép- és dél-olaszországi travertínók szöveti osztályozása, EMBRY & KLOVAN (1971) alapján

<table>
<tr><td colspan="7">AUTOCHTHONOUS TEXTURES
(In situ incrustations)</td></tr>
<tr><td colspan="3">Irregularly laminated fabric (<i>cryptalgal laminites</i>) built up by incrustations on blue-green algae and/or other bacteria</td><td colspan="2">"Reticulate" fabric (<i>microhermal</i>) built up by incrustations on microphyta (e.g. green algae)</td><td colspan="2">Rigid framework (<i>phytohermal</i>) built up by incrustations on macrophyta (e.g. reeds, mosses)</td></tr>
<tr><td colspan="3">Stromatolitic travertine</td><td colspan="2">Microhermal travertine</td><td colspan="2">Phytohermal travertine</td></tr>
<tr><td colspan="7">DETRITIC TEXTURES
(Incrusted grains, limited or no transport)</td></tr>
<tr><td colspan="5">Less than 10% >2mm</td><td colspan="2">Greater than 10%>2mm</td></tr>
<tr><td colspan="7">← Phytoclastic grains →</td></tr>
<tr><td colspan="2">Uncemented</td><td colspan="5">← Cemented →</td></tr>
<tr><td colspan="4">With calcareous matrix = 2 mm</td><td>Without Calcareous matrix</td><td rowspan="2">Matrix supported</td><td rowspan="2">Grain supported</td></tr>
<tr><td colspan="2"><10% > 10%
Phytoclasts</td><td>Matrix supported</td><td colspan="2">Grain supported</td></tr>
<tr><td>Calcareous sand</td><td>Phytoclastic sand</td><td>Phytoclastic wackestone</td><td>Phytoclastic packstone</td><td>Phytoclastic grainstone</td><td>Phytoclastic floatstone</td><td>Phytoclastic rudstone</td></tr>
</table>

Note that biogenic textures are made up by calcareous incrustations on in situ plant supports. The detritic textures are formed by arenitic to ruditic, incrusted fragments mostly of plant templates (phytoclasts). In the matrix supported lithologies the phytoclastic matrix is arenitic to siltitic in size. In wackestone to rudstone textures early cementation of the phytoclasts is suggested by development of an intergranular to intragranular biogenic incrustation fabric ("cryptalgal fabric" sensu MONTY 1976). From FERRERI (1985) modified.

*Megjegyzés: a biogén szövet típusok helybenélő vegetáció által táplált meszes bekérgezések termékei. A detrituszos szövettípusok homok vagy kavics méretű, többnyire vegetáció vázelemek (fitoklasztok) bekérgezett törmelékéből állnak. A matrixvázú litofáciesekben a fitoklasztos mátrix homok-iszap szemcseméretű. A wackestone és rudstone szövettípusoknál a fitoklasztok korai cementációját szemcseközti–szemcsén belüli biogén bekérgezés kialakulása eredményezheti (*MONTY *1976 értelmezése szerinti "kriptoalgás" szövet).* FERRERI *(1985) alapján módosítva.*

common. This lithofacies association characterizes lensoid to tabular bodies, with indistinct stratification, suggesting incrustation processes in swamp paleoenvironments.

3. Microhermal and stromatolitic travertine associated with grain supported phytoclastic travertine (gentle to steep slope facies).

Lithofacies are prevailingly represented by microhermal travertine, stromatolitic travertine (sub-horizontal laminae), "bibliolitic travertine" and phytoclastic (packstone, grainstone and rudstone) travertine. Locally the incrusted fragments show a certain degree of imbrication. Moreover, the microhermal incrustations build up either centimetre scale dome structures with a "reticulate" fabric (irregularly interlaced tubules), or centimetre-thick "biostromal" structures, formed by thin layers of iso-oriented (algal ?) tubules. Normally the microhermal travertine shows gradual transition into stromatolitic travertine, generally characterized by more or less inclined laminae (clino-lamination) whose surface patterns consist of alternating microdams and micropools (few centimetres in plane view). At a larger scale, this lithofacies association and the related sedimentary structures characterize irregularly stratified, dam-shaped bodies (mounds) suggesting gentle to steep slope environments. The mounds may locally coalesce with unconformable contacts showing geometries of "onlap" type.

4. Micro-phytohermal travertine and stromatolitic travertine (pool-gradin facies).

This lithofacies association is prevailingly formed by alternating micro-phytohermal and stromatolitic travertine, locally associated with phytoclastic travertine in which coated grains (i.e. oncolites, sensu LOGAN et al. 1964; PERYT 1983) and pisolithes can be recognized. The lithofacies, showing gradual transitions among them, form lensoid levels (few centimetres to few metres in thickness, a few metres in length) and build up convex-planar bodies. Sedimentary structures, that can be attributed to the action of more or less steadily flowing waters, are also found. The textures and sedimentary structures can be related to pool-gradin environments.

5. Phytohermal and microhermal travertine (waterfall facies).

This lithofacies association characterizes clinostratified (high angle) bodies prevailingly formed by phytohermal and microhermal travertine (mostly incrustations on mosses and green algae). These deposits cover, with distinct angular unconformities, previous travertines forming more or less vertical jumps; they suggest waterfall environments. Waterfall height can reach up to 50 m, with a composite front even several hundred metres in extent.

Although the sedimentary organization of travertine deposits shows the same gross features, two end-members can be distinguished: ambient water travertines and hot water travertines (GOLUBIC et al. 1993; VIOLANTE et al. 1994; PENTECOST 1995; FORD & PEDLEY 1996; D'ARGENIO 2001). To the high values of temperature in the springs, a decrease in abundance, size and diversity of the colonizing organisms corresponds. On this basis, the lithofacies diversity and biogenic imprint, carried by primary travertine textures, provide good criteria of distinction between ambient and hot water travertines, both in the field and at micro-scale (D'ARGENIO et al. 1994; VIOLANTE et al. 1994; D'ARGENIO 2001).

Ambient water travertines

Biological control. The basic components of ambient water travertines are carbonate incrustations on biogenic templates. Benthic organisms are able to organise primary carbonate precipitates along their prevailing growth directions, resulting in a rigid framework (skeletal carbonate body) characterised by fast accretion rates. In these conditions, the space is filled by carbonates resulting from the interplay of carbonate precipitation rate and benthic organism growth rates. This process is also affected by the size of biogenic templates, the bigger being the templates the larger the pore space within the primary carbonate incrustations. Yet, travertine textures are strictly related to the biological imprints of the primary carbonate incrustations, and depend on environmental conditions of the travertine producing systems. In active depositional conditions, biocenoses are largely controlled by temperature and water oversaturation with respect to calcium carbonate (i.e. carbonate precipitation rate), usually showing a positive correlation. Moreover, cyanobacteria and other bacteria can play an active role in the primary precipitation of the travertine carbonates (WEED 1889; GOLUBIC 1973; BUCCINO et al. 1978; FOLK & CHAFETZ 1983; CHAFETZ & FOLK 1984; FERRERI 1985; FOLK et al. 1985; FOLK 1993; CHAFETZ et al. 1998; CHAFETZ & GUIDRY 1999; GUO & RIDING 1999). This is reflected in microscopic characteristics, which are very often comparable to a "cryptalgal" fabrics (sensu MONTY 1976).

Diagenesis. Primary incrustation and diagenesis partly coexist in the travertines and locally differentiation of their effects is difficult (FERRERI 1985). Most common diagenetic processes are neomorphism, micritization, bioerosion, pervasive dissolution and late carbonate ("cement") precipitation. In particular: micritization (biomicritization) tends to homogenize the microstructural features, partially or completely obliterating the primary textural characteristics; bioerosion is prevailingly the product of an interaction of biological corrosion by endolithic organisms (including insect larvae etc.) which altogether may lead to a kind of "biokarst" (e.g. GOLUBIC 1969; SCHNEIDER et al. 1983). Late carbonate precipitation occurs in environments which frequently change from phreatic into vadose and largely contributes to strong lithification of the travertine deposits. As a result, interpretation of the original textural characteristics at times becomes problematic, even though these deposits generally present forward relationships between early diagenesis and depositional textures.

Morphology of travertine bodies. The sedimentary organization of travertine bodies shows a variable pattern according to the inherited morphologic features of the substrate. Travertine depositional systems of Central and Southern Italy developed either at the base of the slopes in large intermontane basins (Rocchetta al Volturno) or also facing coastal plains (Pontecagnano, Paestum), or into narrow incised valleys carved into Mesozoic limestones (Tanagro Valley, Liri Valley). The relationships with the substrate, normally still evident, indicate that the travertine bodies, are controlled by the original landforms as far as their overall morphology is concerned. The travertine deposits in turn modify this pre-exiting morphology, gradually becoming independent from it (*Table* 2). In this process the morphology modifies from gentle slopes with flowing water sheets to steeper slopes with rapids and waterfalls. The latter deposits cover the previous flat or

Table 2 Relationships among lithofacies associations, geometry of sedimentary bodies, sedimentary environments, parent waters and substrate

2. táblázat. A litofácies együttesek, az üledékes kőzettestek geometriája, az üledékképződési környezet, a kicsapódás forrásául szolgáló víz és az aljzat közötti összefüggések rendszere

1 **Lithofacies associations**	2 **Lithofacies**	3 **Geometry of sedimentary bodies**	4 **Parent waters**	5 **Sedimentary environments**	6 **Morphological modification of the substrate by incrustations**
Calcareous sand with travertine intercalations	– Calcareous sand – phytoclastic wackestone; – phytohermal and stromatolitic travertine	Tabular sand bodies with lensoid travertine intercalations	Calcium carbonate-rich, standing waters	Shallow lakes and minor swamps with occasional inundations	Incrustations filling flat depressions
Phytohermal travertine associated with poorly sorted phytoclastic travertine	– Phytoclastic-phytohermal travertine; – phytoclastic wackestone; – bibliolitic travertine	Poorly stratified bodies (tabular or lensoid)	Calcium carbonate-rich waters, slowly flowing	Swamps with frequent inundations reworking incrusted plant fragments	Incrustations filling flat depressions
Microhermal and stromatolitic travertine associated with grain supported phytoclastic travertine.	– Microhermal travertine; – stromatolitic travertine; – phytoclastic packstone, grainstone and rudstone; – bibliolitic travertine	Irregularly stratified dam-shaped bodies (mounds) which locally coalesce with "onlap"–type unconformities	Warm or cold calcium carbonate-rich waters, flowing over inclined surfaces	Gentle to steep slopes, locally canalised	Incrustations covering the toe of the slopes giving rise to increase in the steepness
Microphytohermal and stromatolitic travertine	– Microhermal, phytohermal, stromatolitic and phytoclastic travertine; – phytoclastic sand	Plano-convex to planar bodies resulting from interlaced systems of small pools	Laminar floods of warm or cold calcium carbonate- rich waters	Pool gradin	Incrustations draping previous deposits and evolving into steps down to the slopes
Phytohermal and microhermal travertine	– Phytohermal travertine; – microhermal travertine	Clinostratified to vertical drapes forming curtains or arches	Rapid fluxes of canalised, calcium carbonate-rich waters	Rapids and waterfalls	Incrusted curtains unconformably draping previous travertine deposits

As to the morphology of the pre-existing substrate, travertines of Central and Southern Italy developed either at the base of slopes, among large intermountain basin sides (Rocchetta al Volturno) or facing coastal plains (Pontecagnano, Paestum) or even filling narrow valley tracts (Tanagro Valley, Liri Valley).

A közép- és dél-olaszországi travertínók a korábbi aljzatmorfológiának megfelelően vagy nagy intramontán medencék közötti lejtők alján (Rocchetta al Volturno), vagy parti síkságok mentén (Ponzecagnano, Paestum) vagy keskeny völgykitöltésként (Tanagro-völgy, Liri-völgy) képződtek gently sloping travertines, forming sub- vertical "curtains". The progradation of the steeping slopes leaves a flat surface on the summit of the travertine bodies often occupied by swamps and/or very shallow lakes. Being such morphologies due to constructional and not to erosional events, they should not be confused with terraced landforms deriving from the rejuvenation of the relief. In the Apennines the latter processes may often develop at the same time, because the phases of most active travertine formation are related to the reactivation of the faults accompanying the Pleistocene uplift (e.g. FERRERI 1985; D'ARGENIO & FERRERI 1987; 1992).

Evolutionary trends. Architecture of the travertine terraces shows internal dome geometries (mounds) occurring at different scale. As the bulk of travertine accumulation tends to occur along sectors of steeper slopes. This causes progressive modifications of hydrodynamic systems of incrusting waters over time. Upward-growth of travertine deposits gradually decreases original slope angles, so that the incrusting water flow is laterally displaced towards areas of next steeper slope, accounting for coalescence of the travertine mounds.

Due to the frequent lateral shifting of the incrustation processes, travertines accumulate with an overall wedge-shaped geometry: the original top slopes are gradually transformed into gently inclined ramp areas (upward aggradation), limited downhill by steeper frontal slopes (lateral progradation) which evolve into subvertical escarpments (waterfall facies). These contrasting morphologic modifications result in the formation of new sedimentary environments, including (a) ponds and shallow lakes on the flattened top of the buildup and, (b) "braided" channelling along the increasingly steeper margin of the travertine buildup, later evolving into waterfalls.

Hot water travertines

High temperature leeds to elevated carbonate precipitation rates and to decreased abundance, size and diversity of the eukaryotic organisms colonizing the depositional sites. In this case the basic biological components are connected to thermophilic or even hyperthermophilic microbes that allow a lower degree of the lithofacies diversity.

Recent works on thermal water travertines have been provided by FARMER (2000); FOUKE et al. (2000); GUO & RIDING (1999), ALLEN et al. (2000). FARMER (2000) presents a facies model for the Mammoth Hot Spring travertines (Yellowstone), where microbial carbonates develop at decreasing temperature away from the spring. In this spread, the deposits display carbonates produced by different types of bacteria (from hyperthermophile chemosyntetic to photosyntetic cyanobacteria) and by eukaryotes. PENTECOST (1995) discusses the geochemical characteristics of thermal travertines suggesting that they occur in regions where high CO_2 discharge results from tectonic activity associated with volcanism (deep outgassing processes in tectonically active areas). He noted that high-water temperatures lead to rapid CO_2 degassing and high deposition rates (normally >10 mm/a). Very thick travertine deposits may be formed in this way, showing a low facies diversity (VIOLANTE et al. 1994; D'ARGENIO 2001). As to the travertines of Tivoli, detailed sedimentological studies and SEM analysis (e.g. FOLK et al. 1985; FOLK 1993) allowed to demonstrate a high morphological diversity of the calcium carbonate crystals (primary and diagenetic) due to either biogenic or inorganic precipitation (CHAFETZ & FOLK 1984). Here, as in many other cases of thermal deposits, the general morphology and related vertical evolution of the resulting sedimentary bodies do not appear substantially different from that of the ambient water travertines (D'ARGENIO 2001; ANZALONE, doctorate dissertation, work in progress).

Final remarks

Travertines form miniature depositional systems (FERRERI 1985; D'ARGENIO et al. 1994; VIOLANTE et al. 1994; D'ARGENIO 2001; MARTIN-ALGARRA et al. 2003) and display some characteristics which are typical also of the carbonate platforms. They include ability to modify the morphology of the substrate, to colonize differentiated environments (which may in turn be modified by the organogenic sedimentation), to build a frontal rim and to increase the steepness of the frontal scarp. The morphostructural convergence is mainly due to early lithification processes, producing a firm sediment since the early stages of deposition, and to the self-organisation of the biogenic sediments. This results in carbonate deposits characterized by prevailing upward-growth (an aggradation however, that does not exclude the progradation) and very high accretion rates, relatively even higher than in carbonate platforms.

In conclusion, the sedimentary organization of travertine deposits, regardless of the parent water temperature, shows similar features over many case histories examined; so that two end-members can be distinguished: ambient water and hot water travertines. Temperature of parent waters is an important factor controlling biologic development of travertine producing systems and hence the balance between biotic vs. abiotic precipitates.

Comparative analysis of travertines and carbonate platforms reveals that hot water systems seem to re-produce, at very small scale, the environmental conditions characterized by the microbial (bacteria and archea) activity and water oversaturation, under which Proterozoic carbonate platforms developed; ambient water travertine systems can be instead considered as miniature analogous of the Phanerozoic carbonate platforms which are largely built by the more differentiated eukarya assemblage (D'ARGENIO et al. 1994; D'ARGENIO 2001).

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