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DEPOSITIONAL ENVIRONMENTS AND PETROGRAPHY OF DENİZLİ TRAVERTINES

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ABSTRACT- Quaternary to Recent travertines in the Denizli basin are distinguished in 9 lithofacies according to the field and microscobic features. These are: 1) Crystalline crust, 2) Shrub, 3) Pisolith, 4) Paper-thin raft, 5) Coated gas bubble, 6) Reed, 7) Lithoclast, 8) Pebbly travertines and 9) Palaeosols. Various combinations of the distinguished lithofacies are deposited on slope, depression, mound, fissure ridge and channel depositional environments. In addition, these main depositional environments are divided into subenvironments. As to isotope analysis made of some travertine samples, $d^{3}C$ and $d^{8}O$ values show a wide distribution. The $d^{13}C$ values are between 0.35%o and 6.70%o; $d^{18}O$ values are -6.47%o to -15.10 %o. Consequently, an isotopic grouping have been brought up based on lithofacies variation and depositional environments.

INTRODUCTION

The Denizli basin is an important region in sense of travertine formation both in Turkey and the world. A part from modern Pamukkale travertines where a lot of tourists visit every year, there are extensive travertine masses at different parts of the basin, especially along the northern margin (fig. 1). The total area occupied by modern and old travertines is more than 100 km^2 in the basin and their thickness is up to 60 m (fig. 2). Some of the old travertines have been quarriying by marble industry for a long time.

Travertines are limestones that form where hot ground waters, rich in calcium and bicarbonate, emerge at springs (Guo and Riding, 1998). CO_2 outgassing causes rapid travertine precipitation. Travertines have a complex internal architecture frequently changing both in lateral and vertical directions in short distance. This complexity is originated from many factors such as spring position, underlying topography, chemical composition of travertine depositing waters, organic activity and surfacial waters. Recently, there are increase in the studies made on geochemistry, morphological types, macro- and' microorganic components, stable isotope variations and dating of travertines both in Turkey and the world (i.e. Chafetz and Folk-1984; Pentecost and Tortora, 1989; Guo and Riding, 1998, 1999; Guo et al.,1996; Srdoc et al., 1989, 1994). Most of the studies made on the Denizli travertines are generally focused on Pamukkale and related to hydrogeology of the hot waters, geothermal potential, wasting and conversation. (Koçak, 1971; Şentürk et al., 1971; Canik, 1978; Eşder and Yılmazer, 1991; Gökgöz, 1994; Gökgöz and Filiz, 1998; Ekmekçi et al., 1995). Some studies have been subjected the stratigraphical position of travertines in the basin, dating, morphological classification, relations between travertine and neotectonics-seismicity of the region (Altunel and Hancock, 1993 *a,b* and Altunel, 1996), travertine geochemisty and physico-mechanical features (Demirkıran and Çalapkulu, 2001 and Özpınar et al., 2001). In the previous works, depositional features (lithotypes, facies, etc.), organic and inorganic components, petrography of the travertines have not been sufficiently investigated. Phototrophic microorganisms, their distribution and influence on the travertine deposition investigated by Pentecost et al. (1997) are only confined modern Pamukkale travertines. Aim of this study is to describe the different lithofacies of recent and old travertines in the basin context, according to field and petrographical features and to determine environments where the lithofacies have precipitated. In addition, some stable isotope variations were studied.

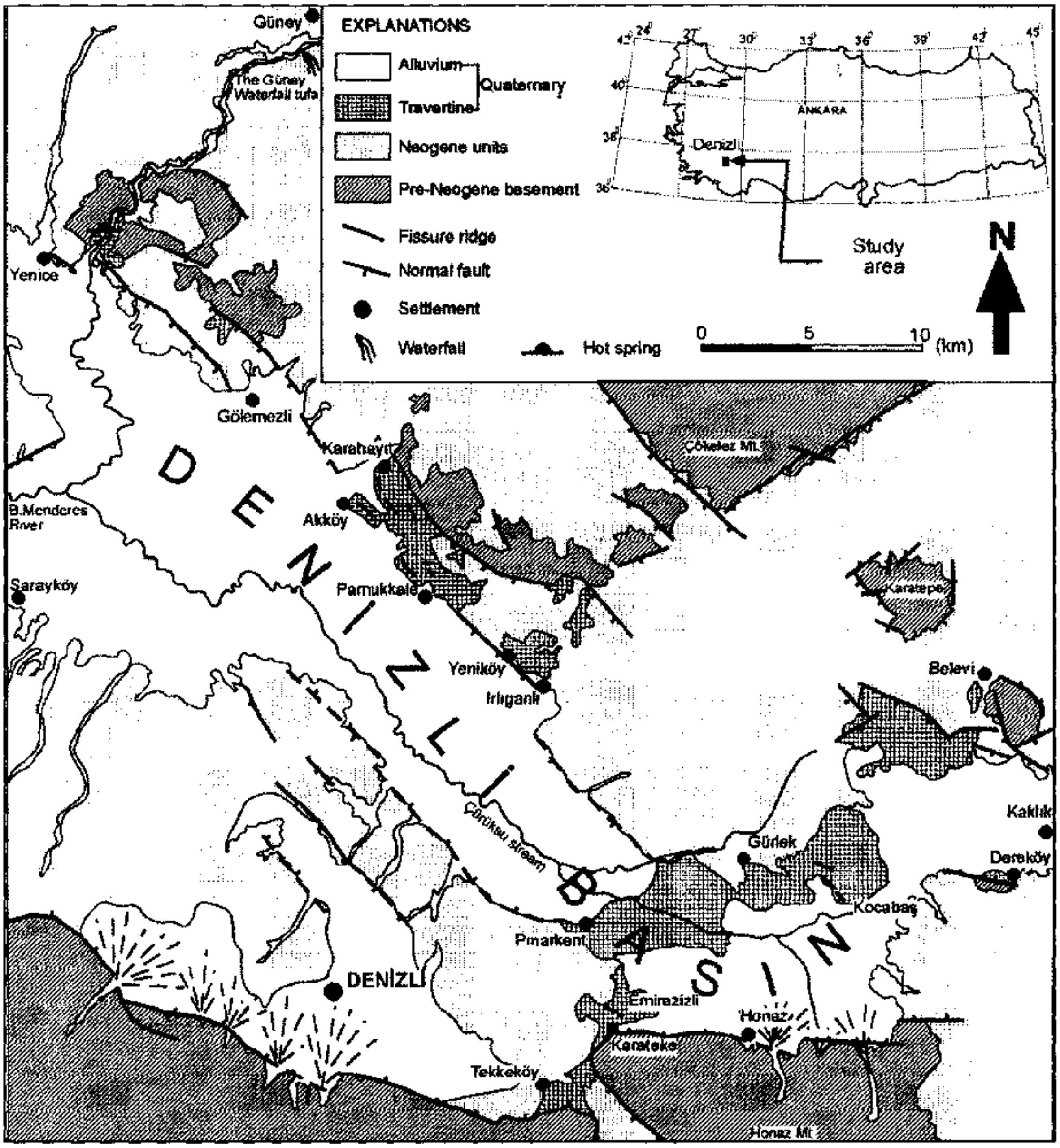

Fig. 1- Simplified geological map of the Denizli basin and distribution of main travertine masses (modified from Sun, 1990).

GEOLOGICAL SETTING

The depression 50 km long, 25 km wide located at the eastern end of junction locality where Büyük Menderes and Gediz grabens was named as Denizli basin (Westaway, 1990, 1993). Pre-Neogene basement rocks of the basin that crop out at the horst areas are consisted of metamorp-hic rocks of Menderes massif represented schist, marble and allochthonous Mesozoic carbonates and ophiolites and Paleogene limestone, dolomite and evaporites. The basin filled by Neogene-Quaternary deposits was bounded by normal faults both in the north and south margins (Fig. 1). The Neogene sequence, which are deposited lake and river environments and Late Miocene (Meotian-Pontian) in age (as ascribed by Taner, 2001), exposes commonly at the basin margins and some uplifted areas in the middle. The basin extends in NE-SW direction. According to Westaway (1993), the extension has begun in the Middle Miocene (ca 14 Ma. ago). Travertine masses in the Denizli basin have deposited where dip-slip normal fault segments display step over along strike (Çakır, 1999). The spring waters take required ions from the basement carbonate rocks for the travertine accumulation. The travertines deposited by emerging waters along the extentional fissures and normal faults rest on the Neogene sediments. Travertines at the quarries to the northwest of Kaklık (Fig. 1) are transitional in lateral and vertical directions with greenish gray, cream-coloured lake-marsh deposits, reddish-brown coloured alluvium, palaeosol and coarse-grained ephemeral river sediments (Fig. 2). Travertines in this region have gained a stepped structure from north to south by normal faulting series. Nevertheless, age of first travertine accumulation in the basin have not been clarified yet, the oldest travertines at Pamukkale are at least 400.000 years in age, as pointed out by Altunel (1996). During our study, some vertebrata teeth and jaws were found at the travertine quarries to the northwest of Kaklık. By the preliminary description, it has been found out that these vertebrata bones belong to Equus, who is an ancestor of modern horse in Quaternary (Ş. Şen and G. Saraç, 2001; personal communication).

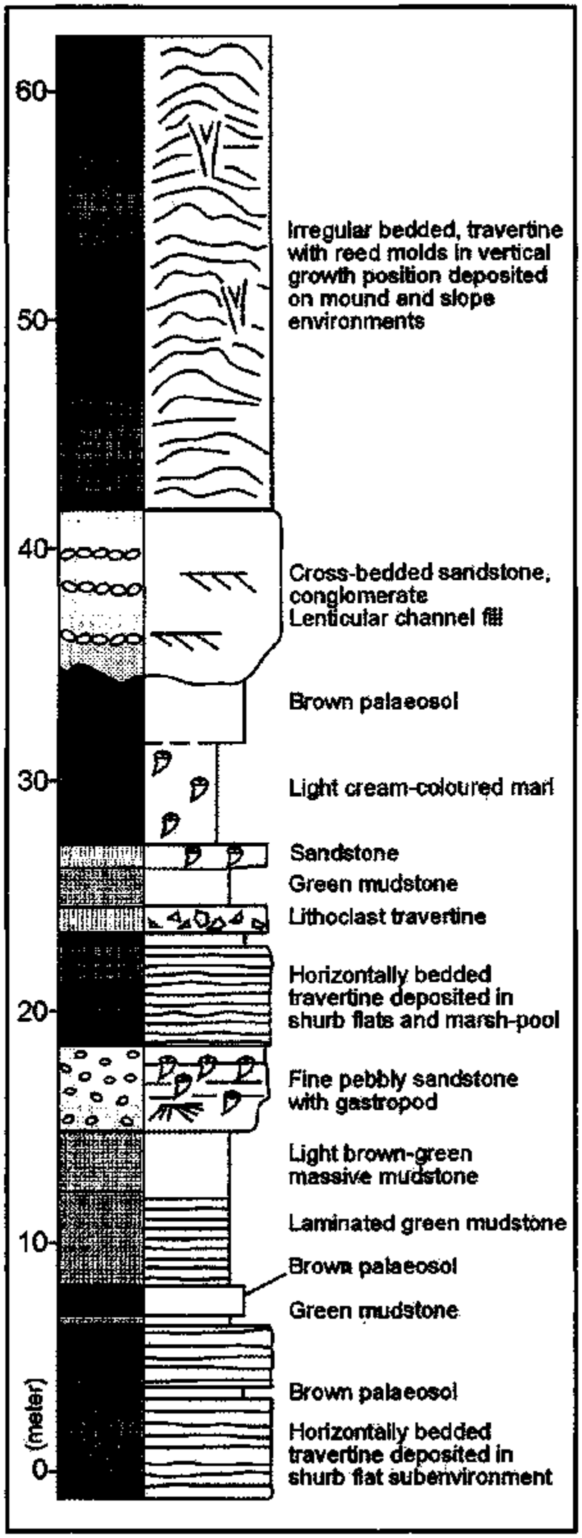

Fig. 2- Measured stratigraphical section at travertines located at the northwest Kaklık (The İlik quarry, southern slope of the Killiktepe).

METHODS

Samples are collected from the different travertine lithofacies, by investigating the field properties. SEM analysis of the collected samples were made by using Jeol JSM-840 type electron microscope in the Turkish Petroleum Corporation Laboratuary, Ankara. In order to perform that, polished surfaces of the rock samples were etched by %5 HCl during 3-5 seconds and than coated by gold in a vacuum system, the images were taken. Stable isotope analyses were made at the Isotope Laboratory of Tubingen University.

PETROGRAPHY OF THE DENİZLİ TRAVERTINES

Travertines precipitated at different depositional conditions display variations of colour, appearance, bedding, porosity, texture, and composition. In this study, different travertine precipitates in the Denizli basin were separated into the lithofacies based on field scale and petrographical features of the samples taken from each lithofacies were investigated.

Mainly travertine lithofacies: 1)Crystalline crust, 2) Shrub, 3) Pisolith, 4), Paper-thin raft, 5) Coated gas bubble, 6) Reed, 7) Lithoclast and 8) Pebbly travertine. Paleosol horizons (9) are formations that point out erosion and nondeposition periods and frequently coincided with travertine sequences.

1) Crystalline crust travertine lithofacies

Crystalline crust travertines (Guo and Riding, 1992, 1998) commonly form as a result of rapid precipitation from fast flowing waters on smooth slope, rims and vertical walls of terrace pools, cliff surface of waterfall subenvironments and in extensional fissures (fig. 3). Crystalline crusts are commonly dense, crudely fibrous, light-coloured, consisting of elongated calcite feathers, developed perpendicular to the depositional surface. The crystalline crusts change from a few centimeters to meter in thickness. The outer crust surfaces are usually ornamented by microterrace pools.

Previously, the vertical crystalline crusts developed in the extensional fissure ridges at Pamukkale were named as banded travertines by Altunel and Hancock (1993a) and Altunel (1996). Crystals in the banded structure are perpendicular to the vertical fissure walls of which depositional surfaces. By reason of that, the banded travertines precipitated along the vertical walls of extensional fissures (Plate I, fig. 1) also have been accepted as crystalline crust travertines in this study. These vertical banded crusts filling the fissure space display slower and entirely inorganic precipitation by degassing of CO_2. Crusts at the Kamara hot spring in the Büyük Menderes valley to the northwest of the Denizli basin and at Karahayıt near Pamukkale are consisted of alternation of white, red, and brown colour layers due to high iron content of the hot spring waters. Guo and Riding (1998) determined that old crystalline crusts were compact and hard, but when young, as at Terme San Giovanni, near Rapolano Terme, Italy, they can be delicate and easily crushed.

In the microscopic appearances, it is seen that micrit and sparit laminae are alternated (Plate I, fig. 2). The micritic laminae commonly are dark-coloured and in millimetric scale. In dark micritic laminae, the solution pores have developed in places. The sparite laminae, which are centimeter and decimeter in scale, may contain iron of various ratio. The spar crystals have grown radially on the micritic basement and organised as bundles in some places. Better development of one side of the crystals gives a cedar tree appearance (Plate I, fig. 3) (Folk et al., 1985). These crystals that are 10 micron in width and 100-200 micron in lenght are distinguished with the smooth crystal boundaries from each others. In addition to unfractured crystals, fractured pieces are also fairly abundant. The fractured crystals are seen as a fill of the interspaces or randomly distributed in a micritic floor (Plate II, fig.1, 2). In SEM images, calcite crystals forming the crust display blade edge like appearances (Plate II, fig.1, 2).

Due to high flow velocity of water, the crystalline crust develops where biogenic activity is limited (Guo and Riding, 1998). Formation of the radial calcite crystals is a result of direct crystallization from hot water. Any trace reflecting the microbial activity is not coincided with the microscopic appearances of the samples. The alternation of light and dark layers have been interpreted as diurnal variation near spring area (Folk et al., 1985; Guo and Riding, 1998).

2) Shrub travertine lithofacies

Travertines represented by small bush-like growths are common deposites on horizontal-subhorizontal surfaces (Chafetz and Folk, 1984; Guo and Riding, 1994, 1998 and Chafetz and Guidry, 1999). They are bounded by the micritic layers from both bottom and top. The shrup lithofacies is the most common one in the Denizli travertines. Individual shrub layers in the macro samples are light cream-coloured, 3-16 mm in thickness and seen as irregular horizons (Plate I, fig. 4).

Under the microscope, they are composed of the crystal associations of spar and micrite organized in different ways. In general, there is not a clear boundary between two kinds of crystal shapes. In thin sections, prepared perpendicular to the bedding, the spaces among the dark-coloured micritic shrub forms that expand upward were filled by secondary spar calcite mosaic (Plate I, fig. 5). Whereas, in the thin sections, parallel or slightly oblique to the bedding, dark micritic clumps in the sparite constitute a mottled texture as islands or patches. The densely and loosely packed micritic fields can be separated in the shrub samples. Completely micritic fields are observed where the shrub forms have densely packed. The densely packed shrubs consist of euhedral and subhedral crystals, 5-10 urn in size, without having any internal architecture. These have been commonly found in the shrub formations in mixed with spar crystals.

Loosely packed micrites, in the form of thin levels in places, comprise abundant diatome (Plate III, fig. 1). The micritic clumps are very common in the mottled texture and form the structures resembling bubble and pustule (Plate III, fig. 8). The cloudy micrites have developed on the spar crystals. They compose of the micritic grains that are 5-15 urn in size and wholly unhedral. In addition, the rod-shaped micrite crystals and calcified tubes are found within them (Plate II, fig. 3). The spar crytals followed in the form of residue under the micritic clumps support that those areas have become sparmicritization. Kahle (1977) has described this event as micritization forming by dissolution-crystallization in spar crystals from the way of biotic and abiotic. In the samples, the bacterial flaments that is widely seen in the fields where the sparmicritization is present, supporting the micrite has a biogenic origin.

According to Guo and Riding (1994, 1998), shrub forms are ordinary components of terrace pools, but the shrubs in layers are the most common and the thickest lithofacies of shrub flats (shallow, extensive pools) and subsequently marsh-like environments in depressions and on low angle slopes (fig. 3). In the studied travertines, the shrubs display transitions to the crystalline crust, reed, paper-thin raft and irregular radial pisoliths (bacterially mediated). According to Chafetz and Folk (1984), shrub layers represent growing season (spring-summer), whereas micritic layers represent the non-growing season (winter). Bacterial shrubs formed from heated waters, i.e., water temperatures were above ambient water temperatures for a region (Chafetz and Guidry, 1999). For this reason, shrub forms are not observed in cool water travertines (=tufas). Abiotic origin was also proposed for shrubs (Pentecost, 1990). This kind of shrubs display needle crystal shrubs' of Guo and Riding (1994) and 'crystal shrubs' and 'ray crystal shrubs' of Chafetz and Guidry (1999).

3) Pisolith travertine lithofacies

Coated grains as pisoliths are common in travertines. (Chafetz and Meredith, 1983; Folk and Chafetz, 1983 and Guo and Riding, 1998). Pisoliths form in small terrace pools of the steep slopes, and wide pools in depression fields (fig. 3). In addition, pisoliths were found in the self-built channels of Pamukkale during this study. Pisoliths occurred in the wide pools are generally associated with shrub form and micritic carbonate. Grain shape ranges from spherical to discoidal, in control of water agitation and microbial activity (Folk and Chafetz, 1983). Previously, three types of pisoliths are distinguished based on texture: 1) Concentrically laminated (Folk and Chafetz, 1983), 2) Radial shrub (Folk and Chafetz, 1983) and 3) Stromatolitic mammilated(Guo, 1993).

First two types are observed in the Denizli travertines. Concentrically laminated pisoliths were originated from splashing and turbulent water in terrace pools and self-built channels. The grains size of spherical particles are up to a few cm (Plate I, fig. 6). Although their nuclei are always not clear, they have usually grown on a dark micritic nuclei. Crystals forming the nucleus are coarser (10-15 mm) than those in thin micritic layers of the pisolith microstructure (Plate III, fig. 6). The thin micritic layers that cover the radial calcite crystals are entirely ksenotopic, consisted of grains of 3-6 mm in size. There are interfaces that have restricted the growth in pisolith microstructure. The interfaces are microkarstification and dissolution structures that do not show lateral continuity (Plate III, fig. 2, 3) and also transform into a microstromatolitic structure in some places. The microkarstification and dissolution structures point out most probably desiccation periods in the terrace pools. Concentrically laminated pisoliths have been accepted to be inorganic (Folk and Chafetz, 1983).

4) Raft travertine lithofacies

The rafts are thin, delicate and brittle crystalline layers precipitated at the water surfaces of pools and main fissure apertures filled by hot waters of the travertine ridges (Plate I, fig., 7, 8). They are composed of calcite and/or aragonite crystals and their extend quietly limited, in meter scale. Present day rafts are going on to precipitate at the water surfaces of the pools located both on terraced steep slope and near the hot spring orifices at Pamukkale and Karahayıt respectively. Dense raft concentrations are commonly associated with coated gas bubbles at the Çukurbağ hot spring (Plate IV, fig. 8), of which temperature is 58°C. The colours of the rafts range from white to brown, based on chemical composition of the hot water. The horizontal rafts occurred in the main fissure of an old travertine ridge near the Kocabaş, village (Plate IV, fig. 7) are associated with lithoclasts and vertical crystalline crusts (Plate I, fig. 7). The old examples of the rafts are thickened a little due to secondary encrustation in early diagenetic stage, as exemplified by Guo and Riding (1998) from Rapolano Terme, Italy. Previously, the rafts are named as 'hot water ice' (Allen ve Day, 1935), 'calcite ice' (Bargar, 1978), 'calcite rafts' (Folk et al., 1985) and 'paper-thin rafts' (Guo and Riding, 1998). The Similar occurrences are also well known from cool water cave pools (Baker and Frostick, 1951; Black, 1953).

5) Coated bubble travertine lithofacies

The coated gas bubbles are common in depositional environments of travertine such as terrace pools and extensive equivalents in the depressions. The origin of the gas bubbles is microbiologic activity in the base sediments of the pools. They are mainly trapped beneath the paper-thin rafts, among the plants and in the crystals and preserved by rapidly coating by calcium carbonate. Therefore, the coated gas bubbles are usually observed together with the crystalline crust, raft (Plate I, fig. 8) and reed travertine lithofacies. The shape of the bubbles is spherical and oblate and their sizes range from millimeter to centimeter. Guo and Riding (1998) pointed out that some coated bubbles have gained a tubular appearance by joining each other. Chafetz and Folk (1984) have termed the coated bubbles as 'lithified bubbles' and 'foam rock'. Coated bubbles have a similar structure to that of paper-thin raft with an inner micritic layer and an outer (water side) veneer of euhedral, mainly aragonite crystals. The bimineralic wall structure has been attributed to variation in supersaturation level of the water (Chafetz et al., 1991 a).

6) Reed travertine lithofacies

Reed lithofacies are one of the prominent elements in the Denizli travertines deposited marsh-pool, mound and self-built channels. The travertines rich in molds of reed and coarse grass were named 'reed travertine' by Guo (1993) and Guo and Riding (1998). Reed, grass and similar water plant grow in distal areas where hot spring waters cool and dilute due to rain influence. The plant clusters obstacles the water flow and the roots stabilize the sediments and encrusted mostly by micritic carbonate. The remaining spaces from the plants were partly or entirely, filled by the same material. The cylindirical molds up to 2-3 cm wide. The calcite crystals of 20-150 mm that have form from space wall to the center are typical. The reed lithofacies is usually associated with the rafts. The reed travertine lithofacies are ordinary component of both marsh-like shallow depressions drying time to time and reed mound. The organic matter content and pore ratio of the reed travertine are much more than the others lithofacies. The lithofacies is seen at the upper levels of the quarries located to the northwest of Kaklık town.

7) Lithoclast travertine lithofacies

Lithoclasts are penecontemporaneous, angular to subangular travertine fragments in different size, by erosion of the upper slopes and collapse of waterfalls and terrace cliffs. The fragments derived from the slope are commonly light-coloured. The fragments are subsequently deposited at the lower slope and in the depressions. In addition, more locally, some fragments broken off from the upper part of fissure walls have fallen down into the fissure apertures (Plate I, fig. 7). The dark-coloured lithoclast interlayers in the horizontal travertines that have deposited in the shrub-flat and marsh-pool subenvironments of the depressions is 20-100 cm in thickness. This lithoclast interlayers show pedogenic alteration and caliche formation at the lower and upper parts. The brecciation, colour and texture variation are common in the lithoclast travertine lithofacies that has been observed locally.

8) Pebbly travertine lithofacies

Some travertines investigated in the Denizli basin contain sparse rounded pebbles of limestone, marble, chert, radiolarit and serpentinite. The pebbly travertines are seen around the antique tombs between Küçükdere and Irlıganlı villages and some quarry fields located to the northwest of Kaklık. In addition, they have been observed as dropped down pebbles into the fissure spaces of the ridges. These rounded pebbles in the travertines have probably derived by the ephemeral floodings from the basement units of Neogene and the older sedimentary rocks adjacent to the travertine depositional environments. The pebbly travertine lithofacies described here may be partly correlated with 'cemented rudites' recognized in the British travertines by Pentecost (1993).

9) Palaeosol lithofacies

Decrease in water supply and diversion in flow direction result rapid exposure of travertine surface to rain water, subaerial desiccation, biological activities and soil formation. Although palaesol formation is not directly a travertine lithofacies, closely related to the travertines precipitated especially in depressions and lower slopes. The palaesol interbeds in the Denizli travertines are frequently seen at the quarries to the northwest of Kaklık. In the sequence logged at one of these quarries, four different brown-coloured palaesol interbeds were separated ranging from 40 cm to 3 m in thickness (fig. 2). The bed thickness increases from the slope to the depressions. The each palaeosol bed has constituted a sequence boundary between the two travertines. The thickness of palaeosol is related to how long the travertine is exposed.

TRAVERTINE DEPOSITIONAL ENVIRONMENTS

The lithofacies described above have been represented in state of various combinations in different depositional environments. They are found mainly three depositional environments: 1) Slope depositional environment, 2) Depression depositional environment; 3) Mound depositional environments. This kind of classification was previously made at the Rapolano Terme hot spring travertines (Italy) by Guo and Riding (1998).

In addition to the three environments explained above, two additional main types of depositional environments were also defined in this study. One of them is fissure ridge formed by emerging hot waters along the extensional fractures and the other self-built channel called fourth and fifth depositional environment respectively.

1. Slope Depositional Environment

Slope depositional environment are divided into three subenvironment:

a) Terraced slope, b) Smooth slope and c) Waterfall.

a) Terraced slope subenvironment.- The most spectacular and present day examples of the slope environment are formed at Pamukkale (Plate IV, fig. 1). The terrace pools are developed on the slope morphology. The terraced slopes consist of vertical terrace walls, pools and rims confining the margins of the pools. The vertical terrace walls and rims are composed of crystalline crust lithofacies. Paper-thin rafts, pisoliths and coated gas bubbles are the additional lithofacies formed at the base of pools. The terrace pools occur on the prograding slope where waters flow turbulent.

b) Smooth slope subenvironment- The smooth slope forms where the slope dips are between 10-40°, on which the terrace pools have not developed. The recent smooth slope subenvironments at Pamukkale are transitional with terraced slope both in vertical and lateral direction (Plate IV, fig. 1). The dominant lithotype precipitating on the smooth slope is crystalline crust as seen on the walls and rims of the terrace pools. The thickness of crust is range from centimeter to a few decimeters. Feather crystals forming the crusts are perpendicular to the slope surface. Smooth slopes develop where waters usually flow in laminar. Thicker crystalline crusts represent rapid deposition under high flow rates whereas thinner crust precipitated by slower flow (Folk et al., 1985; Guo and Riding, 1998). But thin crystalline crusts were deposited by alternating with shrub layers on the low-angled slope where water supply and flow velocity are low. Thin lithoclast levels are even observed at lower parts of slope.

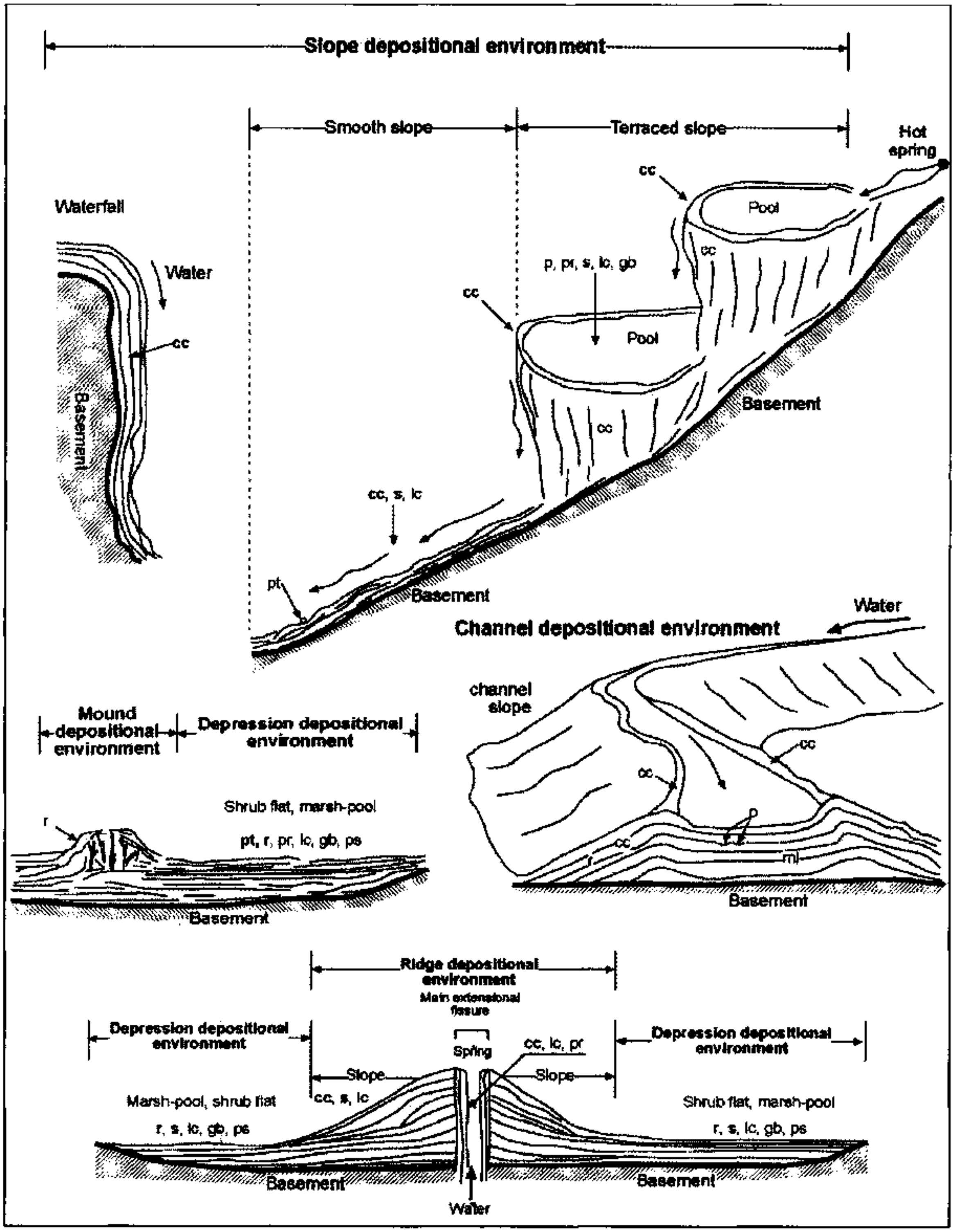

Fig.3 - Depositional environment and subenvironments of travertine lithofacies. cc: crystalline crust, s: shrub, p: pisolith, pr: paper-thin raft, gb: coated gas bubble, r: reed, lc: lithoclast, pt: pebbly travertine, ps: palaeosol, ml: micritic laminae, Bold letters indicate the dominant lithofacies.

c) Waterfall subenvironment- The waterfall subenvironment is much more local and restricted than the others. An active waterfall is located at the left slope of B. Menderes river valley, three kilometers south of Güney town in the northwest of Denizli (fig. 1). It is forming by cool spring waters of 16°-18°C. Therefore, these porous travertines are considered as tufa that calcium carbonate encrusts the plants. At the same locality there are inactive counterparts.

A second inactive example has been formed on the steep slope facing to the north of Keltepe, along a fault scarp, near Dereköy (fig. 1). The waterfall travertines are deposited on a vertical substrata, resembling an overhanged curtain (Plate IV, fig. 3). The overhanged deposits have been mainly composed of crystalline crusts. The waterfall travertines have been passed into the smooth slope at the lower altitudes in the time, towards north.

2- Depression depositional environment

These kinds of depositional environments have been introduced during the studies made on Rapolano Terme travertines locating south of Florence, Italy (Guo, 1993; Guo and Riding, 1998). They are flats and hallows in areas of relatively low topography and divided into two subenvironments: a) Shrub flat, b) Marsh-pool. The depression depositional environments are located in front of the slopes and around of the fissure ridges (Plate IV, fig. 8).

a) Shrub flat subenvironment- Shrub flats are subenvironments in which the horizontal and subhorizontal, travertines have deposited. The travertines deposited in these environments are light-coloured, thin-bedded laterally extensive and consist of mainly shrub lithofacies (Plate IV, Fig. 5,6). The shrub flat travertines comprise some lithoclast interbeds. Long-term erosion periods and short-term precipitation interruptions result palaeosols and desiccation surfaces respectively. In addition, red mudstones and conglomerates interpreted as products of floodjngs and ephemeral streams are associated with the shrub travertines (fig. 2). In the studied area, lower parts of the quarries in Belevi and northwestern of Kaklık (Killiktepe and just north of the Denizli Cement Factory) composed of the travertines of shrub flat subenvironments (Plate IV, fig. 4,5,6). Transitions from the shrub flats to marsh-pools subenvironments are represented by alternation of light and dark coloured layers in a travertine unit as seen on the wire-cut surfaces (Plate IV, fig. 6).

At the bottom of the Alimoğlu quarry located to the southern slope of the Killiktepe, a shrub flat travertine unit is up to 5 m thick. The thickness of 5 m at the north decreases to 2.5 m in distance of 90 m. In the same direction, the colour is become darker laterally. The unit are underlain by a brown palaesol bed and overlain by gray, green-coloured thin mudstone deposited in the marsh. In the other quarry near Alimoğlu, four different travertine units have been observed from the bottom to the top, which are precipitated in the shrub flat subenvironments (fig. 2). Their thicknesses change between 1.5 and 5 m.

b) Marsh-pool subenvironment. - Dominant rock types of the marshpool subenvironments are horizontal, gray, brown-coloured travertines that are rich in reed lithofacies. The marsh-pool deposits are interbedded with light-coloured travertines of the shrub flat subenvironments and transitional in lateral direction. They comprise lithoclastic interlayers and common pedogenic indications. Gastropod tests are locally abundant. The travertines near Kocabaş village deposited in the marsh-pool subenvironments of the depressions located around the fissure ridges have not been sufficiently consolidated yet. These are darker and more porous relative to the slope travertines. Therefore, we think that

Kocabaş mass is younger than the travertines at the quarries in the north, four km far from there.

On the other hand, these types of travertines that are widespread at the Honaz, Karateke, Pınarkent and Gürlek areas have formed a plateau stepped from the south to the north (fig. 1). The travertines of these areas are darker, more porous, rich in organic content, with high pedogenic effects and reed appearance in lithofacies and much more in tufa character. On the road cuts between the railway and the highway near Pınarkent, angular travertine lithoclats in different sizes eroded from southern part of the plateau were redeposited as colluvium on a slope surface of 25-30°.

3- Mound depositional environment

Reed mound depositional environment are those that the water plants densely located in depressions and near lower slopes. The travertines of this environments have been previously introduced as 'mound depositional system' and its reed mound fades by Guo and Riding (1998). In the studied area, travertines of the mound environments have developed in association with the horizontally bedded travertines of shrub flat and marsh-pool subenvironments belonging to the depressions, at the upper parts of the quarries both around Killiktepe and just north of the Denizli Cement Factory in the northwest of Kaklık (fig. 2). The most prominent deposits of the environment is reed travertine lithofacies. The reed clusters in the growth position expand upward. At the slopes of the mound, the beds dip away from the crest with angles of 10°-35°. The subsequent lithofacies such as micritic laminae, paper-thin rafts and coated gas bubbles are accompanied by the reed travertines. Some voids of the reeds were filled by micritic laminae and paper-thin rafts.

4- Fissure-ridge depositional environment

Fissure ridges (Bargar, 1978) are narrow linear mounds formed where hot spring waters emerge along a joint or fault on an elevation (Guo and Riding 1998). Fissure ridges entirely have diverse depositional morphology relative to the slope environments. In the Denizli basin, both active and inactive examples of the fissure ridges are observed (Altunel and Hancock, 1993a; Altunel, 1996; Çakır,1999; Özkul and Alçiçek, 2000; Özkul et al., 2001). The fissure ridges at Pamukkale and Kocabaş have been investigated earlier in neotectonic and seismic aspects (Altunel and Hancock, 1993 a, *b).* According to Çakır (1999), fissure ridges occurred along the northwest margin of the basin are preferentially developed at the ends of the normal fault segments or in step-over zones between them. The most fissures are parallel to the faults, but some are oblique. Although the ridges are located along the northwest margin of the basin, there are a few examples occurred near the southern margin and in central parts, as is well seen at the west end of the Honaz fault (Bozkuş et al., 2000) and around Kocabaş respectively. B. Menderes valley (near Yenice), Gölemezli, Pamukkale-Karahayıt, Akköy, Kocabaş and Honaz are main locations where the ridge morphologies are observed completely or partly, (fig. 1; Plate IV, fig. 7 and 8).

Both the Kamara ridge in the valley of Büyük Menderes river and the Kırmızısu fissure ridge near Karahayıt are active and all the others inactive. The ridges seen straight or sinuous in plan view are 100-1400 m long, up to 20 m high and 20-125 m wide at the base. The width of individual fissures is maximum in the middle and become narrow towards both terminations. Fissure width of east-west trending Kuşgölü ridge is 7 m in the middle, 5 m in the western end, at the northwest of Kocabaş village (Plate IV, fig. 7). Vertically banded crystalline crust lithofacies are precipitated on the walls of fisures that the hot waters emerge (Plate I, fig. 1), The crystalline crusts in some fissure fills are associated with coarse-grained lithoclasts and crystal rafts and coated gas bubbles (Plate I, fig. 7). The fissure space that the hot water does not emerge are filled by red palaesol, angular travertine lithoclasts, and gravels.

On the both slopes of the ridges, the bedded travertines are deposited in flanking away from the main ridge axes. The dips of the bedded travertines range from almost vertical to 5°. The terrace pools in macro- and microscales have been formed on some ridge slopes. The inclined travertine layers on the fissure slopes include almost all the travertine lithofacies. The most prominent lithofacies are micritic laminae, crystalline crust, shrub, rafts, and lithoclast. The lithoclasts have been resulted by both erosion of the upper slopes near the crest and repeating extensional fracturing in time. The inclined layers distally pass into the adjacent flats and depressions around the ridges (Plate IV, fig. 8). The facies in the fissure slopes rapidly changes in short distances, even a few meters. Rapid facies variations in short distance are typical feature for fissure ridges (Guo and Riding, 1999).

5- Self-built channel depositional environment

Self-built channels are linear travertine masses built up by spring waters in flow direction. Active and inactive examples of the channels are common in Pamukkale and around Kocabaş. The inactive channels are partly destroyed, eroded and collapsed in places due to human activities and natural processes, such as earthquake shaking, as seen in Pamukkale (Altunel, 1994). The channel formation are realized either by natural process or man-made for irrigation. Marginal slopes range from vertical to flanking surfaces. Morphologic and structural properties and distribution of them have been previously investigated by Altunel (1994) and Altunel and Hancock (1993a). They have sinuous shape in plan view and cut-cone or 'M'-shaped (term of Altunel and Hancock, 1993a) in cross section. The channel thalweg are restricted by rims from the both sides. The rims have developed along the points where precipitation is maximum, similar to those that in the terrace pools.

The self-built channels show lithofacies variations in a short distance as well as the fissure ridges and the terraced slopes. The channel thalweg grow as gradually upward in time by alternation of micritic laminae and crystalline crusts. The pisolith clumps observed in some hollows placed along the thalweg are formed by agitated water. At the same time, the channel slopes are developed in small scale on the both sides by overflowing and splashing water. The slopes are composed of inclined crystalline crusts, thin micritic layers and reed lithofacies. The combinations and the ratios of the lithofacies change from place to place along the channels.

STABLE ISOTOPES

Oxygen and carbon stable isotope analyses were performed on the nine samples of the Denizli travertines. $d^{3}C$ isotope values changes between 0.35 and 6.7 %o while $d^{18}O$ values varies from -6.47 to -15.10 %o (Table 1). Groundwater isotopic characteristics are modified in case of water emerging from spring. Main reasons of this event are intensity of depositional rate and kinetic effect that accompany to rapid degassing of CO_2 (Usdovski and Hoefs, 1990).

Both biotically induced geochemical processes such as photosynthesis and decreasing of temperature on during flow process, evaporation, mixing from soil profile or surface waters effect the variations of isotopic values (Chafetz et al., 1991b; Guo et al., 1996).

$d^{18}0$ %o PDB and SMOW with $d^{13}C$ %o PDB values of the travertine examples of Denizli basin and their bivariate distribution

Table 1- CaCO3, $\delta^{18}O$ and $\delta^{13}C$ (PDB) values of some samples taken from Denizli travertines

Sample No	Locality	Lithofacies	$CaCO_3$	$\delta^{13}C$% PDB	$\delta^{18}O$% PDB	$\delta^{18}O$ SMOW
D1	Kömürcüoğlu quarry	Shrub	100.00	0.35	-8.51	22.14
D2	Mayaş quarry	Crystalline crust	96.34	5.00	-15.10	15.34
D3	Kömürcüoğlu quarry	Shrub	100.00	0.51	-8.70	21.94
D4	Yenicekent	Crystalline crust	97.92	4.36	-13.58	16.92
D5	Kaklık Cave	Raft	96.00	1.87	-9.21	21.42
D6	Kocabaş prison	Reed	95.06	3.49	-7.95	22.71
D7	Ballık	Pisolith	99.29	2.04	-6.47	24.24
D8	Jandarma spring	Crystalline crust	94.60	6.70	-9.99	20.61
D9	Modern Travertien, Pamukkale	Crystalline crust	96.82	5.70	-11.18	19.39

show three different areas that indicate shrub+raft, pisolith+reed and crystalline crust (fig. 4).

The variations of stable isotope values in the lithofacies deposited within the different environments (i.e. smooth and terraced slopes, shrub flats and marsh-pools of depressions) under the various conditions

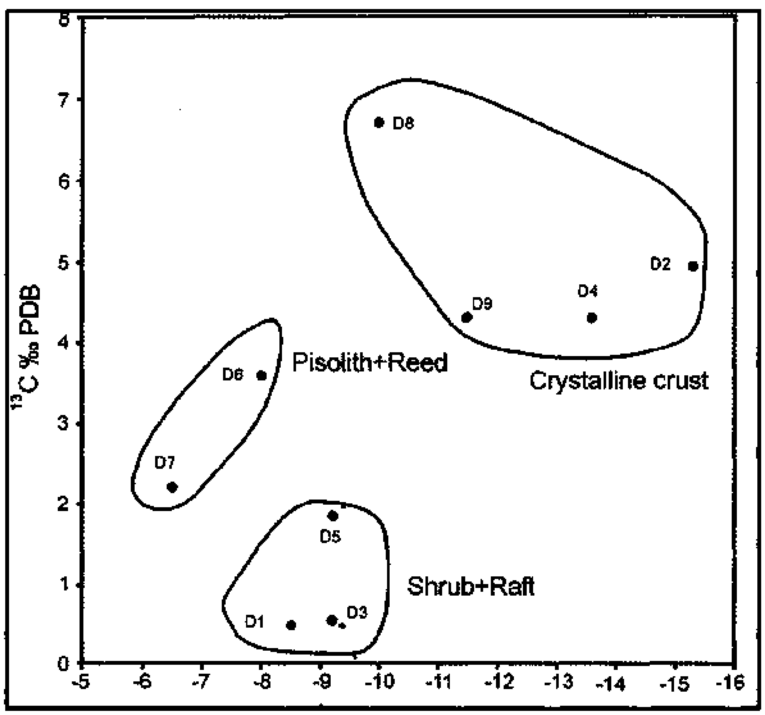

Fig. 4- Bivariate plot of $\delta^{18}O$ ‰ SMOW and $\delta^{13}C$ ‰ PDB values for the samples taken from the Denizli travertines (see Table 1).

(i.e. water temperature, flow velocity and distance from spring, surface area and biological effects) are possible. Isotopic fractionation at the thermal waters going away from the source cause a getting rich of $d^{13}C$ when removing of $d^{12}C$ together with continuously degassing of CO_2 from the thermal waters at the orifices (Chafetz et al., 1991b). Similarly, the increasing of microbiologic and photosynthetic activities in pools and depressions also result $d^{13}C$ enrichment of the system (Guo et al., 1996). All these data show that going away from the spring, travertines are enriched relatively in terms of $d^{13}C$. The same event is valid for $d^{18}O$ as well. Cooling of spring water in the flow direction and leaving of $d^{16}O$ from the system by evaporation increase $d^{18}O$ value. Linear relation of increasing of both these two isotopes in relation with distance of spring has been revealed in many studies on recent and fossil travertines (Chafetz and Lawrence, 1994; Guo et. al., 1996).

This linear relation could not be observed at the isotope values at the lithofacies representing the Denizli travertines. The $d^{13}C$ values of the shrub, raft and pisolith lithofacies, precipitated in the pools and flats away from the springs, display a distinct decrease unexpectedly (Table 1), although the expected increase of $d^{18}O$ values has been appearantly realized.

CONCLUSIONS

Conclusions inferred in the study are as follows:

1- Hot water travertines of the Denizli basin have been separated into lithofacies in field scale. These are: Crystalline Crust, Shrub, Pisolith, Paper-Thin Rafts, Coated Gas Bubbles, Reed, Lithoclast, Pebbly Travertine and Paleosol Horizons. Petrographical investigations (including SEM studies) have also been made on the representative samples taken from each lithofacies.

2- The travertine lithofacies are found in different rates in the depositional environments. The crystalline crust lithofacies are seen commonly on the smooth slopes, rims of the terrace pools, vertical surfaces of the waterfall subenvironments and in extensional fissures of the travertine ridges. The light-coloured shrub lithofacies is the most common and typical component in the shrub flats of the depressions and comprises abundant diatome and bacterial filaments.

3- The dark-coloured reed travertines are particular to the reed mounds and marsh-pool subenvironments in the depressions. The reed travertines are the second order lithofacies in widespread, in related to the shrub travertines. Pisolith, Paper-Thin Raft, Coated Gas Bubble, Lithoclast and Pebbly Travertine Lithofacies are the local and restricted occurrences. The solution cavities and microkarstic features seen in a pisolith inner structure reflect more probably desiccation periods in the terrace pools where pisoliths formed.

4- The Travertines in the study area are mainly precipitated on the slope, depression, fissure ridge, mound and self-built channel environments. The slopes and the depressions are divided into smooth, terraced and shrub flat and marsh-pool subenvironments, respectively. Transitions in the vertical directions have been observed usually from the depression to slope or mound depositional environments.

5- The travertine precipitation in the depressions have been ceased by palaeosol formations, green mudstones and marl beds deposited in the marsh and shallow lakes.

6- According to the stable isotope analysis of the travertine samples, the values of $d^{13}C$ and $d^{18}O$ changes between 0.35 to 6.7 %o and -6.47 to -15.10 %o, respectively. When $d^{18}O$ %o PDB and SMOW and $d^{13}C$ %o PDB values are intersected with each other, the clumping occurrences in three different fields represent shrub+raft, pisolith+reed and crystalline crust lithofacies. Such a isotopic clumping supports that the travertines have precipitated in different depositional conditions and environments. $d^{13}C$ values are unexpectedly low in the travertine lithofacies that characterize the pools and stagnant water conditions. This statement means that the biologic induce of the $CaCO_3$ precipitation in the environment have not been enough effective enough.

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PLATES

PLATE - 1

Fig. 1 - Light-coloured, vertical crystalline crust (cc) filled in a extensional fissure. Light and dark coloured travertines on the right are deposited in the shrub flat (sf) and marsh-pool (mp) subenvironments respectively. Kocabaş village, the Fidan travertine quarry. Marker as scale =13 cm

Fig. 2 - Thin section views of white, fibrous crystalline crust (cc) developed perpendicular to depositional surface and dark micritic interlayers (m).

Fig. 3 - Thin section view of the crystalline crust. Better development of one side of the clump of the calcite crystals display a cedar three appearance.

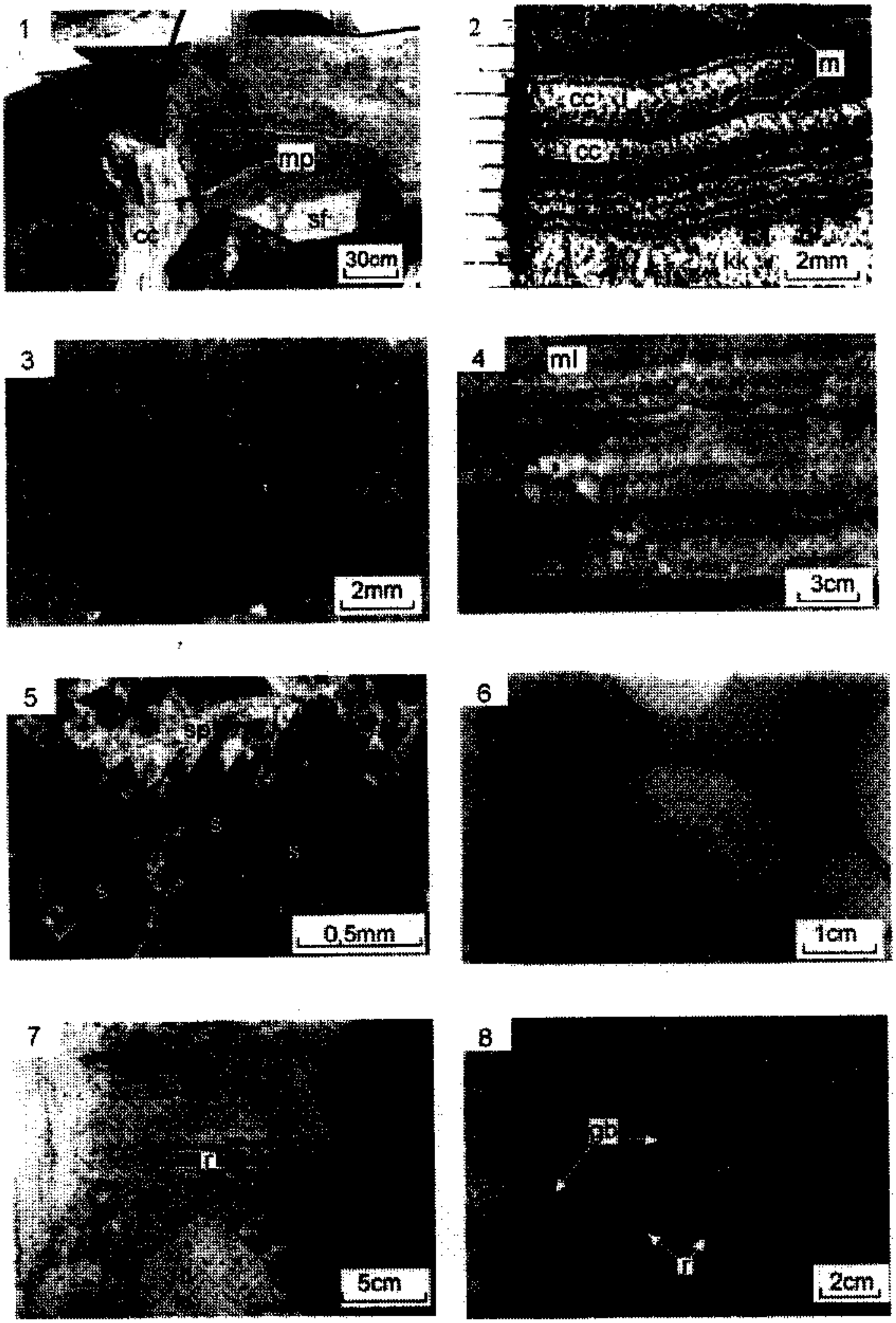
Fig. 4 - Light-coloured, dendritic shrub layers (s) expanding upward in the growth position and dark micritic laminae (ml). The wire-cut surface, the Ece subquarry, south of Belevi village.

Fig. 5 - Thin section views of dark and micritic shrub forms (s) expanding and branching upward in the growth position. The peripheral voids between the shrubs are filled by sparite (sp).

Fig. 6 - Pisolith travertine. Thin section views of the pisolith grains composed of smooth concentric laminae.

Fig. 7- Paper-thin raft (r) travertine laminae precipitated in the space of an extensional fissure and the lithoclasts travertine (lt) dropped down into fissure space. The Kuşgölü fissure ridge hot spring travertines, northwest of Kocabaş village.

Fig. 8 - Modern paper-thin raft (r) and coated gas bubbles (gb) formed together. The Çukurbağ hot spring, Pamukkale.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cc
mp
sf
30cm
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m
cc
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kk
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2mm
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ml
3cm
5
0,5mm
6
1cm
7
5cm
8
2cm

PLATE - II

Fig. 1, 2- SEM photomicrographs of smooth-edged, elongated calcite crystals (Fig. 1) and crushed crystalline crust (cc) in a micritic ground (Fig. 2).

Fig. 3- SEM photomicrographs of micrites (m) developed on the relics of spar crystals (sp), due to spar-micritization and calcified bacterial filaments (bf) at the upper left corner.

Fig. 4- SEM photomicrographs of alternation of the micrite interlayers (shown by rows) and calcite layers with radial growth in a pisolith grain. Microsolution pore (mp) on the upper right was filled by light coloured, secondary lime mud (lm).

Fig. 5, 6, 7- SEM photomicrographs of euhedral-subhedral spar crystals growing on the micritic ground. Rhombic edges of the crystals are preserved as seen in Fig. 7 or partly fractured or rounded (Fig. 6 and 7).

Fig. 8- Radial calcite crystals (cc) developed perpendicular to micritic ground (m).

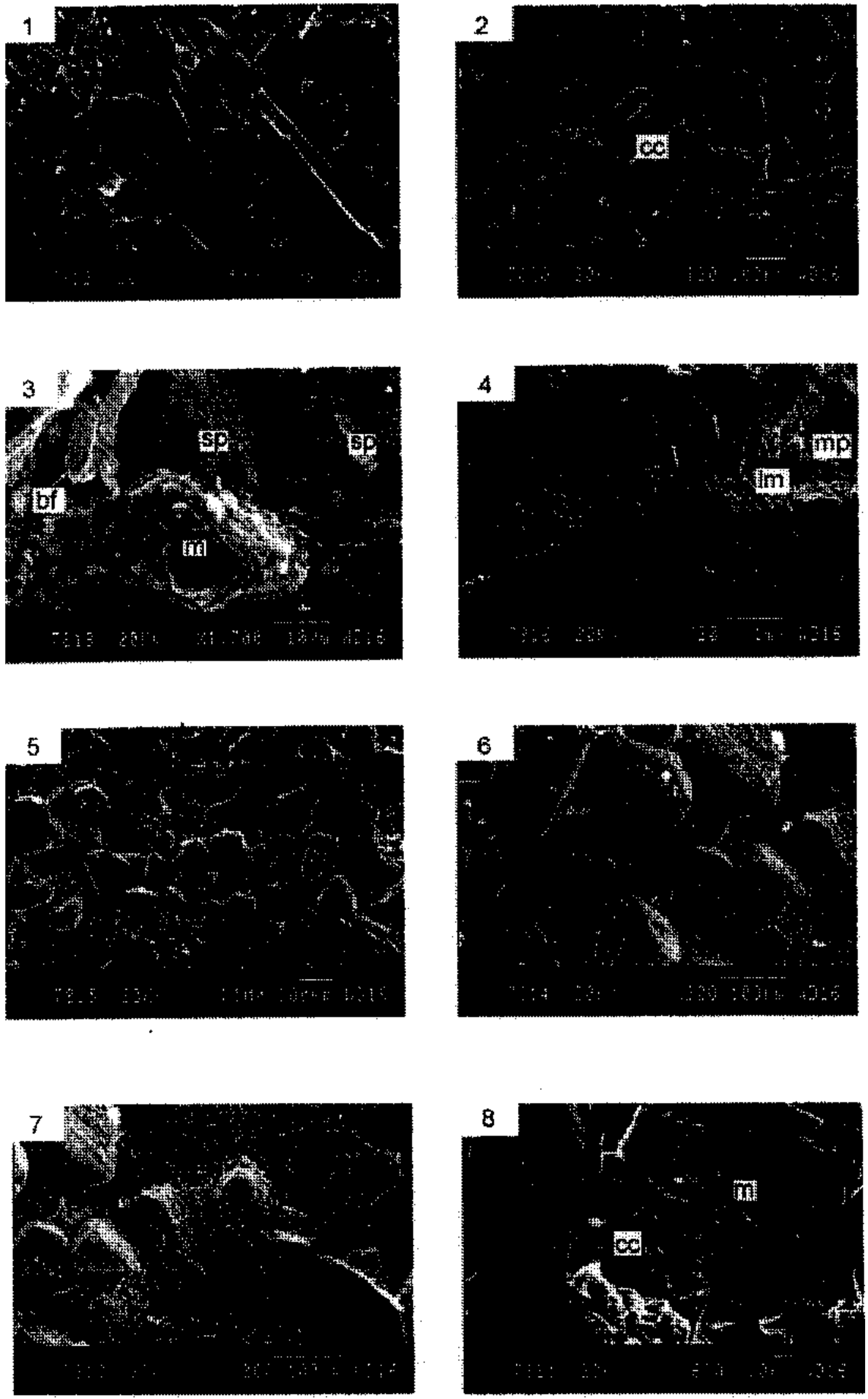

1
2
cc
3
sp
sp
bf
4
mp
lm
5
6
7
8
cc

PLATE - III

Fig. 1- SEM photomicrograph of diatome relics (d) on a micritic ground of the dark coloured travertines precipitated in a marsh-pool subenvironment.

Fig. 2- SEM photomicrograph of microkarstification (mk) in internal structure of a pisolith grain and microstromatolith structure.

Fig. 3- SEM photomicrograph of close up view of a pore resulting from microkarstification between pisolith interlayers.

Fig. 4- SEM photomicrograph showing radial calcite (rc) crystals covered by thin micritic interlayers (ml) in a pisolith structure.

Fig. 5- SEM photomicrograph showing calcite crystals with radial/feathery growth in a pisolith structure.

Fig. 6- SEM photomicrograph showing the aggregate composed of ksenohedral coarser micritic grains (mg) in the nucleus of a pisolith.

Fig. 7- SEM photomicrograph showing the euhedral spar crystals as a pore fill.

Fig. 8- SEM photomicrograph showing probably bacteria-induced structure in the micritic levels of the travertines.

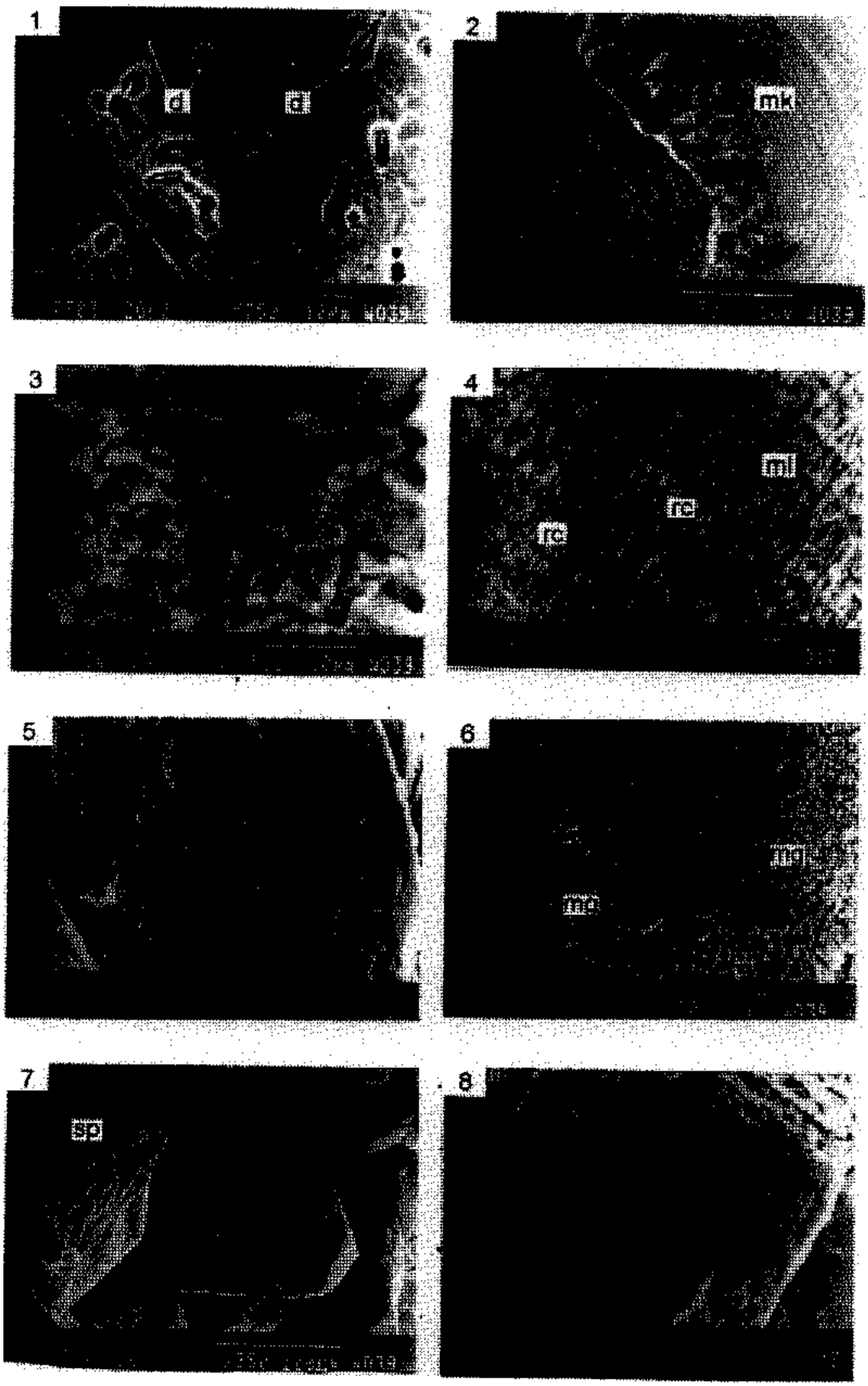

1
d
d
2
mk
3
4
ml
rc
rc
5
6
7
sp
8

PLATE - IV

Fig. 1- Smooth and terraced slope subenvironments of a slope depositional environment at recent Pamukkale travertines. ss= smooth slope, ts= terraced slope.

Fig. 2- Microterrace pools developing on a vertical wall. The Kırmızısu hot spring, Karahayıt, Scale: Marker=13 cm.

Fig. 3- Vertical travertines deposited a waterfall subenvironment resembling an overhanged curtain (ohc) and composed of mainly crystalline crust lithofacies, The northern slope of Keltepe, near Dereköy village.

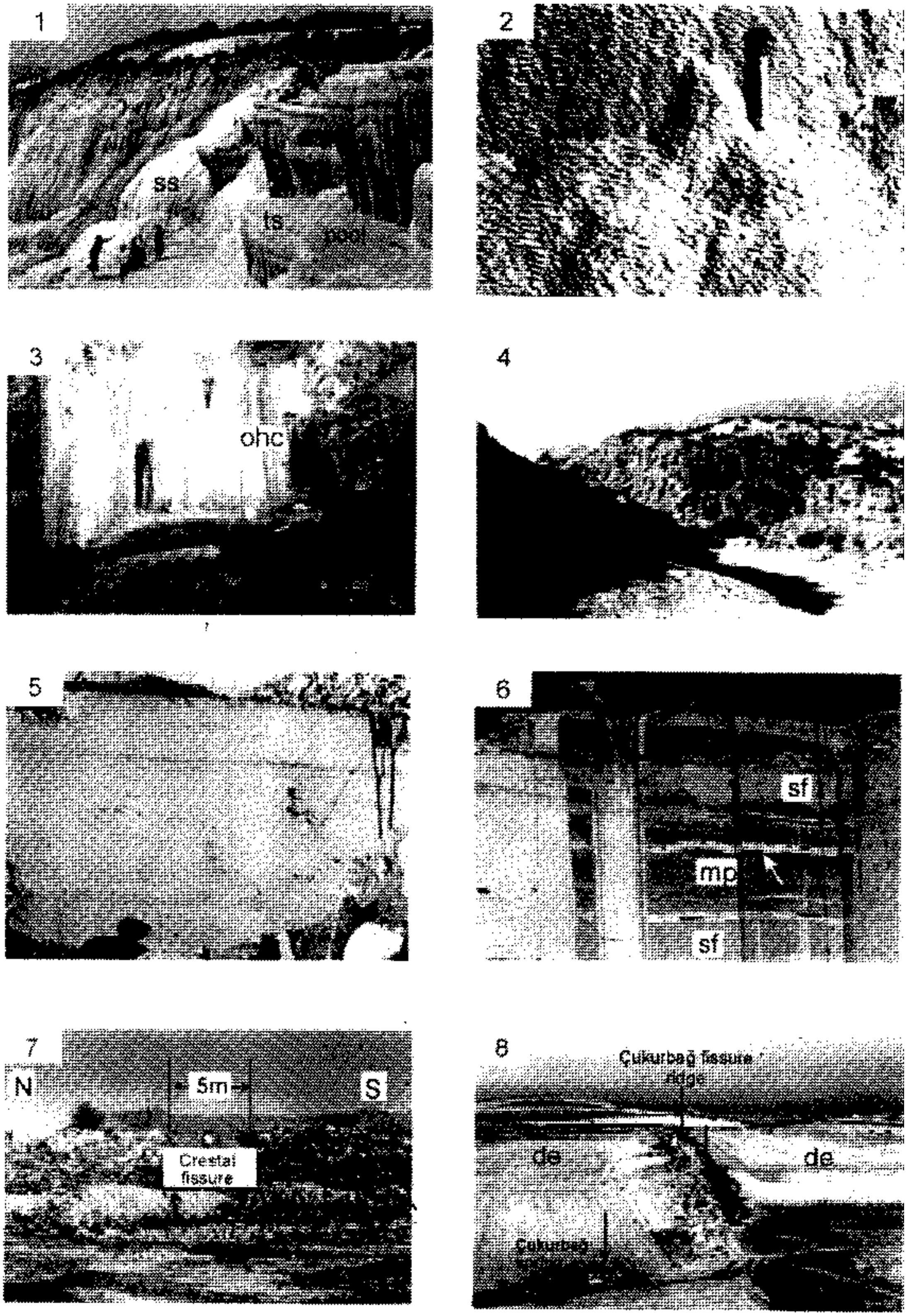
Fig. 4- General view of bedded travertines deposited in shrub and marsh-pool subenvironments of depressional fields. Emek guarry, Kocadüz locality, northwest of the Denizli Cement Factory.

Fig. 5- Horizantal bedded, light coloured travertine deposited a shrub subenvironment, wire-cut surface, the İlik quarry, southern slope of Killiktepe, northwest of Kaklık.

Fig. 6- Horizontal, light coloured shrub flat (sf) and dark colured marsh-pool (mp) travertines deposited in the depressional field neighbouring a fissure ridge and stratified layers of white crystalline crust lithofacies (arrowed).

Fig. 7- The view of the Kuşgölü fissure ridge from the west. E-W trending main fissure at the west part of the ridge is 5 m in thickness.

Fig. 8- North-west trending the Çukurbağ fissure ridge (arrowed in the middle) and adjacent depressional deposition environments (de) with low topography lying on the each sides of the ridge. The Çukurbag thermal spring located at the southern end of the ridge (arrowed in the lower left), Pamukkale.


1
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ts
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2
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ohc
4
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6
sf
mp
sf
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N
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S
Crestal
fissure
8
Çukurbağ fissure
ridge
de
de
Çukurbağ