EVIDENCE OF MICROBIOLOGIC ACTIVITY IN MODERN TRAVERTINES: SICAKCERMIK GEOTHERMAL FIELD, CENTRAL TURKEY

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ABSTRACT: Modern travertine deposits are observed in the Sicakçermik hot springs located northwest of Sivas, central Anatolia. They are the carbonate deposits of crustal (spongy) and/or alabaster-textured formations controlled by both organic and inorganic processes. The structures formed under the influence of inorganic processes include the accumulations on the fissure and joint ridges. These structures are adjacent to the hot water emergence spots representing the points of rapid hot water flow and sudden release of CO_2. The structures developed under the influence of organic processes form in areas at relatively farther distances from the hot water emergence points. These structures were described to be "waterfall or cascade deposits"; "terrace-mound travertines"; and "shallow lake fans" by different researchers. They are recognized in the field by special identifying trails such as manganous-ferrous travertine shrubs resembling ivy, siliceous stromatolites, and ferrous pisoids, 3 to 12 mm in diameter.

All the modern travertine samples examined are dominantly formed by subidiomorphic prismatic-tabular calcite crystals. Scanning Electron Microscopy revealed that calcite crystals forming the pisoids are characterized by zonal growth. Stromatolitic formations, on the other hand, bear regular joints developed as a consequence of sudden cooling and some special structures indicative of bacterial activity (in the form of nodule, spheroid, ellipsoid, column, filament and honeycomb or grape bunch structures). In addition, secondary dissolution vugs and pores giving way to the release of CO_2 are associated structures with the stromatolitic formations. The data collected from all the utilized techniques suggest that the microbiological formations observed in the travertines of Sicakçermik hot spring were produced by the sulfate-reducing, boring-budding bacteria such as Coccoids, Pedomicrobium, Beggiatoa sp., Thiobacillus sp., as well as blue-green algae (Cyanobacteria).

The travertine occurrences produced by both organic and inorganic processes have an annual average of 3-5 cm deposition in thickness. The hot water emergence points and their flowpaths manifest seldom-found natural features. These natural monuments are irresponsibly destroyed for several reasons. The authors argue that these formations, significant from the point of view of their occurrence mechanism as well as their final products, must be preserved. If accomplished, a modern natural monument similar to that in Pamukkale (Turkey) and Yellowstone National Park (Wyoming, USA) could develop within a reasonable length of time.

INTRODUCTION

Travertines have been variously described (e.g. Julia 1983) and classified (e.g. Scholl 1960; Irion and Müller 1968; Buccino et al. 1978; Meredith 1980; Julia 1983; Chafetz and Folk 1984; Heimann and Sass 1989; Pedley 1990; Ford and Pedley 1992; Altunel and Hancock 1993; Pentecost 1993; Guo and Riding 1994 and 1998). These researchers concluded that the most common criterion for classifying travertines is their depositional morphologies. An ideal classification for travertines should be applicable to: a) those deposited in different depositional environments, b) old and modern/active travertines, and c) travertines of different scales. As indicated by Chafetz and Folk (1984), the depositional morphology is controlled by environmental conditions. Accordingly, the most prominent modern travertines (e.g. Tivoli and Rapolano in Italy; Mammoth Hot Springs in Yellowstone National Park and Bridgeport in the USA; and Pamukkale in Turkey) were classified upon their morphological features.

Old (inactive) travertines with economic values are also preserved as natural monuments. For instance, the travertines in the general area of Pamukkale (western Turkey) are utilized as thermal resorts and preserved as a natural open museum.

As of now, no special attention has been paid to the modern travertine deposits in the Sicakçermik geothermal field (Figs. 1a,b). The area has been exploited for the thermal tourism for about four decades. The thermal water of the study area has been utilized in thermal resorts. The modern deposits of travertines have been continuously destroyed.

Previous studies on the Sicakçermik geothermal field area have dealt mostly with the hydrogeology of the area (e.g. Erisen et al. 1996) and the industrial use of old travertines (e.g. Ayaz 1998). This paper deals with the origin, morphology, and the environmental aspects of the Sicakçermik geothermal field.

MATERIAL AND METHOD

The materials used in this study were samples collected from the modern travertine deposits and water from the hot spring. The structural classification of the modern travertine features was based on the macroscopic field descriptions. A series of petrographical examinations were carried out to highlight the formation mechanism of the modern travertine deposits. Microtextural features were determined using the Scanning Electron Microscopy (SEM; model Jeol JSM-840) and Energy Dispersive Analysis (EDS; model Tracor TN-5502). Geochemical evaluation of the trace elements was carried out on the results of Atomic Absorption Spectrometry (model Hitachi Z-8200 Polarized Zeeman). Annual deposition rate of the modern travertines was determined based on the seasonal

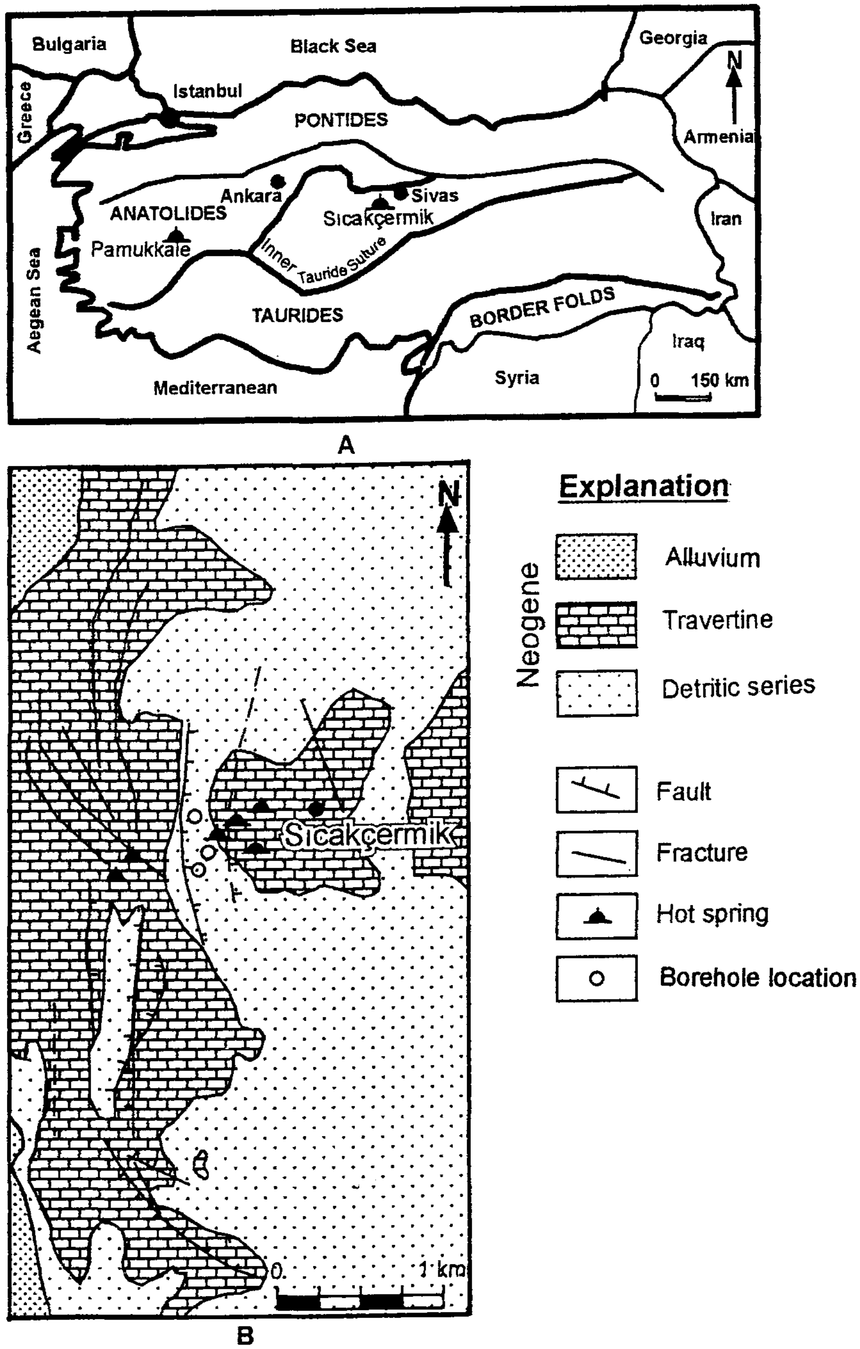


Figure 1. a) Location map of the study area. b) Simplified geological map of the study area

measurements and observations. An attempt was made to estimate the thickness and areal distribution of the "destroyed" modern deposits by utilising the recent anthropogenic events in the area.

GEOLOGICAL SETTING

The basement of the stratigraphic series in the study area comprises Akda metamorphic rocks of Paleozoic age including quartzite, quartzous schist, kalkschist, micaschist and marble type of rocks. Pazarcik volcanic rocks and Incesu formation of Tertiary age unconformably overlie the metamorphic basement. The former consists of basalt and andesite and the latter includes claystone, siltstone, conglomerate, and sandstone bearing the signs of a continental facies and lacustrine limestone. The modern travertine deposits overlie these units with an angular unconformity (Ayaz 1998; Erisen et al. 1996). As for the tectonic elements which yield the formation of the geothermal field, Bingöl (1989) established a relationship with the dip-slip normal faults striking N-S and NE-SW as well as the secondary tension cracks associated with these fault systems.

HYDROCHEMISTRY

The discharge of free flowing hot springs in the study area is around a constant value of 3 liters per second, however, the artesian wells draw a total of 367 liters per second which is utilized in thermal resorts. For the sake of the completeness of the study the results of chemical analyses of five hot water samples collected from two springs and three wells in 1989 in Sicakçermik geothermal field are presented in Table 1. High values of the bicarbonate component as well as the trace elements such as Li, B, I, F, and As in Table 1 are typical for mineral waters. Plotting of cations of Mg^{2+}, Ca^{2+}, and Na^{+} and anions of SO_4^{2-}, Cl^{-}, and HCO^{3-} into piper diagram would yield the water class of Ca + Mg > Na + K (carbonate and sulfate dominated water). According to AIH (Association of International Hydrogeologists) classification, it is Na-Ca-HCO_3 dominated hot-mineral water.

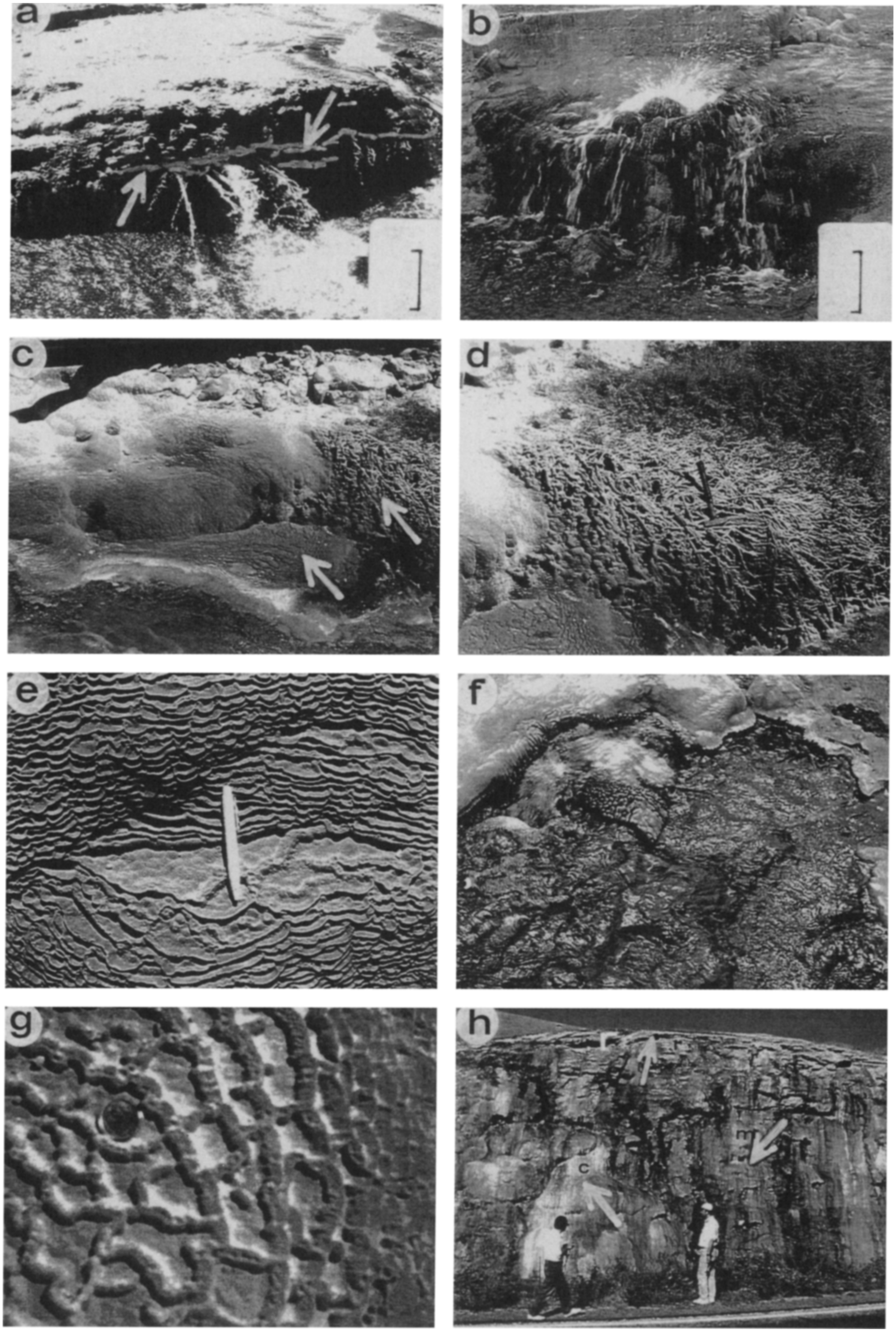
MORPHOLOGICAL CLASSIFICATION OF TRAVERTINES

Travertines display a wide variety of fascinating textures and structures that are obvious even to a casual observer. They are usually preservation areas strictly protected by governmental regulations in some parts of the world. Sicakçermik geothermal field too manifests a marvelous landscape feature continuously interrupted by human activities. The modern travertine deposits in the Sicakçermik area yield four distinct types of morphologies developed by both organic and inorganic processes. The details of these unique features are described in the following subsections.

i. Fissure-ridge travertines: This term was used by Bargar (1978), Chafetz and Folk (1984), and Altunel and Hancock (1993) to describe travertines developed in different parts of the world. This type of travertine deposits develop in the Sicakçermik geothermal field in the form of ridge accumulations along the fissures and joints brought by hot water emerging from discontinuities. They include banded and stratified structures. The banded levels are thought to have been produced by the existence of SiO_2 in hydrothermal solutions. These levels, with the colors of beige, yellow, orange, maroon, and dark red, reach up to 10-30 cm and 40-60 cm in thickness at the modern (active) and old (inactive) sites, respectively (Fig. 2a). The areal extension of the old travertines is as large as 1-2 square kilometers whereas the modern ones are restricted to much narrower areas due to the destruction by the heavy tourist traffic around the thermal

Table 1. The results of chemical analysis of hot water samples collected from the springs and wells in the Sicakçermik geothermal field.

	Hot Spring or Well Location				
	SÇM-1 (spring)	SÇM-2 (spring)	MTA-1 (well)	DSI-1 (well)	DSI-2 (well)
Temperature (°C)	35	35	46	49	49
PH	7.56	7.54	7.52	7.32	7.46
Specific conducticity (μmho/cm)	2100	2100	2000	2200	2400
Evaporation residue (mg/lt)	1290	1272	1232	1224	1560
K^- (mg/lt)	39	40	40	40	44
Na^- (mg/lt)	220	215	213	210	240
Ca^{2+} (mg/lt)	164	159	121	178	125
Mg^{2+} (mg/lt)	78	78	94	83	76
As (total) (mg/lt)	0.1	0.01	0.01	0.01	0.02
B (total) (mg/lt)	2.3	0.9	2.2	0.9	2.2
Li^+ (mg/lt)	0.8	0.8	0.8	0.9	1.0
SiO_2 (mg/lt)	27	44	27	27	27
$HCO3^-$ (mg/lt)	1135	1098	1074	1220	1031
CO_3^{2-} (mg/lt)	10	10	10	1	10
SO_4^{2-} (mg/lt)	69	65	72	63	69
Cl (mg/lt)	226	223	214	215	232
I (mg/lt)	0.5	0.5	0.5	0.5	0.5
F (mg/lt)	2.2	2.2	2.2	2.4	2.4
NO_2 (mg/lt)	0.1	0.1	0.1	0.1	0.1
NO_3^- (mg/lt)	1	1	1	1	1


a
b
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resorts. The elongation of the travertine ridges adjacent to the discontinuities follow a NE-SW direction.

ii. Waterfall or Cascade Deposits: These features have a transition in a horizontal direction with the fissure ridge-type formations. The term was introduced by Herlinger (1981). These are the deposits on the paleotravertine crusts adjacent to the vents giving way to the CO_2-rich hot hydrothermal waters. These locations are typical places of stromatolitic structure developments (Fig. 2b) as a consequence of organic processes dependent upon the rapid flow of hot water. The abundance of microorganisms controlling the organic processes is influenced by the velocity of water flow, sudden release of CO_2, and density of light. Turbulent water flow and relatively high pressure of hot water at the spring cause a rapid precipitation of carbonate. Calcification of shrub type plants along the lines of waterfalls or cascades is one of the common events encountered in the study area (Figs. 2c,d). The microscale waterfalls or cascades have a transition with the terrace deposits which develop where the flow velocity and the pressure of hot water decrease.

iii. Terrace-mound travertines: Bargar (1978) first used this term to describe the deposits found on sloping ground or areas where the slope angle flattens out. As for their dimensions, they show a variety of sizes from a few cm to several meters. They are found in the form of the colonies of micro-pools with somewhat laminated and undulated morphology, developed on the lobous shaped main terrace (Fig. 2e). Similar structures and descriptions were made in a study by Schreiber and others (1981). The rate of deposition is higher at the upper levels of the main terrace than the lower levels. This is attributed to the cooling off of the hot water at the lower parts of the main terrace. In addition to these features, terrace-mound travertines include pisoid formations as well. Pisoids are observed around the "travertine circle" at the edges of the active main terraces. These are the places where wave and/or turbulence activity is relatively high, algae and cyanobacteria can easily cling, and carbonate deposition is extensive.

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Figure 2. a) Fissure-ridge type modern travertine formations developed in a poorly stratified manner due to SiO_2 banding (vertical scale: 1/40). b) Micro-cascade/fall deposits and stromatolithic structures (vertical scale: 1/40). c) Undulated-calcified structures on shrubs and other plants developed by the hot water emerging from the micro-falls/cascades. d) A close-up view of calcified structures produced by a rapid deposition. e) Modern terrace groups developed in the form of relatively laminated/undulated micro - pools. f) A close-up view of a shallow lake-fan (notice the distinct travertine encrustment of algal origin encompassing the shallow lake). g) A close-up view of micro-pools forming the shallow lake-fan. h) In inactive travertines: r- Fissure-ridge accumulations, c- Micro-fall/cascade deposits, — Micro-terrace formations.

iv. Shallow lake-fans : The terminology was first introduced by Chafetz and Folk (1984). The deposits of this type are found in small ponds on old main terraces where the slope angle is significantly reduced and flattens out. The bottom of each pond is flat and the depth of water in the pond is quite shallow. These ponds receive their water either from upper heights or they are fed by hot waters of main terrace as a consequence of periodical turbulences or floods. Owing to the rapid calcite deposition, a small-scale natural barrier develops around each pond. Chafetz and Folk (1984) and Folk (1999) attribute these features to the accumulation of long filamentous blue-green algae and nannobacteria. The growth of these barriers causes an increase in water turbulence, which accelerates the process of travertine encrustment of algal origin (Fig. 2f). These ponds also host the formation of modern ferrous pisoids and, to a lesser extent, manganous stromatolites (Fig. 2g).

The four distinct morphologies of travertine deposits are also found on the old (inactive) travertines (Fig. 2h). Approximately 10 m in thickness, this old travertine series was contaminated and destroyed.

EVIDENCE OF MICROBIOLOGIC ACTIVITY IN TRAVERTINES

There are several types of organic deposits in the geothermal field of Sicakçermik as described by Risacher and Eugster (1979), Chafetz and Butler (1980), Meredith (1980), Schreiber et al. (1981), Chafetz and Meredith (1983), Chafetz and Folk (1984), Love and Chafetz (1988), Guo and Riding (1992, 1994, 1998), Renaut et al. (1998), and Chafetz and Guidry (1999). These organic deposits are: a) ferrous pisoids, b) manganous-ferrous travertine shrubs, c) siliceous-ferrous-manganous stromatolites (Figs. 3a,b,c,d). These features present fascinating views in the field. Their formation mechanism shows a variety of patterns. Their macro- and micro-textural features are described in the following subsections.

i. Field Description : Formation of iron-rich pisoid usually take place in shallow lakes and pools and seldom at the edges of the relatively well-preserved main terraces bordering those pools. Beige and orange in color, the diameter of these pisoids ranges from 3-12 mm. A weak calcite-cementation holds the individual pisoid grains together. They crumble easily in the hand. Those deposited particularly in winter and summer seasons have very soft texture and easily disintegrate. Their formation process can be observed in a single summer season. Ferrous pisoids of soft texture and 3-4 mm in diameter which still continue to precipitate in the preserved shallow lake areas are shown in Figure 3a. Those with a diameter of 8-10 mm which formed in about a decade (based on continuous field observations) are shown in Figure 3b. These type of pisoids are distinguished in three major zones separated by 3-4 mm-thick calcitic laminae rich in iron and manganese. They can be categorized as "bacterial oncoliths".

Iron - and manganese - rich shrub fabrics form on low - angle slopes in microfalls/microcascades as well as at the edges of microterraces. Shrub fabrics can be considered somewhat equivalent to "fossil bacteria stromatolithes" described by Walter (1976). Travertine shrubs in the Sicakçermik geothermal field manifest a distinct stratigraphic sequence resembling grape bundles occasionally with the lobous structure at the macroscale. During their deposition they are continuously in contact with the turbulent, high-velocity water (Fig. 3c).

The other common type of organic deposit in the Sicakçermik geothermal field is the algal mat of siliceous-manganous-ferrous stromatolith type as described by Ghiorse (1984), Nealson et al. (1989), Skinner and Fitzpatrick (1992), Ehrlich (1996), and Chafetz et al. (1998). As can be seen in Figure 3d, their central portion is relatively porous or composed of fragments of plants or trees. These structures are surrounded by carbonate laminations repeated hundreds even thousands of time. Amongst those laminations, the siliceous ones are white in color; manganous ones are brown to black; and ferrous ones are red to maroon. They occasionally present "zebra structure" owing to the mixture of those colors. Shrub fabrics of tabular, cummulate shape, spherolitic or lobous bundles have developed on the external face of these structures reaching up to 2-3 m in thickness with about 20-30 m in lateral extension.

ii. Petrographic and Microtextural (SEM-EDS) Properties

Although it is common to see a detritic mineral (calcite or quartz) at the core of the pisoid formations, some pisoids lack this nucleus (Fig. 4a). The pisoids are formed by regular envelopes in a concentric manner from the nucleus to outward. A weak spari-calcite cement is observed between the pisoid grains (Fig. 4b). Regular zonation is also observed in pisoids (Figs. 4a,b,c). This structure is thought to have developed as a result of interpretation of the trace elements such as Si, Fe, and Mn which were diagnosed through the EDS and AAS examinations. These type of textural definitions were also presented by other researchers (e.g. Chafetz et al. 1998; Jones et al. 1997 and 1998; Renaut et al. 1998). Examinations of pisoids also revealed the existence of Cyanobacteria and Pedomicrobium sp. type of boring-budding bacteria forming the radial zones between the low-Mg calcite crystals (Figs. 4d,e). In addition, special patterns

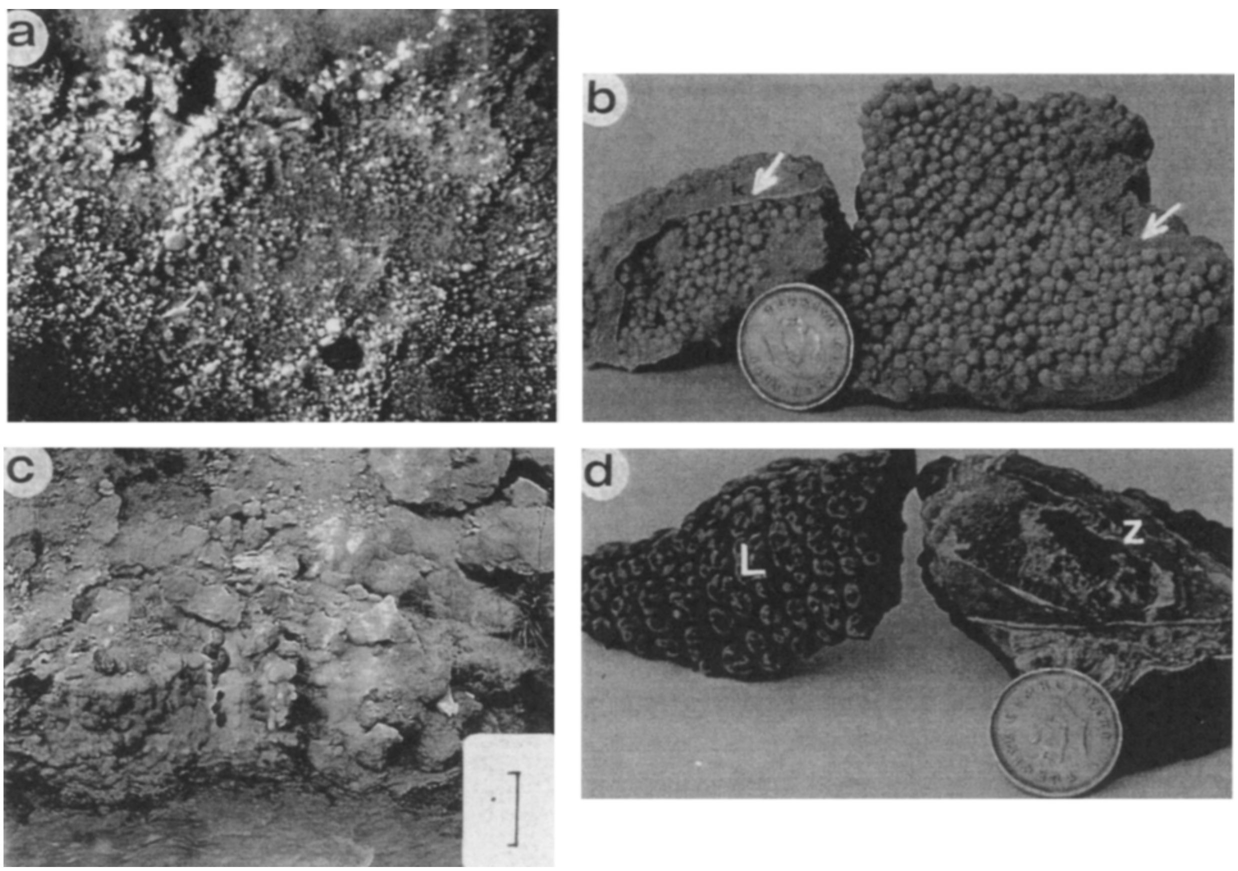

Figure 3. a) A close-up view of soft-textured ferrous pisoids in a micro-pool forming the shallow lake - fan. b) A view of the compact and petrified ferrous pisoid grains and iron- and manganese-rich calcitic lamination among them. c) Iron- and manganese-rich shrub structures developed on the slope of a micro-fall/cascade. The upper part is destroyed (vertical scale: 1/40). d) Siliceous-manganous-ferrous stromatolithic algal structures (the internal structure is of zebra type – Z -; the upper surface is lobous –L-).

indicating the effect of algae/bacteria were determined in shrubs and stromatoliths through SEM studies. Travertine crust with the shrub fabrics has a porous structure at its center surrounded by rows of calcite developed in "column shape" manner (Fig. 4f). It is very likely that a bacteria colony having a shrub fabric forms the nucleus of each calcite crystal. The area between the branches of a single shrub is usually filled with sparite. These features may develop in shallow water conditions as well. Chafetz and Folk (1984) attribute the growth and upward branching of shrubs to sulfate reducing bacteria under the influence of phototrophic conditions. Figure 4g shows the lobous sphereoidal structures in

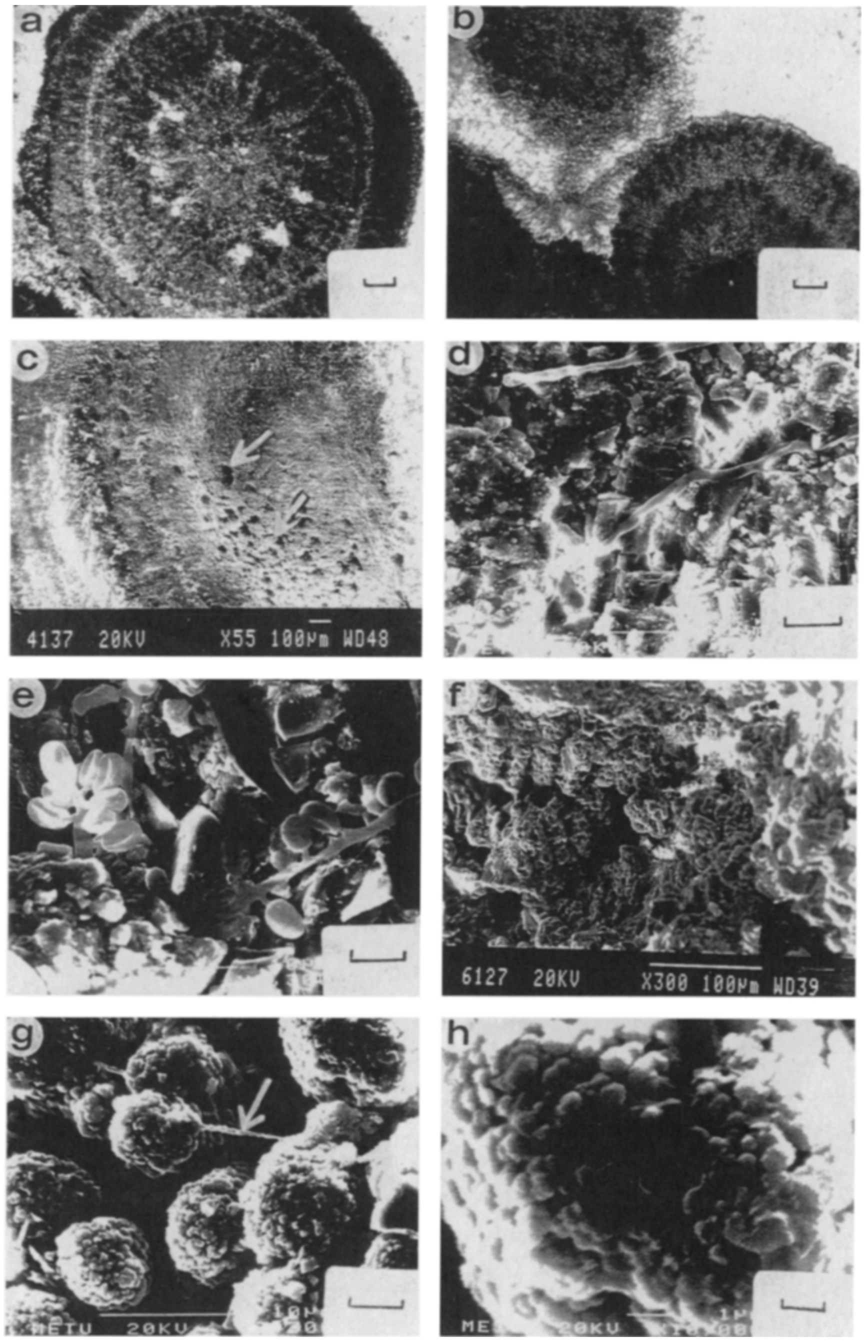

Figure 4. a) Photomicrograph of a ferrous pisoid grain (plane light, magnification: 10x25, 5 mm = 375 µm). b) Photomicrograph of weak sparicalcite cement binding pisoid grains (plane light, magnification: 10x25, 5 mm = 375 µm). c) SEM photomicrograph of envelopes forming pisoids and borings of bacterial/algal origin on those envelopes. d) SEM photomicrograph of bacteriform bodies and algal filaments in micrites forming the pisoid envelopes (1 cm = 5 µm). e) SEM photomicrograph of boring-budding bacteria of Coccospore type in micrites forming the pisoid envelopes (1 cm = 5 µm). f) SEM photomicrograph of column-shaped microcrystalline micrite forming the inner structure of travertine shrubs. g) SEM photomicrograph of lobous spheric bundles of spheroidal character in stromatolithes and binding mucus matter (1 cm = 5 µm). h) SEM photomicrograph of a bumby structure on the outer surface of a lobous spherics (8 mm = 1 µm).

stromatoliths resembling grape bundles. The mucus matrix between lobous bundles (Fig. 4g) and the bumpy structure on the outer face of the lobous sphere (Fig. 4h) are typical features of stromatoliths. These structures were interpreted to be the products of algal or bacterial activity by some researchers (e.g. Golubic 1969; Walter 1976; Folk and Chafetz 1983; Chafetz and Folk 1984; Love and Chafetz 1988; Guo and Riding 1992; Folk 1993; Guo and Riding 1994; Jones et al. 1997a,b and 1998; Chafetz et al. 1998; Renaut et al. 1998; Guo and Riding 1998 and Casanova et al. 1999).

ENVIRONMENTAL ASPECTS

Although the initial housing construction took place in a

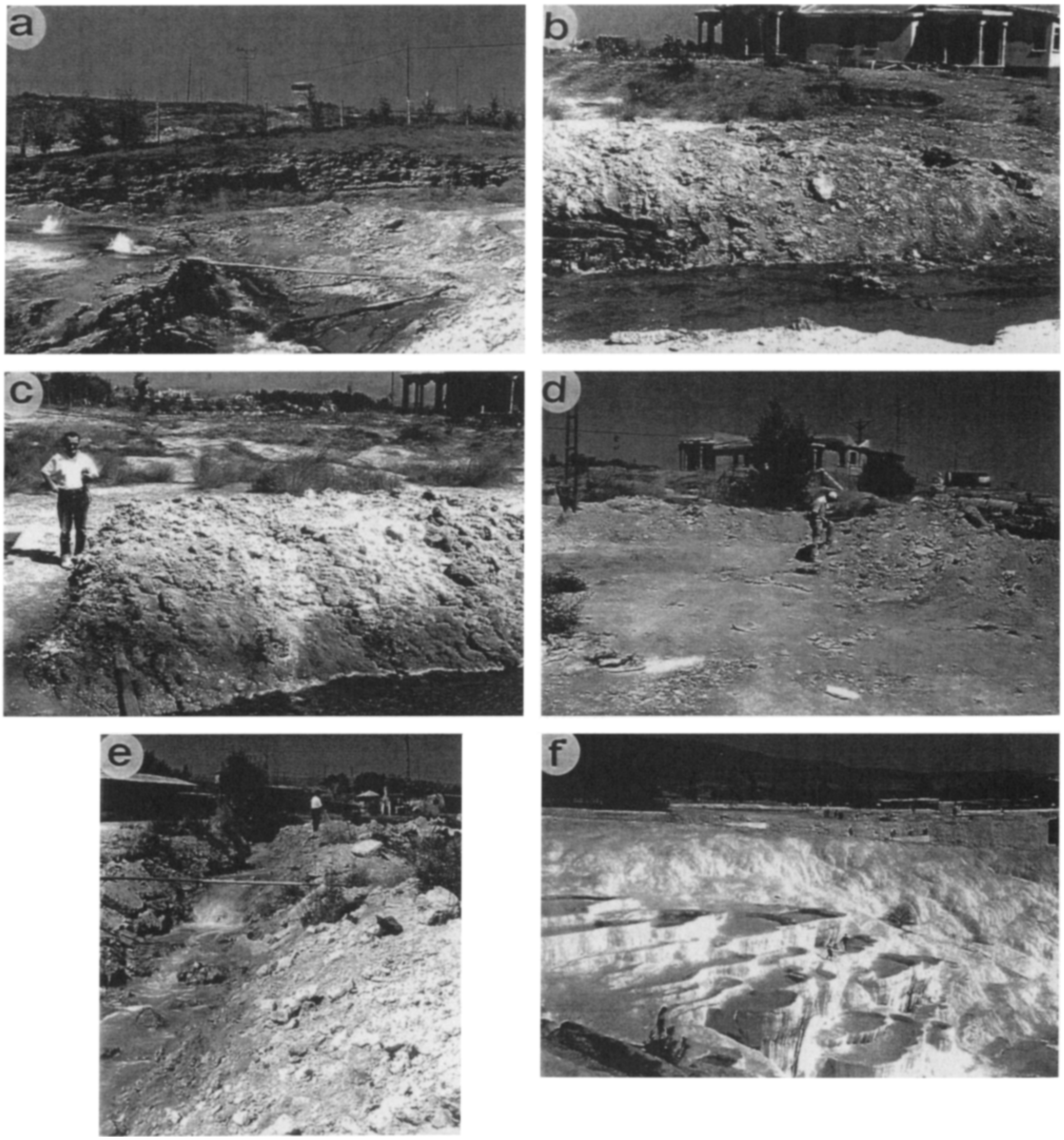

Figure 5. a) Residential developments nearby the hot springs area. b) Incrustation of modern travertine deposits. c) Cascade developments on the slope of a nearby roadcut. d) Flow channel of the hot springs along with the scraped mateials on the banks. e) Stockpiled travertine deposits waiting to be utilized for construction purposes. f) Travertine dams and pools formed by hydrothermal overflowing water in Pamukkale, Turkey.

comparable distance from the hot springs area, the recent developments came as close to the springs field as several ten meters (Fig. 5a). The intensity of the tourist traffic therefore has been continuously increasing. The calcium carbonate deposition in the Sicakçermik geothermal field and neighboring areas is very rapid (Figs. 5b,c) allowing the formation of incrustation around the springs and wells. The channel of flowing hot water is often scraped (Fig. 5d) to prevent the filling of the stream bed with the modern deposits. The scraped material is accumulated on the banks of the flow channel (Fig. 5d) or stockpiled in a nearby spot (Fig. 5e) for the utilisation as construction material, mostly in the form of aggregate spread on dirt roads.

Incrustation of travertine deposits is annually destroyed thus preventing the formation of fascinating cascades as in the examples of Pamukkale, Turkey (Fig. 5f) and Mammoth Hot Spring, Yellowstone, USA. Figure 5c shows (mid-section of the photo) the recent travertine developments prior to the settlements in modern time.

The topography in the vicinity of the Sicakçermik geothermal field is dominated by gently rolling slopes mostly smaller than 10°, very suitable for the formation of a natural cascade.

Removal of travertine incrustation in the Sicakçermik geothermal field is likely to continue in years to come. At the moment, no preventive measures are taken by local authorities against the destruction. Considering the rapid deposition of travertine, the area holds the potential to form a sizable cascade similar to those in Figures 5b,c in only a few decades. If the human destruction during the last few decades had been prevented, the areal extension of the modern travertine deposits would have spread in several hectares similar to Pamukkale and Mammoth hot springs.

CONCLUSIONS

The modern travertine deposits formed under the influence of both organic and inorganic processes in the Sicakçermik geothermal field present fascinating morphologies considered as a natural museum. Inorganic structures developed as a release of CO_2 release near the spots of hot water emanations whereas at further distances from those spots form the organic morphologies controlled by the bacterial/algal activities. Although the investigated thermal field is considered to be unique in regard to the formation of unique morphologies its areal extension is not as large as it should be. The reason for this is that the chemical composition of the hot spring is suitable for the use in the health facilities. Another factor restricting the areal expansion of those morphologies is the proximity of the thermal field to a major residential area, the City of Sivas. The hot springs in the area are extensively utilized in thermal resorts by the municipality. Similar problems arose for the travertines of Pamukkale owing to the consumption of the thermal spring waters in the nearby resorts. Particularly during the period between 1970-1995 heavy consumption of spring water in Pamukkale resorts cut down the amount of water feeding the cascades leading to a dramatic color change from unique whiteness to darker tones of white to beige. Soon after this happened a series of preventive measures were taken by the environmental protection societies and the site began to gain its original scenic view. For the Sicakçermik field, we strongly believe that the modern travertine deposits spread over much a narrower area than they should. Owing to the human interaction with the site, the expected scenic views did not have chance to develop. Modern deposits in the Sicakçermik area are periodically scraped to prevent the filling of channels. Should preventive measures be taken by the local authorities, the area offers the potential to form a sizable and fascinating cascades similar to the world-famous cascades such as Mammoth and Pamukkale springs.

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