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A review of tufa and travertine deposits of the world

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Abstract

A general review of the nature and classification of tufas is presented and the available literature is summarised. An attempt is made to standardise the terminology currently in use and to distinguish clearly between ambient temperature deposits (tufas), thermal deposits (travertines) and speleothems. Consideration is also presented of the physico-chemical and biological processes, often acting together, which are responsible for the precipitation of freshwater calcium carbonate within tufa systems. These processes appear to be climatically controlled. Therefore, tufas may be of value in palaeo-environmental reconstruction, especially if intercalated with peaty material. While the majority of tufa deposits are of post-glacial age some of the most spectacular carbonate precipitates are thermal travertines.

The second part of the paper deals with a world-wide survey of the principal deposits of tufa and travertine. Space prevents a fuller account of the European deposits and the reader is referred to Pentecost (1995) for a wide range of specific examples from Europe and Asia Minor.

Keywords: Tufa; Travertine; Biofilms; Depositional models; Ambient; Thermal; Classification; World review

1. Introduction

The term "tufa" has had a long usage within English speaking cultures although the United States of America is a notable exception. Tufa as a general name covers a wide variety of calcareous freshwater deposits which are particularly common in late Quaternary and Recent successions. Today they form under a wide range of climatic regimes from cool temperate to semi-arid. Carbonate deposition frequently is extremely local at such sites as waterfalls (e.g. Janet's Foss, Yorkshire) and springs. Tufas may also cover wide areas, sometimes kilometres in length, where a great variety of lithofacies are developed from well cemented and massive transverse fluvial barriers to loose and thinly laminated lime muds (e.g. Plitvice National Park, Croatia).

Descriptive terms used in studies of tufas are confused and some are inaccurate. The term tufa, derived from *tophus*, as used by Pliny, was extensively used in Roman times to describe crumbly whitish deposits (either calcareous tufa, or volcanic tuff). The definition is now clearer since use of the term tufa in defining pyroclastic materials has virtually been abandoned in favour of well established term "volcanic tuff". Tufa is the product of calcium carbonate precipitation under a cool water (near ambient temperature) regime and typically contains the remains of micro- and macrophytes, invertebrates and bacteria. Typical examples are well seen in

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Roman buildings at Pompeii near Naples (Fig. 1) where, in addition to a dimension stone, it is also used for decorative purposes in alcoves.

A rival term adopted by modern workers, especially in the United States, Spanish speaking countries and parts of Europe is travertine, derived from *lapis tiburtinus* or Tibur stone, from the river upon which Rome stands. Unlike our definition of tufa, see later, the Roman occurrences, still being quarried at Bagni di Tivoli some 30 km east of Rome, are of hydrothermal origin and generally contain no macrophytes or invertebrates. Travertines are dominantly hard, crystalline precipitates (some can be friable), frequently with thin laminations and with shrub-like bacterial growths. The travertines commonly pass laterally into more typical open tufa fabrics in areas where the water has cooled to near ambient temperatures. Consequently, to avoid confusion, in this article we reserve the term tufa for all cool or near ambient temperature freshwater low-Mg carbonates regardless of degree of lithification. The term travertine is thus restricted to all "freshwater" thermal and hydrothermal calcium carbonate deposits dominated by physico-chemical and microbial precipitates, which invariably lack in situ macrophyte and animal remains.

This is compatible with the suggestions of Pentecost (1993) and Pentecost and Viles (1994) who, whilst adopting the term travertine for all deposits, separate them on the basis of temperature. They adopt the term "meteogene" for deposits which are CO_2 sourced from soil and atmosphere, and the term "thermogene" for deposits where the CO_2 is sourced from a range of situations including hydrolysis and oxidation of reduced carbon, decarbonation of limestone or directly from the upper mantle. Meteogene deposits form principally in limestone areas whereas thermogene deposits are more common in regions of volcanic activity. According to Pentecost (1995) the waters at active meteogene sites show a depletion in ^{13}C whereas thermogene waters generally are enriched. It is also pointed out by Pentecost (1995) that the rapid degassing and cooling of waters at active thermogene sites leads to a higher precipitation rate than at meteogene sites.

A further, and as yet ill-defined group of travertine-like calcium carbonate deposits, occurs in evaporite lakes and evaporative hyperalkaline situations

Fig. 1. Tufa blocks extensively used in house construction within the Roman town of Pompeii, Italy.

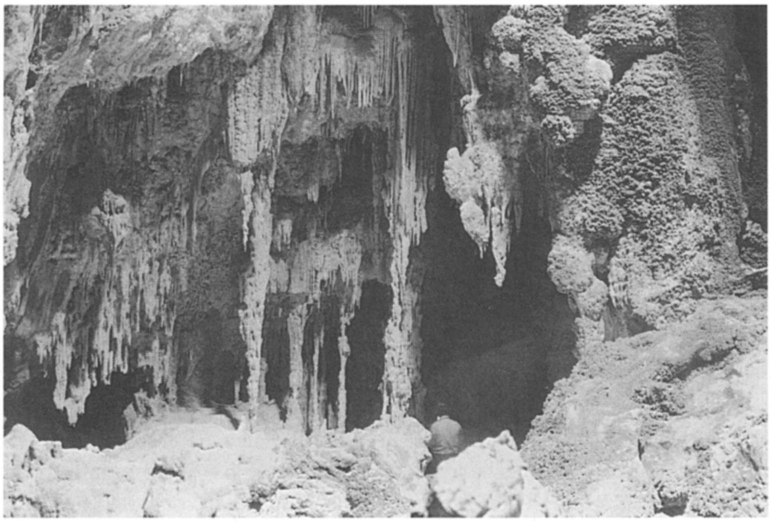


Fig. 2. Tufa speleothems developed at a cave entrance, Daylight Hole, Markham Cave, Chillagoe, Queensland. Australia.

often associated with relatively high ambient temperatures. Again these are dominantly microbial and physico-chemical constructions therefore it appears appropriate to include them in the travertine classification.

It is important to reiterate the fact that lithological hardness is no indication of genetic affinity for there are many crystalline and hard tufas, as well as friable travertines. Tufas are usually distinguishable from travertines, even in ancient deposits, by the comparatively high diversity of contained plants, including macrophytes, and animals. Where confusion in the field is most commonly encountered it is where tufa and travertine are interlayered, such as in distal areas of thermal flow which have cooled sufficiently to permit colonisation by micro- and macrophytes (e.g. margins of the Mammoth Hot Springs, Wyoming, USA). Nevertheless, the water chemistry of these cooled waters may contain elevated amounts of sulphur, carbon dioxide and other elements not normally associated with ambient water tufa precipitates. Some of these peculiarities will be inherited in the precipitated carbonates.

Speleothems (Pia, 1933), are deposits common in caves (stalactite, flöe calcite etc.) but also frequently encountered as an infill to pre-existing tufa and travertine fabrics, and consequently, can appear deceptively like travertine. Speleothems are produced in unlit and poorly lit cavities and inter-particle sites, from ambient temperature waters dripping from cavity walls (Fig. 2) and seepages through tufas. Rarely do these cements contain any biological material but principally are formed by physico-chemical precipitation of calcium carbonate. Speleothems may be considered as the inorganic end member of a continuum which, at the other extreme is represented by biomediated tufa. It is recommended (Pedley, 1990) that the term tufa be adopted for all varieties of non-hydrothermal and fluvially related freshwater calcareous deposits containing bacteria, plants and animals, regardless of degree of crystallinity or age. The term ''sinter'' should be restricted to siliceous hot spring deposits and not applied to calcareous tufa, travertine or to speleothems.

2. Self-regulating systems

Tufas are self-regulating systems in that they appear to defy the rules of what we have come to expect from natural fluvial regimes. They develop under the influence of flowing freshwaters and yet their systems tend to be aggradational rather than degradational. They generate their own carbonate sediments and exclude virtually all other siliciclastic materials. Their naturally regulated flow regimes rarely suffer spate conditions. Many carbonate clasts within tufa systems are cyanoliths or oncoids which are biogenic entities and increase in size, frequently with clast size being inversely proportional to flow rate. Indeed many of the largest clasts are found in virtually static sites and grow both downwards into the substrate as well as towards sunlight. True detrital material also occurs but generally is derived from local tufa degradation.

Furthermore, tufa systems commonly develop reefs (phytoherms) which range from small patches or cushions especially near pool margins, to major barrage constructions (also known in the literature as tufa dams, weirs or tetaratas, Jakucs, 1977). These develop transversely across river valleys by a combination of macrophytes, microphytes and procaryotes (Fig. 3). By this process, abnormally high local watertables can be achieved and maintained. Finer tufaceous carbonate sediments can accumulate upstream of the constructions and uniquely horizontal fluvio-lacustrine terraces will result from later drainage and partial erosion of such sites. Even after periodic incision of the river, fragments of these horizontal terraces may remain although better cemented barrage fragments will best survive. All this is achieved because of the unique association between procaryotes and plants, and physico-chemical precipitation.

3. Tufas

Several independent schemes of sedimentological or geomorphological classification have been proposed (Symoens et al., 1951; Butzer and Hansen, 1968; Irion and Muller, 1968; Golubic, 1969; Geurts, 1976; Nicod, 1981; Szulc, 1983; Chafetz and Folk, 1984; Viles, 1988; Viles and Goudie, 1990a). Many others are based on botanical criteria such as Schneider (1977), Schneider et al. (1983), Pentecost and Lord (1988) and Pentecost and Viles (1994). Yet others are process based (e.g. Julia, 1983). These schemes have led to great confusion; however, the bones of a satisfactory scheme, based on petrology and facies associations, are to be found in Buccino et al. (1978); Ordoñez and Garcia del Cura (1983);

Fig. 3. Submerged transverse tufa barrage in the Krka River, Skradin Falls, Croatia.

Ferreri (1985); Pedley (1990); Golubic et al. (1993) and Violante et al. (1994).

If the lowest common denominator in the field, the lithofacies association, is first considered, it is clear that the complexity of lithofacies in tufa systems derives directly from the influence brought about by underlying substrate irregularities. Violante et al. (1994) suggest two fundamental depositional morphotypes. The first involves damming of a river, often within a gorge section, by means of one or more transverse orientated tufa barrages ("Barrage Travertine System"). This directly compares with the "fluvial barrage model" of Pedley (1990). The second system of Violante et al. (1994) involves the formation of a valley-side-sited, wedge-shaped sedimentary body ("Slope Travertine System"). This conforms directly with the "perched springline model" of Pedley (1990).

The barrage system is now known in fine detail from work carried out on active systems in the Plitvice National Park, Croatia (Golubic, 1969; Kempe and Emeis, 1985; Srdoc et al., 1985) and in Ruidera National Park, Albacete Province, Spain (Ordoñez and Garcia del Cura, 1983; Ordoñez et al., 1986; Pedley et al., 1996) and in Holocene and active sites in Derbyshire and N. Wales, UK (Pedley, 1987, 1993). The perched springline or slope system is now well documented in central and southern Italy (Pedley, 1990; Golubic et al., 1993; Violante et al., 1994). However, the two distinct systems represent composite end members of a spectrum of interrelated systems. For example the barrage system may contain aspects of the braided fluvial model, and of the lacustrine model of Pedley (1990); the perched springline (slope) system also encompasses elements of the cascade and paludal models of Pedley (1990). Each natural system rarely is entirely of one model system. One notable exception is waterfall or cascade tufa which can be developed locally to the exclusion of other tufa fabrics (e.g. Janet's Foss, Yorkshire). Most natural tufa occurrences are, however, composed of elements of the following models which are described in more detail in Pedley (1990).

3.1. Fluvial

(a) *Braided fluvial model*: cyanolith and oncoid dominated shallow braided rivers with phytoclastic lenses, small marginal phytoherms associated with microdetrital lime muds, asymmetrical flow-aligned bacterioherm (stromatolite boundstone) growth on stream bed. *Examples*: Duero Basin, Spain; Ditton, Kent and part of the Lathkill valley, Derbyshire, UK; Carl Creek, Queensland, Australia.

(b) *Barrage model* (barrage system): developed commonly in gorge sites from the damming of flowing water by a number of arcuate, downstream facing transverse phytoherm barrages or dams (Fig. 4). Lime muds accumulate in the ponded upstream areas and may be associated with smaller marginal phytoherm patches (Fig. 5). Barrages are narrow but may be the sites of macrophyte colonisation. *Examples*:

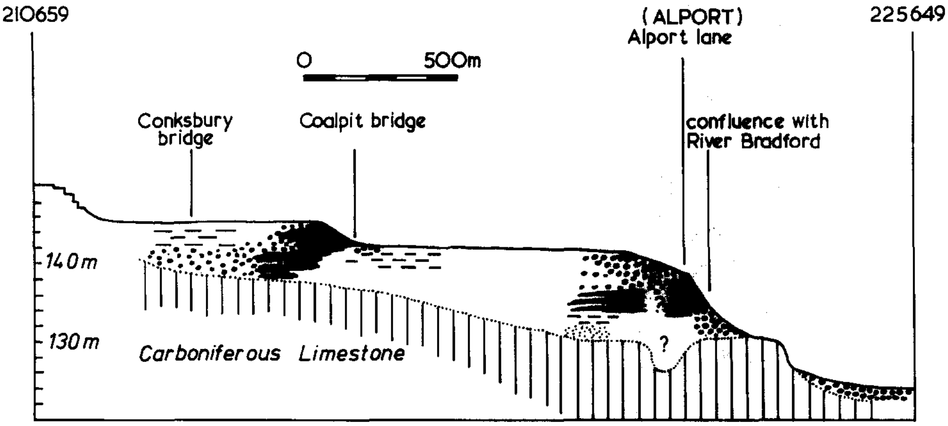


Fig. 4. Profile of barrage tufa systems parallel to flow of the River Lathkill, Derbyshire, England. Phytoherms in solid black, oncoids shown as circles and dots, and marly tufa by broken horizontal lines (modified from Pedley, 1993).

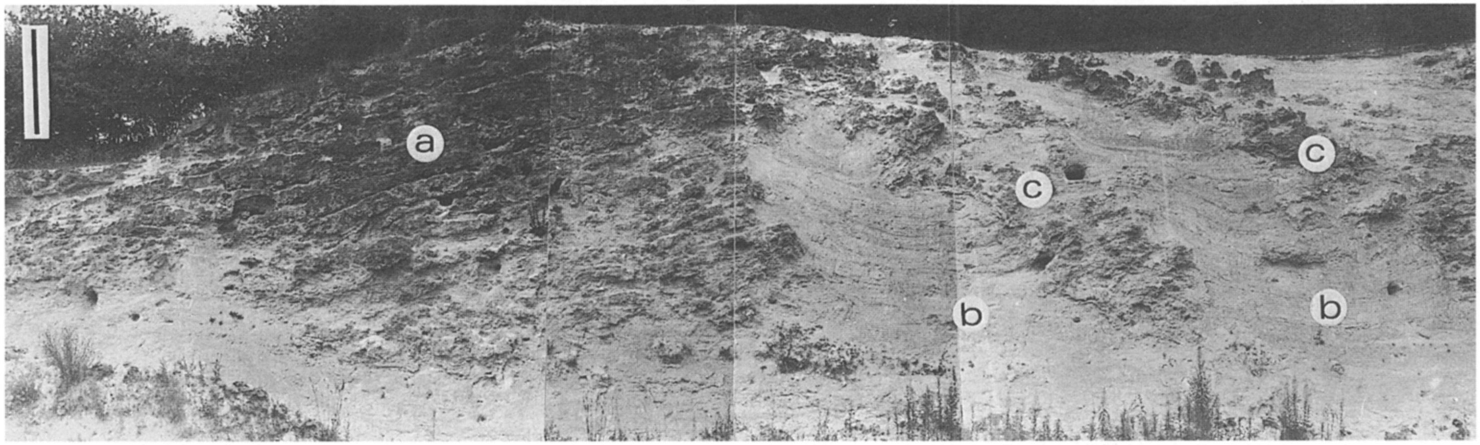


Fig. 5. Phytoherm framestone barrages (a), laminated lime mud pool deposits (b), associated with secondary phytoherm deposits (c), within a Holocene barrage tufa deposit, Caerwys quarry, North Wales (modified from Pedley, 1993).

Fig. 6. Typical Holocene perched springline tufa deposit in the upper reaches of the Rio Tajuna, showing the characteristic flat top and steep front of the lobate deposit. Upstream of Brihuega, central Spain.

Plitvice National Park, Croatia; Ruidera Pools Natural Park, Spain; Caerwys; Lathkill and Wye valleys, UK; Band-e-Amir, Afghanistan; d'Immouzer and Ida du Tanane, Morocco; Onilahy valley and Sept-Lakes, SW Madagascar; Turner Falls, USA; tufa springs, Mt. Etna, Queensland, Australia.

3.2. Perched springline (slope system)

(a) *Proximal.* Lobate or multilobate, convex to flat surfaced deposits, thickening away from source and developed from a spring or stream system resurgence some way up a pre-existing valley side (Fig. 6). Distributaries develop on the surface of the deposit and become foci for precipitation, The steeper faces, where tufa growth is fastest, may bear microterraces, gutter cascades and gullies (some containing stromatolite hemispheroid growths). Areas closer to source in well developed sites may become subhorizontal and partly ponded (Fig. 7), with very slow aggradation associated with paludal conditions.

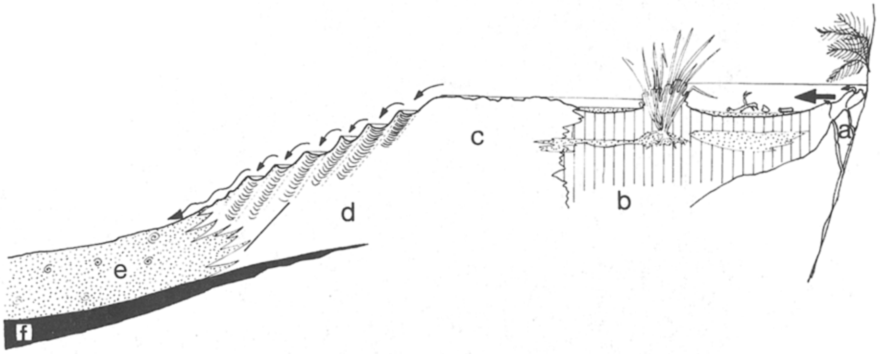


Fig. 7. Simplified perched springline tufa model involving paludal developments (b), close to a resurgence point (a). A thick lobate framestone deposit partly built by terracettes (c) forms the main feature. Distal deposits are dominated by microdetrital tufas (e) and palaeosols (f). Modelled from deposits near Cozo Marotta, southeast Sicily (modified from Pedley, 1990).

(b) *Distal*. Typically these are low-angle sheet-like deposits of fine intraclast tufa, but with rare phytoclast lenses associated with local channels. Palaeosol levels are common. *Examples*: Noto, S. Italy; Rochetta a Volturno, Central Italy; Matlock, UK; "Crons" of Belgium. The vast Antalya complex, S.W. Turkey is dominated by perched springline systems but has built out subsequently into a multi-terraced deposit also including paludal and lacustrine aspects.

3.3. Lacustrine

Associated with large static bodies of freshwater where lake margins often are sites of "algal bioherms" or bacterioherms. Generally these reefs are microbial in origin and consist of laminar stromatolite-like encrustations growing laterally and upwards from the lake margins (Fig. 8). Frequently the top of these bacterioherms are flat (controlled by water depth) and bear a pronounced overhang.

Where water depths are less than 5 m, it is common to find stands of the alga *Chara* and the associated production of sand grade microdetrital carbonate. Much of the lake floor commonly is covered in lime mud which may be associated with the products of seasonal algal blooms within the water column. *Examples*: Green Lake, New York; Quaternary Pyramid Lake, Nevada; Miocene Ries Crater, Germany; lakes associated with barrage tufas at Ruidera Pools Natural Park, Spain.

3.4. Paludal

Many European tufas develop on poorly drained slopes which are colonised by hydrophytic macrophytes, bryophyte hummocks, and rarely by lichens. Calcium carbonate-enriched waters seeping through this cover deposit "spring chalk" on the surfaces of the vegetation (Fig. 9). Small ephemeral pools may develop on the valley bottoms and may persist long enough to allow carbonate encrustation of associated macrophytes and aquatic vegetation. Microdetrital tufa (lime mud) may also accumulate locally within the pools, partly from precipitation on site and partly from material washed in from the surrounding marshy slopes (Fig. 10). Coarser lithoclastic material may enter the system by this route and leaf fall may also

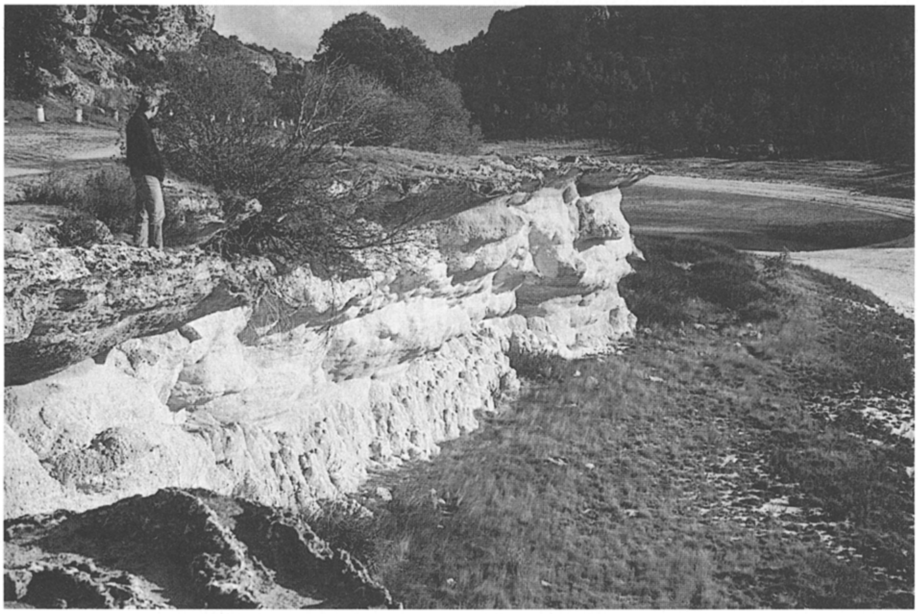


Fig. 8. Recent marginal lacustrine stromatolite build-ups consisting of conical growth-forms (base), mammilated lateral growths (middle) and overhanging stromatolite developments (top). The original water level coincided with the top of the overhang, Laguna Lengua, Ruidera Pools National Park, near Ossa de Montiel, Albacete Province, central Spain.

lead to the deposition of humus-rich layers (gyttja) within shallow, standing water bodies. *Examples*: Tanagro valley, central Italy; Hula valley, Israel.

3.5. Subaerial associations

It must be noted that all tufa systems are susceptible to local switching within drainage patterns and short-term fluctuations in water table which may lead to gully incision. Indeed, Golubic (1969) emphasises that tufa development is cyclic and that deposition is terminated at the end of a natural cycle by incision and erosion of the deposits. Relatively elevated areas become sites of palaeosol development (Fig. 11) or general karstification. Indeed, it is not unusual to find surface-cemented screes and alluvium associated with extremely thin tufa developments in subaerial settings such as in the Chalk uplands of eastern England. Condensation of faunas frequently is associated with these omission surfaces and there may be a dominance of pulmonate molluscs. Internally, there may be the development of vadose calcite cements and speleothems and the mobilisation of Fe and Mn which frequently precipitate about the fluctuating air/water interface.

4. Travertines

These are higher-temperature systems under our proposed nomenclature. In a survey Waring (1965) listed several thousand thermal springs around the world of which several hundreds are noted as depositing "tufa" (travertines under our nomenclature); no details are given but there is a bibliography of over 300 items.

Travertines show less macrofacies diversity than tufa systems on account of their relatively limited lateral extent and biota. They do, however, present an almost bewildering array of microlithologies asso-

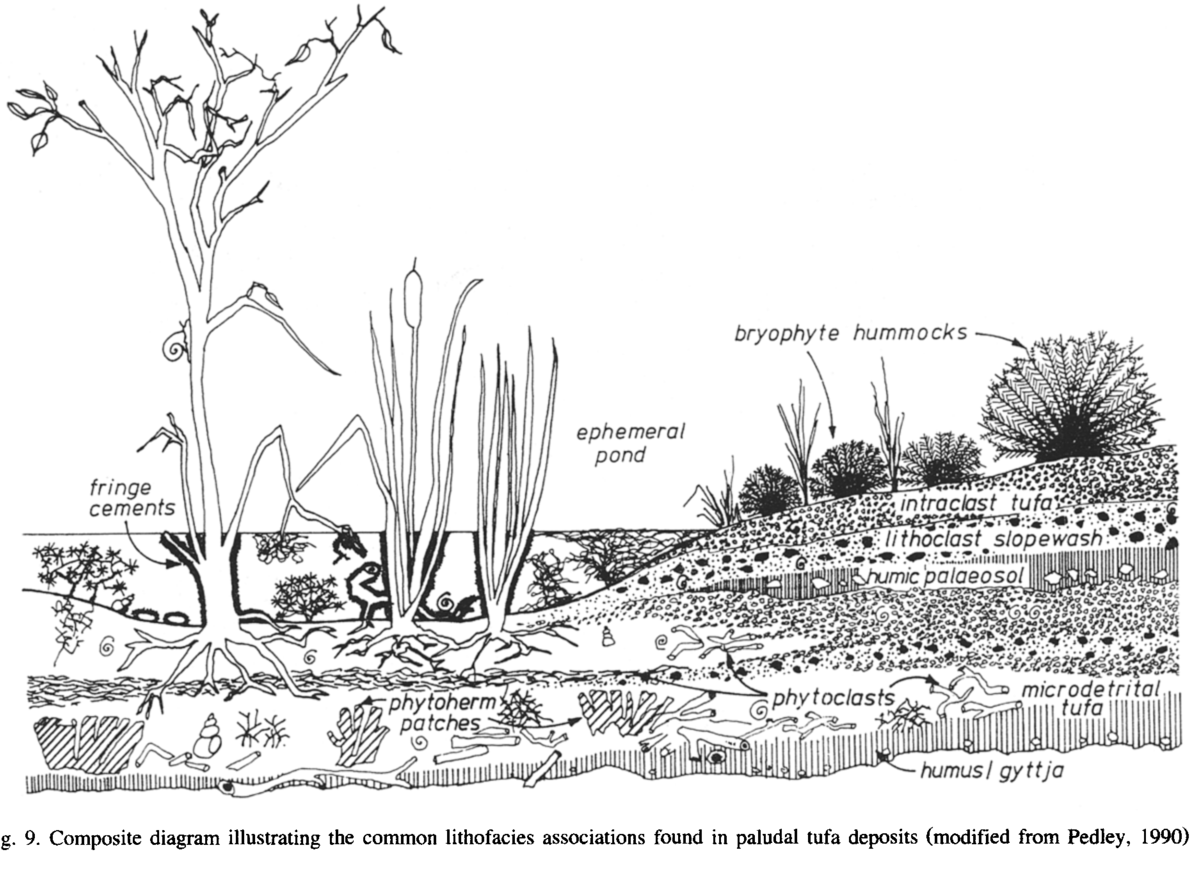


Fig. 9. Composite diagram illustrating the common lithofacies associations found in paludal tufa deposits (modified from Pedley, 1990).

Fig. 10. Profile section parallel to transport of a Recent paludal tufa. The pale beds are microdetrital tufa with small phytoherm patches and local erosion surfaces; the dark beds furthest from the observer are humic palaeosols with peats and sapropels. 5 km east of El Jardin village, Albacete Province, central Spain.

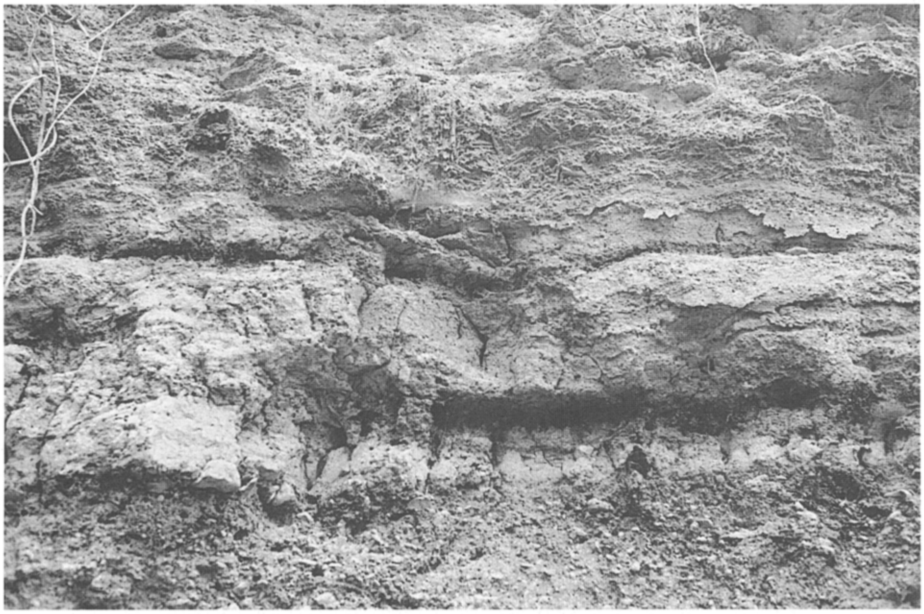


Fig. 11. Details of a Holocene paludal tufa showing an oncoidal bed (lower third of view), two thin palaeosols in the middle (black), and phytoclast tufas (above). Hydro-electric power station section 3 km east of Alcarez, Albacete Province, central Spain.

ciated with bacterial and physico-chemical precipitation. As water temperature falls towards ambient conditions, higher orders of organisms are able to colonise and the system grades imperceptibly into a tufa-depositing situation. However, the thermal waters frequently contain a range of toxic substances (e.g. sulphide and other mineral salts) which adversely affect thermophile bacterial colonisation processes and may prevent climax community development. From our survey we recognise two principal systems:

4.1. Fissure ridges

In areas prone to faulting, hydrothermal hot waters (and gasses) frequently rise along linear resurgences. Much of the crystalline carbonate precipitates in the immediate vicinity of the fissure and narrow, but high calcium carbonate travertine mounds result. Some develop a characteristic cleft-like median valley or elliptical depression above the resurgence and this may subsequently develop into a thermal pool. Pinnacles develop from point-sourced waters. Internal bedding consists of regular, steeply dipping, planar laminae, sometimes with small rimstone pool developments distally. *Examples*: Parts of the Pamukkale deposit, Turkey; Rapolano Terme, central Italy and present in most thermal areas.

4.2. Terraces

Complex terraced travertine deposits develop as lobate planar sheets away from thermal resurgences. Generally they are steepest proximally, where they are often associated with terracettes, terrace gutters, small cascades and descending flights of shallow arcuate pools (Fig. 12). Point-source resurgences often develop into pinnacles or towers (see above) whereas distal areas may carry waters cool enough to permit localised stands of rushes. The deposits are well lithified in the form of smooth-topped sheets. A variant of these is the range front sheets which develop as wide planar spreads down upfaulted graben flanks from thermal fissures. *Examples*: Pamukkale (in part), Turkey; Mammoth Hot Springs, Yellowstone, USA; Bagnaccio Bullicame; Bagni di Tivoli, Italy; Blumberg and Stuttgart deposits, Germany; Hammam–Meskoutine, Algeria; Coal River Springs, Yukon, Canada.

5. Saline tufas or travertines

A number of evaporative lacustrine and hyperalkaline sites also produce tufa and travertine-like precipitates and extinct systems of the same origin also occur. Deposits take the form of tower- and

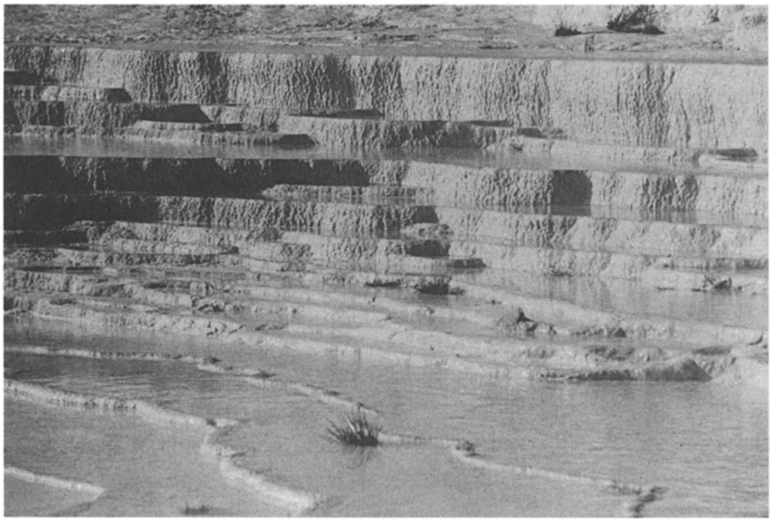


Fig. 12. Recent travertine terraces showing characteristic vertical rimstone walls and terraced pool developments. Pamukkale, Turkey.

Fig. 13. Holocene and Recent tufa towers in a saline lake. The localised build-ups are not restricted to the lake margins but grow where lake bed freshwater springs dilute the brines. Mono Lake, California.

pyramid-shaped masses which are developed within the standing water bodies (Fig. 13). The precise mechanism of formation is uncertain; however, they may represent the resurgence points of freshwater, sometimes thermal, into the saline lakes containing waters already at elevated temperatures. This freshwater ingress would permit locally the dilution of the lake brines, thereby facilitating growth of bacteria and cyanobacteria in addition to physico-chemical precipitation caused by CO_2 degassing. From the constructional viewpoint the deposits might be considered as travertines. However, it is salinity rather than temperature which has excluded the macrophytes. Nevertheless, on the basis of their limited biota they are here classified for convenience as travertines. *Examples*: Searles Lake and Mono Lake, California and hyperalkaline lakes in Jordan, Oman and Israel.

6. Lithological associations

Many attempts have been made to classify tufas and travertines petrologically with varying success. Attempts to use vegetation associations are often of value (e.g. Pentecost and Lord, 1988) on account of the wide variety of macro and microphytes available according to flow regime and climate (see table 1 in Pentecost and Viles, 1994). Macro- and micro-vegetation invariably are major components of many tufa systems and serve to distinguish tufa deposits from travertines (Fig. 14). On the other hand, bacteria and cyanobacteria frequently play a dominant role in travertine precipitation (Folk, 1994). Bacteria and cyanobacteria in particular are fundamental agents in the growth of bacterioherm fabrics including the circumrotatory forms (oncoids and cyanoids).

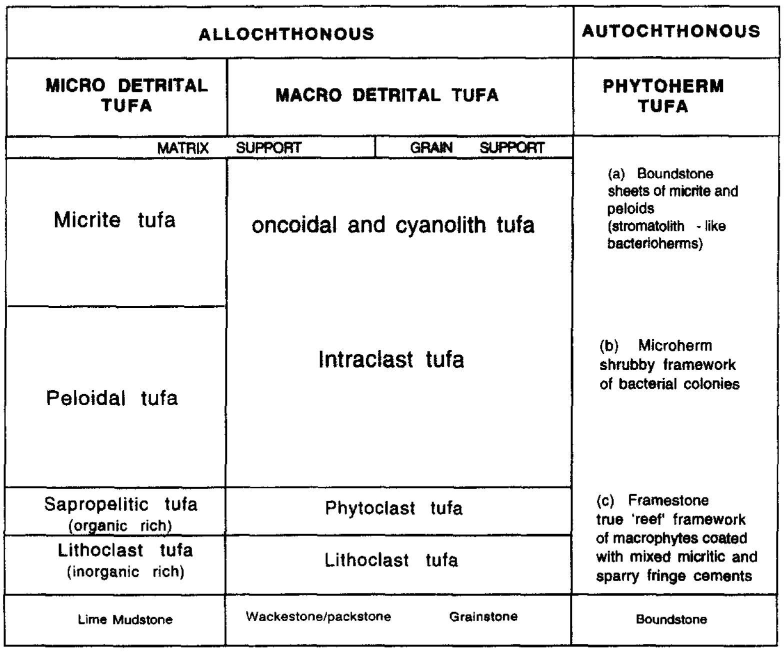
Others have adopted a sedimentological approach (Ordoñez and Garcia del Cura, 1983; Pedley, 1990) or a petrological approach (e.g. Buccino et al., 1978; Ferreri, 1985; Violante et al., 1994). All are valuable, but a fruitful approach would be to combine elements of each into a scheme such as that proposed in Fig. 15 based on Buccino et al., 1978; Ferreri, 1985; Pedley, 1990 and Violante et al., 1994. Here, allochthonous accumulations (microdetrital, phytoclast and intraclast tufa) are separated from autochthonous deposits (phytohermal constructions where there is an in situ organic framework). The scheme conforms to the classification of Dunham (1962) the terminology for which is inserted at the bottom of Fig. 15; however, it also includes an essential separation of lithological types based on

Fig. 14. A typical waterfall site producing modern tufas in association with macrophyte hummocks (bryophytes) and hanging angiosperm roots. Caves (extreme left) develop behind the overhangs. The tufa fabrics often show vertical layering. Plitvice National Park, Croatia.

genetic origin of the various dominant allochemical components such as oncoids or cyanoliths, intraclasts, phytoclasts and lithoclasts. As these can make up widely variable percentages and an equally wide range of component sizes (often equally related either to mechanical transport, or to semi-in-situ biological growth in the case of cyanoids and oncoids), there is no appropriate nomenclature according to clast size for phytoclast tufas.

7. Precipitation processes

Traditional theory has focussed on tufas being wholly physico-chemical precipitates which deposit close to resurgent points, riffles and waterfalls where calcium carbonate enriched waters rapidly de-gass (e.g. Sweeting, 1972; Braithwaite, 1979; Lorah and Herman, 1988). The degassing, principally of CO_2, generally is associated with a cooling of the waters



ALLOCHTHONOUS			AUTOCHTHONOUS
MICRO DETRITAL TUFA	**MACRO DETRITAL TUFA**		**PHYTOHERM TUFA**
MATRIX SUPPORT		GRAIN SUPPORT	
Micrite tufa	oncoidal and cyanolith tufa		(a) Boundstone sheets of micrite and peloids (stromatolith - like bacterioherms)
Peloidal tufa	Intraclast tufa		(b) Microherm shrubby framework of bacterial colonies
Sapropelitic tufa (organic rich)	Phytoclast tufa		(c) Framestone true 'reef' framework of macrophytes coated with mixed micritic and sparry fringe cements
Lithoclast tufa (inorganic rich)	Lithoclast tufa		
Lime Mudstone	Wackestone/packstone	Grainstone	Boundstone

Fig. 15. A scheme for the classification of tufa deposits on the basis of fabric type. Based on the more usual terminology applied to tufa deposits but also applicable to thermal travertines.

away from source and results in the precipitation of tufaceous carbonate on all available surfaces whether animal, plant or rock. Pentecost (1995) points out that active tufa precipitation is severely limited by low temperatures as this severely restricts soil respiration and limestone dissolution. Thus, regimes with higher rainfall and temperatures should encourage tufa formation. There is some general support for this idea in that the Late Quaternary Atlantic climatic optimum appears to be associated with an acme in tufa precipitation.

Generally it is believed that the $CaCO_3$ is taken up into percolating meteoric waters which first have passed through soil profiles above limestone lithologies. Here, biogenic elevated CO_2 levels inherited from the soils act on the underlying karstic surfaces and calcium carbonate is removed into solution (Geissner, 1959; Atkinson and Smith, 1976; Atkinson et al., 1978; Drake, 1980). The enriched solutions then travel variable distances within the subsurface before emerging at springs. This of course implies a very close genetic relationship with speleothems.

Alternatively, seasonal temperature shifts affecting the solubility of CO_2 and calcite have been cited by Rodrigo et al. (1993), and Brunskill (1969) as a principal factor initiating inorganic carbonate precipitation "whitings" and lake chalk deposition in Lake La Cruz, Spain and Green Lake, New York. There is some indication that this process is a self-regulating mechanism which prevents eutrophication within otherwise organic-rich lake environments. Nevertheless, phytoplankton photosynthesis probably assists the development of these precipitates.

Currently, tufas are seen to be a product of both physico-chemical precipitation and biogenic precipitation associated with biofilm colonisation (Adolphe et al., 1989; Pedley, 1992, 1994). There is usually a close association between the biofilms and organic nutrients often released from decaying vegetation. Heterotrophic bacteria actively metabolise the carbon and nutrients from this material, but appear to precipitate calcium carbonate outer shells as an involuntary byproduct (see later). A useful summary of the salient precipitation processes appears in Violante et al. (1994). In essence, during physico-chemical precipitation the degree of water saturation with respect to $CaCO_3$ increases as pCO_2 of water decreases in the downstream direction and this is a requirement before precipitation can commence. A rise in CO_3^{2-} content must also occur before precipitation can commence and this is often assisted by turbulence along the river course and by temperature change (see reactions in Dandurand et al., 1982; Violante et al., 1994). A pH of c. 8 is also necessary. As free CO_2 decreases within the waterbody following the rise in pH values, physico-chemical precipitation decreases.

However, uptake of C and HCO_3 by means of photosynthesis and bacterial metabolic process leads to further CO_3^{2-} activity. Macrophyte-induced precipitation, often in the form of surficial precipitates on the stems of submerged vegetation (e.g. *Chara*), may occur. Nevertheless, much of the precipitation will be biomediated as micrite by means of delicate procaryote–microphyte biofilms (Pedley, 1992, 1994). These biofilms consist of microbial communities, generally dominated by diatoms, cyanobacteria and heterotrophic bacteria (Fig. 16), which often are united in a common coating of extracellular polymeric substances (EPS). Over a hundred species of bacteria and cyanobacteria have been identified in European deposits, though only a dozen are common and these are dominated frequently by *Phormidium* (now *Lyngbya*), or *Schizothrix* (Pentecost, 1990, 1992). Precipitates have been recorded both on diatom stalks, within the sheaths of cyanobacteria (e.g. *Rivulariacea*) and also within the communal EPS. Coccoid heterotrophic bacteria frequently show a calcified outer shell. Bacterial colonies typically develop as polynucleate bodies which develop ultimately, by further precipitation, into peloids after death of the individuals. Furthermore, the sticky biofilm surfaces and individual mucus sheaths to filamentous blue greens also trap and stabilise detrital lime mud (Pentecost and Riding, 1986; Pedley, 1994) and in this respect show the close genetic link between biomediated tufas and marine stromatolites (Pedley, 1992). Thus, there is a shift in precipitation mechanisms from a dominantly inorganic system at the resurgence point to a predominantly biogenic one further downstream (Merz and Zankle, 1991). Precipitates from both processes frequently alternate and build thick encrustations over vegetation (Fig. 17).

The biofilm process is further complicated by relative exposure to turbulence, detritus damage and

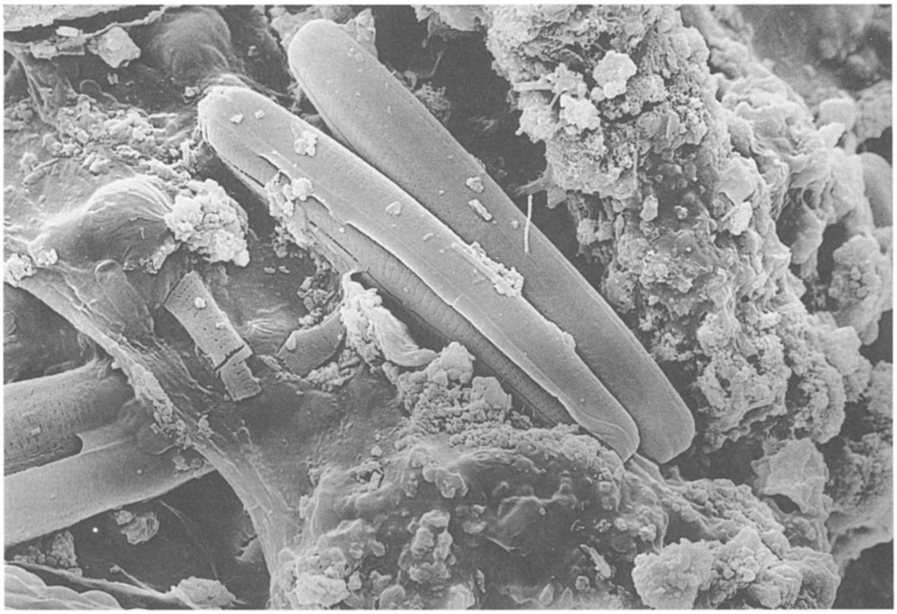


Fig. 16. Scanning electron micrograph of part of a Recent biofilm containing micrite peloids, diatoms and extracellular polymeric substances (mucilaginous coatings). River Lathkill, near Alport, Derbyshire.

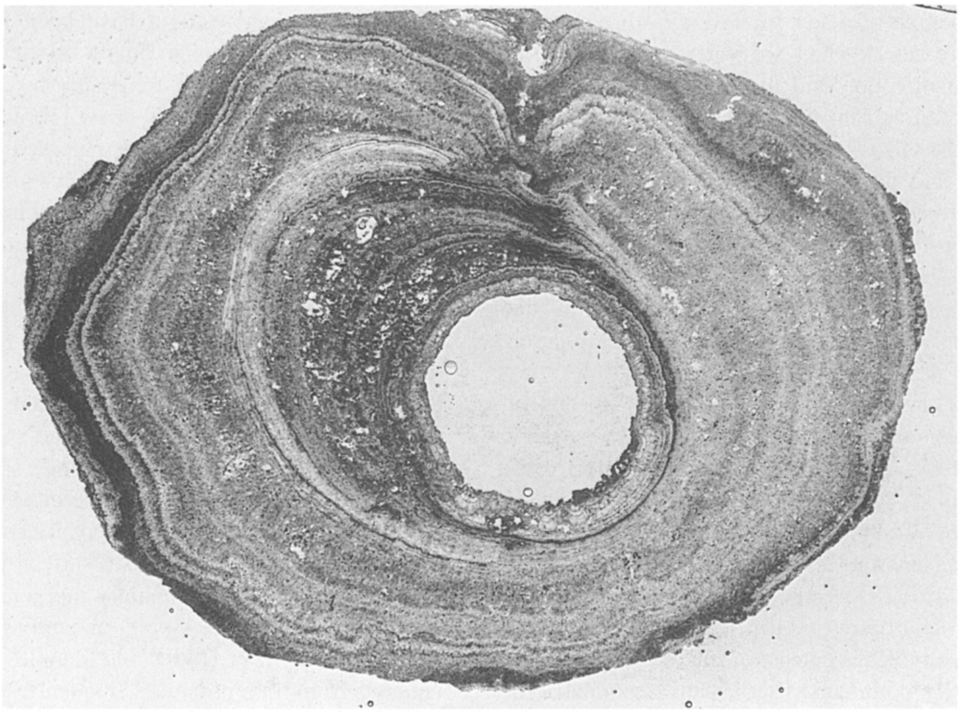


Fig. 17. Typical cyclic isopachous fringes of calcite spar (light shade) and micrite (dark) encrusting grass. Note the eccentric development of microbially biomediated micrite on the downstream side of the encrustation. Diameter of the central hole (once occupied by the grass stem) is 9 mm. Holocene Gordale tufa, near Malham, Yorkshire.

burial at any site. In protected situations biofilms may readily become established even close to resurgence points. Also objects within the flowing water body will have sheltered leeward sides upon which microbial growth will be encouraged. Finally, in the case of static water bodies all sites potentially are capable of developing biofilms in addition to precipitation from whitings. Generally, biofilms dominantly produce mud-grade carbonate either in the form of micrite, or peloids (bacterial clump deposits). Physico-chemical precipitates on the other hand tend to be sparry, rather than micritic, and frequently develop as isopachous fringe cements with well developed palisade and micro dog-tooth morphologies (Pedley, 1992, 1994).

In active travertines the precipitation processes are very fast (Folk, 1994) often taking only hours to produce significant deposits, whereas the processes in tufas are considerably slower. It is important, however, to state that the relative emphasis placed on inorganic versus organic precipitation in tufas and travertines varies according to the researcher. At present there is no clear consensus, though both processes are here considered to be important.

8. Diagenesis

The majority of tufas consist of low-magnesian calcite and tend to be quite stable. Nevertheless, considerable sparmicritization can occur as a direct result of the microboring activities of cyanobacteria, fungi and other micro-organisms (Chafetz et al., 1994). On exposed faces these can readily destroy clear sparry calcite fabrics, converting them into cloudy spar and micritic areas containing ill-defined boundaries.

Many tufas have escaped this destructive process and retain sharp internal fabric boundaries (Fig. 18). Nevertheless, there is a tendency in Quaternary and older tufas to have received additional inorganic

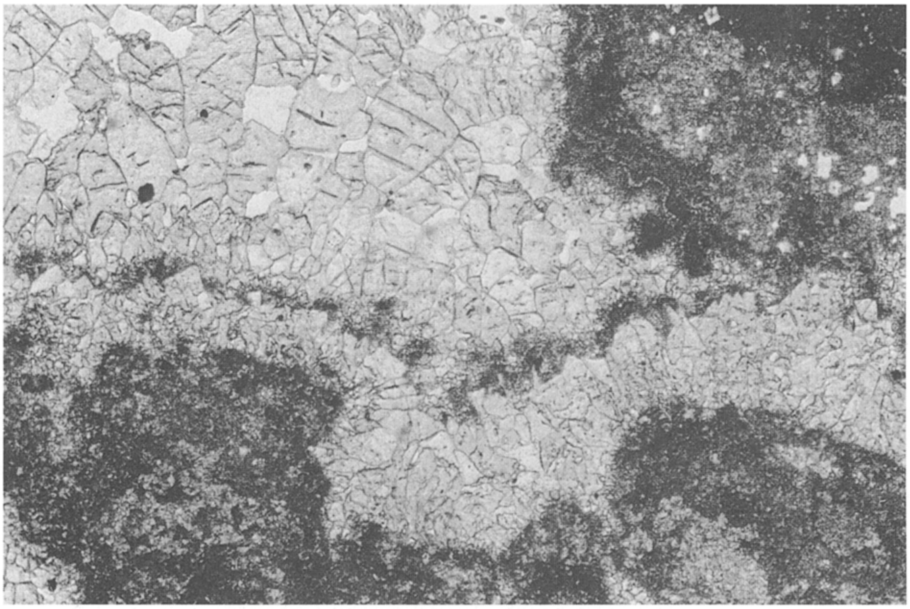


Fig. 18. Fabric detail within a Neogene tufa illustrating the preservation of sharp fabric boundaries and late stage occlusion of the remaining cavity by calcite spar cement. Perfectly preserved micrite fringe cement (middle) above an initial broad spar fringe with rhombic terminations. Width of field 1.5 mm. Pliocene (?) tufa at Morata del Tajuna. south of Arganda, Madrid.

carbonate cements which progressively occlude the available porosity ("speleomorphization" of Golubic, 1967). It may well be that much of this cement entered the buried cavernous fabrics concurrently with surficial tufa deposition. It is not, however, true tufa but a form of cavern infill akin to speleothems.

9. Palaeoenvironmental considerations

Some writers, notably Nicod (1981), Pazdur et al. (1988a,b), Goudie et al. (1993), Taylor et al. (1994), have related variations in tufa sequences to climatic changes. In temperate regions it is likely that tufa deposition coincides with the warmer and wetter phases of the glacial/interglacial sequences, i.e. with interglacials, whilst in Holocene times growth was apparently greatest during the early Holocene climatic maximum. In contrast with temperate regions tufa growth maxima in subtropical, semi-arid regions coincide with the wetter and generally cooler pluvial phases. Correlation of sequences in semi-arid and subtropical areas with those of temperate regions is fraught with difficulties.

Most consider that temperature variations control soil activity (bio- and physico-chemical) and that it is the karstic dissolution resulting from this which controls the availability rate of calcium carbonate from which tufas are precipitated. However, Griffiths and Pedley (1995) propose that atmospheric pCO_2 might be the overriding control on tufa precipitation, especially in lake and barrage systems where diffusion at the air/water interface is significant. Recently, Andrews et al. (1993) have demonstrated that the oxygen isotope ratios in active modern British tufas is constant. Although many factors can cause variations in the $\delta^{18}O/\delta^{16}O$ ratios it is generally considered in tufas that climate (temperature) is the most likely variable causing shifts in ratios (Andrews et al., 1993). The hypothesis has been applied to a core taken from a British Holocene barrage tufa system in N. Derbyshire with convincing results (Andrews et al., 1994). Here, the stable isotope record varies in a non-random pattern with depth suggesting that there has been a corresponding climatic change over time. This opens up the possibilities of applying the technique to other sites with good pollen biostratigraphies to test whether the isotopic shifts bear any relationship to vegetation change. The technique, however, may not universally be applicable if there is excessive diagenetic alteration or in thermal (travertine) systems according to Chafetz et al. (1994).

One of the greatest obstacles to palaeoenvironmental studies is the need to obtain absolute ages for the deposits. Providing that peat or sapropel material is interlayered with the tufas then conventional radiometric dates can be obtained from carbon 14 (Taylor et al., 1994). This assumes that no "hard water effect" is evident. If, however, tufas alone are present carbon 14 dates may be spurious because of the "hard water effect" (see Bradley, 1985 for details). The problems of obtaining absolute ages from tufas are discussed further in Srdoc et al. (1986); Viles and Goudie (1990a) and Drysdale and Head (1994). Thus it is that many unquestionably Holocene tufas have yielded older Pleistocene radiometric dates. This is because the carbon isotopic signature of the tufa is a composite signal involving some carbon which has its origin in the contemporary atmosphere, but with additions of geologically ancient carbon atoms derived from the dissolution of bed-rock. Additionally, secondary and often much later carbonate cements within the plethora of primary cavities can potentially give rise to quite different, and younger, dates from adjacent parts of the same layer within a deposit (see Geyh and Schleicher, 1990). Nevertheless, Taylor et al. (1994) demonstrate convincingly that apparently valid radiocarbon dates can be obtained from Holocene tufa carbonates providing that only the true microbial precipitates are carefully selected, and all physicochemical cements are avoided. Further investigations are necessary to confirm this hypothesis. U–Th dates have been obtained for pre-Holocene travertines and Hennig et al. (1983) list some 140 dated examples from archaeological sites (and 660 speleothems). The problems of accurately dating Holocene tufas may in future be overcome by the application of uranium series dating techniques (see review in Smart, 1991). Alternatively, amino acid dating methods (Benson and Hare, 1975; Sykes, 1991) appear to hold considerable potential for tufas, if it is applied to the associated molluscs.

A significant question relates to the dramatic reduction in tufa development in Europe from about 3500 yr B.P. Clearly this period closely ties in with accelerated deforestation, farming and soil erosion. It is tempting to correlate this decline with human activities. Compounding the effects of this land clearance is the application of crop fertilizers in recent times and extensive land drainage. All may have a profound influence on the rate of absorption of carbon dioxide in percolating groundwaters. Additionally, falling water tables and reduced discharge rates in recent times may also be coupled with a general lowering in the rate of limestone solution and consequent availability of calcium carbonate for freshwater precipitation.

The following survey of the world's tufa deposits inevitably is selective. It builds on Ford and Pedley (1992), and on other surveys such as Ford (1989) and the work of Merrill (1895) on "onyx". In addition, numerous accounts of individual deposits exist but their literature is in vernacular languages and difficult to locate. Few deposits have been investigated scientifically and then often by a single method, commonly radiocarbon dating. Many deposits have yet to be described.

10. Tufa deposits of Europe

As some 300 sites in Europe and Turkey have been catalogued by Pentecost (1995) no attempt to cover them all again has been made here.

The country entries are arranged geographically starting with the "home" of tufa, Italy and working northwards and then eastwards across Europe.

10.1. Italy

The classic travertine deposits of Bagni di Tivoli, east of Rome, have been quarried for over 2000 years. Blocks have been used for such buildings as the Colosseum which alone is said to have required 200,000 tonnes of travertine blocks. Many other public buildings of the Roman city took large amounts of the easily shaped stone. In more recent times buildings such as the Vatican have taken vast quantities. Blocks of tufa were also much used in Pompeii (Fig. 1). On an international scale slabs of polished travertine from Rapalino, northwest of Pisa have recently gained favour as the frontage decor of

McDonalds fast food establishments. Many other deposits have been worked in Italy for ornamental "travertine marble".

Many of Italy's travertine deposits are of mildly thermal character, probably reflecting the recent history of vulcanism though the hot waters are usually diluted with a meteoric input (Pentecost, 1995).

The Bagni di Tivoli deposits spread over thousands of square metres of hillside at each of three main localities and the maximum height is around 80 m. They have been investigated in some detail by Chafetz and Folk (1984) and by Pentecost and Tortora (1989). The travertine is quarried in 10-m-high benches cut into the deposits which originated from weakly thermal springs; these are still discharging and slowly renewing the deposits. Barrages and cascades have been built up and impound lakes which have become filled with laminated bacterial mud tufa. Sloping mounds, fans and cones merge into terraces covering the lake muds. Surfaces show micro-"shrub" growth textures. Bacterial sheaths, pisoids, laminated "stromatolites" and coated bubbles also occur. Precipitation seems to vary from bacterial in good conditions around 20°C, to dominantly inorganic in less favourable, cooler conditions. Whilst most of the deposits are late Pleistocene to Holocene, the date of initiation has not been established. Both large-scale and small scale lamination is present: the thick annual laminae (average 7 mm) may have up to 200 fine diurnal laminae 0.1 to 0.5 mm thick, indicating a growing season of around 200 days, and a non-growing winter season when even the weakly thermal waters precipitate little or no calcium carbonate.

The classic deposits of Bagni di Tivoli are only one group of about a hundred known tufa and travertine deposits in Italy, mostly in the northern Apennines (Pentecost, 1995). Many are sufficiently indurated to be quarried for constructional or ornamental travertine and there is an intensive industry producing several different types of slabs and blocks at various localities around Serre di Rapolano, near Siena (V. Coli, n.d.) and nearby in the Colle Val d'Elsa. Some are currently active with meteoric cool waters whilst others are at least weakly thermal. At Terme San Giovani, near Rapolano, there are fluvial sheets and terraces diversified by an elongate dome some 80 m long, 20 m wide and 10 m high. Apparently sited over a fracture, water emerges from a fissure along the crest and the deposit is referred to as a Fissure Ridge (Chafetz and Folk, 1984). The deposit is largely made of layers of micritic "shrubs" of bacterial origin which show progressive loss of detailed microstructure by diagenesis with increasing age. Local classification refers the different types of travertine to phytostromal, phytoclastic and microkarstic–pedogenetic origins (V. Coli, n.d.). Older inactive deposits in the quarries are up to 20 m thick and individual quarries have recorded as much as 5 million m^3 of reserves (V. Coli, n.d.). Nearby, at the Bagno Vignone, travertine is deposited at up to 15 cm per annum from thermal waters which reach 50°C and have a high CO_2 content.

In the Lazio province north of Rome a series of volcanic structures still issue thermal waters, particularly around the town of Viterbo. Among these, the Bagnaccio Bullicane thermal springs emerge at 64°C: as they cool downstream they outgas CO_2 and H_2S and absorb atmospheric oxygen with a progressive change towards aerobic conditions. Sulphur is precipitated in the hotter parts of the channels down the mound sides. The mound thus demonstrates a gradational change from thermal inorganic travertine to biogenic tufa. Another spring near Viterbo is Le Zitelle where as much as a centimetre of carbonate may be deposited in a few days. Both physico-chemical degassing and biologic intervention are important. The precipitate is about 75% aragonite and 25% calcite, with occasional rhombs of dolomite (Folk, 1994); the latter may be preparation artefacts. SEM studies have shown that nanobacteria occur throughout the carbonates and have probably been overlooked previously on account of their small size.

In the same general area north of Rome, mildly thermal travertine sheets cover wide areas at Fiano Romano and at Canino (Manfra et al., 1976). These deposits are low mounds with scattered barrages.

In the Central Apennines the Rocchetta a Volturno perched springline tufa deposits cover an area of about 10 km^2 in the Volturno valley north of Naples (Golubic et al., 1993; Violante et al., 1994). The deposits form two terraces along a valley side about 450 and 550 m above sea level, which were formed by accumulation on barrage cascades with small associated basins behind. They have formed in the last 75,000 yr, apparently from springs draining a

Jurassic to early Miocene carbonate massif, and cover late Miocene clastic rocks (Brancaccio et al., 1986, 1988; Golubic et al., 1993). Six lithofacies have been described (Golubic et al., 1993): waterfalls, pool terraces, steep slopes, gentle slopes, periodically-flooded swamps and shallow lakes. The algae *Oocardium* and *Lyngbya* and the cyanobacteria *Phormidium* and *Schizothrix* are particularly important in carbonate accumulation as these epiphytes coat mosses, leaves and earlier crusts with fresh tufa. Several stages in diagenesis have been recognized: closure of algal tubes; peripheral crystal growth and recrystallization, plus what are in effect micro-speleothems both forming sheets on earlier deposits and infilling cavities.

Near the coast south of Salerno, the ancient Roman city of Paestum was built on a sheet of tufa from about 2500 B.C. Later parts of this were quarried to raise to defensive walls. Springs at the upper end of the town were channeled through it but built barrages and eventually drowned the town in younger tufa about 1500 yr ago. Cascades, barrages and lagoons have been recognized in both older and younger tufa (D'Argenio et al., 1993).

Cool water tufa deposits dating from 2400–1950 yr B.P. have been described from the Tanagro Valley in southern Italy (Buccino et al., 1978). Several square kilometres of sheets of phytohermal and phytoclastic tufa are associated with faults cutting a valley fill. They appear to be paludal valley-bottom tufas with perched springline deposits higher up the slopes.

Other tufa deposits have been quarried to varying extents in southern Italy, particularly the perched spring line tufa deposits at Cozzo Marotta near Noto in southeastern Sicily (Conti et al., 1979; Pedley, 1990) (Fig. 7). So much thermal travertine has been deposited at Toscana that it forms a dome up to 80 m high and 2 km long; as much as 1 m per annum is said to be deposited in places there. Also in Sicily the Ippari Valley has extensive sheets of fluvial braided tufa near Vittoria.

An unusual tufa deposit occurs at Adrano on the southwest flank of the volcanic Mt. Etna. Covering some 4 km^2 it appears to be largely of Holocene age and its calcium carbonate has been derived from the weathering of the volcanic rocks (Romano et al., 1987).

10.2. Malta

Perched spring line tufa deposits resting on Miocene clays and limestones have been described in the Fiddien Valley of Malta (Pedley, 1980).

10.3. France

France has many tufa deposits, particularly in the south. They have been noted by Adolphe (1981), Casanova (1981), Nicod (1981), Vaudour (1994) and Pentecost (1995). At Tourtour in Provence meteoric waters percolating through gypsum and dolomite beds yield spring-line tufa terraces, barrages and lacustrine deposits on resurgence. An overhanging "balcony" at Cotignac (Var) has had cavities formed by solution which have been been enlarged artificially by troglodytes. Karstic erosion has resulted in a natural bridge through a tufa mass at d'Entraygues on the river Argens near Vidauban. Numerous sites were briefly noted in Languedoc by Fabre (1986). Most of the 13 sites in Provence and Languedoc investigated by Ambert (1979, Ambert, 1982) and by Vaudour (1994) showed a history of growth in the early Holocene followed by progressive interference by human activities such as deforestation and land drainage so that only limited deposition occurs today in sheltered localities.

Springs at Roquefort les Cascades in the northern Pyrenees have deposited sheets of tufa investigated for their carbon and oxygen isotopes by Dandurand et al. (1982). They found considerable disequilibrium in the ^{18}O content, which differed on average by c. 5°C from observed temperatures.

At Condat, in the Dordogne, a fossil tufa deposit has yielded both biostratigraphic and isotopic evidence of an interglacial date (Preece et al., 1986). A Mousterian site was dated by applying the uranium series disequilibrium method to tufa in the Dordogne (Schwarcz and Blackwell (1983).

Near the margins of the Massif Central three petrifying wells are commercially exploited: one at La Grotte de Perou St. Alyre, near Clermont-Ferrand, originates from a thermal spring rising from underlying granite. Travertine encrusts objects suspended in the spring to a thickness of more than a centimetre in a few months. It is also made to fill latex moulds to yield solid casts in a year or so (Pentecost, 1991b).

In northern France the St. Antonin tufa deposit near Bayeux includes an alternation of barrages with calcretes and caliches. The chalk country around Tournus, Burgundy, on the east flank of the Paris Basin has many small tufa deposits, either oncolites or various encrustations on stream beds, pebbles and sunken vegetation: cyanophytes, algae and mosses are the main agents of deposition (Freytet and Plet, 1991).

Some 40 further sites of tufa deposition in France have been listed by Pentecost (1995).

10.4. Spain

Spain has many tufa deposits, 17 of which are listed by Pentecost (1995).

In the Beceite area of northeast Spain tufa terraces along the Matarrana river have been dated by U/Th methods to three periods, 267,000 ± 32,000, 111,000 ± 3500 and 8000 ± 2000 yr. These dates support floral and faunal determinations corresponding to the Riss/Wurm interglacial and to early Holocene periods when the climate was wetter than the present (Martinez-Tudela et al., 1988). Tufa deposits were noted in his studies of the karst phenomena of the Rio Aragon Basin of the Pyrenees by Ek (1973). U/Th and ESR methods of dating were applied to tufa deposits in the Baixo Alentejo by Gaida and Radtke (1983).

In Central Spain, the Checa tufa deposit is a spring-line terrace some 8 m high and covers some 880 m^2 which appears to be fed by a perched spring. Mosses provide the nuclei for an annual growth rate of around 4 cm (Weijermars et al., 1986). Many other examples of braided and barrage fluvial tufas occur in central Spain, notably in the Duero Basin (Fig. 18). Active oncoidal tufas are forming in the Dulce river, Guadalajara (Ordoñez et al., 1980).

At Priego, Andalusia, springs rising from dolomite and gypsum beds in the karst massif yield sulphate-rich waters which precipitate tufa on resurgence.

Ruidera Pools National Park is developed around a series of tufa barriers and associated lakes in an arid region of southeastern Spain near Ossa de Montiel, Albacete (Fig. 8). Though smaller than Plitvice, the barrages rise vertically up to 7 m above the bottom of a gorge cut in Mesozoic limestones; tufa growth is predominantly on the crests. The fifteen lakes are floored with fine detrital tufa locally rich in *Chara* and the bivalve *Unio* in the shallower areas (Ordoñez et al., 1986). In recent years abstraction of water has meant a drop of some 7 m in lake level, resulting in 7-m-high tufa terraces being exposed around the shores (Fig. 11).

Other Spanish tufa deposits awaiting full description are at El Jardin to the southwest of Ruidera and

Fig. 19. A tufa cascade. Janet's Foss, below Gordale, near Malham, Yorkshire (photo by A.C. Waltham).

Brihuega, east of Guadalajara (Ordoñez and Garcia del Cura, 1983) (Figs. 6 and 10). Massive tufa deposits are also present around Velez in the gorge of the Rio Guadalfeo, south of Granada, and near Mezquitilla, east of Malaga; both of these are inactive tongues within thick sheets of alluvial breccia flanking mountains in the Betic Cordillera.

10.5. Britain

In Britain tufa deposits are widespread and Pentecost (1993) has provided a catalogue of 159 active and inactive sites of which about half are associated with the hydrology of the Carboniferous Limestone. The tufa cascades at Gordale Scar in North Yorkshire encrust a steeply descending gorge but they appear to be growing only in limited patches today whilst other parts of the deposit are being eroded, perhaps because of more acid drainage from peat bogs entering the system as a result of changing agricultural practices. Further down the same stream the related cascade at Janet's Foss is still growing (Fig. 19) and the slightly warmer microclimate may account for the different growth pattern (Pitty, 1971; Pentecost and Lord, 1988). Clapham Beck, near Settle, and Waterfall Beck, northeast of Malham Tarn, each have several small deposits (Pentecost, 1992b). A survey of 29 tufa localities in the Yorkshire Dales showed that 17 were no longer active (Pentecost and Lord, 1988).

The tufa at the Knaresborough petrifying well in east-central Yorkshire is derived from the Permian Magnesian Limestone where water cascades over a low cliff from perched springs; the spring water is unusually rich in $CaSO_4$ and the tufa is moderately rich in dolomite. The deposit has been briefly described by Pentecost (1991b).

Further south, in Derbyshire, the floor of Lathkill Dale has four complexes of low fluvial tufa barrages with associated detrital and lacustrine deposits (Burek, 1977; Pedley, 1993; Andrews et al., 1994; Taylor et al., 1994; Griffiths and Pedley, 1995) (Figs. 4 and 17). A substantial barrage is still active close to the mouth of Lathkill Dale where it meets Bradford Dale at Alport-by-Youlgreave (Pedley, 1993); the second is about 1 km upstream near Raper

Fig. 20. A heavily vegetated and partly quarried tufa barrage. Pudding Springs, Lathkill Dale, Derbyshire.

Lodge; the third is some 2 km further upstream below the village of Over Haddon and the fourth 2 km higher upstream at Pudding Springs (Fig. 20). The intervening stretches include sheets of detrital and lacustrine tufa deposited in the ponds behind barrages. The lacustrine tufa is interlayered with organic sapropels and ^{14}C dates obtained from both tufa and sapropel are similar. Much of the dale is without tufa between the barrages. One sheet has been drilled to a depth of 11 m demonstrating that it grew as an infill of a former incision of the river. Active deposition in Lathkill Dale is minimal today with a peak in mid-summer, when there is some evidence of diurnal cycles of algal growth. Sparry calcite laminae apparently accumulate during winter months when flow is greater and temperatures lower. Stable isotope studies (Andrews et al., 1994) have demonstrated a relationship to early Holocene climatic warming and later Holocene cooling whilst pollen profiles are related to changes in tree cover associated with the climatic change and with Neolithic farming practices (Taylor et al., 1994). A further factor in tufa accumulation may be the increase in atmospheric CO_2 during Holocene times (Griffiths and Pedley, 1995). The absence of tufa between the occurrences may be due to concealed springs and lead mine drainage temporarily diluting the river water. The course of the adjacent River Wye in nearby Monsal Dale similarly has relics of early Holocene fluvial barrage tufas now extinct and partly degraded and only visible in sections of the river banks (Pedley, 1993; Taylor et al., 1994). The more recent erosion may be due to changes in water chemistry caused by Buxton's sewage works further upstream!

Also in Lathkill Dale at Alport-by-Youlgreave an extensive fossil tufa deposit forms a cliff some 6 m high and 150 m long close to the lowest active barrage on the River Lathkill (Pedley, 1993). It rises 5–10 m above present river level though there may be as much as 4 m thickness concealed beneath the cliff foot. It is totally inactive; bulbous shrubby forms and encrustations overhang caves where there are miniature barrages, barely 10 cm high. It seems likely that the Alport tufa is an interglacial or interstadial barrage deposit of the River Lathkill but the only available date of "more than 49,000 years B.P." is at the limit of ^{14}C dating methods.

Fig. 21. Moss-covered tufa cascade slope, Matlock Bath, Derbyshire.

Matlock in Derbyshire is noted for its petrifying well where tufa is deposited on objects suspended in the water; articles such as top-hats, birds nests (some artificial), eggs in cups etc. are coated with some 5 mm of tufa in 10 years or so. The currently active deposits at Matlock are derived from a perched spring line at the top of a bank of tufa some 50 m above river level and 500 m long, largely concealed by roads and buildings (Fig. 21), though a cascade 5 m high can be seen on the river bank. The springs rise close to the line of two vertical mineral veins and deep circulation may take place along these. Weakly thermal at about 18°C, isotope studies have suggested that the rising water is meteoric having circulated deep underground for as much as 15 yr (Edmunds, 1971). West of Matlock there are extensive spring-line tufa deposits on a steep slope at Dunsley Springs in the Via Gellia; here Thorpe et al. (1980) have noted that tufa deposition is now limited to turbulent sites in an incised channel. The main period of deposition was around 9000–4000 yr B.P. The adjacent Marl Cottage in Via Gellia is built of large blocks of tufa from this deposit.

Two tufa deposits in Derbyshire owe their origin to leachate drainage from old waste heaps related to the former lime-burning industry: these are at Wormhill Springs, 6 km east of Buxton, and at Brook Bottom Springs near Harpur Hill, 2 km south of Buxton (Fig. 22). The sheet of tufa at Wormhill Springs is largely covered with vegetation, mainly watercress, but the deposits at Brook Bottom comprise a series of mini-barrages up to 1 m high along some 200 m of stream course. The ponds behind the barrages are largely filled with a fine-grained precipitate. The fronts of the barrages have a striking rippled flowstone appearance with microgours. No algae have been detected and the growth seems to be physical by degassing. No investigation of these anthropogenic deposits is known to have been made. Similar deposits are known from other old lime works, e.g. at Clydach, Dyfed.

A sheet of tufa deposited in a former shallow pond in the entrance to Elderbush Cave in the Manifold Valley, Staffordshire, enclosed caddis-flies and small rodent skeletons (Bramwell and Shotton, 1982).

At Caerwys in north Wales, a large tufa deposit has been quarried for agricultural lime for many years (Campbell and Bowen, 1989) (Fig. 5). The fluvial barrage deposit is up to 12 m thick and fills a small valley about 1 km long over a height range of 46 m. The complex rests on fluvial deposits covering Silurian slates downstream from springs rising from the Carboniferous Limestone. Studies by Preece et al. (1982) and by Pedley (1987) (summarized by Campbell and Bowen, 1989) have shown that this deposit is of post-glacial age ranging from around 9000 to 7000 yr B.P. and there is no active deposition today. Together with the underlying fluvial deposits, peat layers and soils the Caerwys section provides one of the most complete Holocene sequences in Britain. The quarry faces show laminated banks of shrubby and micritic tufa, overhangs with caves and stalagmites, pool deposits overgrown by flat sheets of tufa, pisoid lenses and interbedded humus layers. A nearby deposit at Ddol forms a sheet below springs from the Carboniferous Limestone instead of barrages (Preece and Turner, 1990).

Many British caves have crumbly white tufa speleothems in their entrances. Though stalactitic in morphology, they can probably be classified as slow-growing cascade tufa deposits. At Ingleborough Cavern in northwest Yorkshire mosses and liverworts encrust the pendulous tufa stalactites and show reduction in the size of the thallus with decreasing

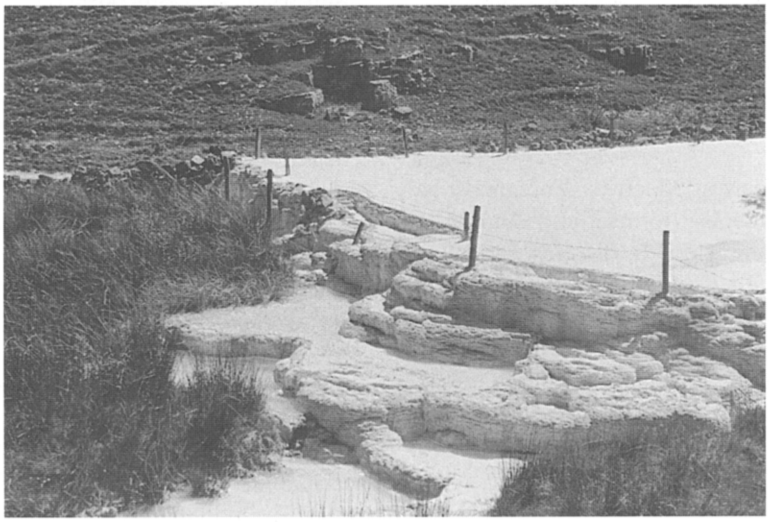


Fig. 22. An unusual series of inorganically precipitated tufa barrages downstream from quarry waste. Brook Bottom, near Buxton, Derbyshire.

light intensity in the cave (Piearce, 1975), though the processes of deposition do not appear to have been investigated yet. Comparable stalactitic masses of tufa occur in Victoria Cavern, near Settle, north Yorkshire, and in the roof of Peak Cavern's Vestibule at Castleton in Derbyshire; they are in a zone of greatly reduced daylight, but no studies of their growth mechanism are known to have taken place.

In many archaeological cave sites both the crumbly white tufa and more solid crystalline layers are often interfingered with archaeological deposits but few studies of the mechanisms of deposition are known to have been made.

Small scale spring-line and paludal tufa deposits occur in streams on the Jurassic limestones of north Yorkshire, the East Midlands, the Cotswolds and Dorset as well as on the Cretaceous Chalk of southern England (Pitty, 1971; Kerney et al., 1980; Preece, 1980; Thorpe et al., 1980; Pentecost, 1993). At Launde in the Lower Jurassic country of east Leicestershire two thin sheets of spring-line tufa containing terrestrial gastropods are separated by a peat layer; they apparently lie beneath the Chalky Boulder Clay (Horwood, 1912) and are thus possibly of Hoxnian age. Comparable Holocene(?) spring-line deposits occur at several localities in Leicestershire, Northamptonshire and Rutland, where Jurassic limestones outcrop upslope above Lower Jurassic clay formations. In Northamptonshire, tufa blocks were quarried for building purposes, e.g. Brixworth Church. At Priory Mill, Chipping Norton, Oxfordshire, a sheet some 500 m long on a gentle slope of Upper Lias lies below springs emerging from Middle Jurassic limestones (Thorpe et al., 1980). Tufa deposits rich in diatoms occur at Cloughton Wyke, north of Scarborough. At Thatcham Reed Beds and at Marsh Benham near Newbury in the Thames Valley springs rising from the Chalk have deposited sheets of spring line tufa (Thorpe et al., 1981; Pentecost, 1993). Extensive springline, streambed oncoids and crustose tufa deposits at Ditton near Maidstone, Kent, lie on calcareous sandstones of Lower Cretaceous age, though the springs apparently rise from the nearby Chalk. Comparable sheets occur at several localities in the Test and Itchen Valleys north of Southampton (Pentecost, 1993). On the Jurassic outcrops of southern England a variety of crons similar to those in the Jurassic country of southeast Belgium have been noted by Pentecost (1991a). An inactive sheet of springline tufa flanks the Purbeck limestone outcrop at Blashenwell south of Corfe Castle in Dorset. It is rich in microlith flints and terrestrial gastropods and appears to have been deposited during Mesolithic times (7000–4000 B.C.) (Bury, 1950). Small areas of spring line tufa occur on Chalky Boulder Clay in east Yorkshire.

A small amount of tufa has been deposited in a stream at Inchrory, Glen Avon, in Banffshire, Scotland, since Flandrian times (Preece et al., 1984). Small inactive deposits are recorded from the Pentland Hills (Pentecost, 1978).

On the Isle of Man there is an unusual tufa deposit on the east side of Bay Ny Carricky on the south coast. A cascade-type deposit some 50 m long covers a sea-cliff some 3–4 m high, with pendulous tufa masses screening off small grottoes. Water still trickles down this deposit and is derived from springs at the base of a calcareous till and raised beach sand resting on Carboniferous Limestone.

10.6. Ireland

Tufa deposition is actively occurring in County Offaly (Preece and Robinson, 1982). Small scale stream deposits occur at Glenasmole (Statham, 1977). Lake margin deposits with *Rivularia* in Lough Ennel have been partly killed off by farm fertilizer effluent. A scatter of other Holocene localities have been listed by Pentecost (1995).

10.7. Belgium

Many small tufa deposits arise from springs in the Jurassic strata of the Lorraine region of southeast Belgium and northeast France (Symoens et al., 1951). They have been described as "Crons" by Van Oye (1937) and Van Oye and Hubert (1937). One such cron at Cron de Lahage includes a cascade deposit 50 m high. A chronology of some crons based on palynological studies was proposed by Couteaux (1969) and related to Holocene climatic changes by Gullentops and Mullenders (1972). Extensive valley deposits including an eroded barrage occur in the Ruisseau Banse–Annevoie (Symoens et al., 1951); one with a "foyer" was described at Annevoie–Rouillon by Paepe (1965). Inactive valley deposits with remains of barrages occur at Villers-devant-Orval.

10.8. Germany

There are many tufa sites in Germany but the literature tends to be in local publications difficult to locate. Scattered deposits along the Rhine Graben and around the Eifel volcanic region suggest a connection with deep circulation but no proof has been adduced as yet.

At Kartstein in the Eifel District, inactive tufas are interlayered with volcanic ashes and yield Palaeolithic artefacts from a mid-Pleistocene interglacial (Brunnacker et al., 1982).

Near Westerhof village, some 30 km north of Gottingen in southern Germany a small stream in a forest flows from a spring in the Upper Muschelkalk (Triassic) and deposits an estimated 12.6 tonnes of tufa per annum (Jacobson and Usdowski, 1975; Usdowski et al., 1979).

In the Schwabian Alps of southern Germany springs on Jurassic limestones give rose to numerous tufa deposits including a cascade 30 m high at the Uracher Waterfall in the Erms Valley (Gruninger, 1965).

A variety of tufa deposits were classified according to their features and topographic relationships in the Schwabian Alps by Stirn (1964). The mechanisms by which carbonate encrusted algae, cyanobacteria, mosses and various leaves and twigs was described by Irion and Muller (1968), who seemed to regard the process of deposition as mainly inorganic though stimulated by the biologic substrates.

The Gnadensee arm of Lake Constance is characterized by algal and cyanobacterial encrustations on leaves and twigs; the crusts break down to provide fine carbonate sediments on the lake floor where oncolites are also common (Schottle and Muller, 1968).

At Tittmonig in Bavaria, ^{14}C dates appear to suggest an interstadial date for tufas on a postglacial terrace (Gluckert, 1973).

A tufa deposit at Bad Laer in the Teutoberg Forest described by Hiltermann (1977) was formed from a brine spring during the post-glacial climatic optimum.

Near Stuttgart in southern Germany, tufas include shrubby layers resulting from calcification of branching microbes, laminar microbial mats, peloidal layers, and encrustations round gas bubbles (Koban and Schweigert, 1993).

In eastern Germany, a sequence of Middle Pleistocene archaeological deposits in the Steinrinne "travertine" quarry at Bilzingsleben contains both inorganic laminated "lacustrine limestone" overlain by later apparently fluvial tufa up to 8 m thick (Harmon et al., 1980).

Also in eastern Germany sequences of archaeological deposits within weakly thermal travertines occurs at Ehringsdorf, Weimar and Taubach (Steiner and Wagenbreth, 1971). The former was found to have numerous cavities infilled with later calcite precluding determination of U/Th dates (Schwarcz, 1980), but bone concentrations suggest deposition during at least two interglacial episodes between 100 and 250 Ka. The nearby Burgtonna bone-bearing tufa deposit has yielded dates of 104–111 Ka (Hennig et al., 1983).

At Laegerdorf in northern Germany an unusual laminated tufa was found to be deposited on a quarry ledge by micritic calcite adhering to the polysaccharide mucus sheaths of diatoms (Winsborough and Golubic, 1987).

10.9. Switzerland

In Switzerland, an unusual show cave is within an ancient tufa barrage at Höllgrotten at Barr, where some 300 m of passages are connected by artifically enlarged tunnels (Gigon, 1965). Höllgrotten (= Hell Grotto!) is in an inactive tufa mass flanking the gorge of the River Lorze incised into alpine molasse covered by late Pleistocene gravels and moraines; partial splitting off of the mass from the gorge wall has opened fissure caves now well-decorated with stalactites and stalagmites dated at no more than 10,000 to 20,000 yr old.

10.10. Austria

Lacustrine algal tufa encrusts shore-line boulders and gravel in several alpine lakes, e.g. the Attersee, east of Salzburg, Austria (Schneider et al., 1983).

Similar deposits occur at Fendels in the Tirol (Huckreide, 1975).

At Jessnitz and other sites in the North Calcareous Alps there are several small postglacial deposits some of which have yielded mammal remains (Fischer, 1956).

At Bad Cannstatt and nearby Blumberg the reaction of deeply circulating meteoric CO_2 with gypsum beds yields highly carbonated springs which deposit tufa terraces.

10.11. Croatia

Croatia is famous for the fluvial barrage deposits at Plitvice along the gorge of the river Korana which have been designated a World Heritage Site (Figs. 14, 23 and 24). The gorge is some 12 km long and

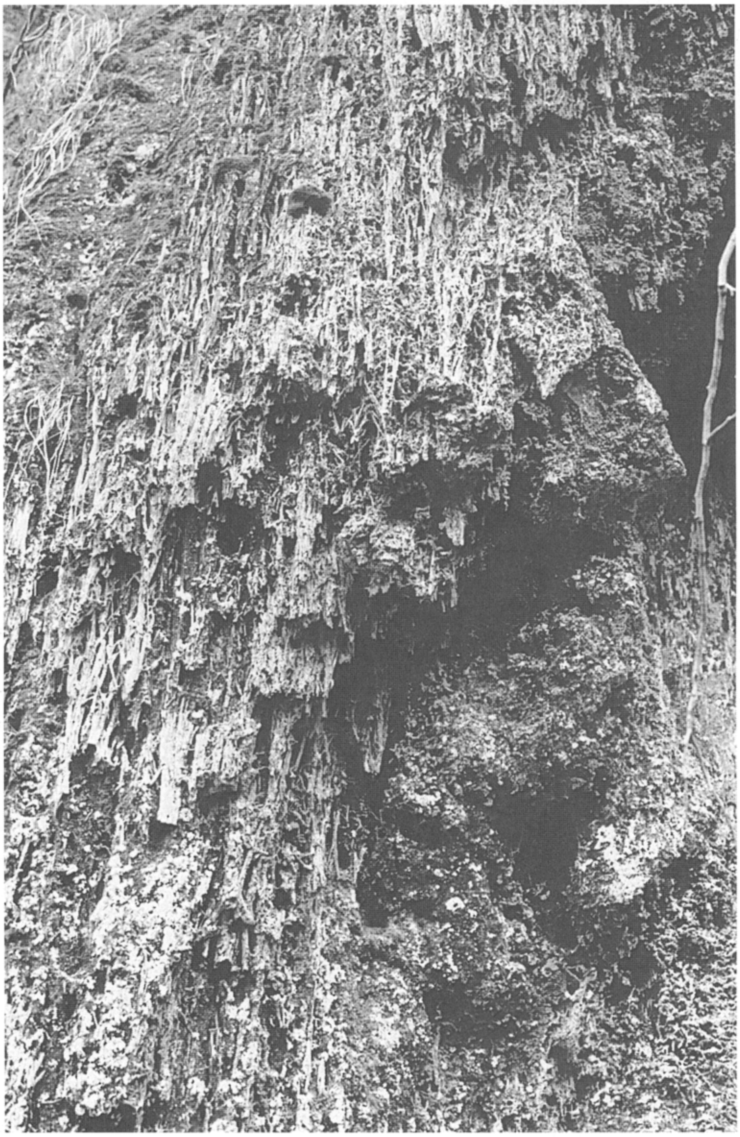


Fig. 23. Abandoned and desiccated tufa sheet once covering roots and mosses. Plitvice National Park, Croatia.

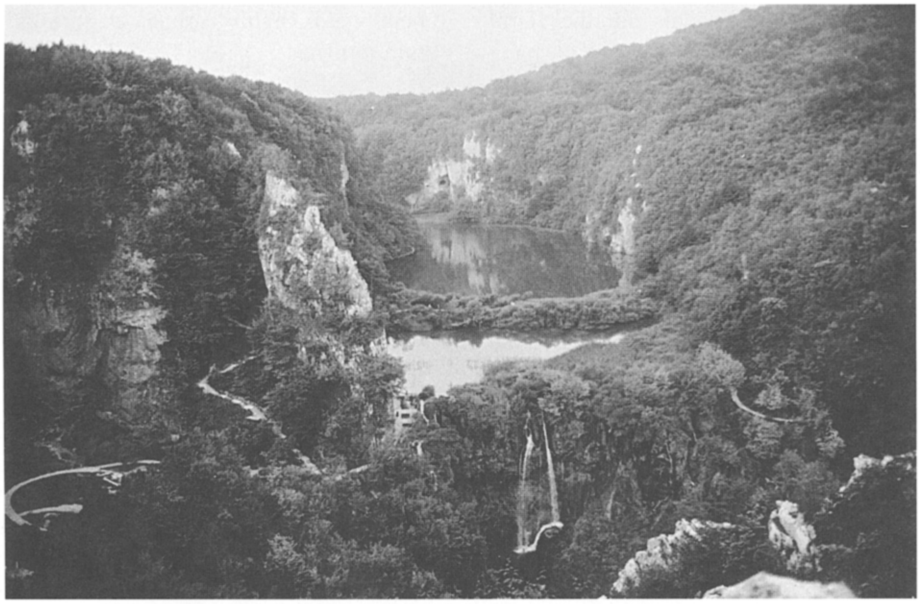


Fig. 24. Tufa barrages and lakes. Plitvice National Park, Croatia.

Fig. 25. Part of the Skradin Falls barrage. Krka Falls National Park, Croatia.

the growth of tufa barrages up to 30 m high has created a series of lakes with spectacular waterfalls. Several of the barrages enclose small tufa caves. Investigations by local karst geologists (e.g. Sobat et al., 1985) have shown that no tufa is deposited until several kilometres downstream from the springs as the water is too cold at 7°C. On warming to at least 12°C in the Croatian summer both de-gassing of CO_2 and enhanced growth of algae takes place and tufa is deposited (Stoffers, 1975; Srdoc, 1980; Srdoc et al., 1983, 1986). Debate has centred on whether the microflora are active inducers of precipitation or merely passive surfaces suitable for encrustation. Kempe and Emeis (1985) concluded that the biota played a focal role in removing CO_2 from solution, acting as a substrate for precipitation and encrustation, and in trapping micritic calcite in their extracellular mucus. Following detailed petrographic studies Chafetz et al. (1994) agreed with this but noted that cm-thick crystalline spar layers formed as coatings especially at waterfall sites and were later micritized by the action of microbes. Isotope studies have shown that there were two main periods of deposition, c. 37,000 to 25,000 yr B.P. and since 6500 yr B.P. Growth continues and up to 50 cm of tufa has been added in the last 35 yr. Kempe and Emeis (1985) estimated that as much as 50,000 tonnes of calcite were precipitated each year and that the whole barrage plus lake floor complex is being raised by an average of 1 cm per annum. An earlier phase of dam development has been dated to 120 Ka and there is some evidence of a still earlier phase at c. 420 Ka (Kempe and Emeis, 1985).

There are many deposits elsewhere in Croatia: perhaps the best known are the Skradin Falls in the Krka National Park (Zalokar, 1940) (Figs. 3 and 25). These falls (commonly known as the Krka Falls) are on the Krka River some 10 km inland from Sibenik on the Dalmatian coast. The Falls constitute a fluvial barrage complex some 45 m high which holds back a lake 8 km long. The Krka barrage is probably the highest in the world. Other barrages further upstream have been partly quarried away or reduced by hydro-electric diversions. The base of the Skradin Falls is not far above sea level in an incised valley drowned by the post-glacial rise in sea-level. The present dams are thus Recent in age, though there are relics of older deposits on the valley sides.

10.12. Greece

Greece has wide areas of karst and thermal spring activity associated with Mediterranean vulcanicity but its tufa deposits are small and little known. Few descriptions have been located. A Quaternary tufa sheet at Naoussa in Greek Macedonia has been noted by Faugeres (1981).

10.13. Czech Republic

Eastern Europe has many tufa and travertine deposits associated with hot springs, though the alleged therapeutic value of the waters has meant that most have been buried by the construction of thermal baths and related facilities. A classic example is the hot springs (73°C) of Karlovy Vary (Carlsbad) in the western part of the Czech Republic which deposit multi-coloured tufa when the water temperature has dropped (Cohn, 1862). Much of the area has been built over so that the details of the deposits are obscured; also pumping of hot water has interfered with tufa deposition.

Escaping mildly thermal oilfield waters at Tucin have deposited a small sheet of tufa (Vanura, 1943).

Tufa has been recorded at several other localities in the Czech Republic (Mitter, 1981; Pentecost, 1995).

10.14. Slovakia

Extensive tufa deposits in the valley of Hincava, south of Propad in Slovakia, have been subject to karstic erosion resulting in collapse dolines. Mounds of thermal tufa occur at Ganovce, at Lucky and at Spisske–Podhradie.

10.15. Hungary

Hungary has many tufa deposits, mostly of thermal character in association with the tectonic history of the Pannonian basin. Some 500 localities scattered throughout Hungary with tufa and travertine deposits were noted (but not listed) by Schweitzer and Scheuer (1995). They distinguished five categories: (a) cold karst springs and streams, below 14°C; (b) lukewarm and warm springs; (c) soil, layer and "crack" springs; (d) post-volcanic warm or hot springs; (e) mixed or heterogeneous springs and waters. Regrettably some of their categories are not well defined and the criteria for recognizing them are not clearly expressed but it does seem that there are varying degrees of mixing of cold purely karstic springs and thermal waters. Schweitzer and Scheuer (1995) also distinguish ten different types of tufa cones built up round springs, though their diagram suggests that they are mostly variations on a theme. These authors also describe a sequence of up to twelve levels of tufa deposition in several areas; some date back as far as the Miocene and an outline correlation with river terraces on the Danube and its tributaries has been proposed.

Anna-Barlang (= Anna Cave) at Lillafured in Hungary is a large tourist cave system within a tufa hill seemingly comparable with Höllgrotten in Switzerland (Kovanda, 1974; Szunyogh, 1989). Some 600 m of chambers have been partly linked by artificial tunnels for tourists. The ceilings show moulds of tree-trunks, leaves and roots in massive tufa but the lower walls are more crumbly detrital tufa. Owing to incision of the adjacent Szinva and Garadna valleys the whole tufa hill is gradually sliding downhill and breaking up into joint blocks so that the cave shows increasing evidence of instability and rock-bolts have been emplaced to hold some features in place (Szunyogh, 1989).

In the Buda Hills, on the west side of Budapest, there are several extensive tufa deposits outside caves, some of which are of hydrothermal origin. The spring-line tufa sheets are thought to be related to former thermal springs on the margins of fault blocks (Scheuer and Schweitzer, 1974; Kretzoi and Pecsi, 1982; Schweitzer and Scheuer, 1995) and to relatively shallow residual volcanic heat beneath. In places the older tufa encloses mammalian remains which suggest a late Pliocene to early Pleistocene date (Janossy and Kordos, 1977). Present day tufa deposition in Budapest is being reduced by the over-pumping of wells sunk to supply thermal baths. Together with pumping from coal mines in the surrounding country the effect has been a steady decline of the water table.

Lake-margin deposits were noted in northern Hungary by Kovanda (1974).

A series of inactive sites related to former weakly thermal springs in the Gerecse Mountains include bone-bearing tufas in up to eight phases of deposition dating back to the Pleistocene. Localities include Dunaalmas, Sutto, Tata and Vertesszollos (Hennig et al., 1983; Scheuer and Schweitzer, 1974). Uranium-series dates were obtained from the tufa deposits at Vertesszollos (Schwarcz and Latham, 1984) ranging back to at least 350 ka B.P. Primitive human remains and implements were found at the last-named locality in tufas associated with Tata River terraces dating back to the Eemian interglacial.

10.16. Romania

There are scattered cold-water spring deposits of tufa in Romania (Fodor et al., 1982).

10.17. Poland

Many small tufa deposits in valleys in the Cracow Uplands and Holy Cross Mountains of southern Poland have been studied by Alexandrowicz and Gerlach (1983), Pazdur and Pazdur (1986) and by Pazdur et al. (1988a,b). The latter found that the growth pattern of small barrages and lacustrine deposits showed a reasonably consistent relationship with Holocene climatic curves derived by other means. Pentecost (1995) lists eleven sites of tufa deposition in Poland.

10.18. Estonia

Several small Holocene tufa deposits have been reported in this Baltic Republic by Lookene (1968a,b).

10.19. Latvia

In spite of its far northern latitude Latvia has about hundred known tufa sites, mostly valley-side cascades (Danilans, 1957).

10.20. Russia

European Russia has very few tufa sites in spite of its vast areas (Pentecost, 1995).

10.21. Norway

Norway has a scatter of paludal and cascade tufa deposits, mostly in Gudbrandsdalen (Nordhagen, 1921). These must be among the world's mostly northerly deposits.

10.22. Sweden

Though mainland Sweden has few karst areas, the island of Gotland has widespread Silurian carbonates and tufa has been quarried at several localities for agricultural lime. Spring-line sheets have revealed a sequence of tufas with plant fossils (leaves) and mammal bones from various post-glacial climatic zones (Hulth, 1898). Hulth also includes brief comments on other Swedish, Norwegian and Danish deposits.

The most northerly known tufa deposit is a series of cyanobacterial crusts in a pond near Abisko (68°N) (Kann, 1941).

A variety of other localities in Germany, Switzerland, France, Spain, the Czech Republic, Slovakia and Hungary have been noted by Irion and Muller (1968), Schwarcz (1980), Hennig et al. (1983), Julia (1983) and Pentecost (1995).

11. Tufa deposits of Asia

Asian tufa deposits are surveyed below geographically from west to east.

11.1. Turkey

Pleistocene to Recent vulcanism and tectonics in Asia Minor have led to a scatter of thermal travertine deposis. Widespread areas of limestone have also contributed a variety of karstic tufa springs.

As with other Mediterranean countries Turkey was a source of ornamental "travertine marble" in ancient times and a variety of Greco-Roman ruins are partly made of travertine blocks.

A major tourist attraction in southwest Turkey since Roman times is the series of thermal travertine terraces at Pamukkale, on which the ancient Roman city of Hierapolis was built (Figs. 12 and 26). Similar to the Mammoth Hot Springs travertine terraces in Yellowstone National Park, USA, some of the individual terraces and pools are taller and narrower owing to the steep slope. The largely aragonitic deposits are fed by springs rising at 35 to 59°C along a basin-margin fault system. The tufa terraces occur in patches totalling some 13 km^2. Altunel and Hancock (1993, 1994) have classified the deposits as: (1) terraced mounds; (2) fissure ridges; (3) range-fronts; (4) eroded sheets; and (5) self-built channel tufas. The first category covers most of the tourist attractions and they were deposited by waters emerging at 35°C; the second category was built from hotter waters at 56°C along fissures parallel to faults along the graben margin; the third are old travertine sheets draped down ancient fault scarps; the fourth are flat-lying sheets much quarried for building stone; the fifth category appears to be unique — channels depositing tufa both in their beds and as levees which have built up thin meandering walls as much as 10 m high; however, some of these have been artifically enhanced by masonry or even concrete and natural foundations are rarely visible. The shape of the rimstone pool barrages in category 1 above and the microgours on some of their faces has been related to a combination of flow rate and gradient (Ekmekci et al., 1995). A limited amount of U/Th isotope age data is available and indicates that the fissure-ridges have been active for 54,700 ± 5600 yr, whilst the older deposits date back to at least 400,000 yr.

Near Pamukkale other inactive travertines are associated with Quaternary volcanic rocks. Further north, at Bursa, south of the Sea of Marmara, extensive travertine terraces surround thermal springs and lie discordantly on Neogene sediments. A massive bluff of inactive travertine dominates part of the city centre in Bursa. Elsewhere in western Turkey the sediments have been washed out from beneath travertine sheets leaving natural bridges or Yerkopru.

The Taurus Mountains near the south coast of Turkey have several areas of tufa and tufa-cemented conglomerates which correlate with uplifted karst erosion surfaces dating back to the Miocene (Erol, 1990).

Near Antalya braided tufa terraces cover an area of over 650 km^2 and reach 270 m in thickness (Burger, 1990). These are the largest known tufa deposits in the World (Pentecost, 1995). Eleven levels of tufa terrace have been identified at up to 300 m altitude, and U/Th dating suggests the highest may be more than 300 Ka yr old. Perched springline tufas merge into braided tufa plains and rest unconformably on Pliocene sediments. Breaks in tufa deposition with the development of lower terraces may be related to climatic changes. Barrages which once held up lakes have been eroded during downcutting phases, some of which have resulted in spectacular waterfalls such as the Dudenbasi Falls. Lake fills are of soft marly tufa. There are widespread calcretes representing case-hardening of tufa sheets. In the most recent development a river draining the Kestel polje in the high Taurus sinks into a cave system within the tufa sheet and rises again to cascade directly into the sea over a cliff 30 m high northeast

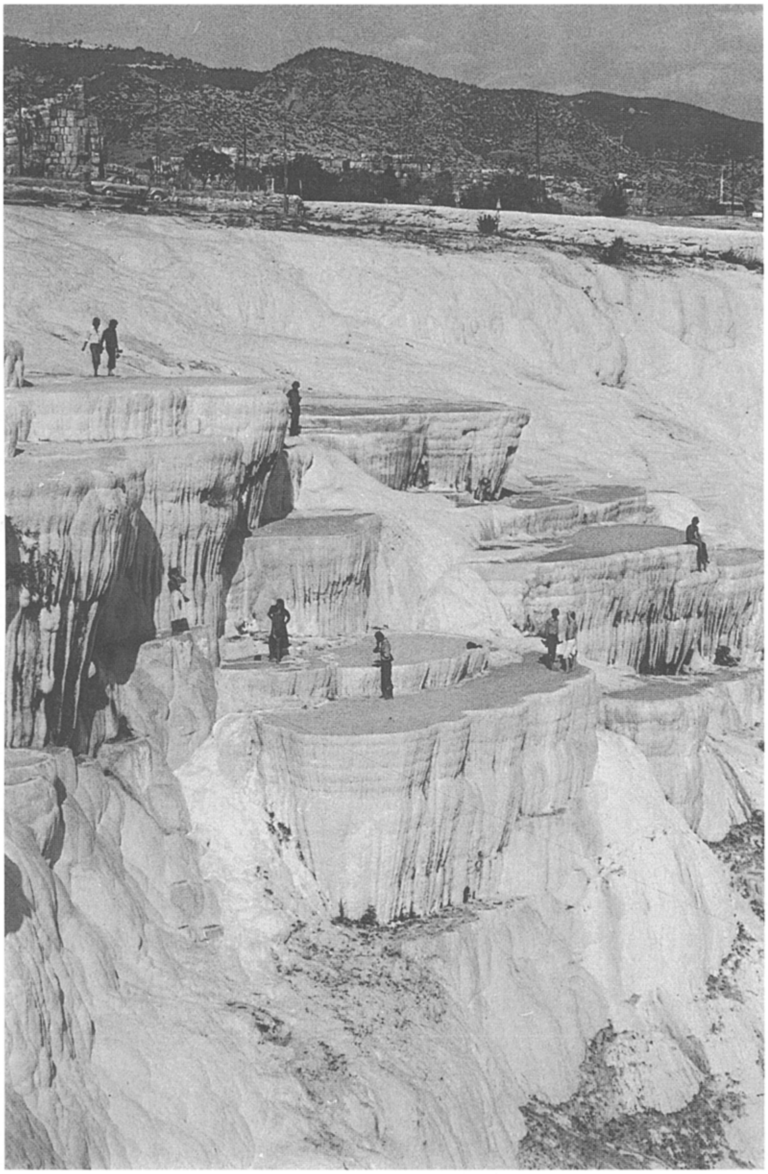


Fig. 26. Thermal travertine barrages and pools on a steep slope, Pamukkale, Turkey (photo by A.C. Waltham).

of Antalya (Fig. 27). The river is fed by springs draining a cool forested area with a soil cover but near the coast it flows into an arid area with high evaporation and much tufa is deposited as drapes down the sea cliffs. It seems likely that both inorganic processes resulting from degassing and evaporation and biogenic processes in the warm waters have played a part. Inactive tufa sheets spread along some 30 km of the Antalya coast. They are said to extend below sea level and to be indicative of fluctuating sea levels (Vita-Finzi, 1969).

In the eastern Taurus, along the Zamanti valley, upfaulted non-calcareous rocks cause springs to rise from deep sources where the long residence time and slightly higher temperature (15°C) yield waters supersaturated in calcite with much resultant tufa deposition. Field observations indicate that preferred sites for deposition are algae-covered pointed leaves (Bayari et al., 1994). Micro-crystals of calcite formed in flowing water are often swept away downstream.

Large calcareous cyanobacterial microbialites have been found largely submerged in the alkaline Lake Van in eastern Turkey (Kempe et al., 1991). Freshwater springs rich in calcium rise through the floor of this large alkaline lake (pH 9.7) and have built chimney-like towers up to 40 m high in as much as 100 m of water. The mechanism appears to be similar to that in Mono Lake, California (see below), but the salinity is not so high, and the lake level has not yet fallen far enough to expose the towers. Comparable submerged deposits are also known in Lake Tanganyika. At such depths photosynthesis plays little part and divers have reported the towers as clothed in a dark cyanobacterial mat rich in *Pleurocapsa*. The porous structures are built of aragonite and have been compared to the Precam-

Fig. 27. Tufa cascades 30 m high over a sea cliff bear Anatalya, Turkey (photo by A.C. Waltham).

brian stromatolite *Conophyton* though they are not laminated. Clusters of spheroids of inorganic calcite occur on the tips of some towers.

11.2. Israel

In northern Israel, sheets of tufa totalling some 18 km^2 occur in the Hula Valley and appear to have been deposited intermittently over the last one million years (Heimann and Sass, 1989). The tufa sheets include laminar and branching fabrics with numerous pisoids and peloids and appear to be generally of paludal type. They interdigitate with coarse gravels and with volcanic lavas. Deposition seems to have been affected both by tectonic factors affecting the hydrological regime and by climatic changes during the Pleistocene. The near termination of precipitation at c. 25,000 yr ago can be related to tectonic uplift causing falling water tables and to progressive desiccation in post-pluvial times.

At Nahal Zin and adjacent sites in the Negev Desert, Israel, fossil spring line tufa mounds are interlayered with archaeological strata with evidence of hominid occupation; they were deposited in wetter climatic conditions than the present during the Middle and Late Pleistocene (Schwarcz et al., 1979; Schwarcz, 1980). A scatter of uranium-series dates has been obtained for tufas in the Arava Valley (Livnat and Kronfeld, 1985).

11.3. Jordan

The Zarqa Main terraces and hot springs near Madaba are fed by hydrothermal springs rising up the Dead Sea Rift marginal fault; water emerges at up to 70°C and flows across a terrace to fall down cascades 30 m high which form a tourist attraction. The Romans had baths here.

In central Jordan low hills rise some 50 m above a marble terrane and are capped by "fossil" hyperalkaline tufa deposits. In today's very arid environment there is no deposition but detailed investiga-

Fig. 28. The massive but thin-walled barrage and lake at Band-e-Amir, Afghanistan (photo by W.E. Renshaw).

tions (Clark et al., 1991) have shown that the tufa enclosed reeds and other plants, and was deposited from waters with a pH of 12.5. This hyperalkaline system was rich in $Ca(OH)_2$ and absorbed CO_2 from the atmosphere so as to deposit calcite in contrast with the more normal degassing mechanism. Isotope studies, thermoluminescence and ESR techniques suggest an age of around 700–900 Ka B.P. in a wetter Middle Pleistocene climate than the present. Deflation erosion of the surrounding desert has left relics of a former tufa sheet isolated on hill tops. Similar deposits are known in nearby parts of Israel.

11.4. Oman

Hyperalkaline tufas similar to those of central Jordan also occur in Oman where modern and fossil tufas occur in patches 200–300 m wide and 3 m thick over a length of 7 km along an ultramafic outcrop near Nizwa in the mountains of northern Oman (Clark and Fontes, 1990; Clark et al., 1992). Weathering of peridotite yields spring waters rich in $Ca(OH)_2$. Crusts of calcite can be seen forming on the pools as CO_2 is absorbed from the atmosphere. A history through the last 35,000 yr shows an alternation of bio-mediated and inorganic tufa deposition. The bio-mediated periods are thought to correspond to late Pleistocene and early Holocene pluvial climates (Clark and Fontes, 1990).

11.5. Afghanistan

The Band-e-Amir lakes in the Hindu Kush, some 200 km west of Kabul, are held up by tufa barrages on three sides (de Lapparent, 1966; Brett, 1970; Lang and Lucas, 1970) (Fig. 28). Whilst similar to the Plitvice Lakes they are not confined in a gorge but lie across a broad valley at an altitude of nearly 3000 m. The surrounding area is semi-arid but receives water from melting snow each spring and this percolates through limestone formations to rise as perennial springs. The barrages extend for some 12 km along the valley and are particularly striking in that they form nearly vertical walls some 10 m high though some are little more than 3 m thick. This may reflect the sparsity of vegetation available for encrustation in the semi-arid climate in Afghanistan in contrast to the woodlands around Plitvice. However, Cyanophytes, Chlorophytes, Charophytes and *Equisetum* have been recorded by Lang and Lucas (1970) and some evidence of seasonal lamination was noted. Evaporation may also play an important role in accelerating vertical tufa growth here. The upper ends of the Band-e-Amir lakes receive spreads of fluvial sand which may affect pH locally. A sequence of barrage growth, destruction and re-growth has been proposed by Jux and Kempf (1971). They argue that there has been growth during at least two interglacial periods as well as in the Holocene, interrupted by higher run-off and incision with consequent destruction during glacial periods. The present barrages are therefore entirely post-glacial. The nearby Ajdar Valley has a single barrage.

11.6. India and Nepal

Few records of tufa have been located for the Indian sub-continent (Parihar and Pant, 1975), though there are known to be some derived from the Deccan traps (A. Pentecost, pers. commun.). Parihar and Pant briefly recorded a deposit dominated by bryophytes at Sahasradhara, Dehra Dun. They regarded the bryophytes as important in providing a substrate for other algae.

In the Nepalese Himalayas Waltham (1971, 1996) described a massive sheet of tufa deposited upon colluvium at Kursangmo (also known as Guru Gsang Phug). Tufa drapes and stalactites were present and a cave extended 30 m beneath the tufa sheet. Still in Nepal but on the northern slope of the Himalaya, at Jomosom, near Mukintah, travertine dams have formed close to thermal springs from major fault zones.

11.7. Pakistan

The ancient Greek city of Taxila, west of Rawalpindi in Pakistan, is partly built of large blocks of tufa quarried nearby (A.C. Dunham, pers. commun.).

11.8. Thailand

Thailand has large tufa and travertine cascades at Ban Sai Yok, near the Burmese border, comparable in style to those of Pamukkale in Turkey, though on a smaller scale. There are other deposits over the border in Burma (Myanmar).

11.9. Philippines

The curiously named Salt Springs of Mindanao in the central Philippines, once figured on a postage stamp, appear to be travertine domes of thermal origin.

11.10. China

In China's vast karst landscapes there are many tufa deposits, both large and small. Sweeting (1995) noted many of them though she gave few detailed descriptions. No other summary account has been located. In western Sichuan Province the adjacent Huanglong and Jiuzhaigou Districts are on rivers draining the eastern borders of the Tibetan Plateau; they flow through gorges with some hundreds of tufa barrages, cascades, fluvial sheets and caves with impounded lakes, which form tourist attractions (Sweeting et al., 1991; Sweeting, 1995). The barrages range up to 40 m high, comparable with those at Plitvice in Croatia. Over 200 dams with many and varied colours due to the algae have built up on the Huanglong River giving the area the status of a World Heritage Site. At least one contains a cave system within the tufa. The tufa barrages are unusual in being close to the snow line at altitudes of around 3000–4000 m though there is little evidence of a history of Pleistocene glaciation and deglaciation. Cold winters and dry summers mean that deposition is largely in spring and autumn. Experiments in the Haunglong stream (Dreybrodt et al., 1994) showed that deposition was greatest in fast flowing water owing to greater degassing. Both the magnesium content and pH increased downstream. A similar series of fluvial sheets and barrages occurs at Pashuitai of Chungtien also in Sichuan Province. Further southeast on the Guizhou plateau a massive tufa cascade occurs where the Baishui River falls over the side of a limestone gorge; here the Huangguoshu Falls form the focus of a tourist area (Waltham, 1984) (Fig. 29). The Falls are 67 m high and 80 m wide; the tufa wall is up to 10 m thick and behind the tufa drapes a series of small caves is traversed by a tourist footpath (Sweeting, 1995). ^{14}C dates of around 40,000 yr have been obtained from the back of the wall. Both the Baishui and other nearby rivers have a series of tufa barrages and cascades; a kilometre upstream stands the Doupo Fall, a tufa cascade 20 m high and 100 m wide, whilst a similar distance downstream is the comparable Luositan Falls and together these three give a complex broadly comparable with the Plitvice bar-

Fig. 29. Massive waterfall cascade tufa deposits with small barrages in the river below. Hangguoshu Falls, Ghizou, China (photo by A.C. Waltham).

rages though with only minor impounded lakes (Wang, 1983). Elsewhere in Guizhou Province tufa dams are common; along the Xiangshuihe River tufa dams up to 30 m high have formed, though growth is minimal now owing to the diversion of the underground river into a hydroelectric dam system. Tufa now forms in the outflow of the latter at rates up to several centimetres per year. Outgassing is regarded as the main factor causing deposition.

In the classic tower karst area around Guilin tufa sheets covered in mosses spread from springs along the Li River and there are large pendulous masses of inactive tufa on cliff faces, some with small trees growing on them.

Tibet, in spite of its cold dry climate and high altitude, has a scatter of tufa deposits, mostly either calcareous crusts on colluvium or associated with geothermal springs (Waltham, 1996). In eastern Tibet, northeast of Amdo, a large tufa deposit flanks the Sanqu river valley, displacing the river southwards (Waltham, 1996). The tufa is up to 50 m thick and has been dated at 6000–5000 years B.P. The upwelling water is at 10–12°C showing at least a mild geothermal influence; algae are abundant in the warm waters (Sweeting et al., 1991).

11.11. Japan

Southwest Japan has a scatter of tufa deposits (Yoshimura et al., 1996a). A sheet deposit at Shirokawa is 380 m long and exhibits biologically controlled annual layers. Rapid deposition covers articles within a few years. At the entrance to the Akiyoshi-Do tourist cave is on a cat-walk built above a small barrage some 5 m high. As the light levels falls going into the cave the biota changes from algae and mosses to cyanobacteria and the pH decreases (Yoshimura et al., 1996b).

In the volcanic areas of Japan there are numerous geothermal springs which deposit travertine in a manner similar to Mammoth Hot Springs in Yellowstone National Park (Kitano, 1963).

11.12. Southeast Asia

Many of the large caves explored in Southeast Asia have large pendant masses of cave tufa hanging from the walls of the entrances, but little attempt has been made to study the mechanisms of deposition. It can be surmised that high evaporation rates are coupled with biologic activitity with decreasing effect of the latter as light levels fall off inside the caves. Good examples are in the giant caves of Mulu in Sarawak, in various parts of southern China, and the Batu Caves of Malaya.

12. Tufa deposits of Africa

12.1. Morocco

Near Taza in northeast Morocco the river resurging from the Chiker Caves falls over an impressive series of tufa cascades. The lime is derived from a limestone basin in the catchment area some 5 km away. Further west the Oum er Rbia river drains a large area of limestone in the Atlas Mountains and its gorge has low tufa barrages for some 20 km.

Massive cascade tufas, barrages and lacustrine deposits occur at d'Imouzzer and Ida du Tanane in Morocco (Muxart, 1981; Weisrock, 1981a,b). Three generations of tufa deposition have been recognized, with deposition in laminae on moss cushions and lichens common. Laminae are dark winter layers with carbonaceous detritus alternating with clear summer layers enclosing growing algae. Growth is up to 4 mm per annum and most of the deposit is less than 10,000 yr old, but older deposits around 70,000–100,000 yr old have been recognized.

Tufa barrages and cascades up to 10 m high also occur at Ouzoud, east of Marrakech in the Moroccan Atlas Mountains; they appear to be deposited from cold meteoric springs.

12.2. Algeria

In Algeria, the multi-coloured travertine cascades at Hammam–Meskoutine are derived from a series of hot springs, some nearly boiling at 98°C. Terraces, cascades and pools held up by travertine barrages become progressively discoloured by algae and bacteria as the thermal waters cool downstream. Several other thermal springs deposit travertine at Hamman Salahine, Hamman Bou Akkaz, Hamman Beni Cuecha, Hamman Bradaa and Hamman N'Bails. Most of these were used by the Romans for baths.

Also in Algeria there are alluvial fans with two groups of tufa deposits at several localities on the south side of the Aures Mountains. The two developments are (a) in sheets up to 0.5 m thick at the foot of alluvial fans debouching on to terraces and (b) in cone-shaped masses generally less than 1 m thick in the wadis cut into the terraces; pollen studies have shown the tufas to be late Pleistocene to early Holocene age, i.e. with little distinction in the age of the two developments. The climate is thought to have been a little more humid than at present, particularly in winter (Ballais and Cohen, 1981).

12.3. Tunisia

Like Algeria, Tunisia has several thermal springs once used as baths by the Romans and still depositing travertine, including Ain Djebel Oust and Hamman Zriba.

Massive travertine deposits comparable with those in Italy have been quarried as building and ornamental stone in Morocco, Algeria, Tunisia and Libya. Little information is available, but some is known to be marketed via the Italian ornamental stone companies around Rome and Siena, where it is probably confused with Italian stone.

12.4. Egypt

Travertine sheets were worked for ornamental purposes in ancient times, though the record is confused as the material is variously referred to as alabaster or onyx! At least some of it was stalagmitic material obtained from ancient caves.

Inactive sheets of tufa as much as 20 m thick cap limestone plateaux in the Kharga, Kukur and Dungul regions of Egypt (Gardner, 1932; Said, 1990). At least four phases of deposition dating back to the mid-Tertiary have been claimed though dating has proved difficult. According to Butzer and Hansen (1968) there are two types of tufa deposit at Kukur near the Aswan Dam: one is a spring line deposit whilst the other is associated with intermittent sheet-flood run off.

12.5. Chad

A towering tufa spring mound occurs at Abbe Lac in Chad.

12.6. East Africa

Many of the lakes in the East African Rift Valley have lacustrine carbonate masses deposited under shallow water by cyanobacterial growth, often referred to as stromatolites in regional literature. Old shore lines are demonstrated by uplifted relics of equivalent Pleistocene deposits. A few inflowing streams have barrages and associated deposits. Many of these are associated with thermal springs, particularly along fault lines. No comprehensive description has been traced, though Casanova (1986) has given a brief outline of travertine deposits in Lakes Bogoria, Magadi and Turkana in Kenya, and Lakes Natron and Manyara in Tanzania (Casanova and Hillaire-Marcel, 1992). The deposits have been referred to both as travertine and as stromatolites. Vincens et al. (1986) have isotopically dated old tufas at levels up to 9 m above the present level of Lake Magadi as around 4000 yr old. Oncolite nodules are widespread on the lake floors and in older uplifted deposits. Lakes in the rift valley of southern Ethiopia, particularly Lake Stephanie, have comparable uplifted shore-line tufa deposits (Grove et al., 1975).

Tropical weathering of basic volcanic rocks in Rwanda has released enough calcium to permit the growth of lacustrine tufa deposits.

12.7. South Africa

In South Africa Marker (1971, 1973, 1985, 1988) has described several tufa deposits in the semi-arid Transvaal and along the Gaap Escarpment in the North Cape Province. In the Transvaal most occur as sequences of fluvial terraces and cascades in gorges draining from the dominantly dolomite plateau. A few deposits in the Campbell area are worked for ornamental travertine. Marker has noted that many are extinct or have the minimal activity today; she argues for most deposition having been in the waning phases of pluvial periods when karstic activity was greatest. Partridge (1985) has proposed that increased rainfall will lead to erosion and incision as observed in some deposits being channelled; consequently he has argued that tufa deposition is best correlated with moderate increase of rainfall only. A large mound of tufa near the Umzimvubu River, Port St. Johns, has been worked for ornamental slabs used mainly in interior panelling (King, 1963). Tufaceous sediments were found to have been deposited by cyanobacterial activity in a sink-hole lake in the western Transvaal (Gow, 1981).

The early hominid skulls found at Taung, Sterkfontein, Makanpansgat etc. in South Africa are all from deposits in collapsed caves, confusingly referred to as tufa, travertine, stalactite, calcareous breccia or cave earth (Young, 1925; Peabody, 1954; Marker, 1971, 1972, 1973, 1974, 1975; Butzer, 1974, 1980; Day, 1986). While there is little doubt that the bone-bearing deposits were formed within caves and are thus strictly neither tufa nor travertine but some form of stalactitic material, the caves are often associated with long inactive spring-line tufa sheets outside. Quarrying for agricultural lime has destroyed many of these but an outline stratigraphy extending back over 2.5 million years has been deduced, apparently controlled by climatic oscillations in this arid area (Day, 1986).

12.8. Namibia

Etosha Pan in the arid climate of Namibia has ''stromatolites'' around its margins and oncoids with algal encrustations on its bed (Smith and Mason, 1991).

12.9. Angola

In Angola thermal springs up to 45°C have built travertine terraces at Ochilesa on the bank of the River Quime.

12.10. Madagascar

Spectacular tufa spring mounds and barrages form a tourist attraction in the valley of Les Sept Lacs at l'Onilhay in southwest Madagascar (Nicod, 1981; Salomon, 1981); however, compared with Plitvice the lakes are small, the largest only 60 m long and 5 m deep, and the barrages are low, less than 5 m high. The springs are now mostly inactive and only limited deposition of tufa is taking place. Overhanging barrages have numerous pendants of tufa and shallow caves have many stalactites and stalagmites. A finely granular calcareous deposit rather like mondmilch occurs on top of some barrages, coating mosses. Much of the calcium carbonate is derived from nearby limestones but some may be due to tropical weathering of the basalts in the massive escarpment overlooking the valley releasing calcium. Also in Madagascar thermal springs at Diego-Suarez at the northern tip of the island and at Betafo in the centre deposit large quantities of travertine.

13. Tufa deposits of America

The tufa deposits of America are surveyed by geographical arrangement of States from east to west, followed by Canada, Central and South America.

13.1. Virginia

In the eastern United States tufa cascade and small barrage deposits are scattered in the valley and ridge province of the southern Appalachians where aggressive allogenic waters are the norm. Over 50 deposits in 17 counties of Virginia have been described by Hubbard et al. (1985, with annotated bibliography) and in a comprehensive report on *travertine–marl* by Herman and Hubbard (1990, with several important contributions from other authors, e.g. Schwarcz (1990) including a note on the algal flora by Pentecost, 1990a). Travertine is the term they use to describe the more solid concretionary carbonate deposits whilst marl includes loosely aggregated tufas. Some deposits spread several hundred metres across alluviated valleys. Springs generally rose from deep circulation in fault zones, and some are weakly thermal. A detailed study of the fluvial cascades and small barrages in Falling Spring Creek in Virginia showed that the principal factor in tufa deposition was degassing by turbulence over stratigraphically-controlled waterfalls (Hoffer-French and Herman, 1990; Lorah and Herman, 1990). Loss of CO_2 often did not commence until some hundreds of metres downstream from the springs and deposition was most rapid at waterfalls. Travertine deposition occurs in three areas at Warm Springs, Hot Springs and Healing Springs, where the springs have a thermal water input from deeply circulating groundwaters mixed with locally-derived meteoric water. Some of the latter rose through the stream beds to merge with thermal water issuing from head springs or even from caves. Temperatures up to 38°C were recorded in Warm River Cave. Although algae, bacteria and diatoms were present in the tufa, they were not regarded as being very significant in calcite precipitation. In some cases land clearance and agricultural practices led either to erosion or to so much silting that there is little deposition today (Kirby and Rimstidt, 1990). Deposition is highest in the summer months when run-off was minimal and temperatures high according to Lorah and Herman (1988), and these are the conditions when bacterial and algal growth are greatest (Pentecost, 1990a). The run-off from the occasional hurricane was highly destructive for tufa and could result in the removal of whole cascades, exposing bare bedrock.

Throughout Virginia tufa deposits have been quarried for use as agricultural lime, whereby at least some of the carbonate was probably recycled through karstic drainage. Archaeological investigations suggested that the tufa terrace below Falling Spring had been attractive to pre-Columbian Indians.

An unusual cavernous tufa deposit is that in Sweet Springs Creek, Alleghany County, Virginia, where Cesspool Cave has developed within a tufa escarpment. The resurgent springs contain an unusually high proportion of H_2S thought to be derived from oxidation of pyritous shales; this is oxidized by sulphur bacteria to yield sulphuric acid which has attacked the older tufa sheet and converted some to sulphur or to highly soluble gypsum (Hubbard et al., 1990).

13.2. New York State

Lacustrine tufa deposits with associated beaches of calcareous sand derived largely from tufa occur in some of the former glacial lakes in up-state New York, notably at Green Lake near Syracuse (Eggleston and Dean, 1976; Dean and Fouch, 1983). The lake margin tufas are algal encrustations on both rock ledges and submerged vegetation; the crusts form ledges just below water level, and masses of *Chara* occur in slightly deeper water. The absence of waterfalls or any cause of turbulence which might cause degassing suggests that these deposits are primarily of biological origin. Growth is mainly in the summer months as the lake is frozen in the winter. Thompson and Ferris (1990) demonstrated that the cyanobacterium *Synechococcus* was responsible for biomineralization whereby calcite rhombs enclosed the cells.

13.3. Illinois

The Falling Springs tufa deposit near Dupo, St. Clair County, is a cascade below a cave mouth in a limestone cliff. The sheet is composed largely of tufa deposited by a filamentous mat of sheaths of the alga *Phormidium incrustatum* though numerous diatoms are present. Adjacent twigs are coated with *Cladophora*. Clay particles washed out of the cave are scattered through the mass (Davis et al., 1989).

In the western United States nearly 500 tufa and travertine deposits in eleven states were catalogued by Feth and Barnes (1979). Whilst few have been studied in any detail, some are worthy of discussion herein. Some support the concept of correlation with pluvial phases correlating with glacial phases further north, but others are associated with hot springs or with the chemistry of saline playa lakes.

13.4. Oklahoma

In southern Oklahoma, large fluvial barrage and cascade tufa deposits at Turner Falls on Honey Creek, in the adjacent Falls Creek and several other localities in the Arbuckle Mountains are still active in an area of tufa deposits covering some 1600 km^2 (Emig, 1917; Love and Chafetz, 1990; Chafetz and Lawrence, 1994). The deposits are mainly undulating cascade sheets with overhangs; small barrages and pools occur in stream courses with a gentle gradient. The conditions under which tufa is precipitated are comparable with Plitvice in that deposition does not commence until several kilometres below the springs which drain a predominantly limestone upland. Nucleation on algae and mosses is thought to be the predominant mechanism (Srdoc et al., 1989; Love and Chafetz, 1988, 1990). The latter showed that diagenetic recrystallization can effectively conceal the evidence of algal origin with large neomorphic calcite crystals. Inorganic tufa was also deposited in spelean areas, beneath overhangs and in cavities. At least three periods of tufa deposition separated by episodes of stream incision can be reconstructed from relict masses high above the streams and on the adjacent plateau: the sequence reflects the probable influence of climatic changes, perhaps of Pleistocene pluvial phases.

13.5. Colorado

In southwest Colorado, a travertine dome lies beside the highway some 17 km north of Durango (Chafetz et al., 1991; Chafetz and Lawrence, 1994). Some 10 m high, a trickle of water at 33°C rises from an orifice at the top of the dome and layered travertine is deposited on a sloping scarp of Mississippian limestone. Further downstream, tufa deposits line a ditch as the water cools. Deposition is both by degassing and by calcite rhombohedra growing on diatoms and other algae. Within the nearby town of Pagosa Springs, some 30 km east of Durango, a sheet of tufa is spring-fed and consists largely of a gently sloping series of low barrages with braided channels.

On the east flank of the Rocky Mountains a group of springs deposit tufa at Colorado Springs.

13.6. South Dakota

On the southern margin of the Black Hills in South Dakota a karst area around Wind Cave is thought to drain to thermal springs in Fall River at the town of Hot Springs, probably merging with hot waters expelled from the adjacent basin. Resurging at up to 33°C the springs deposit thermal travertine in the bed and banks of the river.

13.7. New Mexico

Sitting Bull Falls in southern New Mexico are cascade deposits in a comparable position to the western end of the Arbuckle Mountains of Oklahoma (Chafetz and Folk, 1984).

At Jemez Springs, north of Albuquerque, fluvial and cascade tufa deposits are accompanied by a fissure ridge dome known as Soda Dam: sinuous microterraces holding up miniature pools cover the flanks of the dome (Chafetz and Folk, 1984).

Cascade deposits and braided stream-bed tufa occur in McKittrick and other canyons of the Carlsbad Caverns National Park on the New Mexico/Texas border (Jennings, 1985).

13.8. Arizona

The Grand Canyon of the River Colorado in Arizona, some 500 km long, has numerous tufa deposits both active and fossil though only outline accounts have been located (Reilly, 1961; Elston et al., 1989). Although generally referred to as travertine in American literature, the bulk of the deposits are porous tufa without any thermal association. In spite of its arid climate today there seems little doubt that the region has been much wetter in the past and such pluvial phases may account for some of the large but inactive tufa deposits. However, an alternative hypothesis has been proposed by Hamblin (1994) whereby the successive major lava dams in the last $1.8 \cdot 10^6$ yr in the western Grand Canyon impounded a sequence of lakes. Some of the lakes extended the whole length of the canyon raising water levels by hundreds of metres. The dams were each removed by erosion within a few thousand years, but during that time water tables were raised to within large parts of the Redwall Limestone and calcareous springs operated as the limestone drained. The tufa covered or cemented lake infill sediments of which remnants occur through much of the Canyon. In the Marble Gorge section of the Grand Canyon a few kilometres upstream from the confluence with the Little Colorado massive sheets of fossil perched spring line and cascade tufa lie on talus sheets rising over 60 m above river level: individual sheets are as much as 16 m thick and incorporate large boulders which have fallen from the cliffs above. The tufa sheets and underlying talus have been eroded deeply by gullies from storm run-off; the tufa probably represents precipitation in a more equitable (pluvial?) climate (Fig. 30). Some 10 km of the canyon of the tributary Little Colorado has comparable masses of tufa, at least one part of which is still active as part of the flow of the Little Colorado comes from a spring mound, the Sipapu; the water rises through a hole in the top of a tufa dome some 10 m high and wide; impure tufa contaminated with mud from storm run-off further upstream forms dams and encrusts boulders along the river bed downstream to the Confluence. In the central Grand Canyon eroded and partly

Fig. 30. Deeply gullied sloping tufa sheet covering Cambrian shales, Grand Canyon, Arizona.

collapsed tufa blocks line the scenic Elves Chasm, whilst massive pendulous sheets of tufa encrust several kilometres of the canyon walls to a height of some hundreds of metres above river level. These apparently perched spring line tufa deposits may reflect pluvial periods, or they may indicate high water-tables in the late Pliocene to early Pleistocene when the Canyon was dammed by some 350 m thickness of lavas near Toroweap Point (Hamblin, 1994). The springs feeding the Elves Chasm area deposits were on the south side of the Grand Canyon owing the slightly increased dip of the strata to the northeast. By contrast the active cave springs of the central and eastern Canyon are on the north side today where the strata dip gently off the flanks of the Kaibab upwarp. Beneath the Surprise Canyon landslide of the north wall tufa and talus fill an old river channel some 60 m above river level, though with indications of spring sources to the south. The tributary Havasupai Canyon stream has many tufa barrages over a length of 15 km (Black, 1955; Giegengack et al., 1979; Hamblin, 1994); among them are five massive tufa cascades, two of them more than 30 m high, where tufa sheets encrust and overhang the eroded sheets of silt from a phase of sedimentary infilling and protects them from further erosion (Figs. 31 and 32): Hamblin (1994) regards these silt fills as dating from the ponded-up waters of lakes associated with the lava dams of late Pliocene and early Pleistocene times; a little alluviation has apparently also occurred in Holocene times. In contrast with Hamblin's ideas, ^{14}C dating of carbonates in the tufa by Giegengack et al. (1979) suggests that most of the visible tufa is less than 3000 yr old and that the incision resulting in the present waterfalls may be no more than 900 yr old; older tufa forms relict masses for several kilometres on the walls of Havasu Canyon. Further downstream in the Grand Canyon warm springs (26–30°C) rise from a fault fissure near Lava Falls and yield a tufa sheet which encrusts vegetation over an area some hundreds of metres across just above river level: whether this should be regarded as

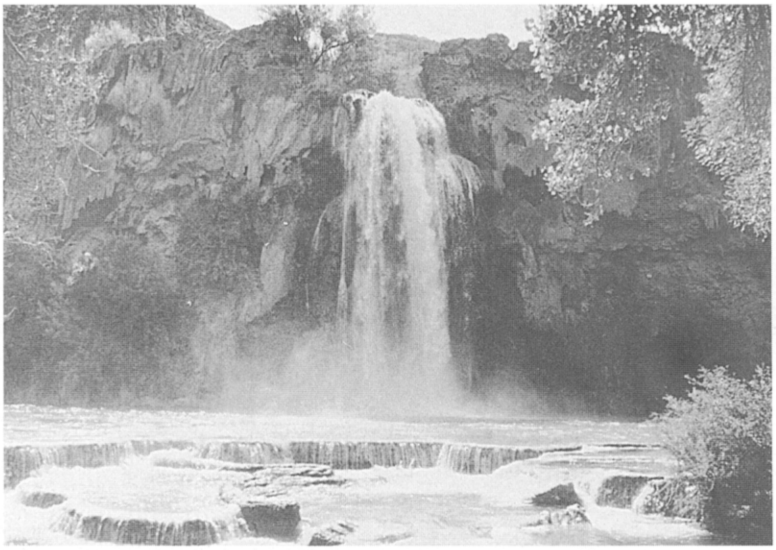


Fig. 31. Cascade tufa 30 m high over a Pleistocene silt fill in Havasupai Canyon, off Grand Canyon, Arizona. Small barrages occur downstream for several kilometres.

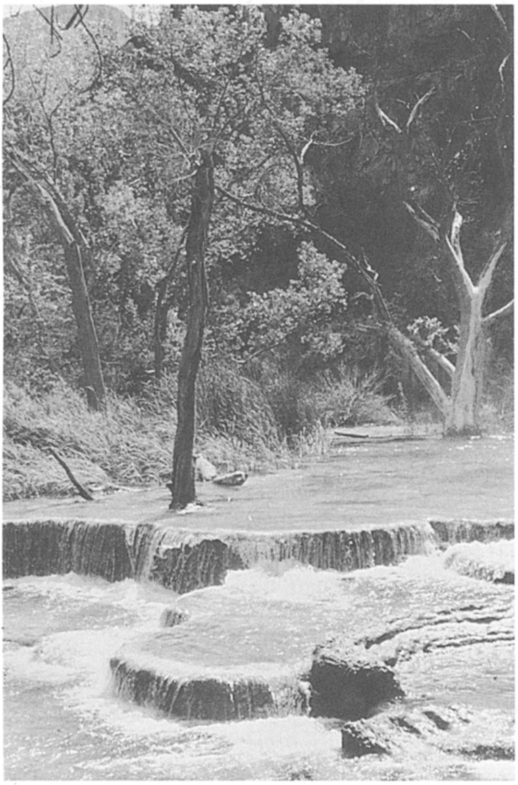


Fig. 32. Small barrages and pools in Havasupai Canyon, Arizona.

a thermal travertine deposit is debatable as summer daytime temperatures may exceed 40°C (Fig. 33). In the western Grand Canyon downstream from the lava dam sites there are tufa deposits whose growth is apparently independent of the dams. The two adjacent tributaries of Travertine Falls and Travertine Canyon respectively yield an active tufa cascade some 20 m high, and deeply dissected and partly collapsed tufa masses (Fig. 34). The tributary Quartermaster Canyon has a mass of tufa and gravel forming a dam more than 100 m high. Lower downstream on the south bank there is also a dome of tufa some 150 m high round a weakly thermal spring, still mildly active. A massive sheet of tufa, now deeply eroded, extends for several kilometres along the north bank of the Colorado nearby.

The apparently conflicting hypotheses concerning Grand Canyon tufa deposits being caused either by Pleistocene pluvial climatic effects or by Plio–Pleistocene lava-dammed lakes will require much further study before the problem can be resolved. The significance of the thermal input also needs to be assessed.

13.9. Wyoming

Most of the geysers and hot springs in Yellowstone National Park in northwest Wyoming deposit

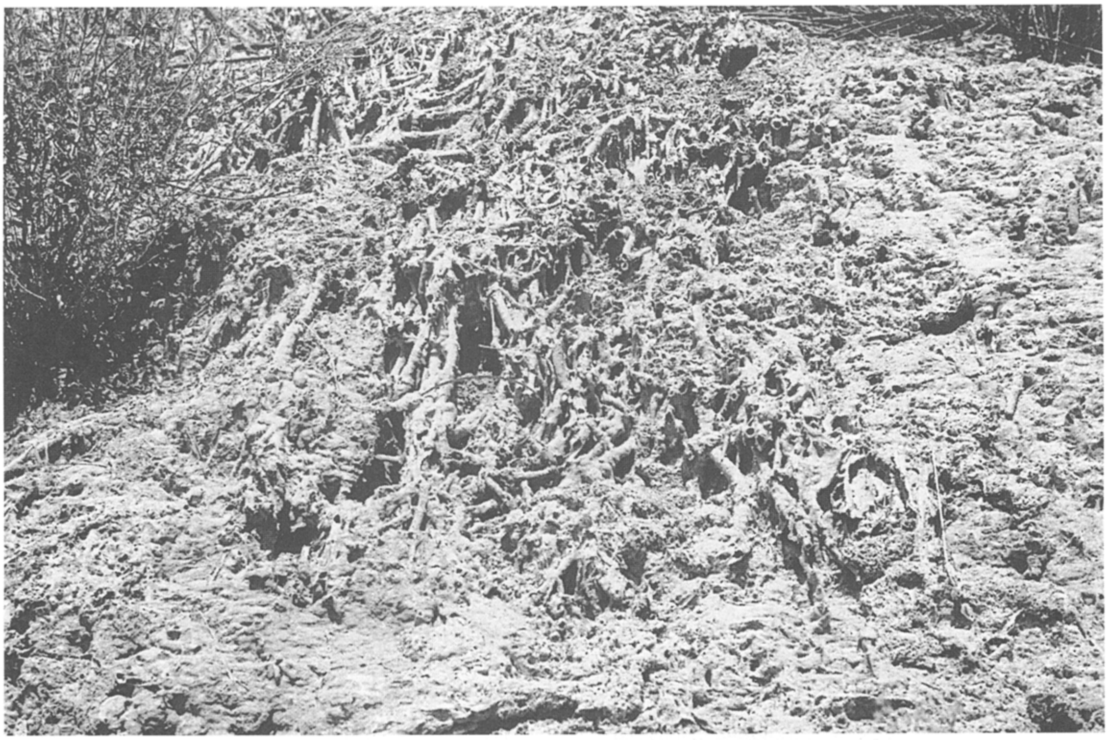


Fig. 33. Tufa encrusting sedges and reeds near Lava Falls, Grand Canyon, Arizona.

only siliceous sinter and so do not concern us here, but Mammoth Hot Springs deposit calcium carbonate in large thermal travertine masses, which grade into more porous biogenic tufa downstream (Fig. 35). Cascades with dams and shallow pools of hot water extend several hundred metres down the hillside and have engulfed trees (Allen and Day, 1935; Keefer, 1976; Bargar, 1978). The dams often overhang and grottoes with stalactites occur beneath the lips. Concealed feeder conduits are sometimes enlarged to the point where the roofs collapse giving lines of pits. These may extend into caves often with excess steam or CO_2 discouraging exploration! The calcium carbonate in the travertine is derived from underlying sedimentary rocks and transported by hot circulating groundwaters warmed by residual volcanic heat. On emergence the hot waters average around 74°C and precipitation starts immediately as a result of evaporation and degassing, i.e. thermal travertine. Downstream cyanobacteria play a part and discolour the deposits when the waters have cooled to below 50°C. Most of the deposition is in the form of microscopic aragonite needles clustered in the form of "shrubs"; the cyanobacteria are present between the needles but are thought only to play a minor part in causing precipitation (Pentecost, 1990).

13.10. California and Nevada

In the Basin and Range province of California and Nevada, saline, ephemeral or dried-up lakes with evaporative travertine deposits are widespread along the shorelines past and present (Rieger, 1992). They are regarded here as hyperalkaline travertine, though often called tufa in local literature. A small thermal input is present in some cases. Precipitation is generally due to a combination of microbial and physicochemnical factors; macrophytes are generally absent. Localities include Searles Lake, with its tufa pinnacles (Scholl, 1960), and Mono Lake (Rieger, 1992), both in California, and Pyramid and Walker Lakes in western Nevada (Osbourne et al., 1982; Newton and Grossman, 1988; Benson, 1994; Benson et al., 1995). At Searles Lake, the Trona Pinnacles form a National Natural Landmark. Three groups totalling some 500 pinnacles are spread over an area 16 × 6 km southwest of the desiccated lake; the groups correspond to different former lake levels, which in turn have been correlated with the Penultimate and Last Glacial wet phases (Scholl, 1960; Scholl and Taft, 1964). Abundant polygonal to ellipsoidal bodies were identified as moulds of algal cells. At The Needles of Pyramid Lake, Nevada, falling lake levels due to evaporation have revealed tufa heads and crusts on boulders and gravel. Aragonitic ooids are common on the lake floor and revealed on the shores as the lake level drops.

Pyramid and Walker Lakes and adjacent playas are part of the Pleistocene Lahontan lake basin, where oscillating lake levels are partly marked by tufa terraces. Uranium-series dating of these has demonstrated that high water levels have a positive

Fig. 34. Travertine Falls, an almost inactive cascade tufa in the western Grand Canyon, Arizona.

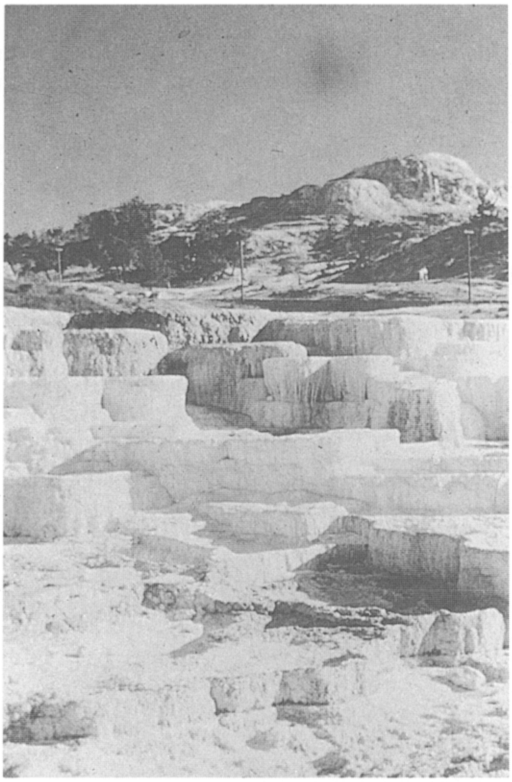


Fig. 35. Travertine barrages and small pools. Mammoth Hot Springs, Yellowstone National Park, Wyoming.

relationship to Pleistocene glacial episodes back to at least 300,000 yr (Yong and Benson, 1988). Dating by ^{14}C methods has shown that tufa deposition reached a maximum in late Pleistocene times from 23,500 to 12,000 yr B.P. with at least three main developments at different altitudes from 1177 to 1337 m above sea level within that period (Benson, 1994). These correspond to spill-over altitudes into other Lake Lahontan sub-basins. Minor oscillations between these levels have been related to glacio-climatic deflections of the polar jet stream across the Lahontan Basin (Benson et al., 1995). Pyramid Lake is moderately warm at 21°C and is fed by hot springs at around 60°C rich in dissolved calcium. Cool freshwater streams flowed in from the surrounding mountains but are now partly diverted into an aqueduct. Pyramid Lake is less saline than Mono Lake (below) and its sediments are rich in *Chara* and diatoms. Bacteria are thought to play some part in tufa deposition. The tufa includes sheets encrusting bedrock, dense laminated travertine, rod-like thinolite and porous dendritic tufa; these and other forms are thought to be related to changes in lake chemistry and temperature. Much of the tufa is in a prismatic form known as thinolite composed of the rare hydrate ikaite ($CaCO_3 \cdot 6H_2O$). Studies by Bischoff et al. (1993) suggest that thinolite is stabilized by the presence of orthophosphate and low (near freezing) temperatures.

Mono Lake in eastern California dates back to the early Pleistocene and has tufa deposits all round its shores, though the principal deposit is at the Tufa Towers State Park on its southern shore (Rieger, 1992) (Figs. 13 and 36). Chimney-like masses of tufa have been revealed by the lake level falling more than 10 m in the last 50 yr owing to diversion of inflowing streams into the Los Angeles water-supply aqueduct, but older towers attracted attention more than a century ago and Russell (1883, 1889) provided extended descriptions of the maze of towers, castles and domes. The chimney-like tufa structures originate where weakly thermal freshwater with $CaCO_3$ in solution rises through the lake floor into the highly saline lake waters. Sudden cooling and a common ion effect reaction of fresh and saline waters have been proposed as reasons for abiogenic precipitation (Dunn, 1953) but Scholl and Taft (1964) have shown that filamentous and spheroidal algae and Cyanobacteria are important as precipitating agents in at least one chimney which still overflows above lake level; brine-fly larvae and pupae contribute to tufa deposition by means of specialized lime-secreting glands. Scholl and Taft (1964) also noted that diagenetic recrystallization gradually obliterates the algal tubules and suggested that the bulk of the Mono Lake tufa was of algal origin, implying that the tufa is lacustrine and only deposited at depths where photosynthesis can occur. Shelves and ledges projecting from some towers correspond to former stands of the lake level. Intergranular precipitates in the lake floor sediments add to the bulk of the tufa. The origin of the calcium carbonate is thought to be leaching from sediments now deeply buried in the northern part of Owens Valley which have been heated by residual vulcanism (the last eruptions were about the 14th and 15th centuries A.D.). Whilst some of the rising freshwater has elevated temperatures they are no higher than

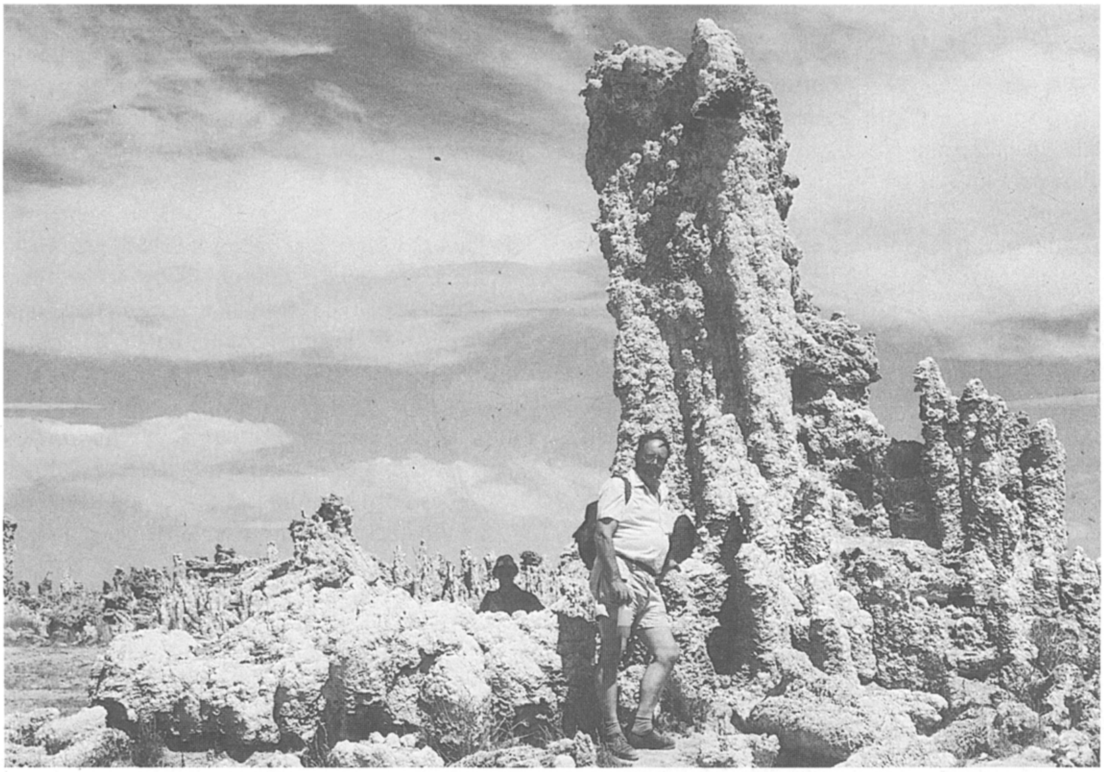


Fig. 36. Tufa towers due to freshwater springs in a saline lake revealed by a falling lake level. Mono Lake, California.

ambient summer air temperatures and so the classification of the Mono Lake deposits is retained as tufa. The high alkalinity of the lake waters mean that even low concentrations of calcium carbonate (11 ppm) lead to precipitation of tufa. "Sand tufa" mini-towers have also been described (Cloud and Lajoie, 1980) and appear to be vertical tubular calcite-cemented structures resulting from water evasion through loose pumice sand.

Some 20 km north of Mono Lake, at Bridgeport, California, thermal waters have built up a fissure ridge travertine deposit.

Birch Creek in Inyo County has a series of small tufa dams and encrustations on the stream bed increasing in amount downstream. Barnes (1965) attributed the deposition to degassing.

13.11. Canada

In spite of the Arctic climate northwestern Canada has several large tufa occurrences, growing mainly in the short summers with some input from thermal waters, as in the warm springs at Banff. The Coal River Springs in southeast Yukon are associated with a series of tufa dams (Geurts et al., 1992; Geurts and Watelet, 1994). The dams are complexes of phytoherms and barrages on a steep slope growing in low-energy water principally by degassing. Microscopic analysis has distinguished several facies: (1) an algal facies coating wood and other vegetable debris; (2) a glomerulitic facies apparently of bacterial origin on the upstream faces of dams; and (3) a bryophyte facies on the crests of dams where upward growth prevails. Bryophytes are also common on the downstream faces. The complex is of Holocene age and covers alluvial terraces left where the river has incised its channel.

In the North West Territories, the Rabbitkettle Hot Springs are a striking feature of the Nahanni National Park. The springs have built a dome-like of thermal travertine some 27 m high and 70 m in diameter. Water at the mild "hot spring" temperature of 21°C wells up in a shallow pool at the top and deposits tufa in a series of pools and cascades down the side of the dome comparable to the Mammoth Hot Springs of Yellowstone. The area has been severely glaciated and it is likely that any preglacial deposit was removed by the ice, so that the present dome is post-glacial. Even so, both the Rabbitkettle and Mammoth Hot Springs deposits are in areas where temperatures well below freezing persist for as much as half the year. Further south, in Alberta, Jackknife Springs flow from a mound c. 30 m high and 100 m in diameter. The two orifices at the top discharge a gentle flow in the summer only. By contrast all the year round flow comes from perched springlines in the Edison and Mount Robson–Wapiti areas of Alberta (Barnes, 1976).

13.12. Mexico

Mexico seems to have vast deposits of travertine, but there is some confusion with the finely laminated flowstone sold as "Mexican Onyx" and used for a great variety of ornaments for tourists throughout Mexico and the American southwest. Brief descriptions of the industry with locations, but not the geology, of travertine quarries in Baja California Norte, and at Tehuacan and Oaxaca near Puebla, c. 130 km SE of Mexico City, have been given by Sinkankas (1959) and Johnson (1965). At least some of the ornamental "Onyx" seems to be flowstone apparently derived from speleothems in unroofed ancient caves, but at least in Baja California some quarries are noted as being in travertine deposits resting on a schist basement, so they may be true tufa cascade sheets. Further south in Mexico, the Chiapas province has large tufa cascades comparable with those of Havasupai in the Grand Canyon.

Laminated tufa with a wide range of fabrics and morphologies forms at several sites near Cuatro Cienegas, Coahuila, Mexico, through micritic calcite either adhering to the polysaccharide mucus of di-

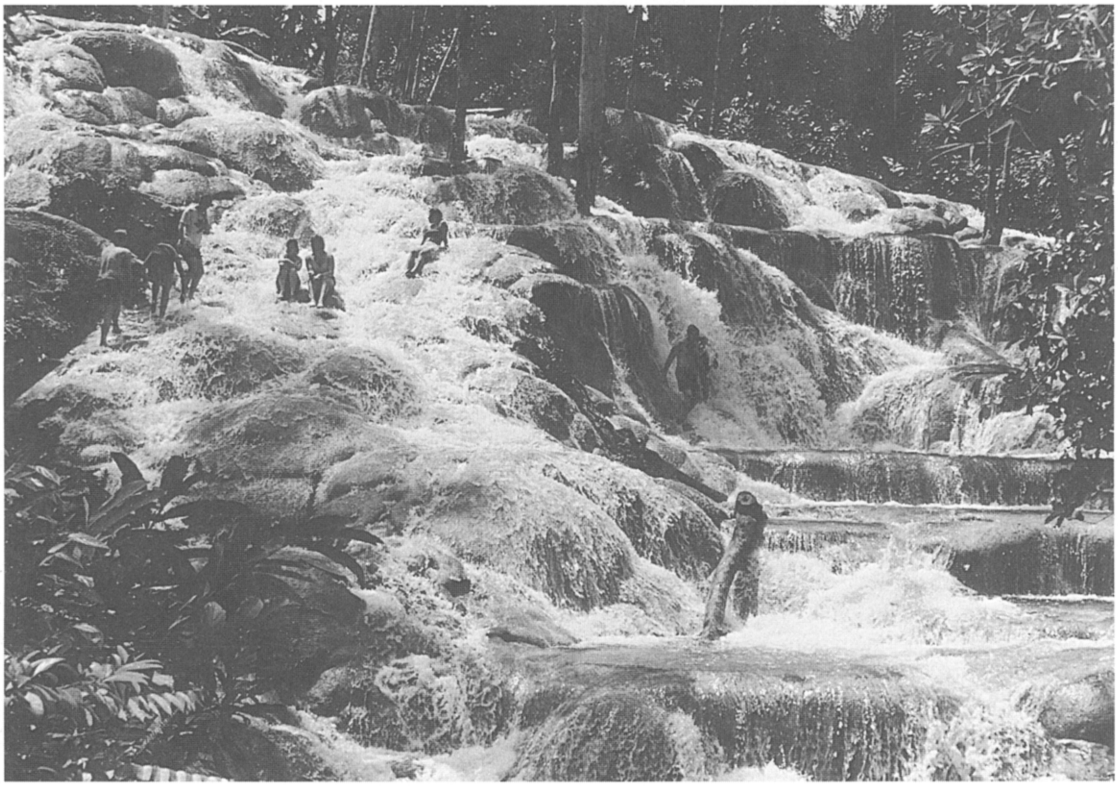


Fig. 37. Cascade and barrage tufas. Dunns River Falls, Jamaica.

atoms or being trapped by them (Winsborough and Golubic, 1987).

13.13. West Indies

In the West Indies many of the overhanging walls of mogotes have pendulous stalactitic tufa deposits, particularly in the heavily forested cockpit country of Jamaica and Puerto Rico. Rivers draining from these karst regions often have tufa deposits too. Dunns River Falls on the north coast of Jamaica are a tourist attraction consisting of a series of fluvial terraces, cascades and barrages (Fig. 37). Comparable tufa cascades over uplifted reef limestone masses occur at several other localities including Ocho Rios on the north coast of Jamaica. The "golden sands" beach at St. Ann is largely made of comminuted tufa grains. "Onyx" travertine is quarried east of Havana in Cuba.

13.14. South America

Extensive cascade deposits comparable with those on the river Krka in Croatia occur on the Rio Salitre, Bahia Province, (Branner, 1911) and at many other sites in Brazil.

Argentina has many tufa deposits including the Puente del Inca where a massive tufa deposit lies on glacial debris which the stream has undermined to form a natural bridge.

Peru is said to have numerous tufa deposits.

14. Tufa deposits of Australia and New Zealand

14.1. Australia

Tufa deposits are scattered through eastern Australia from Queensland to Victoria. Near Mt. Etna, inland from Rockhampton, Queensland, Dunkerley (1981) studied a stream in the wet tropical part of the state which had a series of low tufa barrages over a distance of some 430 m below the spring. Water rose at 24–28°C rich in $CaCO_3$ and degassed rapidly, raising the alkalinity and calcite supersaturation downstream resulting in the deposition of tufa on irregularities in the stream bed. Barrages up to 1 m high were built up with shallow pools behind. The effect of vegetation was not investigated. Further north in the seasonally semi-arid Chillagoe karst Ryan's Creek and adjacent streams had substantial tufa barrages with long pools behind. Considerable evaporation in the semi-arid climate added to the effect of degassing caused much tufa deposition (Dunkerley, 1987). Unroofed large caves at Chillagoe known as daylight holes, such as Markham Cave, have inactive large pendant masses of tufa (Ford, 1978) (Fig. 2).

Tufa sheets and barrages are widespread in the Napier Range of northwest Australia and have developed in a semi-arid tropical climate with savanna vegetation cover (Viles and Goudie, 1990b). Large deposits of draped cascade tufa occur and there are also fluvial barrages and perched springline deposits. Two generations of tufa growth have been recognized probably representing climatic changes from wet to dry to wet. Viles and Goudie (1990b) also note other tufa deposits in the Great Artesian Basin and the Kimberley Ranges. Largely inactive tufa terraces flank Louie Creek and other streams drain the Barkly Tableland to the Gulf of Carpentaria (Drysdale and Head, 1994). Radiocarbon dates suggest that most deposition was principally from 29 to 25 Ka B.P. with a lesser second phase from 14 to 10 Ka BP. The first of these correlates with the Last Glacial Maximum when precipitation may have been higher or evaporation less. Wetter conditions led to incision of the streams with gorge development.

The Carl Creek limestone of northwest Queensland, south of the Gulf of Carpentaria, forms a sheet of tufas and gravels capping a plateau some 25 km^2 in area. Although the age is uncertain it is generally regarded as of Upper Miocene age (see below) (Megirian, 1992).

A series of tufa cascades forms a tourist attraction at Argusta in Western Australia.

14.2. New Zealand

Whilst the bulk of the deposits from the hot springs around Rotorua are siliceous sinter, a small group at Waitiki also deposit calcite as crusts around the shores of nearly boiling pools, effectively a form of thermal travertine. The calcium content of the rising waters in this volcanic area is low but high discharge of CO_2 causes continuous precipitation.

Though temperatures are over 90°C relics of bacterial mucus suggest that thermophile organisms play some part in deposition.

15. Ancient tufa deposits

Few references to ancient tufa occurrences in the stratigraphic column have been located, though there are records as far back as the Permian. Being ephemeral features of landscapes undergoing erosion many tufa deposits have probably been destroyed but logically some should have survived. Whilst the abundance of Neogene tufa deposition may have been influenced by the evolution of diatoms in the Miocene there seems to have been no investigation of such biologic controls in earlier deposits. Scattered records of "nodular freshwater limestone" within fluvial basin margin sequences occur fairly often in stratigraphic literature but without much more detailed descriptions or field visits very few can be identified as ancient tufas. A few examples must suffice here.

The Fossil Forest of Lulworth Cove and equivalent beds on the Isle of Portland, Dorset, England, have been thought to represent an uppermost Jurassic hypersaline lagoon where tufa encased the bases of upright trees, but recent petrographic and environmental studies have suggested that the tufa crusts grew in a brief fresh-water lacustrine episode while the trees were still alive and that both trees and tufa deposition were terminated as water-levels rose and became saline (Perry, 1994).

Around Sully Island near Barry in south Wales, the lacustrine Mercia Mudstones (Upper Triassic) enclose tufa mounds up to 1 m high and 5 m wide, apparently deposited by spring waters rising from partially exhumed islands of Carboniferous Limestone. Whilst much of the tufa is dolomitized, textures including radial crystalline calcite, pisoids and floe-calcite have been recognized in a complex of calcrete and other pedogenic carbonates (Leslie et al., 1992).

The green alga *Cladophorites* formed porous tufa bioherms as a marginal facies of an Upper Miocene lake in the Ries astrobleme crater of southern Germany (Wolff and Fuchtbauer, 1976; Riding, 1979). Laminated travertine veneers encrusted the bioherms during intervals of low lake level.

Tufas of probable paludal origin are preserved in the Cretaceous of the Valencia region of eastern Spain (Monty and Mas, 1979). Fluvial tufas with oncoids (cyanoliths) are recorded in the Palaeocene of the Ebro Basin in northern Spain (Ordoñez and Garcia del Cura, 1977). Eocene tufas, again dominated by fluvial oncoids, occur in the Duero Basin of Central Spain (Nickel, 1983). A tufa deposit of Miocene age, between Morata del Tajuna and Campo Reale has some 30 m of laterally persistent biostromal plant-bearing sheets of grey brittle tufa covering several km^2 and passing into braided fluvial sheets.

A complex series of tufas occurs in northwest Queensland, Australia (Megirian, 1992). They are relics of a sheet some 25 km long flanking a Proterozoic–Cambrian massif. They include springline sheets, cascades, phytoherm barrages, lacustrine and paludal deposits, interleaved with clastic and calcareous gravels in places. An Upper Miocene age has been inferred from enclosed marsupial mammal remains. Megirian (1992) included brief comments on correlation with other mid-Tertiary limestones in northern and central Australia.

In the Cracow area of southern Poland springs deposited some 17 m of tufa covering an area of c. 7 km^2 around the shores of an evaporitic lake in a rift valley of lower Permian age (Szulc and Cwizewicz, 1989): the hard, grey laminated to massive carbonates contain both autochthonous and allochthonous vegetation and indicate perched spring line deposition with fluvial and paludal developments.

Also in Poland the Wozniki Limestone of latest Triassic age appears to be a thermal travertine deposit originating from the outflow of demineralized ore-fluids (Glazek, 1989).

Neogene tufas have also been reported from Budapest in Hungary. Ambert (1981) has outlined a case for correlation of these and other tufas with European interglacial periods, though he admits that dating individual phases is difficult. A sequence of twelve tufa terraces, with some thermal travertines, has been recognized in various parts of Hungary; the earliest terraces date back to the Miocene (Schweitzer and Scheuer, 1995).

Ancient tufas of Villafranchian (?) age (Plio–Pleistocene boundary) have been claimed at Naoussa in Morocco (Nicod, 1981) where they flank a forested karst massif.

In Wyoming, Bradley and Eugster (1969) recorded the occurrence of Eocene travertine (strictly tufa in our definition) in the Creede Formation of the Green River Group. Lacustrine tufa crusts margin the Eocene Lake Gosiute and pass into calcretes on the shore (Eugster and Hardie, 1978).

16. Conclusions

The world occurrence of tufas and travertines demonstrates convincingly the predominantly Late Cenozoic development. Part of this must be a function of non-preservation within the geological record. This is not surprising considering the destructive erosional processes associated with subaerial sites. Nevertheless, Neogene tufa developments progressively increase in numbers towards the start of the Pleistocene and thereafter appear common during humid episodes (interglacials and pluvials) and in Holocene time.

It is now apparent that tufas can effectively develop under a wide range of climatic conditions provided that there is a moderate, but not aggressive, flow regime. It is also clear from occurrences in high latitudes that tufas can withstand prolonged periods of freezing and burial by snow. The presence of tufa deposits, therefore, is not in itself an indication of a particular climatic regime though experience in northwest European Holocene examples does indicate that they rapidly become established subsequent to ice retreat and before the establishment of trees in the deglaciated landscape (Taylor et al., 1994). Less is known about the behaviour of tufas in pluvial and sub tropical sites simply because of the problems of absolute dating.

Nevertheless, an increasing number of absolute dates are available, especially for the Holocene developments and there is now a real possibility of accurately pinpointing the environmental controls triggering tufa development. The next stage forward is to document the palaeoenvironmental variability recorded within them. One approach is to marry biostratigraphic variability data (using proxy-environmental indicators such as Mollusca, Ostracoda and pollen), with geochemical information (e.g. oxygen isotope signatures, Andrews et al., 1994). This technique promises to be as valuable in freshwater microbial carbonates as it has been in conventional marine, foraminiferal work. Tufas hold the best medium-term prospects for detailing regional terrestrial climatic change as they accumulate much more rapidly than peats and lake deposits. Thus, tufas have an untapped potential to provide the best land-based opportunity for accessing shorter-term Holocene environmental change.

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