CHARACTERIZATION OF THE ANTALYA (TURKEY) TUFA DEPOSITS

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ABSTRACT: Carbonate rocks in Antalya (Turkey) which have previously been called travertine should, because of their biogenic origin and deposition in a cool-water regime, be termed tufa. Tufas in Antalya are the products of physico-chemical and biogenic precipitation. In the biogenic process, precipitation was caused by decreasing partial pressure of CO_2 via photosynthesis of algae or bacteria. Following precipitation, the tufas underwent meteoric-vadose cementation and diagenesis. The Antalya tufa basin consists of horizontally-bedded carbonate sediments which are end products of a lacustrine depositional environment. However, a perched springline system has played an important role, serving as a starting point for calcium-carbonate precipitation. The morphology of tufa coastal cliffs is controlled by sea erosion. Thus, terraced morphology, except for small areas (e.g., Masadağı), should be considered a result of erosion. In this study, tufa deposits of Antalya were characterized with respect to mineralogy, sedimentology and surface morphology. In addition, for the future multidisciplinary needs (engineering and environmental) other aspects on tufa formation are discussed.

Keywords: Antalya, characterization, classification, tufa, travertine.

INTRODUCTION

The Antalya tufa terraces cover an area of over 630 km^2 and reach up to 270 m in thickness (Fig. 1). These are the largest known tufa deposits in the world (Pentecost 1995). Although eight levels of tufa were identified by Burger (1990) – situated up to 300 m elevation amsl – it seems more appropriate to group them into five (Nossin 1989). Four of them, the Döşemealtı, Varsak, Düden, and Arapsuyu plateaus, are terrestrial; the fifth is submarine, and occurs down to a depth of 90 m below sea level. The elevations of the plateaus range between 150-300 m for Döşemealtı, 60-150 m for Varsak, 30-60 m for Düden, and 0-30 m for Arapsuyu (Fig. 2).

After establishment of historical Attelia, in the second century BC. by Attalos II, a king of Pergamon, and later during Roman, Byzantian and Ottoman periods, Antalya tufa was used for construction purposes. Today, Antalya is a famous tourism center with almost one million fixed population. For many engineering and environmental projects, geological information has been essential. Previous geological studies are not sufficient today to meet needs of geotechnical, environmental and coastal engineering works. In some studies (DSİ,1985; Burger 1990; Özüş 1992), rocks were named as travertine , however, travertine classification is not applicable in the field and especially for geotechnical studies, engineering rock mass properties have not been determined properly. In a geotechnical study (Dipova 2002), rocks were classified according to tufa classification of Pedley (1990) and it was stated that this classification was applicable in the field. Glover and Robertson (2003), after classifying using Pedley's system, focused on origin of Antalya Tufa dealing with regional tectonic regime.

Characterization of Antalya tufa deposits including the origins of the materials and the sedimentary basins, the occurrence of terraces (constructional or erosional), as well as the nomenclature and classification of the carbonate deposits of Antalya, have long been debated by the geologists. In this paper, the characterization of carbonate deposits of Antalya including precipitation processess, diagenesis and paleoenvironmental conditions as well, will be presented and some geological aspects for multidisciplinary needs will be discussed.

REGIONAL GEOLOGICAL SETTING

Antalya is located at the southern margin of the Western Tauride Belt. The main rock units of the region are divided into two major groups: allochthonous and autochthonous units (Fig. 3). One of the main autochthonous units is the Anamas-Akseki (relative autochthonous); this unit consists of platform-type carbonate sediments deposited from Late Cambrian to Eocene. Another autochthonous unit is the Beydağları (relative autochthonous), consisting of platform-type carbonate sediments of Jurassic to Miocene age (Poisson 1977; in Akay et al. 1985). Together, these two units comprise the basement over which allochthonous units were emplaced and younger autochthonous units deposited comformably.

The younger autochthonous units are divided into two groups. The first group comprises sediments deposited in the Antalya Miocene basin. The basin contains sandstone, conglomerate, limestone, clayey limestone, brecciated limestone, claystone and shale. The basin opened during the Oligocene and closed in the Late Miocene. The second basin is an Upper Miocene-Pliocene basin located west and south of the Aksu River. The basin opened in the Messinian and closed in the Early Pliocene, and contains conglomerate, sandstone, limestone and calcareous claystone (Akay et al. 1985).

The youngest autochthonous unit of the area is the Antalya tufa (Plio-Quaternary), which extends from the Aksu River in the east, to the Antalya Nappes in the west, and to the Beydağları in the north. The Antalya tufa unconformably

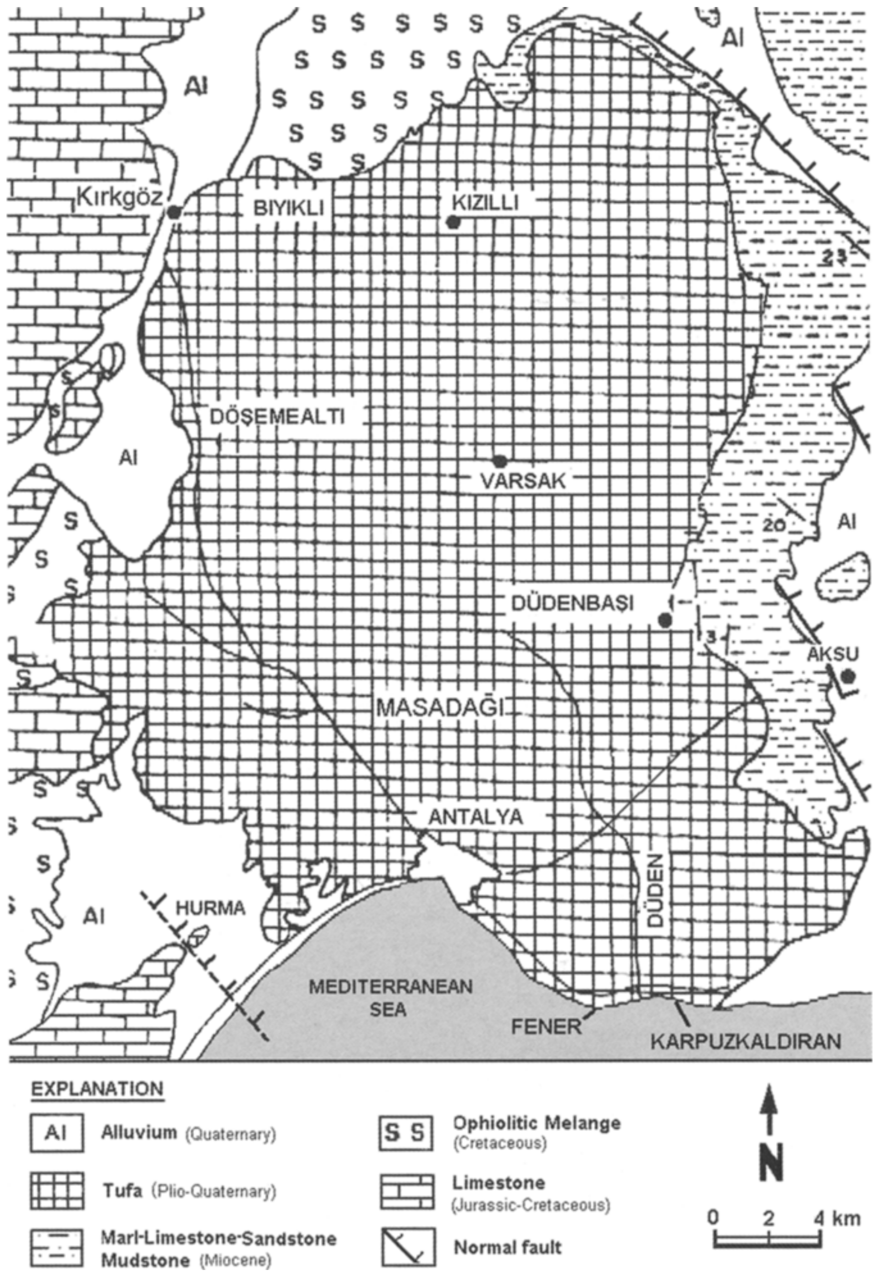


Figure 1. Geological map of the Antalya region (modified from DSI 1985).

overlies Miocene deposits to the east and a Cretaceous ophiolitic complex to the west. Below the tufa layer, the boundary between the Miocene deposits and the ophiolitic complex is unclear.

The main allochthonous unit of the area is the Antalya Nappes, comprising mainly marine sediments deposited in the basin between the Beydağları unit and the Anamas-Akseki unit. After deposition was completed, the Antalya Nappes were thrust over the Beydağları and Anamas-Akseki units. The Antalya Nappes are represented by Late Cretaceous limestones and ophiolitic sequences (Fig. 3).

ORIGIN OF THE ANTALYA TUFA

Deposition of the Antalya tufa was closely related to the Miocene-Pliocene evolution of the Aksu Basin. During the Late Miocene-Early Pliocene, the structure of the Aksu Basin was influenced by right-lateral strike-slip faults, which exploited pre-existing structural weaknesses. These weaknesses resulted from interaction between the uplifting and extruding Anatolian plateau and extensional western Turkey and the Aegean. The Pliocene sediments drape a block-faulted topography that opened to the south as an asymmetrical graben. During the Late Pliocene-Early Pleistocene, the Aksu Basin formed as a half-graben system

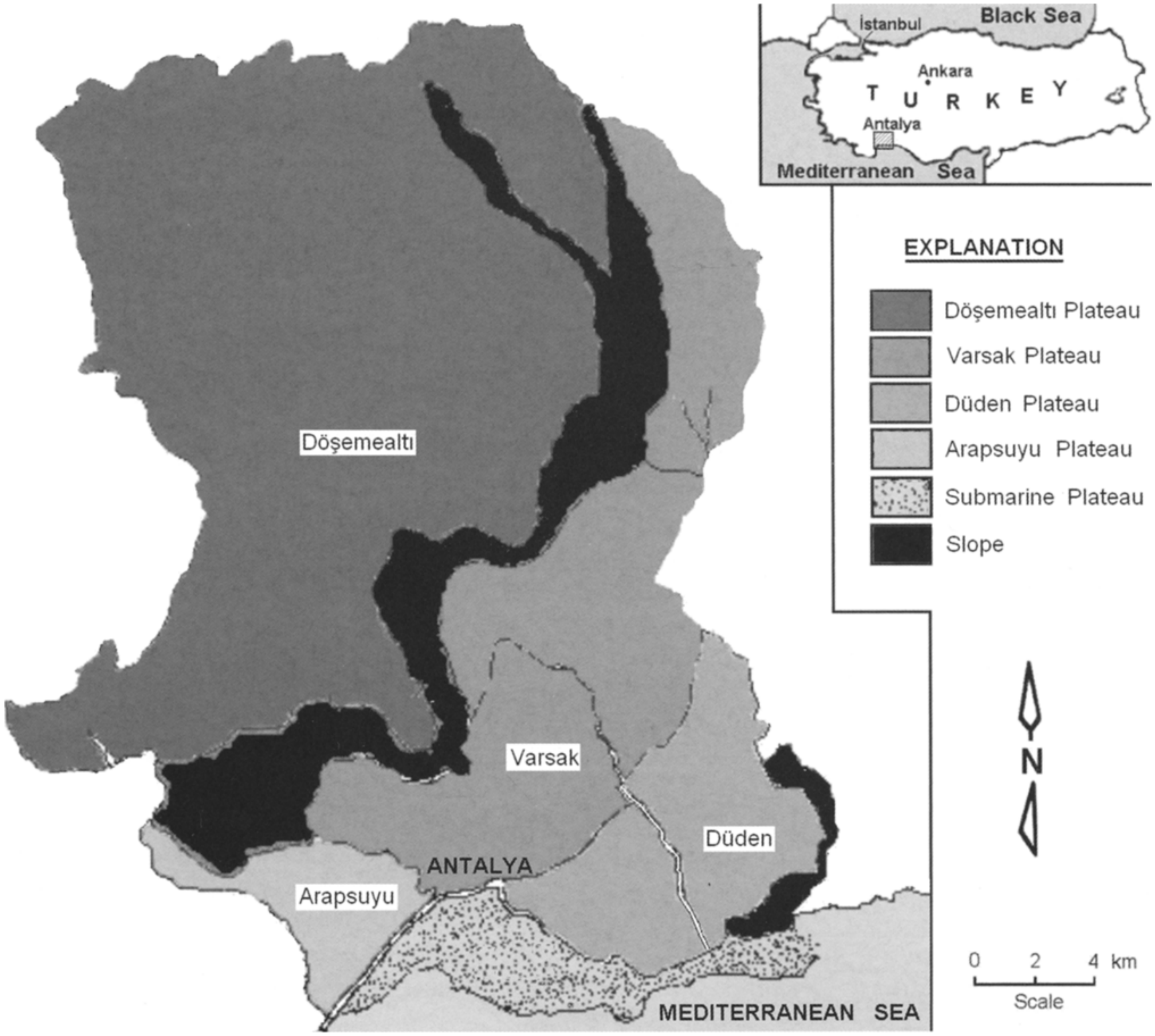


Figure 2. Geomorphologic units of the Antalya region (after Nossin 1989).

in response to a combination of N-S and NE-SW (i.e., orthogonal) extensional faulting (Fig. 4), while the adjacent Tauride Mountains were progressively uplifted. Antalya tufa deposits accumulated in the basin opened as a result of the half-graben system, during pre-glacial time, after extensional faulting had largely ceased within the main Aksu Basin (Glover and Robertson 1998).

The half-graben model for the Antalya tufa is identical to the half-graben lacustrine model of Scholz et al.(1990). At the western margin of the graben, fan deltas in front of the fault are typical. A continuation of the block fault is exposed at Hurma (Boğaçay Plain) (Fig. 5); the fault resulted in an elevation difference between Domuzburnu Hill and Küçükdağ Hill, creating a deep valley. Today this valley is covered by lagoonal and alluvial sediments; however, the valley continues in front of a lagoon barrier, below the sea (Fig. 5). Another piece of evidence in favor of the half-graben model is the thickness of the tufa. While Özüş (1992) recorded a 250-m thickness from borehole data in the west, the thickness of the tufa at the eastern margin is less than 30 m. Today, tufa is located between two sets of normal faults. Other fault sets may have been concealed by the tufa deposits.

The source of carbonate for tufa deposition in the basin is a cluster of springs near Kırkgöz. These springs drain from Jurassic-Cretaceous limestones (Beydağları) that have undulated surfaces with abundant chasms, depressions, sinkholes, and caverns, thus representing a typical karstic terrain. Groundwater drained from the limestones supplies the Kırkgöz springs and contains 160 gr/l Ca; free CO_2 in this spring water is 105 mg/l (DSİ 1985). By degassing of CO_2 via pressure effects, $CaCO_3$ begins to precipitate. Precipitation continues around the springs because some CO_2 is still available.

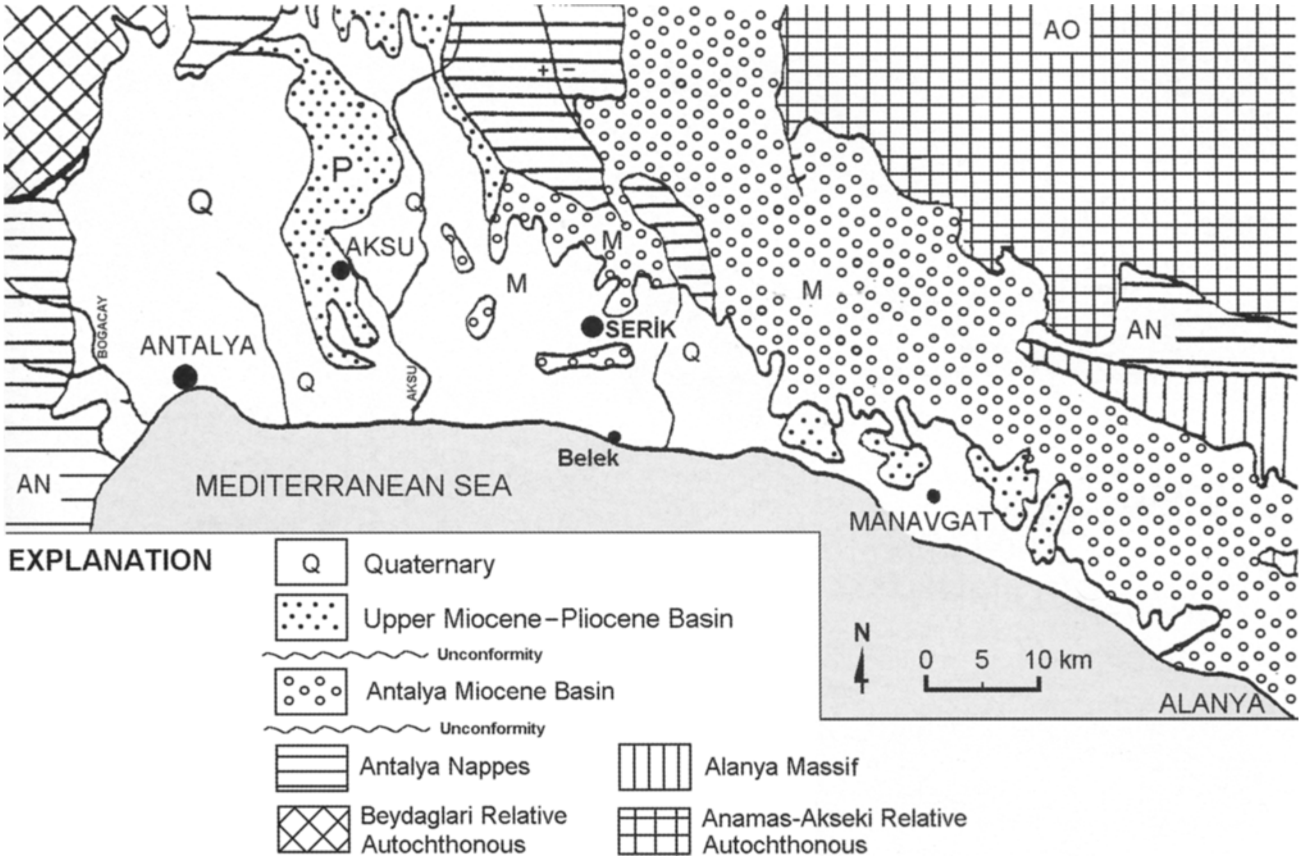


Figure 3. Regional geological setting (after Akay et al. 1985).

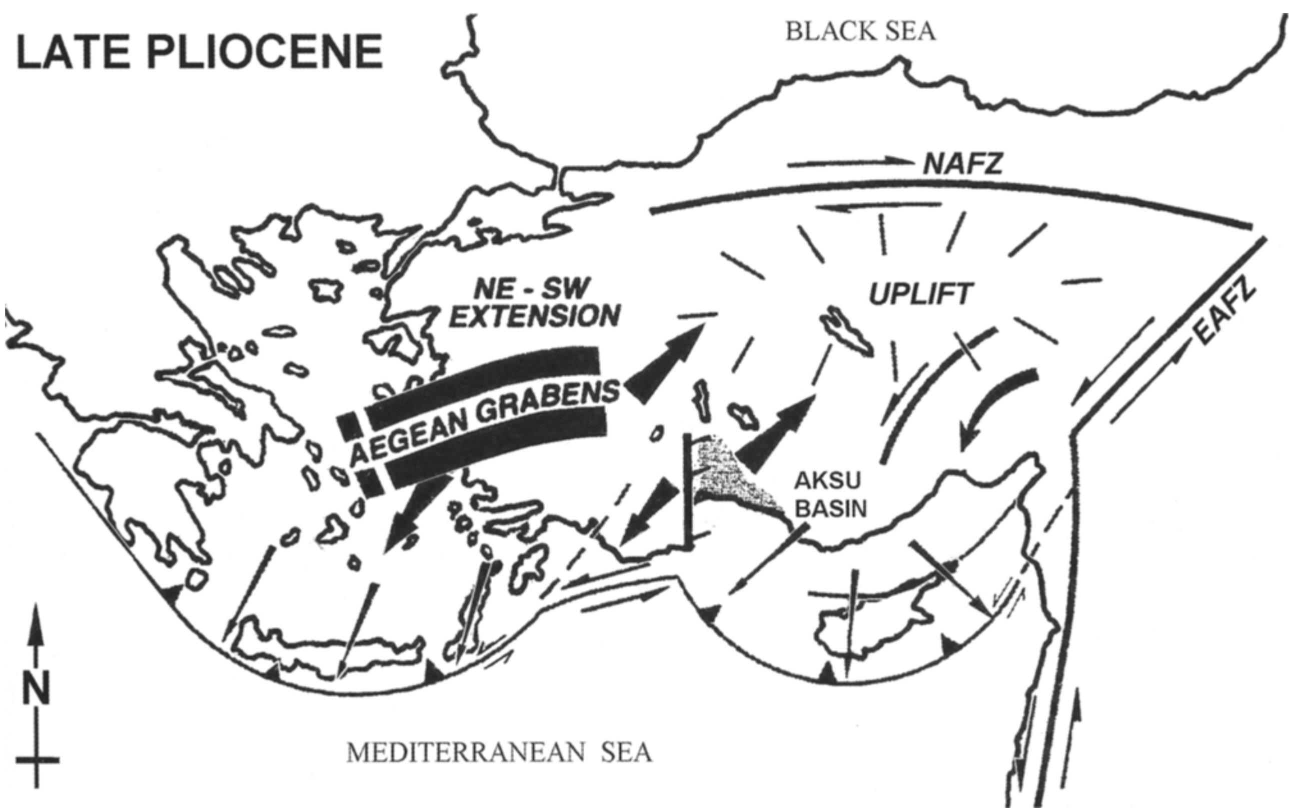


Figure 4. Sketch diagrams of the regional tectonic regime during the Late Pliocene, and resultant stresses on the Aksu Basin (Glover and Robertson 1998).

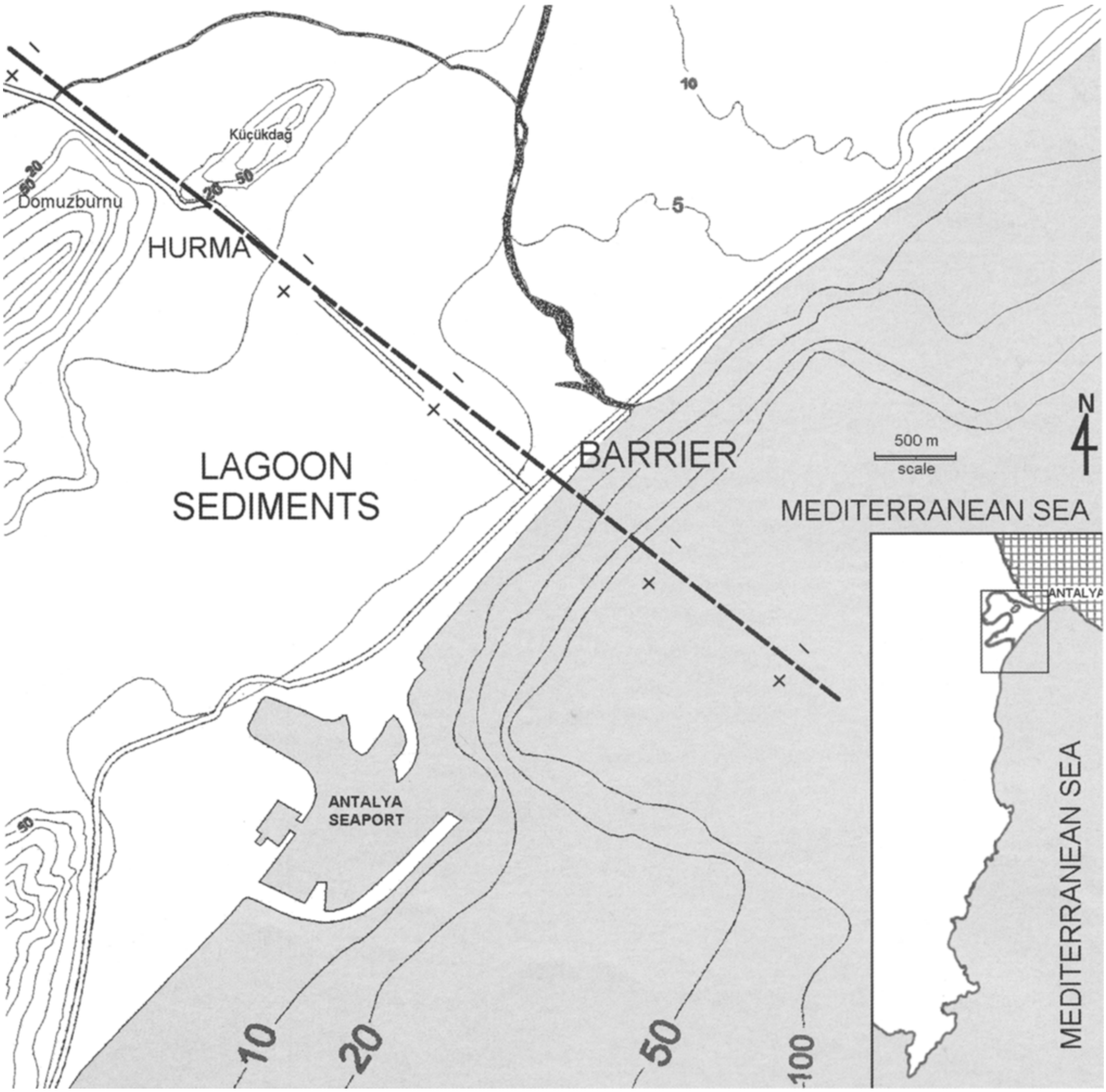


Figure 5. Submarine remnants of block-faulted topography. Bay-mouth barrier and lagoon deposits covered the fault plane.

Significant tufa deposition ceased prior to the Mid-Pleistocene. Glacial periods were too cold and wet, while interglacials were too arid, for extensive tufa formation. Instead, late erosion resulted in well-developed terracing of the Antalya plain. Subsequent depositional modification of these terraces has continued until the present day, producing a thin veneer of slope pools, waterfall deposits, fluvial deposits and terrace-mound deposits in localized areas. Tufa deposition today is quite limited despite continued emergence of highly supersaturated spring waters (i.e., at Kırkgöz). Minor deposition occurs mainly in highly turbulent waterfalls and small streams. Fine carbonates also precipitate at source springs and areas of ephemeral water supply, where algal mats remain after evaporation of shallow water (Glover and Robertson 1998).

CLASSIFICATION OF ANTALYA TUFA

In the literature, some tufa researchers (Pentecost and Lord 1988; Schneider et al. 1983) prefer a botanical approach to tufa classification, naming the deposits on the basis of associated vegetation. Geomorphological and petrographical approaches are the other approaches, which have been suggested by Buccino et al. (1978) and Ordonez and Garcia del Cura (1983). The following classification, which was redefined by Pedley (1990) and based on the classification of Buccino et al. (1978), Chafetz and Folk (1984), and Ordonez and Garcia del Cura (1983), is believed to be the most suitable one. The classification system conforms to the limestone classification of Dunham (1962), which emphasizes depositional texture, and that of Folk (1959), which is based on relative abundance of grain types. In Antalya Tufa, paleosols are commonly seen as carbonate rich terra-rossa. Paleosols were developed when tufa precipitation stopped and as a result of surface weathering. However being extensive in Antalya tufa (especially Düden Plateau), reaching up to 1,7 meters thickness, paleosols were not classified as a tufa facies (Dipova 2005).

Autochthonous Deposits

Phytohermal framestone.-- This term defines a living, anchored framework of erect or recumbent hydrophytal and semi-aquatic macrophytes, typically colonized by a dense and often felted microfilm of cyanobacteria, coccoid bacteria, fungi and diatoms. These are cemented by thick fringes of low-Mg calcite isopachous cements. Void fills of phytoclastic, micritic and detrital tufa are abundant.

Phytohermal boundstone (stromatolitic tufa).-- This tufa type is dominated by heads of skeletal stromatolites (several centimetres to over 1 m in diameter) and spectacular lamination (Fig. 6). These heads consist entirely of cement fringes formed in intimate association with oscillatoriacean cyanobacteria. Coarse detrital intraclastic tufa deposits and "oncoids" generally occur with these phytoherms.

Shrubs (Chafetz and Folk 1984).-- Shrubs or bushlike forms are the most abundant and well-developed in the shallow-lake fill deposits. Formation of shrubs requires a biologically harsh, shallow pool of water. They are composed of upward-radiating branches composed of chains and groups of leaves (the individual bacterial clumps). Individual shrubs range from 1-8 cm high.

Orthochemical grains (tufa chalk).-- Orthochemical grains are those which were deposited directly by precipitation from water in the basin (Folk 1959). The orthochemical grains are of two types. The first is microcrystalline calcite – very fine-grained (1-5 microns) carbonate precipitate which settled to the bottom of the basin. Abundant microcrystalline calcite (micrite) may be of two origins. Micrite may settle as an orthochemical component, which is produced directly from water by extracellular calcite precipitation during photosynthesis of micro-organisms (Viles 1988). Alternatively, micrite may comprise transported particles following erosion of formerly deposited tufas. The second type of orthochemical grain is sparry calcite. These are large crystals of calcite on the order of 0.02-0.1 mm, which appear clear or white when viewed with a hand lens or in plane light under a polarizing microscope. Sparry calcite is generally seen to fill interstitial pore spaces among grains. Sparry calcite can also form by re-precipitation of primary depositional grains and micrite during diagenesis.

Allochthonous Deposits (Clastic Tufa Deposits):

Macrodetrital tufa.

Phytoclastic tufa: These deposits typically consist of allochthonous, cement-encrusted plant fragments, comprising leaves and transported branch fragments forming a "grain-supported fabric" (Fig. 7A). Phytoclasts are cemented together following deposition, though some earlier cement development around phytoclasts may have occurred prior to or during their transport (Pedley 1990).

Cyanolith "oncoidal" tufa (oncolites): All stromatolites in the tufa environment are composed of cyanobacteria/cement-fringe associations, and the shape of these is determined by prevailing levels of environmental energy. Generally the highly spheroidal forms dominate rivers, whereas strongly oblate spheroidal forms are typical of sluggish flow regimes, and free-form growth forms (mammilated to irregular branching) of static conditions. Detrital woody fragments often form the nuclei to these cyanoliths and are

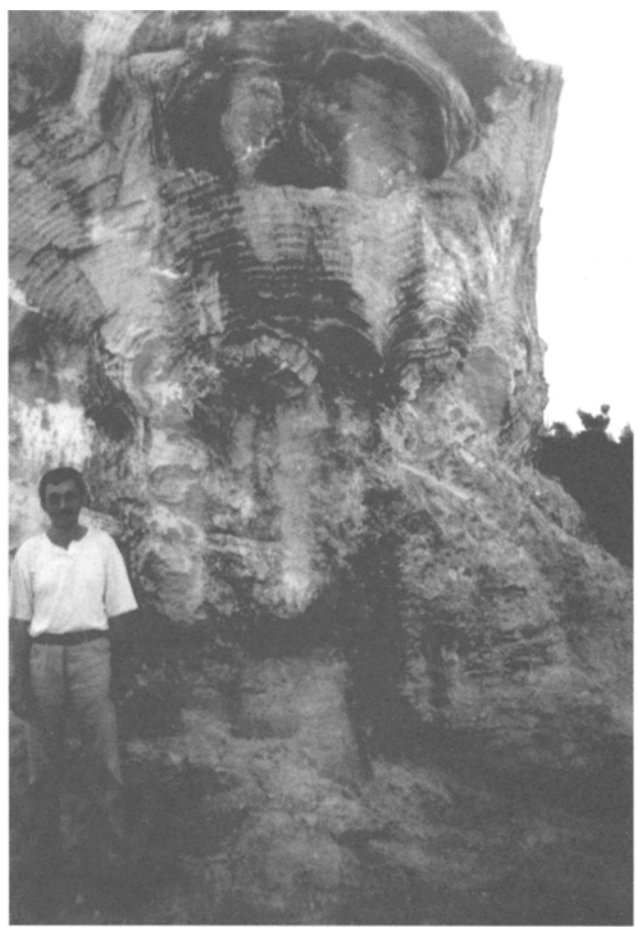


Figure 6. Stromatolitic tufa (north of Varsak).

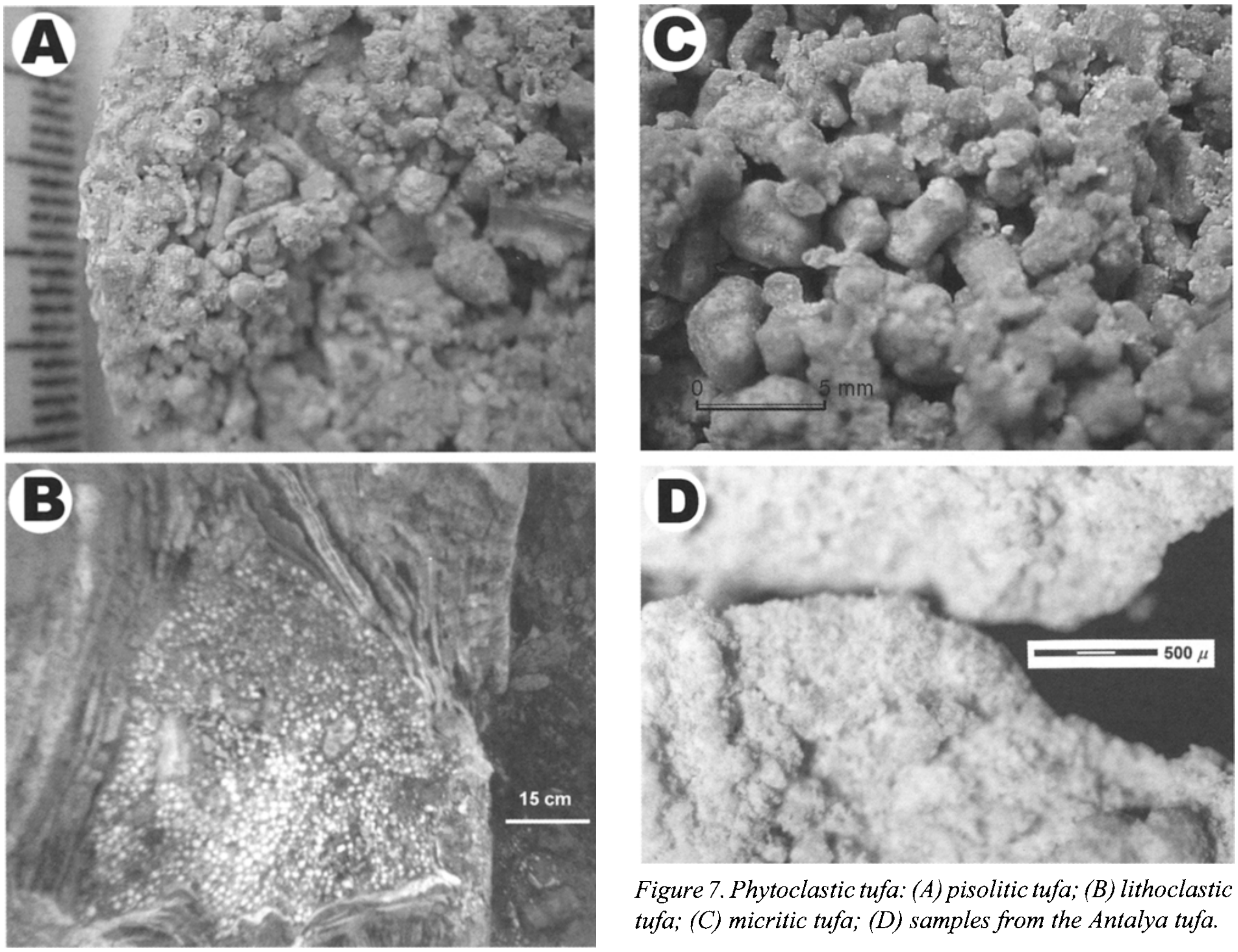


Figure 7. Phytoclastic tufa: (A) pisolitic tufa; (B) lithoclastic tufa; (C) micritic tufa; (D) samples from the Antalya tufa.

rolled along as cylinders. Still others have gastropod nuclei (Pedley 1990).

Pisolitic tufa: These pisoliths are spherical to subspherical, pea-like, and 4-8 mm in diameter (Fig. 7B); this type of tufa occurs interbedded with bacterial shrub layers and in open spaces between stromatolites. Pisoliths form in a depositional environments of little agitation and rich in bacterial activity, and in semi-stagnant shallow ponds. They may form *in situ* without the necessity of any rolling, and by encrustation of tufa intraclasts by bacterial colonies (Folk and Chafetz 1983).

Intraclastic tufa (Detrital tufa facies): Many associations are dominated by silt- and sand-sized detrital tufa fragments derived from break-up of earlier cements and phytohermal frameworks. These are carried during spate to be deposited as calciclastic grain-supported materials in fluvial channels; they also accumulate around phytohermal frameworks in static-water bodies where supporting frameworks have decayed.

Lithoclastic tufa: Lithoclasts are carbonate clasts that are derived from formerly deposited tufas by erosion, transported by a fluvial agent and then deposited in a new depositional basin. Lithoclasts are angular to subrounded and are poorly sorted (Fig. 7C); they are deposited as thin (<1 m) beds or lenses and show cross-bedding, unlike intraclastic tufa.

Microdetrital tufa.--

Micritic tufa: The finest sediments consist of micrite (1-5 microns) (Fig. 7D). This ubiquitous carbonate comprises the majority of lake, pond and marsh deposits (spring chalk), and forms thin sheet deposits on slopes in association with bryophyte hummocks, and locally fills phytoherm frameworks. It may be structureless in thin section, but frequently is clotted (grumose texture). Micrite may be transported or directly precipitated from water between clasts. It is difficult to ascertain its exact mode of origin.

Peloidal tufa: Peloid is a nongenetic term for tufa grains composed of micrite. Although only detectable petrologically, peloid is possibly more common than structureless micrite. The peloids (smooth elliptical outlines to free form) are also grouped into polynucleate masses 10-70 microns in diameter. Deposits may be grain-supported (especially in phytohermal frameworks), but commonly "grow" or compact to form clotted textures.

DEPOSITIONAL ENVIRONMENTS OF THE ANTALYA TUFA

The majority of tufa in the Antalya basin consist of horizontally-bedded, carbonate-dominated sediments. This fact implies that the dominant depositional environment was lacustrine. However, a perched springline system played an important role as a point of origin. The perched springline system itself includes paludal and lacustrine aspects. Generation of the terraced morphology was completed after closure of pools by sedimentation from paludal/lacustrine systems. Fluvial systems provided the final process to shape the extensive planar appearance. After reaching a higher elevation, a cascade system developed whereby water flowed downward. In a braided-river environment, paludal/lacustrine environments also developed as secondary aspects.

Perched Springline and Slope Environments

This was the initiating mechanism of the Antalya tufa. Calcium carbonate may precipitate immediately around the spring outlet, and this turns the spring into a raised, fan-shaped mound. The top of each mound is almost flat and contains paludal pools restricted by massive phytohermal rims. When waters pass over the rim, the water velocity and turbulence are high, resulting in thin layers of tufa which develop at a high rate. However, in the pools, slow precipitation – mostly of biogenic origin – occurs in a sluggish regime. Burger (1990) termed these pools as "travertine basins"

A spring mound grows vertically and spreads laterally. This lateral spread operates like a protruding tongue that moves around a fan making the fan larger (Fig. 8). After a substantial amount of spread, a wide plateau had developed above the slope. On this plateau, fluvial, paludal and lacustrine systems continued contributing to deposition. On the slope, initially microdetrital sediments dominated; however, when rims of the pools grew steeper, cascade-system phytohermal sediments were precipitated. However, the perched springline model is not preserved well; Masadağı is perhaps the best location for observing evidence for this model in the Antalya tufa. At that location, pools of different dimensions, local paludal deposits, and microdetrital deposits in the slope area, are clearly observable (Fig. 8). Glover and Robertson (2003)

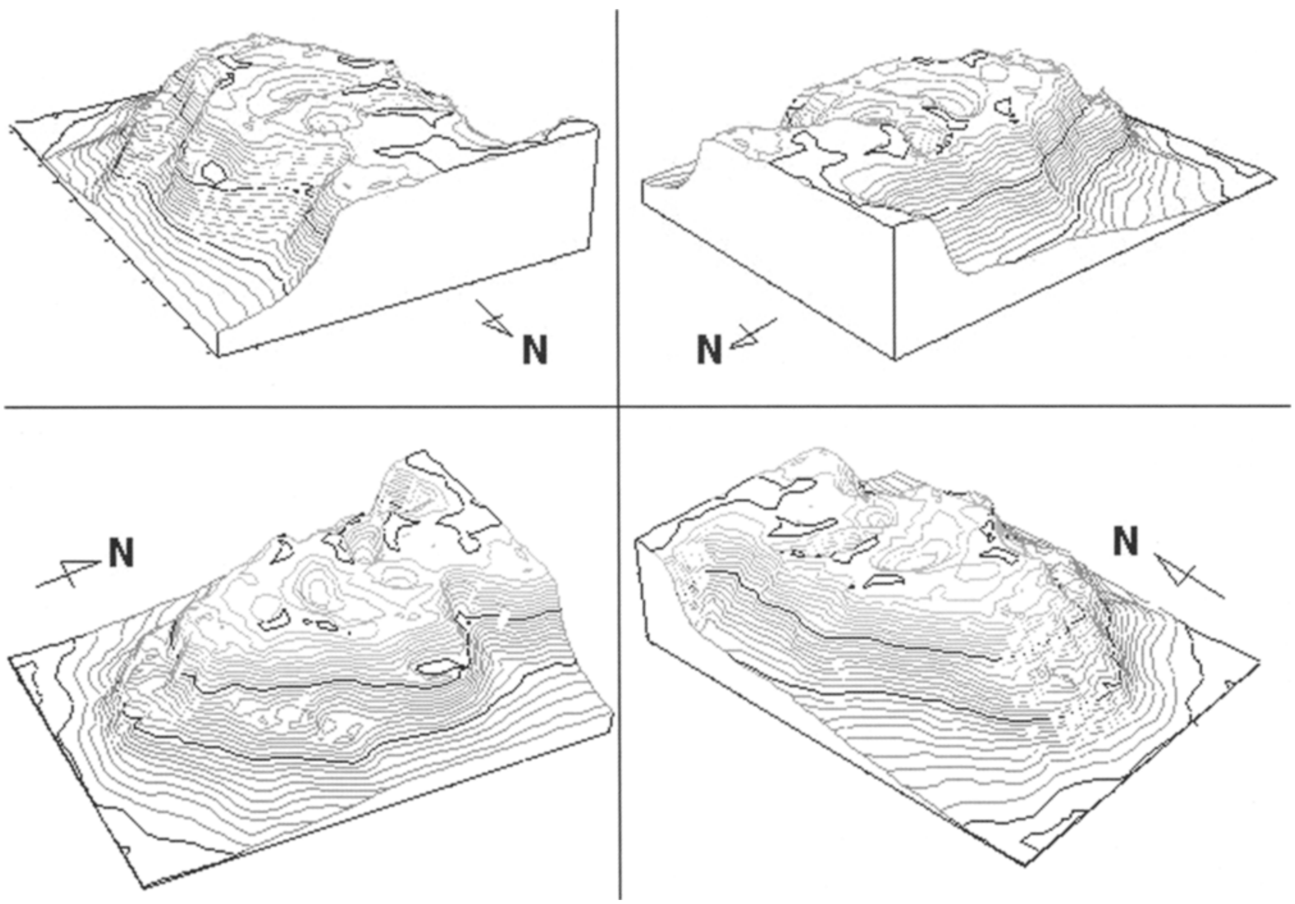


Figure 8. Perched springline model for the Antalya tufa (Masada□ı).

interpreted morphology of Masadağı as karst-related sinkholes. Karstic features observed in the depressions are of secondary origin and elongate appearance of depressions is related to interlinked pool system. Bedding in the pools is seen to dip inwards around the edge, however in the cross-section bedding planes are concave which is related to biogenic precipitation. Curtain caves, which were detected during borings are the other evidences that the morphology of Masadağı is of primary depositional origin.

Cascade Environment

This is a high-energy environment where water flows turbulently from cliffs. Curtains of moss build out from the fall rim and become covered by steeply inclined sheets of carbonate derived from carbonate-rich water that flows from the cliff. Tufa curtains develop as hanging bodies on the rim. Blind caves often develop behind the tufa curtain, and curtain-like stalactites may grow there (Fig. 9). This development continues until the load of the hanging curtain exceeds the tensile strength of the curtain. At the coastal cliffs of the Düden Plateau, cascade deposits are visible from a distance of 6 km (Fig. 10).

Fluvial Environment

This model is characterized by thick, braided, cyanolith-dominated deposits (Pedley 1990). However, in the Antalya tufa, minor volumes of fluvial-system deposits are observed. These sediments – of meandering-river origin – are observed as thin lenses; cross-bedding is widespread (Fig. 11). Laterally extensive fluvial system deposits are observed on the Düden Plateau. On this plateau upper 5-7 m thick weakly cemented tufa layer is of partly paludal and fluvial. Clast types in fluvial deposits are dominantly lithoclasts, phytoclasts, and lumps of sparry and microcrystalline calcite. Another means of fluvial deposition is the barrage model, commonly applied in regions of non-braided streams and normal-water flow. Evidence for this model was not found in the Antalya tufa.

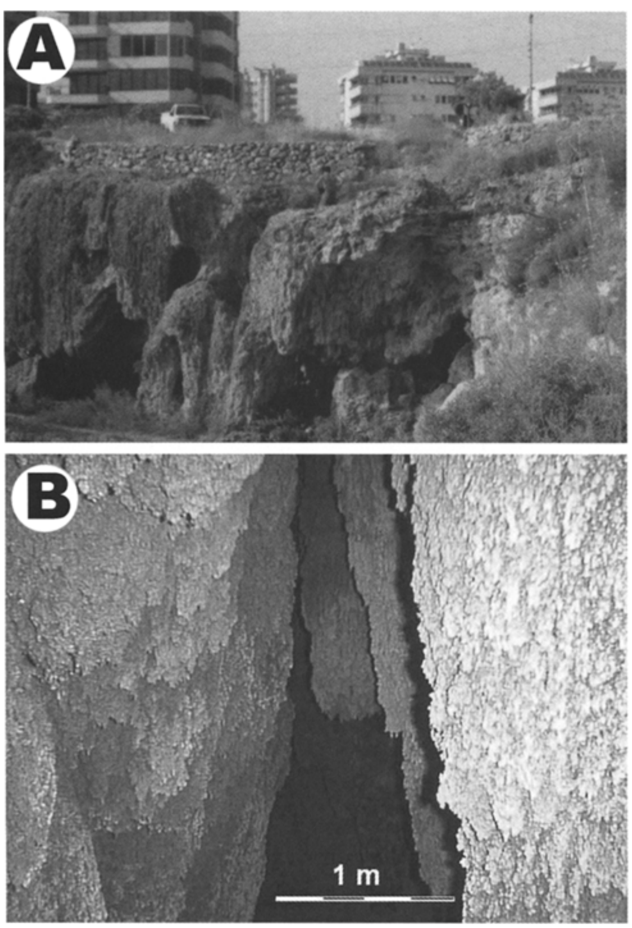
Lacustrine Environment

While the term lacustrine is used for large bodies of deep water, as a tufa- depositional environment, this term is used for open lakes that do not dry for long periods regardless of lake dimensions. When water flows on the surface of a low-angle slope, there is an opportunity for colonization by macro- and microphytes. Such build-ups may create obstacles to water flow. As water flows over the barriers, stromatolites grow up on the barrage. The heights of these phytoherms or stromatolites are indicators of maximum water level. Thus is an elliptical water body (pool or lake) constructed.

Mammilated stromatolites reflect a nearshore, shallow, calm to wavy environment. Stromatolites grow laterally and vertically causing elevated lake margins and also deepened and enlarged lake bodies. Pisoliths of the Antalya tufa formed in open spaces among these stromatolites.

Paludal Environment

This model is similar to the lacustrine model, but the pools generally are not open and water levels are low. These



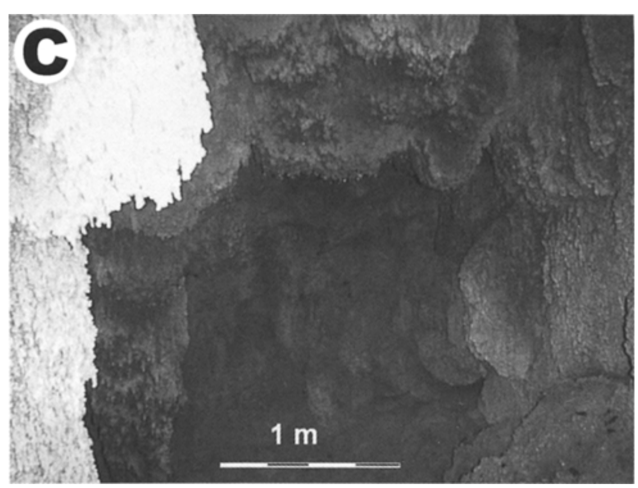


Figure 9. (A) Vertical deposition (B and C); vertical cavities (blind caves) (Fener region).

Figure 10. Precipitation on sea cliffs at Karpuzkaldıran.

Figure 11. Cross-stratification in meander deposits.

marshy pools develop on poorly drained slopes, alluvial valley bottom spreads, and in oxbow-lake-like wetlands of meandering rivers. Spring-fed waters seep sluggishly through the bryophyte carpet and between hummocks, leaving behind a surface tufa coating on all the vegetation (Pedley 1990). The stagnant water regime results in cyanolith development and leaves may be the dominant phytoclastic build-up. Surfaces of vegetation are covered by carbonate and when the plant tissues decay this material accumulates in the pools. At present, paludal deposition is negligible because of land drainage and river-bed improvement for urban development. At the beginning of 20th century, on the Düden Plateau, there were many living lacustrine and paludal environments. Today, along the Düden River, microdetrital-calcite precipitation closely related to living cyanobacteria (eg. *Schizothrix*) can be observed in small pools (Fig. 12).

PRECIPITATION PROCESSES IN THE ANTALYA TUFA

Traditionally, tufas have been considered wholly physico-chemical precipitates that deposit close to resurgent points, riffles and waterfalls where calcium-carbonate-enriched waters rapidly de-gas (e.g. Braithwaite 1979; Lorah and Herman 1988). The degassing, principally of CO_2, was generally associated with cooling of waters away from their source(s) and resulted in precipitation of tuffaceous carbonate on all available surfaces, whether animal, plant or rock. Thus, environments with higher rainfall and temperatures should encourage tufa formation. At present, the tufas are seen as products of both physico-chemical and biogenic precipitation associated with biofilm colonization, in which – rather than degassing – precipitation is the cause of decreasing partial pressure of CO_2 by photosynthesis of algae or bacteria.

By way of comparison, precipitation processes in tufas are slower than in travertines because decreasing pCO_2 by photosynthesis is slower than degassing. In the Düden River, tufa precipitation is visible as overgrowths on/around mosses. The mosses thus appear to stimulate calcite precipitation by intake of carbon dioxide for photosynthesis. Calcite, which crystallizes around mosses, makes a mould

Figure 12. A small pool near the Düden River; an example of a modern paludal environment.

of their form. This precipitation is a dynamic process wherein the lower part is progressively covered, while growth at the apex proceeds. However, uptake of CO_2 by organisms during photosynthesis is the general mechanism; where CO_2 is in short supply in the water, they obtain CO_2 by utilizing HCO_3. This process results in release of OH^- which could locally increase supersaturation within the sheath of the organism. In this way, precipitation occurs as impregnations rather than as grain accumulations (Merz-Preiß and Riding 1999).

In Antalya, in small pools of paludal-environmental character, present-day calcite precipitation can be observed. Algae or bacteria such as *Zygnema, Scytonema, Schizothrix, and Diatom* are abundant in these pools. Daylight photosynthesis of blue-green algae results in net removal of CO_2 from the water during the day. Calcite crystals can be observed hanging on the algae. In the most recent (<1 year) precipitates, several crystals hang over on a single algal fiber, while in relatively older precipitates (e.g., at 2 m depth in a completely filled pool) the numbers of crystals increase. In diagenetic rocks, spar micritization produces completely coated calcite tubes (Fig. 13). Results of X-ray diffractometric analysis (Fig. 14) and elemental analysis by SEM carried out on many tufa samples show that the dominant component of these rocks is calcite.

METEORIC CEMENTATION AND DIAGENESIS

Cementation and diagenesis are important factors for final appearance of tufa deposits. After precipitation or deposition of grains, meteoric cementation and diagenesis begins in the

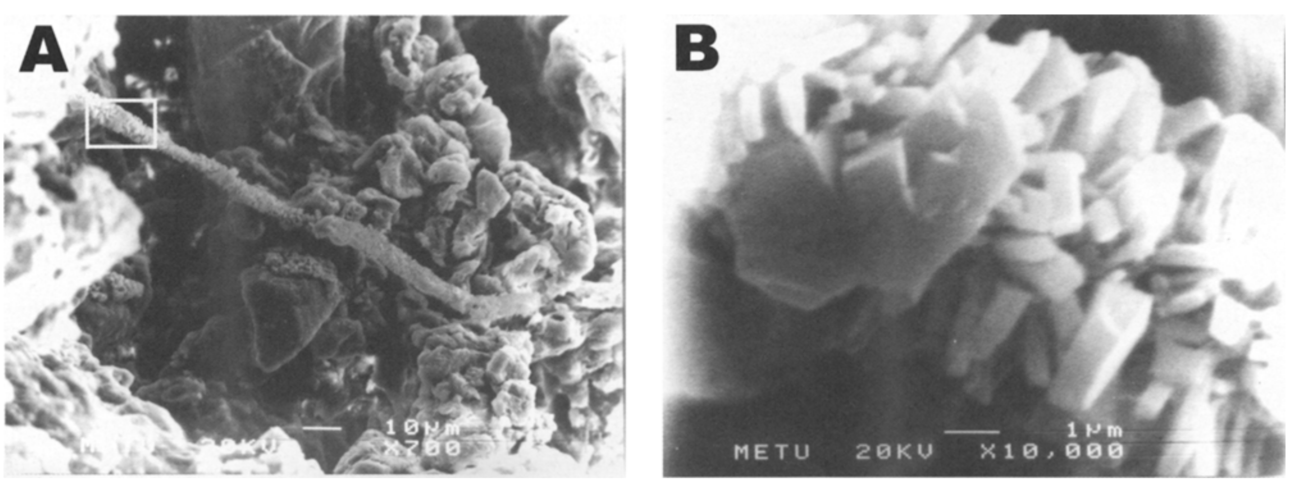


Figure 13. SEM views of calcite: coating on fibrous algae (left); close-up view of white rhombs (right).

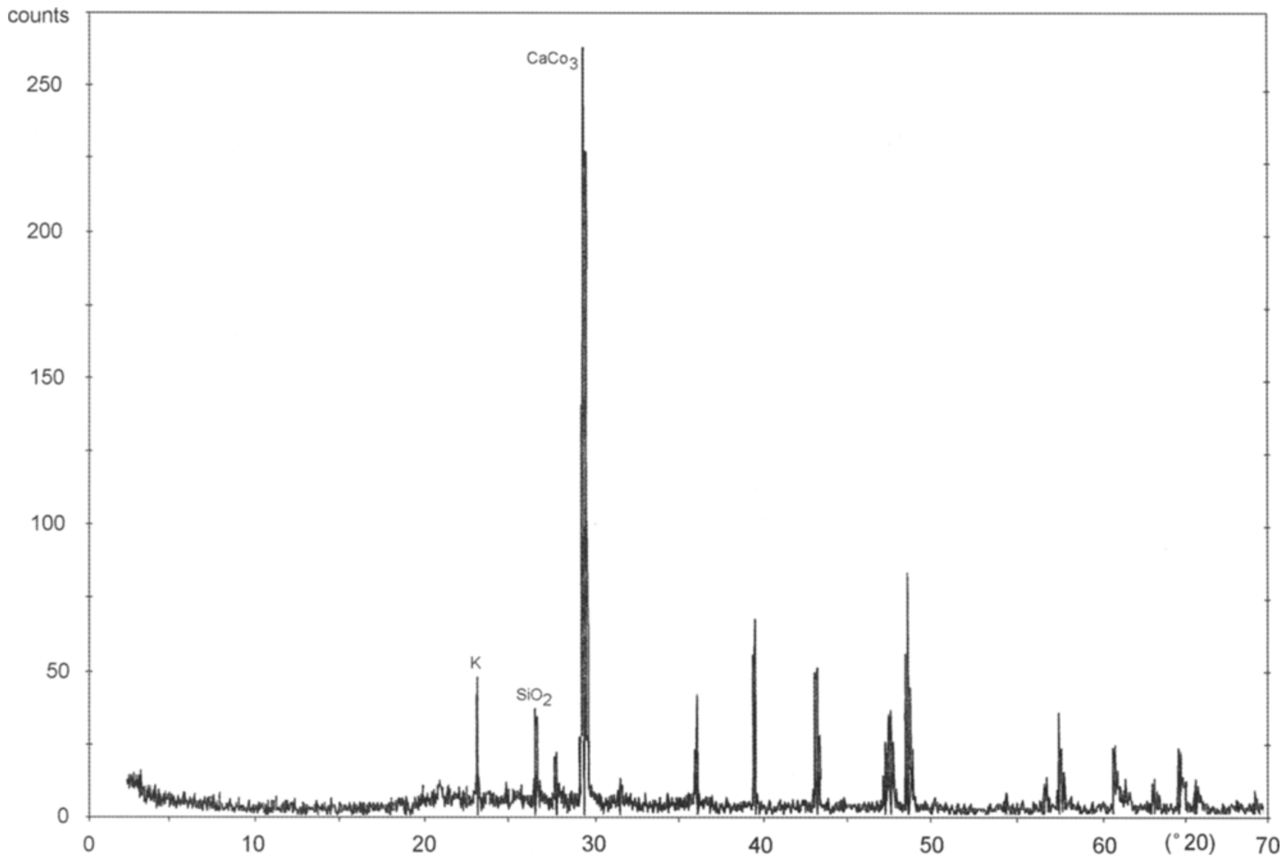


Figure 14. Results of X-ray diffractometric analysis of a sample of Antalya tufa.

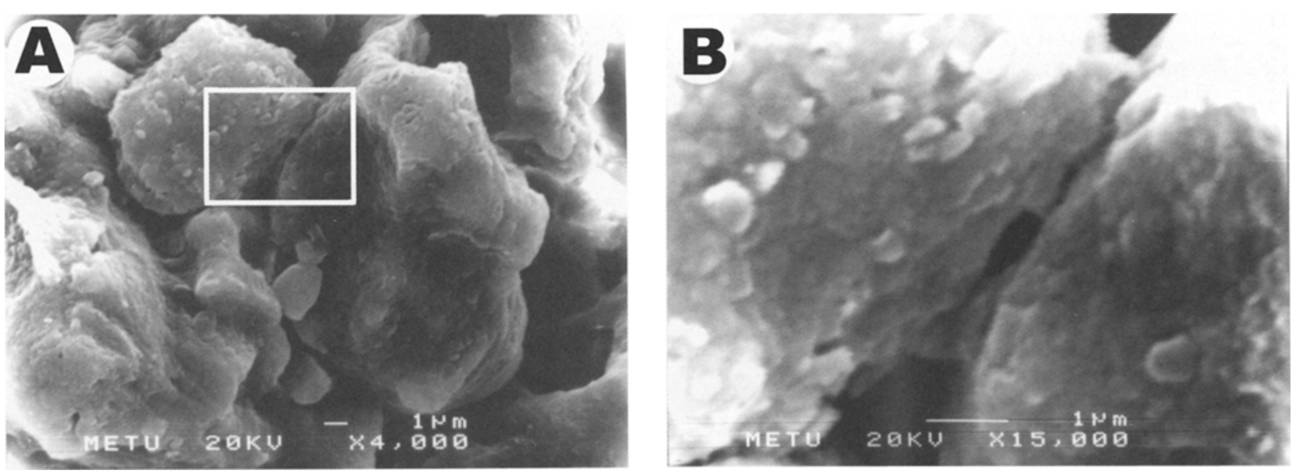


Figure 15. SEM views of meniscus cementation between tufa grains (left); close-up view (right).

vadose zone. Carbonate sediments in the vadose zone have often suffered less diagenetic modification with respect to phreatic zone (Pingitore 1976). Recent sediment samples, taken from 4-6 m depth, show only thin meniscus cements, concentrated at grain contacts (Fig. 15), that are detectable only via SEM analysis. In phreatic zone sediments or in sediments wherein water seepage is available, sparry-calcite cement develops at grain contacts and possibly as void fillings.

Diagenesis of tufas and travertines has been studied extensively by some researches (eg. Chafetz and Folk 1984; Chafetz et al 1991; Guo and Riding 1994). Considering dominant depositional environments in Antalya are paludal and shallow lacustrine and in meteoric-vadose environments, the Bermuda Model (Land et al. 1967) was adapted to tufa.

The five-stage model presented below is a modification of the Bermuda Model to meteoric-vadose cementation and diagenesis of the Antalya tufa. Assumptions for this model are that the basin of deposition is subject to 1) continuous hard-water supply; 2) seepage through the bottom; and 3) biogenic loss in pCO_2 of water.

Stage I is the initial sediment, consisting of allochthonous grains and grains of micritic or sparry calcite which directly precipitated by degassing, uptake of CO_2 or HCO_3 pumping. Stage II involves precipitation of low-Mg calcite on the surfaces of grains. The cement is generally asymmetric, or located at grain contacts as meniscus cement. Bacteria and algae remain undisturbed between cemented grains at this early stage (Fig. 16). Stage III involves the loss of Mg from high-Mg calcite, leaving a sediment of low-Mg calcite. Stage IV is the main diagenetic event of dissolution of fine crystals and reprecipitation of $CaCO_3$ as drusy sparry calcite. The main feature of this dissolution-reprecipitation process is a loss of internal structure in the former grains. Reprecipitated sparry calcite is observed as patches in fine micritic matrix (Fig. 17A). Aggrading neomorphism is typical in this stage as calcitization and replacement of skeletal grains (Figs. 17B, C) or pseudospar formation (Fig. 17D). Stage V involves further precipitation of calcite to fill remaining voids. In some tufas of limestone appearance, this final stage rarely produces a fully-cemented rock.

PALEOENVIRONMENTAL CONSIDERATIONS

Variations in tufa deposition are related to climatic changes as well as to the other factors. A cool climate is ideal for tufa precipitation. High temperatures enhance soil activity, CO_2 intake and karstic dissolution, which control the availability of calcium carbonate from which tufas are precipitated. However, especially in lake and barrage systems where diffusion at the air/water interface is significant, atmospheric pCO_2 might be the overriding control on tufa precipitation (Griffiths and Pedley 1995; Pentecost 1994). On the other hand, under cold and hot conditions, negligible precipitation occurs. Because cold results in low evaporation and warmth in dry air, both are mainly erosional conditions (Marker 1971).

Burger (1990) obtained U-Th dates for the Antalya tufa deposits and listed eight dated examples. With an age of 300 ka, the oldest datable tufa is situated 230 m above sea level. With a minimum age of 212 ka and a maximum of 327 ka, the average age of these tufa occurrences may be 250 ka, implying that the Antalya tufa formed during the Mid-Late Quaternary. Glover and Robertson (2003) tested Burger's (1990) results and concluded that the Antalya tufa is more than 600 ka old.

Today, three of the four continental Antalya tufa plateaus are inactive; the only exception is the Düden Plateau. The Düden River supplies fine sediments for fluvial deposition and hard water for paludal precipitation. As stated above, present climatic conditions are not ideal as they were in the past; this causes minor precipitation and results in weakly cemented, porous sediments. However, on the Varsak Plateau, in which the city of Antalya is located up to 1980's, several meters of tufa were eroded, leaving behind terra-rossa-type soil cover. Carbonate ions were transported to lower tufa layers as surface water percolated through the ground. This caused a kind of reprecipitation resulting in dense, hard, limestone-like tufa.

DISCUSSION

Terminology Conflict

The term "tufa" is derived from *tophus*, which originally described calcareous, whitish, porous deposits. "Travertine", the common alternative term, is generally applied to well lithified, older calcareous tufa deposits.

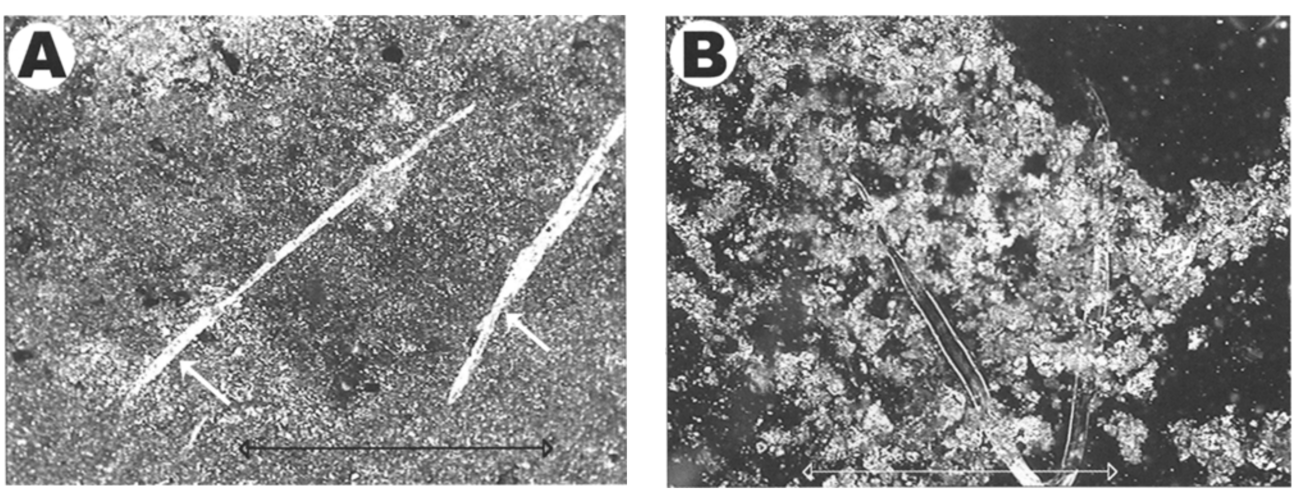


Figure 16. (A) Photomicrograph of micritic tufa. Cyano-phyto is visible (arrow), but cementation between grains is not, (B) Photomicrograph taken from an undisturbed cyano-phyto-bearing tufa (length of bar: 500 microns).

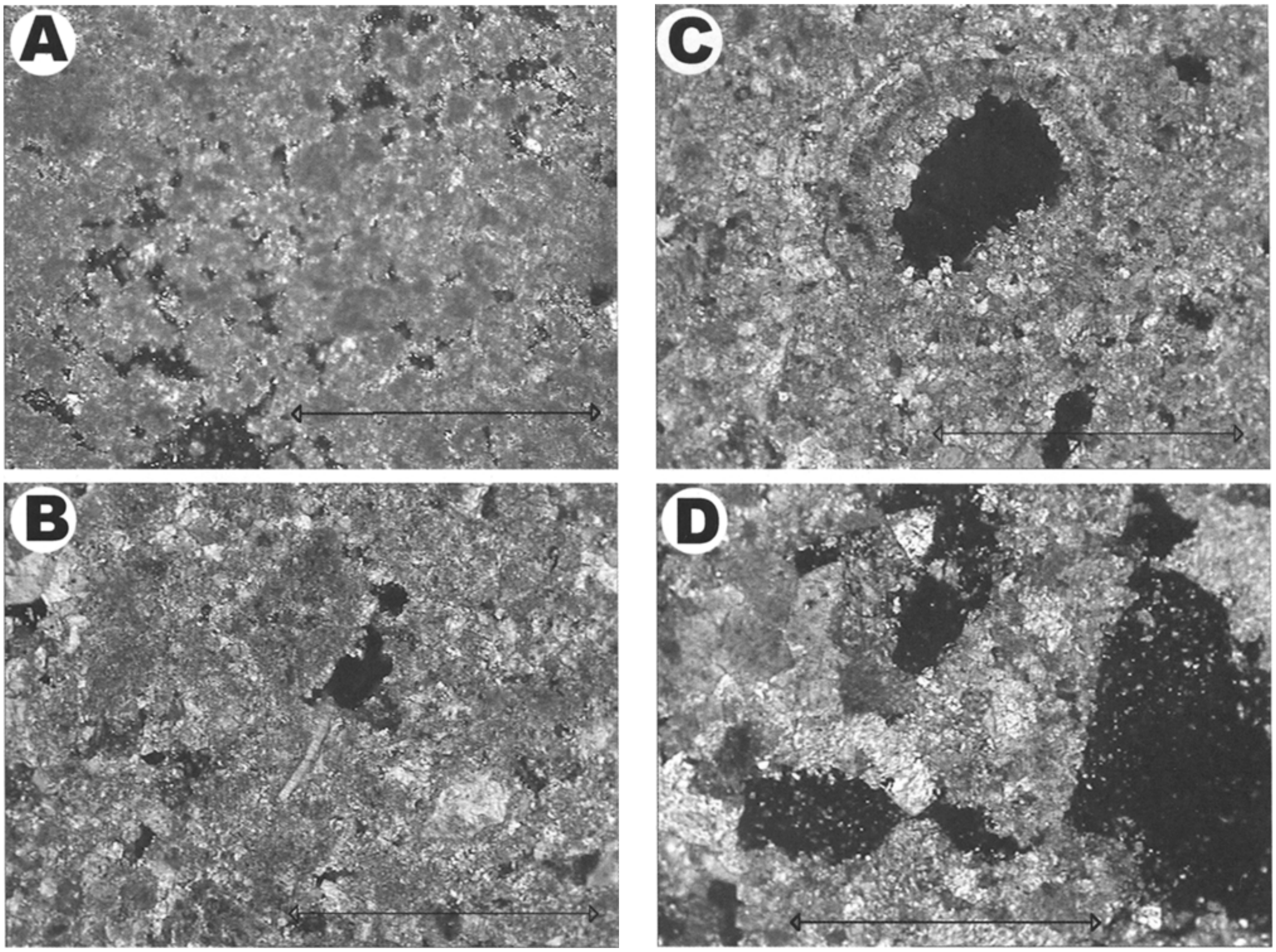


Figure 17. (A) Photomicrograph of reprecipitated sparry calcite, observed as patches in fine micritic matrix; (B) and (C) Photomicrographs of aggrading neomorphism visible as replacement of skeletal grains; (D) Photomicrograph of pseudospar formation during diagenesis of tufa (length of bar: 500 microns).

Pentecost (1995) prefers the term travertine for all deposits, separating them on the basis of temperature. He used the term "meteogene" for deposits where the CO_2 was sourced from soil and atmosphere, and "thermogene" for deposits where the CO_2 was sourced from hydrolysis and oxidation of reduced carbon, decarbonation of limestone or from the upper mantle. In order to draw distinctions among cool-water precipitates, diagenesis level may be a criterion, by defining weak, slightly cemented deposits as tufa, and hard, diagenetic rocks as travertine. However, in the field it is quite difficult to make such distinctions insofar as travertines commonly pass into typical tufa fabrics. To avoid confusion, the term tufa should be restricted to all cool or near-ambient temperature freshwater, low-Mg carbonates regardless of degree of lithification, as suggested by Ford and Pedley (1996). Thus, for the calcium-carbonate deposits of Antalya, use of the term tufa seems to be more appropriate.

Coastal Cliffs and Terraced Morphology

Erosion of the Antalya tufa sea cliffs is a cyclic phenomenon. Mechanically speaking, the base of the cliffs is the weakest part of the cliff wall due to stress release and fatigue (Fig. 18b). Another major factor is the dissolution of calcium-carbonate-type rocks in fresh water-sea water intrusion zone, resulting in "flank margin caves". In marine erosion of coastal cliffs, physical erosion is the most influential factor, so wave height and velocity determine the intensity of the destructive force. Repeated wave impacts result in fatigue of the rock. Long-term and progressive chemical and mechanical erosion results in notching. Notches, together with flank margin caves, results in a volume decrease at the base of the cliff, causing high tensional stress at the top of the cliff. When this stress exceeds the tensile strength of the rock mass, tensile cracks develop (Fig. 18c). In this way, a prismatic rock block occurs between the crack and the sea (Fig. 18d). Thereafter, the tilt of the rock block can be

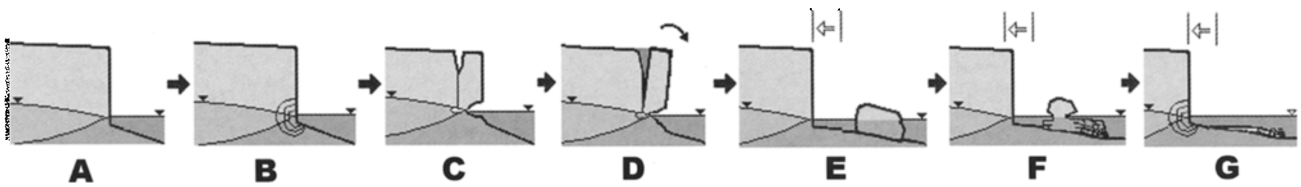


Figure 18. Coastal-cliff retreat mechanism for the Antalya tufa.

explained via a simple "toppling" mechanism. As marine erosion continues, the forces that induce the block to topple increase (Fig. 18e). When the rock block suffers from further marine erosion, the cliff-erosion cycle continues on the cliff wall behind the toppled block (Fig. 18f).

Similarly, present-day slopes between terraces (continental cliffs) may have been produced when past sea level was high enough to cover the Varsak Plateau. The lowest terrace (below sea level) may be an example of such a mechanism. If the proposed mechanism is valid, the geometry of continental and sea cliffs is an issue that must be addressed; this issue may be explained by sediment supply/erosion balance. Today, the Düden Plateau is more resistant to sea-cliff retreat; because cascade deposition as tufa curtains and sediment transportation by the Düden River continues, deposition balances or exceeds volume loss by marine erosion.

A second alternative mechanism for these terraces may be tectonic origin. Some lineations, detected by remote-sensing methods (satellite images), seem to match terrace edges (Ayday and Dumont 1979); however, no supporting field evidence has been obtained to date.

A third alternative mechanism is the constructional theory suggested by Burger (1990). Burger explained the occurrence of the "spur of Antalya" (Masadağı) as "filled travertine basins". In the present study, Masadağı is interpreted as perched springline system deposits which include paludal and lacustrine systems (Burger's basins). This system is important for the Antalya tufa by serving as a point of origin. However, on other parts of the slope – for example, between the Döşemealtı and Varsak plateaus – this mechanism cannot be detected. Most of the slope face is horizontally bedded tufa, suggesting the dominance of a lacustrine system.

In conclusion, most of the deposits are horizontally bedded, possibly implying that the tufa is primarily a planar unit. However, terraced morphology – except for small areas (e.g., Masadağı) – is likely a result of erosion.

Cavities

Cavities in the Antalya tufa are of two origins. The first type comprises primary voids; this kind of cavity develops behind cascade curtains, in front of shallow pools, and between stromatolitic bodies. These cavities are generally observed to be filled with fine grained tufa and terra-rosa. Vertical curtain cavities are quite abundant, especially on Masadağı and along sea cliffs. During vertical drilling, drill rods may drop several to tens of meters; however, through inclined drilling, the widths of these cavities are found to be around 1 m.

The second type comprises solution cavities. The Döşemealtı Plateau is not an aquifer, and this unit transmits water through a karstic conduit system. Between the Kırkgöz springs and Düdenbaşı, a 36-mg cation/ion difference was detected by Altuğ (1977). This shows that water transmitted through the Döşemealtı Plateau is not the cause of the karsification. However, surface karstification is widespread on the plateau. In lacustrine tufa units, solution pipes are quite abundant, and these pipes join underground openings, which generally developed around bedding planes. The Varsak and Düden plateaus have been shaped by surface erosion, young fluvial deposition and paludal precipitation. Some cavities on these plateaus parallel lineations, as noted by Aydar and Dumont (1979).

CONCLUSION

1. The term "tufa" is more appropriate for the unit which previously has been named the Antalya Travertine. Deposition in a cool-water regime and its biogenic origin support this new designation. The use of the classification system introduced by Pedley (1990) is suitable for geological and engineering-geological investigations of the Antalya tufa; this system is based on both the fabric and the depositional environment.

2. The Antalya tufa deposits accumulated in the Aksu Basin, which formed as a half-graben system in response to a combination of N-S and NE-SW extensional faulting, while the adjacent Tauride Mountains were progressively uplifted. The Antalya tufa is dominated by horizontally-bedded, carbonate-dominated sediments; this may imply that the dominant depositional environment was lacustrine. However, a perched springline system played an important role as a starting point and construction mechanism for the terraced morphology. The perched springline system itself includes paludal and lacustrine aspects. The terraced morphology was completed after

closure of pools by sedimentation via paludal/lacustrine systems. Fluvial processes were the last to contribute to the extensive planar appearance. After reaching a higher elevation, a cascade system developed where water flowed downward. In a braided-river environment, paludal/lacustrine environments also developed as secondary aspects.

3. The tufas are the products of both physico-chemical precipitation and biogenic precipitation associated with biofilm colonization. In the biogenic process, precipitation was the cause of decreasing partial pressure of CO_2 by photosynthesis of algae or bacteria. In Antalya, modern calcite precipitation can be observed in small pools where a paludal environment dominates. X-ray diffractometric and SEM analyses have revealed that the collapsible tufa deposits consisted almost entirely of calcite.

4. Most of the deposits are horizontally bedded, implying that the tufa is primarily a planar unit. However, terraced morphology – except for small areas (e.g., Masadağı) – is likely a result of erosion. A present-day coastal cliff-retreat mechanism may be the explanation of other slopes when sea level was at those altitudes.

5. Cavities in the Antalya tufa are of two origins: primary and karstic. Primary cavities develop behind cascade curtains, in front of shallow pools, and between stromatolitic bodies. Between the Kırkgöz springs and Düdenbaşı, a 36-mg cation/ion difference was detected by Altuğ (1977), demonstrating that water transmitted through the Döşemealtı Plateau is not the cause of karstification. However, surface karstification is widespread on the plateau. In lacustrine tufa, solution pipes are abundant, and these pipes join underground openings which generally developed at bedding planes.

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