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Allan Pentecost et Heather Viles

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Essais

A REVIEW AND REASSESSMENT OF TRAVERTINE CLASSIFICATION

Allan PENTECOST and Heather VILES, Division of Life Sciences, King's College London, Camden Hill Road, London W8 7AH, United Kingdom, and St. Catherine's College, Oxford OX1 3UJ, United Kingdom.

ABSTRACT This paper provides a review of the classification of travertines with emphasis on their morphology. Three criteria are used to describe them: geochemistry, microfabric and morphology. Geochemically, travertines may be divided into two groups, the meteoric travertines, where the carrier carbon dioxide originates in the soil and epigeal atmosphere, and the thermal (thermogenic) travertines where the carbon dioxide comes from thermally generated sources. Many travertine fabrics are influenced by bacteria and plants. These include 'stromatolitic' forms, many oncoids, shrubs, tufts, mats and moss travertines. Morphologically, travertines are conveniently divided into autochthonous (spring mounds and ridges, cascades, barrages, fluvial and lacustrine crusts, paludal deposits and cemented rudites) and the allochthonous or clastic travertines (valley-fills, back-barrage deposits, alluvial cones). Travertine deposits often include a wide range of fabrics and morphologies in one system. They are influenced locally by discharge, slope, vegetation, climate and human activity. Intergradations occur, both within travertine types but also with other freshwater deposits, e.g. calcrete and lake chalk. The influence of travertine deposition on the local hydrology and geomorphology is also discussed. The review emphasises the significance of scale and hydrology and aims to provide a unified scheme of travertine classification. Manuscrit reçu le 23 août 1993; manuscrit révisé accepté le 16 février 1994.

RÉSUMÉ *La classification des travertins : revue et réévaluation.* Cette revue met l'accent sur la morphologie des travertins. Leur description repose sur trois critères : la géochimie, la microfabrique et la morphologie. Du point de vue de la géochimie, les travertins peuvent être divisés en deux groupes : les travertins d'eau météorique, où le dioxyde de carbone provient du sol ou de la surface, et les travertins d'eau thermale, où le dioxyde de carbone provient de sources thermales. La fabrication des travertins est souvent influencée par la présence des bactéries et des plantes, ce qui comprend des stromatolithes, de nombreux oncolithes et diverses formes caractéristiques. Du point de vue de la morphologie, les travertins sont autochtones (monticules, cascades, barrages, encroûtements fluviaux ou lacustres, dépôts palustres et rudites cimentées) ou allochtones (dépôts de remblaiement de vallée, de remplissage amont de barrage, de cônes alluviaux). Les dépôts travertineux comprennent souvent un assortiment de fabriques et de morphologies comprises dans un seul ensemble selon le débit, la pente, la végétation, le climat et les activités humaines. On discute également de l'effet de la mise en place du travertin sur l'hydrologie locale et la géomorphologie. Cette revue fait ressortir l'importance de l'échelle et de l'hydrologie et tente de faire ressortir une vision intégrée de la classification des travertins.

ZUSAMMENFASSUNG *Überblick über und Neubewertung der Travertinklassifizierung.* Dieser Aufsatz gibt einen Überblick über die Klassifizierung der Travertine unter Hervorhebung ihrer Morphologie. Bei ihrer Beschreibung werden drei Kriterien benutzt: Geochemie, Mikrostruktur und Morphologie. Geochemisch kann man die Travertine in zwei Gruppen aufteilen: die Verwitterungs-Travertine, wo das Träger-Kohlendioxid aus dem Boden und der epigenetischen Atmosphäre stammt, und die thermischen Travertine, wo das Kohlendioxid aus thermisch erzeugten Quellen kommt. Viele Travertin-Strukturen sind durch Bakterien und Pflanzen beeinflusst. Dies umfaßt "stromatolithische" Formen, zahlreiche Onkoide, Sträucher, Büschel, Matten und Moos-Travertine. Morphologisch teilt man am besten die Travertine in autochthone (Bodenerhebungen und Rücken Wasserfälle, Dämme, Fluß- und Seeverkrustungen, Sumpfablagerungen und verkittete Rudite) und in allochthone oder klastische Travertine (Tal-Auffüllungen, Ablagerungen hinter Dämmen, alluviale Kegel). Die Travertin-Ablagerungen enthalten oft eine große Auswahl von Strukturen und Morphologien in einem einzigen System. Sie sind örtlich beeinflusst durch Wasserführung, Böschung, Vegetation, Klima und menschliche Aktivitäten. Intergradation kommt vor, sowohl innerhalb der Travertin-Typen aber auch mit anderen Frischwasser-Ablagerungen, z.B. Kalkkrusten und See-Kreide. Auch wird der Einfluß der Travertin-Ablagerung auf die örtliche Hydrologie und Geomorphologie diskutiert. Der Überblick hebt die Bedeutung von Maßstab und Hydrologie hervor und sucht ein vereinheitlichtes Schema der Travertin-Klassifikation zu geben.

INTRODUCTION

The word *travertine* is a corruption of *lapis tiburtinus*, a Roman building stone mentioned by several early authors (e.g. Plinius, Statius, Vitruvius). The stone was quarried near the town of Tibur (Tivoli) and probably brought to Rome by boat along the Anio, but the original quarries have not been located and have most likely been excavated out of existence.

Another, softer rock known as *tufa* is mentioned around the same time and was also used for building, but extant descriptions appear to refer to forms of consolidated volcanic ash which are very extensive around Rome. However, the term was exported at an early date — probably before the 12th Century, to Britain, France and Germany where it was termed 'Tuff', 'tufa', 'towfe', or 'tuff', and used for both volcanic ash and softer, poorly consolidated freshwater carbonates. In the early 19th century various prefixes, e.g. 'Kalktuff', 'tuf calcaire', 'calcareous tufa' show that a distinction was being sought between volcanic ashes and travertine.

Today, both *travertine* and *calcareous tufa* are applied to a wide range of freshwater fluvial and lacustrine carbonates. The terms are to a degree interchangeable. We know precisely what is meant by travertine, as it is still quarried at Tivoli, and the term is frequently reserved for resilient forms, sufficiently strong to be sawn and used as load-bearing masonry. Most people use the term *calcareous tufa* for the softer varieties which would be unsuitable for building (e.g. Flügel, 1982; Burger, 1990). Recently, Hubbard and Herman (1990) advocated the use of 'travertine-marl' as a general term for surficial carbonates deposited from springs and streams, including unconsolidated deposits containing some clay, while Julia (1983) uses travertine as a general term for "all the carbonate incrustation on plant remains (in place and debris) without reference to pore volume or density".

The distinction between travertine and tufa is based mainly on the degree of cementation, which is neither easy to define in terms of its limits nor measure. The need to distinguish between travertines, tufas and deposits such as lake-chalks, calcretes and stromatolites has been recognised for many years and a number of schemes have been proposed but there is still much confusion. No 'standard' classification exists because most authors have described deposits from limited areas, of which few if any, contain the whole range of known travertines.

The delimitation of rock types with respect to their formation processes facilitates the recognition and understanding of freshwater carbonate facies throughout the geological record. It is indispensable in survey work where a researcher may only be interested in a particular travertine type. With a substantial literature on the recognition and classification of travertines, particularly in the last decade, we decided to look at all of the descriptions, seek common ground and provide a summary of available knowledge. Our principal aim is to present a unified classification, emphasising travertine morphology and its influence on other landforms. The review covers both actively forming and inactive travertines and the classifications should be appropriate to travertine deposits of all

ages. However, less is known of travertines deposited prior to the Pliocene, and most of our examples belong to the Quaternary.

TRAVERTINE CLASSIFICATION SCHEMES

Three main criteria have been used for travertine classification; 1) geochemical 2) fabric and 3) morphology. Classification schemes based on these criteria are not mutually exclusive, but it is convenient to consider them separately.

GEOCHEMISTRY

A recent proposal by Pentecost (1993) separates the travertines according to the origin of the carrier carbon dioxide. This is reflected to a considerable degree in their composition (bulk and isotopic) and provides a division dependent upon the source and interaction of the carbon dioxide.

Two classes of travertines are recognised: a) the meteorogenic travertines and b) the thermal, or thermogene travertines. In the former, the carrier CO₂ originates in the soil and epigeal atmospheres forming deposits primarily in limestone terrains. These travertines are the most widely distributed and often display characteristic fabrics. Their stable carbon isotope compositions range mostly from about 0 to -11‰, reflecting the depleted ¹³C of soil CO₂ (Deines, 1980).

The second group consists of 'thermal' travertines. Waters responsible for these deposits are normally hot and the carrier CO₂ results primarily from the interaction between hot rock and CO₂-rich fluids (Ohmoto and Rye, 1979). The carbon dioxide comes from a range of sources including hydrolysis and oxidation of reduced carbon, decarbonation of limestone or directly from the upper mantle, mainly in areas of volcanic activity. The high concentrations of carbon dioxide are capable of dissolving large volumes of carbonate. Rates of degassing and deposition from these hot waters tend to be rapid, providing distinctive fabrics and a stable carbon isotope composition usually in the region -4 to +8‰. This ¹³C enrichment often reflects the heavier carbon released from decomposing marine limestones, but significant contributions from mantle CO₂ can result in the deposition of travertines depleted in ¹³C. These travertines have a more restricted distribution, being located primarily in regions of recent volcanic activity. It is important to distinguish between these travertines, and those formed from hot meteorogenic waters resulting from deep circulation. The latter possess low CO₂ levels derived from soils and are invariably depleted with ¹³C, with no thermal source of CO₂. An alkalinity titration is often sufficient to distinguish between them.

FABRIC

The term fabric refers to the architecture of the deposit (*i.e.* the arrangement, density and size of the building units). Density is related to deposit porosity and the nature of the porosity provides valuable clues to the mode of deposition. Bacteria and plants in particular can influence the travertine fabric. Also of importance is the rate of deposition, the mineralogy, and the extent of diagenesis (Viles and Goudie, 1990a). Travertine fabrics provide the basis of several

classification schemes, most of which emphasize the influence of plants. Prát (1929) classified Czechoslovakian deposits into moss and algal types and Pevalek (1935) distinguished four types: *Cratoneuron*, *Bryum*, *Agrostis-Schizothrix* and *Schizothrix*. The same theme was adopted by Irion and Müller (1968) and in some cases, distinct fabrics result from particular plant growths, e.g. *Vaucheria*-tufa (Wallner, 1934; Pentecost, 1990a), *Schizothrix*-tufa (Schafer and Staf, 1978) and *Cratoneuron*-tufa (Pentecost, 1987). The fabric of some cool-temperate and alpine travertines is modified by colonisation by tube-dwelling Diptera, e.g. *Lithotanytarsus* (Thienemann, 1950, Symoens *et al.*, 1951).

Fabrics influenced by bacteria are quite common but can be difficult to recognize. A number of thermophilic bacteria, including *Chloroflexus* can produce striking thread-like forms in some thermal deposits. These are known particularly from Mammoth Hot Springs, Wyoming and Le Zitelle, Italy. More subtle effects may be produced by other bacteria where they assist in pool-shrub formation (Chafetz and Folk, 1984; Folk *et al.*, 1985) and other feather-like structures, but their identity is not yet known. Cyanobacteria are commonly found on travertines of all types and produce a range of small radiating structures. In some cases they produce striking daily or seasonal laminae as a result of movement, selective trapping and/or photosynthesis (Golubić, 1969; Pentecost, 1990a).

Larger plants also leave their mark. Decay of leaves, branches and twigs provides a distinctive mouldic porosity. Leaf moulds of marsh plants are common in travertine. Exceptionally, moulds of fruit and even bird feathers are encountered. Ordoñez and Garcia del Cura (1983) present a petrographical classification scheme for travertines in central Spain, providing details of different types of deposit found in channels. Pedley (1990) expands on the petrographic theme to include a number of environmental factors.

Deposits devoid of obvious plant life are also common, and often are referred to as 'sinter'. These display a range of fabrics. One of the most striking is 'foam rock' formed when travertine is deposited around gas bubbles. These are mainly thermal deposits, as are many, but not all pisolitic forms. Rapidly deposited aragonite often displays characteristic 'cedar tree' structures consisting of radiating or sub-parallel aragonite crystal bundles (Kitano, 1963). Very large 'ray crystals' are also known from some ancient thermal travertines (Folk *et al.*, 1985). 'Carbonate rafts' are a common feature consisting of thin carbonate sheets which develop at a static air-water interface (Allen and Day, 1935) Dunn (1953) and Bischoff *et al.* (1993) describe several fabrics from the travertine lake towers of Mono Lake, California based on crystal arrangement and porosity, namely 'thinolitic', 'dendritic' and 'lithoidal'. The latter term has also been applied to certain thermal travertines, but is ill-defined. Travertines may also be classified under several broader schemes applied to limestone fabrics in general (Tucker and Wright, 1990).

MORPHOLOGY

Travertine morphologies are extremely varied and reflect accretionary rather than erosive processes. Depending upon the degree of cohesion between the crystals, deposits range

from soft and chalky to dense and massive with high relief. It is important to consider scale in any geomorphological classification, differentiating between major forms (e.g. barrages) and much smaller forms such as oncoids. Ordonez *et al.* (1986) use a three-fold classification describing 'macrostructure' as controlled by position relative to the water table and topography, 'mesostructure' as controlled by ecology and 'microstructure' as controlled by the efficiency of degassing. Much of what follows refers to the travertine macrostructure.

Earlier in the century several attempts were made to classify deposits according to their form and setting. One of the first was by Klahn (1923) who described three forms from German rivers, though Gregory (1911) had previously described in detail the accretionary processes occurring on some Yugoslavian waterfalls. Eisenstuck (1949) developed Klahn's work which was followed by Stirn (1964), Gruninger (1965) and Frey and Probst (1974) in the Swabian Alps. Several independent studies describing barrages and cascades were made at this time, e.g. Matonickin and Pavletic (1962), Heinrich (1967) followed by Jux and Kempe (1971) and Mongini (1973), but no comprehensive classifications appeared.

More recently, the morphology of several thermal travertines have been described by Chafetz and Folk (1984) who recognised five basic forms: waterfalls/cascades, lake-fill, mounds (sloping or terraced) and fissure ridge. Scheuer and Schweitzer (1989) illustrate morphologies of many thermal Hungarian travertines, explaining them in terms of local geomorphology.

In France, Fabré (1986) describes six meteorogenic travertine typologies including an artificial 'travertin anthropique' while Freydet (1990) provides a morphological classification of spring and fluvial travertines in northern France, splitting them into 'moss travertine', 'mobile' forms (oncoids, etc.) and 'encrusted' forms and thus focuses on medium to small scale features. Magnin *et al.* (1991) on the other hand, split travertines in southeast France into two main types; spring and river-valley travertines. Valley-fills include travertine barrages and back barrier deposits, which together form a 'travertine system'. A list of travertine types, classified according their environmental setting is provided by Pedley (1990) namely 'perched springline', 'cascade', 'fluvialite' (braided and barrage types), 'lacustrine' and 'paludal'. This was elaborated further by Ford and Pedley (1992) who also proposed a three-way split into 'cool water', 'thermal' and 'saline' travertines. A study of British deposits revealed that most deposits could be classified satisfactorily into seven groups (Pentecost, 1993) but the scheme is of limited value worldwide because Britain contains comparatively few forms, and thermogenic travertines as defined above, are entirely lacking.

The morphological classification below groups the travertines into nine categories, divided into two sub-groups. The first sub-group contains all of the autochthonous deposits associated with springs, streams, rivers, lakes and marshes and concludes with the allochthonous (clastic) travertines (Table I). The scheme embodies descriptions from many published sources, plus our own observations from a wide range of sites. Virtually all known travertines can be assigned to one

TABLE I
A unified scheme of travertine classification

Factor					
Geochemical	THERMAL (THERMOGENE)		METEOGENE		
	AUTOCHTHON			ALLOCHTHON	
Large-scale features (Morphology and topographic position)	<p>SPRING</p> <p>Fissure ridge</p> <p>Mound</p>	<p>RIVER</p> <p>Cascade Cemented rudites benches</p> <p>Barrage</p>	<p>LAKE</p> <p>Crust</p>	<p>MARSH</p> <p>Paludal deposits</p>	<p>CLASTICS</p> <p>lake and valley - fills, bars, alluvial cones (often cemented)</p>
	AUTOCHTHON				
Small-scale (Micromorphology and Microfabric)	<p>MICROBIAL</p> <p>many ONCOIDS</p> <p>"Stromatolites"</p> <p>Algal tufts eg VAUCHERIA</p>		<p>BRYOPHYTE</p> <p>"moss" and hepatic tufas</p>	<p>INORGANIC</p> <p>"foam rock" carbonate rafts</p> <p>"sinter" most pisoids</p>	<p>CLASTICS</p> <p>intraclasts peloids</p>

of these categories, but we emphasize, along with many previous writers, that 'travertine complexes' consisting of a range of intergrading forms sometimes occur, and may defy all attempts at classification. In the examples cited below, actively-depositing sites are distinguished as (A).

AUTOCHTHONOUS TRAVERTINES

Spring mounds (Fig. 1.1)

These occur in two situations. Emergent spring mounds consist of domes of travertine, < 1 m up to 50 m in height surrounding a spring orifice. The most impressive domes are of thermal travertine and many examples are known throughout the world. Detailed descriptions of a range of Slovakian forms are given by Scheuer and Schweitzer (1985). One the largest is that at Homestead, Utah, (A) measuring 20 m in height. Other well known active sites include Hammam Meskoutine (Algeria) and Mammoth Hot Springs (Wyoming). Impressive mounds may also develop in meteo gene travertines, numerous examples occurring in Australia, e.g. the Great Artesian Basin and the Kimberley region (Viles and Goudie, 1990b).

The second type is the submerged mound which occurs in saline lakes. These result from the mixing of Ca-rich springwaters with saline, carbonate-rich lake water leading to immediate precipitation of calcium carbonate. The results can be dramatic, forming spectacular towers, mounds and 'tombstones'. Good examples are known in the Western Great Basin of the United States and include Mono, Pyramid,

and Searles Lakes (Dunn, 1953; Bischoff *et al.*, 1993) A huge tower is also known from Abbé Lac, Tchad (Fontes and Pouchan, 1975).

Fissure ridges (Fig. 1.1)

These result from build-ups around spring orifices along fractures (joints or faults). The ridges range from 1 to 15 m in height, and may be up to 0.5 km in length. Many inactive ridges are known, e.g. Elephant Back, Mammoth, Hamman Mescoutine (A), and Soda Dam, New Mexico (Chafetz and Folk, 1984). A spectacular actively building ridge occurs at Terme San Giovanni Battista near Siena (Italy).

Cascades (Fig. 1.2)

Two types of cascades can be distinguished at active sites: erosively-shaped deposits, paraboloid in section which are often fluted with their surface morphology largely controlled by spate water trajectory. These are most common on high vertical falls. Examples (all active) include Sitting Bull Falls, New Mexico, the falls at Urach (Germany), Terni (Italy) and Huangguosho (China). Other cascades appear to be indefinitely accretionary and occur where the rate of deposition exceeds erosion. This type only occurs on precipitous rock where deposition rates are high or erosion low. Examples include the falls of Krka and Topolje in former Yugoslavia and those on the Rio Salitre, Brazil (Branner, 1911). Caves are often found behind cascades where the

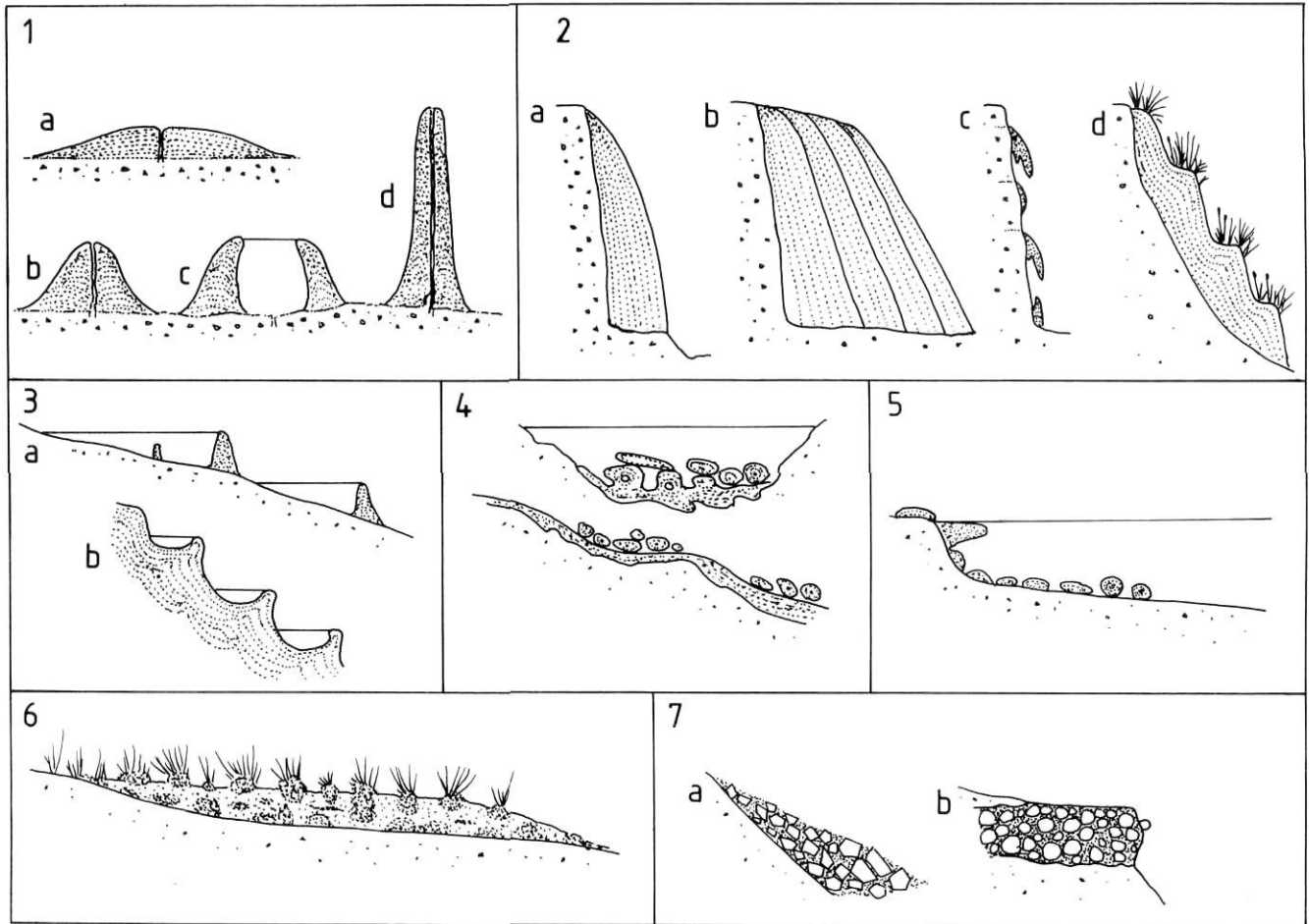


FIGURE 1. Sectional drawings of autochthonous travertine morphologies. 1) Spring mounds and fissure ridges: a) low mound, b) steep mound or fissure ridge, c) mound with central pool, d) tall submerged lake mound; 2) cascades: a) erosion type, b) indefinitely prograding, c) remora, d) cron; 3) barrages: a) large lake barrages, b) barrage system on travertine slope; 4) fluvial crusts: bed veneers and oncoïdes, partially cemented; 5) lacustrine crusts showing reef, small mounds and oncoïdes; 6) paludal deposit showing centres of cementation around plant tussocks; 7) surface-cemented rudites; a) scree, b) alluvial bench.

Coupes des formes de travertine autochthone. 1) monticules de source et dôme allongé à fissure : a) monticule étalé, b) monticule à versants raides, c) monticule troué, d) monticule lacustre submergé élevé; 2) cascades : a) d'érosion, b) en progression continue, c) remora, d) cron; 3) barrages : a) grand barrage de lac, b) ensemble développé sur pente de travertine; 4) encroûtements fluviaux : plaquages et oncoïdes, partiellement cimentés; 5) encroûtements lacustres : formes récifales, petits monticules, oncoïdes; 6) dépôts palustres : cimentation autour de touffes de végétation; 7) rudites à surface cimentée; a) éboulis, b) banquette alluviale.

travertine has built out over a cliff leaving a space behind. One of the best examples is the Olgahöhle in Germany (Schmid *et al.*, 1972). Solutional caves are known in both meteogene and thermogene travertines.

A number of prograding cascade sub-types are recognisable, *e.g.* keeled-cascades where the water flows along a narrow slot before plunging over a prominent travertine nose (Pentecost, 1993). Examples (A) are the Rohrbach (Germany) and Maurienne cascade (France). A frequent form is the Belgian *cron*, characterized by a series of boggy hollows and a rich flora (Symoens *et al.*, 1951 Pentecost and Lord, 1988; Pentecost, 1993). Crons form a link between cascade and barrage types Another common variant, occurring mainly in warmer parts of the world is *Aussenstalaktiten* typified by slow or intermittent water flow over steep slopes (Matonickin and Pavletic, 1962). Pentecost (1993) renamed

these deposits 'remora' as they may include other speleothem isomorphs, *e.g.* flowstone and stalagmitic forms.

Barrages (Fig. 1.3)

These are distinguished from cascades by their vertical accretion leading to water impoundment as pools, ponds and lakes. Barrage height varies from a few centimetres to about 50 m, but most barrages range from 0.2-5 m in height. These build-ups seem to start around local obstructions or on slope-breaks (Lambert, 1955). Lang *et al.*, (1992) recognise two barrage types, namely 'cascade' and 'retention' the latter characterised by clastic backfills. The larger barrages impound spectacular lakes, the best known being that at Plitvice, in the former Yugoslavia (Emeis *et al.*, 1987). Barrages also develop on pre-existing travertine surfaces where deposition rates are high. These structures tend to be smaller 0.3-4 m

and often develop into 'pulpit basins' (Weed, 1889; Geurts *et al.*, 1992). Good active examples are known from Mammoth Hot Springs (Wyoming) and Pammukale (Turkey). Barrage erosion can lead to the formation of natural arches, as in the Auvergne and Provence (France).

Fluvial crusts (Fig. 1.4)

Fluvial crusts include a range of superficial deposits formed in the running water of small streams and large rivers. They develop on a variety of substrata and may be smooth and sheet-like or nodular and coralloid. Detached crusts, called *oncoïds* develop around stone or plant nuclei and may be spherical or spheroidal. Both oblate and prolate spheroidal oncoïds are common and their morphology depends upon the shape of the nucleus (twig, pebble, shell) and the depth of water. It should be noted however that 'oncoïd' is a general term for accretionary pebbles, — other types are known from soil horizons and marine sediments.

Fluvial crusts are to be found along all gradients and merge with cascades/barrage deposits. They are common along river courses in arid regions, *e.g.* the Wadi tufas of North Africa and the Middle East. In Britain, fluvial crusts are the most common type of presently-forming travertine. Thermal travertine crusts sometimes grade into low-relief mounds around spring orifices, *e.g.* Bullicame (Italy).

Lacustrine crusts (Fig. 1.5)

These share some features with fluvial crusts. They consist mainly of oncoïds and superficial coatings on littoral sediments and larger reef-like accumulations. Oncoïds, up to 30 cm diameter occur in regions subject to significant currents (*e.g.* Bodensee, Germany) but are usually in the range 2-15 cm. Oncoïds, which require a rolling action to develop, are formed only where wave action or water currents are significant. Well known modern sites include the Finger Lakes (New York), Karstic Lake, Yugoslavia (Golubić, 1969), lakes near Zahle, Lebanon (Adolphe *et al.*, 1976) and the Oligocene deposits of Limoges (Freytet and Plaziat, 1982). Some unusual lake crusts occur in Lago Grande (Mexico), built around the cyanobacterium *Scytonema* (Pentecost and Winsborough, unpubl. obs.). Travertines occur in lakes with salinities ranging from < 1 to > 300‰ TDS, and evaporation, in addition to degassing, is probably responsible for their formation at many sites. We would argue against the use of 'saline travertine' at present because of the difficulty of assigning limits to the prevailing salinity. There are also problems defining deposits in lakes where salinity varies widely (*e.g.* Great Salt Lake, Utah).

Larger accumulations of travertine are often found attached to sediments or submerged rock walls at lake margins. The deposits usually occur in shallow water (0-10 m), and may form spectacular rim-like reefs at the lake edge. Their origin is unclear, but deposits are associated with 'whitings' in Green Lake (New York), where some form of agglutination process, possibly microbially mediated occurs (Thompson and Ferris, 1990). Similar deposits occur in Lake Annecy, France (Casanova, 1981) and Pozzo Azulas, Mexico. The latter is a small spring-fed lake remarkable for

the occurrence of large blade-like morphologies in deeper waters. Whitings do not appear responsible for these deposits but microbial (diatom) activity is suspected (Winsborough and Golubić, 1987). Other anomalous forms include the 'big heads' of Walker Lake, Nevada, (Newton and Grossman, 1988). Lake crusts, spring-mounds and laminated travertines in general are frequently referred to as 'stromatolites' (*e.g.* Casanova, 1981; Smith and Mason, 1991). The widely accepted definition of stromatolites as 'organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes' (see Walter, 1976) certainly covers some, though not all travertine types. The term is all too loosely applied to these rocks at present.

Paludal deposits (Fig. 1.6)

These are low-relief accumulations often including much carbonate mud. They are found in marsh environments with slow-flowing water and much vegetation. Local centres of consolidation are provided by grass and moss cushions. Deposits occur worldwide but active sites appear to be limited in populated regions where wetland drainage and water-table lowering seem to have led to their demise (Goudie *et al.*, 1993). A well known example occurs at Ehringsdorf, Germany (Steiner and Wagenbreth, 1971). These deposits are often found mixed with marls and chalks, and are often rich in fossils, especially Mollusca.

Surface-cemented rudites (Fig. 1.7)

These travertines intergrade with calcrete which originally referred to such deposits (Lamplugh, 1902). Ironically, travertine best describes such coarse materials cemented at the surface via degassing, while calcretes are now normally regarded as carbonates forming within soil profiles (Wright and Tucker, 1991). Surface-cemented rudites consist of cemented scree, alluvium, breccia, gravel, etc., as a result of degassing to the epigeal atmosphere, but it is not always possible to distinguish between near-surface and hypogeal cementation, the latter resulting from precipitation from calcite-supersaturated groundwaters. Cemented gravels are highly resistant to erosion, forming pronounced benches in many parts of Britain (Pentecost, 1993) and elsewhere.

ALLOCHTHONOUS TRAVERTINES (Fig. 2)

Forming in turbulent environments, travertines frequently undergo erosion soon after they have precipitated. Consequently many travertines accumulations contain a significant proportion of clastic material. Travertine-marls forming in marshy environments are especially prone to redeposition and many predominantly clastic deposits have been identified. Typical morphologies include bars, lenticular 'spreads' in flood horizons, valley-fills and alluvial fans. Back-fills in travertine-dammed lakes often consist of mixture of clastic travertine and lake chalk.

Pedley (1990) further classifies clastic deposits into five types: 'phytoclast tufa' (cemented crusts formed around plants); 'oncoïdal tufa'; 'intraclast tufa' (silt to sand sized particles deposited as grain-supported fabrics); 'microdetrital tufa' (primarily lake chalks) and 'peloidal tufa' (only detectable

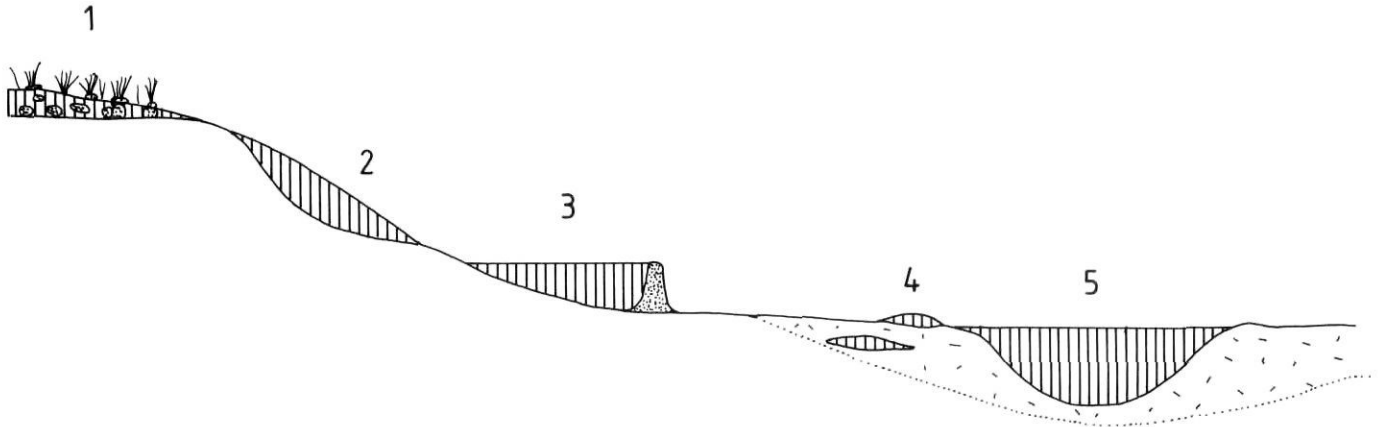


FIGURE 2. Sectional drawing illustrating main forms of allochthonous travertine deposit: 1) paludal complexes, 2) alluvial fans and other slope deposits, 3) back-barrage fill, 4) floodplain bars, 5) valley fill. Stippled area: travertine dam; short dashes: non-calcareous alluvium.

Coupe des principales formes de dépôts travertineux allochtones : 1) ensemble palustre, 2) cône alluvial ou dépôt de pente, 3) remplissage amont de barrage, 4) barre de plaine d'épandage, 5) remblaiement de vallée. Trame pointillée : barrage de travertin; trame en tirets : alluvions non calcaires.

microscopically). Pedley (1987, 1990) uses the term 'phytoherm' to distinguish travertines formed in association with bacteria and plants which have developed *in situ* but include a variable amount of cemented clastic material. The term however is not strictly a plant equivalent to 'bioherm', which has also been used (*e.g.* Lang and Lucas, 1970) and generally understood to imply a mass of cemented bioclasts, the latter consisting of actively calcifying marine organisms (algae, coral, etc.). Travertine algae, though becoming encrusted with carbonate, do not biomineralize in the same way as marine invertebrates and are not strictly bioclasts (see Pentecost, 1990b).

A unified scheme of travertine types employing the three criteria is shown in Table I. Here, the deposits are divided into groups based upon their geochemistry, morphology and fabric. Allochthonous and autochthonous forms are separated and the principal morphological and fabric types are shown.

TRAVERTINE AND GEOMORPHOLOGY

Geomorphology has been seen to influence travertine development, but the deposit in turn can have a major impact on fluvial systems as they affect topography and water flow rates. Thus the presence of barrages can have a dramatic impact on a river system changing the pattern of erosion and alluviation. This in turn has implications for the further development of 'travertine systems', providing clastic materials and a range of new environments for travertine deposition. Golubić (1969) regards travertine barrage systems as having a cyclicity of development followed by degradation and stream incision. In Derbyshire, England the Wye valley travertine barrage system appears to be undergoing degradation as growth has been reduced and erosion proceeds apace (Pedley, 1993).

Where a sequence of travertine deposits exists the paleogeomorphology can be interpreted. Thus Pedley (1987) shows how the Caerwys travertines of Wales developed after initial incision of a tributary of the River Wheeler from a braided stream system with travertine deposition as oncoids

and detrital facies. Subsequently a barrage system developed producing sluggish water flow upstream of a braided stream system downstream. Finally, the River Wheeler tributary breached the main barrage leading to incision, water table lowering and cessation of travertine deposition.

In other cases external events may influence both travertine deposition and the local geomorphology. Heimann and Sass (1989) illustrate how travertine deposition over a wide area prevailed under sluggish water conditions in the Hula Valley Israel for hundreds of thousands of years. Deposition ceased when tectonic activity led to the incision of river channels and water table lowering. Travertine-depositing springs are frequently fault-controlled (Julian and Martin, 1981; Pecsí *et al.*, 1982), and when the faults are active significant changes in water flow are to be expected.

On a smaller scale, deposition of cascade travertine can have a significant impact on slope geomorphology by changing the angle of slope and protecting the underlying surface from erosion. As documented for many areas periodic breaches of travertine falls can occur either because of external changes, or perhaps a combination of the two. As an example, a travertine cascade at Gordale England was abandoned when the stream bed was lowered by flood waters in the early 18th Century. In the Napier Range, NW Australia, cascade deposits commonly show an older, abandoned deposit next to an active accumulation (Viles and Goudie, 1990b). Increasing human impact on travertines is also widespread and well documented and often results in the loss of active deposition. Effects include eutrophication, lowering of the water table, and deforestation as detailed in Goudie *et al.* (1993).

RELATIONSHIPS WITH OTHER FRESHWATER AND TERRESTRIAL CARBONATES

Travertines are frequently found associated with other calcareous deposits. In particular, paludal and clastic barrage back-fills often contain chalks and marls. These are distinguished from travertine by their lack of vuggy porosity, lack

of early consolidation and more or less horizontal bedding. Both travertine and chalk have been found associated in lakes with salinities ranging from <1 to >300 ppt TDS, and mixtures may be referred to as 'travertine-marl'. Autochthonous-allochthonous mixtures are common often leading to difficulties in interpretation.

Travertines are less often associated with calcretes, but this may occur at lake margins, where lacustrine crusts occur adjacent to supralittoral calcretization resulting from rising groundwater. The travertine itself may become incorporated into the calcrete if lake levels fall, and no longer become recognisable. This phenomenon appears to have occurred on a large scale at the margins of the ancient Lake Gosiute (Green River Formation, Wyoming, see Eugster and Hardie, 1978). One of us (A.P.) has noted such occurrences around the lakes of San Salvador, Bahamas and some of the playa lakes near Cuatro Cienegas, Mexico.

Carbonate speleothems are formed in the same way as travertine, namely by the degassing of calcium bicarbonate solutions, though photosynthesis plays no part in their formation and their fabrics are hardly influenced by plant growth. A number of authors refer to these carbonates as travertine (e.g. White, 1976) though we have limited our discussion to surface. The relationships between these carbonates and the hydrological regime is shown in Table II. Considerable overlap between the deposits is possible in marshes and soils where a range of precipitation processes operate, *i.e.* photosynthesis, microbial mineralisation, evaporation, degassing and diagenesis.

CONCLUSIONS

There is considerable interest in the Quaternary freshwater carbonates as they are frequently rich in fossils and provide valuable information on the aquatic and terrestrial

fauna. The travertines have been shown to exist as a variety of forms and there is a need for a simple classification scheme to aid their recognition. The classifications used (geochemical, fabric, morphological) will depend upon the type of investigation under taken. Geochemical classification is of value when considering the groundwater sources and predicting the fabrics. The fabric itself may be used to determine the extent to which the deposition was associated with plants and bacteria, and also the type and degree of diagenesis. This in turn can provide useful information on local environments at the time of deposition. An attempt has been made to classify travertine on morphological grounds considering both the scale of the processes involved (*e.g.* slope, discharge) and the depositional history (autochthonous vs. allochthonous). Knowledge of topography and prevailing climate may now be sufficient to allow at least some prediction of the forms to be expected in a given region.

There is still much to be learnt about travertine deposition however. Periodic structures such as gours and barrages still lack adequate explanation as none of the hypotheses concerning them has been adequately tested. Modelling the process may never be possible in systems with irregular stream beds where turbulence is unpredictable.

Precipitation of carbonates in the presence of plants also gives rise to complications and uncertainties. While it is easy to demonstrate abiotic travertine precipitation in the laboratory, the potential of plants and bacteria for catalysing precipitation of carbonates is well known and cannot be neglected. There is still a need for carefully conducted laboratory experiments involving plants under conditions simulating the natural environment. It would appear that any significant advance in our understanding of travertine formation will require a multidisciplinary approach involving chemists, physicists and biologists.

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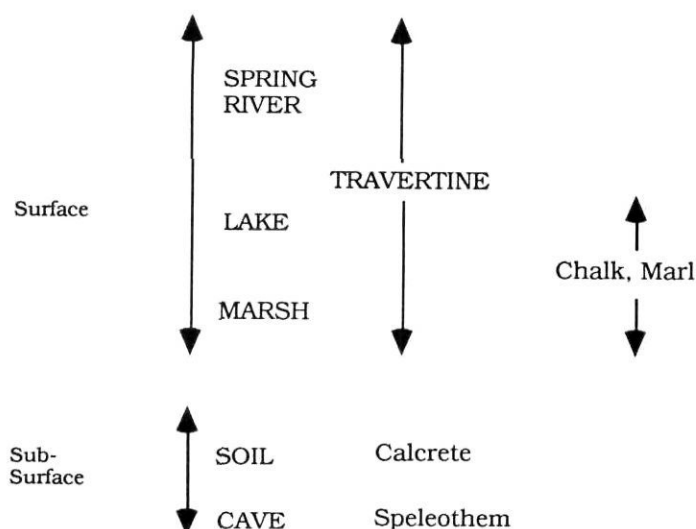
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TABLE II

Travertine in relation to other freshwater / terrestrial carbonates



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