GENESIS OF TEPEES IN THE QUATERNARY HARDPAN CALCRETES, MERSIN, S TURKEY

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ABSTRACT: In the Mersin area, the calcretes are widespread and occur in a variety of forms. The upper surface of the hard laminated crust (hardpan calcrete) represents a distinctive surface morphology of dome-like or slightly elongated dome-like and rarely ridge-like morphologies. These antiformal surface morphologies are interpreted as calcrete-tepee structures. Their cross-sections appear as an upward buckled crust or surface undulation. Troughs are present between the dome-like morphologies, and rarely associated with vertical and subvertical fractures. Petrographic and stable isotope data suggest formation in a vadose zone under subaerial conditions. Semi-arid climatic conditions of Mediterranean type are favourable for calcrete development and furthermore for tepee formation in hardpan calcretes. Thermal and moisture related expansion and contraction seem to be the most likely mechanisms in formation of the calcrete tepees.

Keywords: hardpan calcrete, tepee-structure, pseudo-anticline, expansion, Quaternary, Turkey

INTRODUCTION

The study area is located in the Mersin region (Fig. 1), near the Mediterranean sea. In Mersin, calcretes are widespread and occur in a variety of forms from powdery to nodular to highly indurated laminar crust (hardpan calcrete) (Eren et al. 2004). Different calcrete forms are easily recognizable on the field. The hard laminated crust (hardpan) is a laterally continuous sheet which develop at or near the rock-air interface, and often covers the top of topographic highs in the area. The upper surface of the hard laminated crust has a distinctive surface morphology of dome-like or slightly elongated dome-like and rarely ridge-like morphologies. In this study, these antiformal surface morphologies are interpreted to be tepee structures. Tepees are a distictive sedimentary structure found mostly in modern and ancient peritidal deposits, and also in calcrete profiles and submarine hardgrounds (Assereto and Kendal 1977; Kendall and Warren 1987). In contrast to peritidal tepees, there is little information available concerning calcrete-related tepees. Tepees in calcretes have been reported under different names such as caliche tepees by Kendall and Warren (1987); pseudo-anticlines by Price (1925), Jenning and Sweeting (1961), Aristarain (1970), Watts (1977); caliche anticlines or expansion structures associated with buckle cracks by Revees 1970; and expansion structures by Bretz and Horberg (1949) and Giles et al. (1966). Two main types of tepee structure are recognized in calcrete profiles; (i) tepees associated with an indurated hardpan layer similar to our case, and (ii) tepees in pre-existing shale (Kendall and Warren 1987). This study describes tepees in calcretes in Turkey and discusses their origin.

TERMINALOGY AND METHODOLOGY

Calcrete, synonymous with caliche (Siesser 1973), is a near surface, terrestrial accumulation of predominantly calcium carbonate ($CaCO_3$), which occurs in a variety of forms on and/or within sedimentary rocks, sediments and soils (Wright and Tucker 1991; Goudie 1973; Watts 1980). Calcrete forms as a result of soil-forming processes (pedogenic calcrete; Watts 1980; Aristarain 1970) or ground-water evaporation (ground-water calcrete; Goudie 1973). Hard laminated crust (hardpan), syn. petrocalcic horizon, is an indurated horizon, sheet-like with a sharp upper surface and gradational lower surface, it typically has a complex internal fabric (Wright and Tucker 1991).

The term "tepee" was introduced by Adams and Frenzel (1950) describing antiformal sedimentary structures in carbonates (Assereto and Kendal 1977; Watts 1977). Its ideal form is characterized by sharply inverted V-shapes (Pratt 2002). The term "pseudo-anticline" describes any antiform structure formed by the expansion of indurated carbonate beds where the process and environment responsible for expansion cannot be established (Assereto and Kendall 1977).

This study is mainly based on field observations. During the field work, an area of approximately 140 square kilometres of the Mersin O 33-a4 sheet was mapped on a scale of 1: 25 000. Calcrete occurrences and upper surface morphologies of hardpan calcrete were described. The sizes of the dome-like structures were measured. Forty samples were collected from hardpan calcrete; then thin-sections were prepared and examined under an optical microscope. XRD analyses were performed on all the samples at the laboratory of the General Directorate of Mineral Research and Exploration (MTA), Ankara, Turkey. ICP-AES analyses were carried out at the ACME Analytical Laboratories Ltd., Vancouver, BC Canada to determine the chemical composition of selected samples. Stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) analyses were undertaken at the Southern Methodist University (SMU) laboratories, Dallas, TX, USA. All isotope data are reported in per mil (‰) with respect to the PDB Standard. SEM-EDX analyses were performed at the laboratory of the Middle East Technical University, Ankara, Turkey.

GEOLOGICAL SETTING

The study area is located on the western flank of the Adana Basin where Tertiary and Quaternary units are

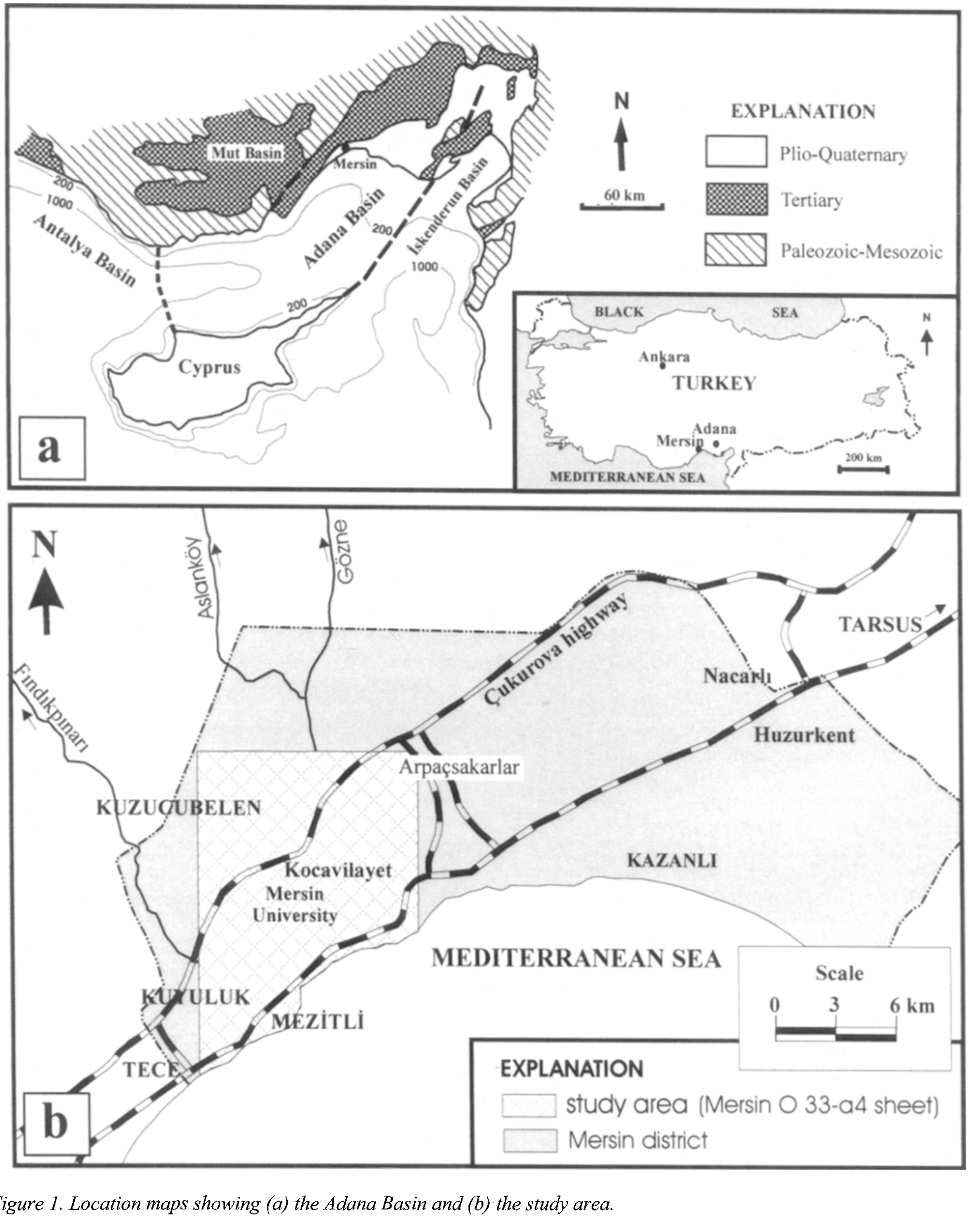

Figure 1. Location maps showing (a) the Adana Basin and (b) the study area.

present (Figs. 2 and 3). The Tertiary units comprise the Karaisalı Formation (Burdigalian-Early Serravalian), Güvenç Formation (Burdigalian-Serravalian), and Kuzgun Formation (Tortonian). The Karaisalı Formation is composed of grey coloured reefal limestone with abundant red algae and corals deposited on topographic highs in a shallow-marine environment. The Güvenç Formation starts with a grey to greenish-grey coloured mudstone-argillaceous limestone alternation at the bottom, and then continues with predominantly grey coloured marlstone

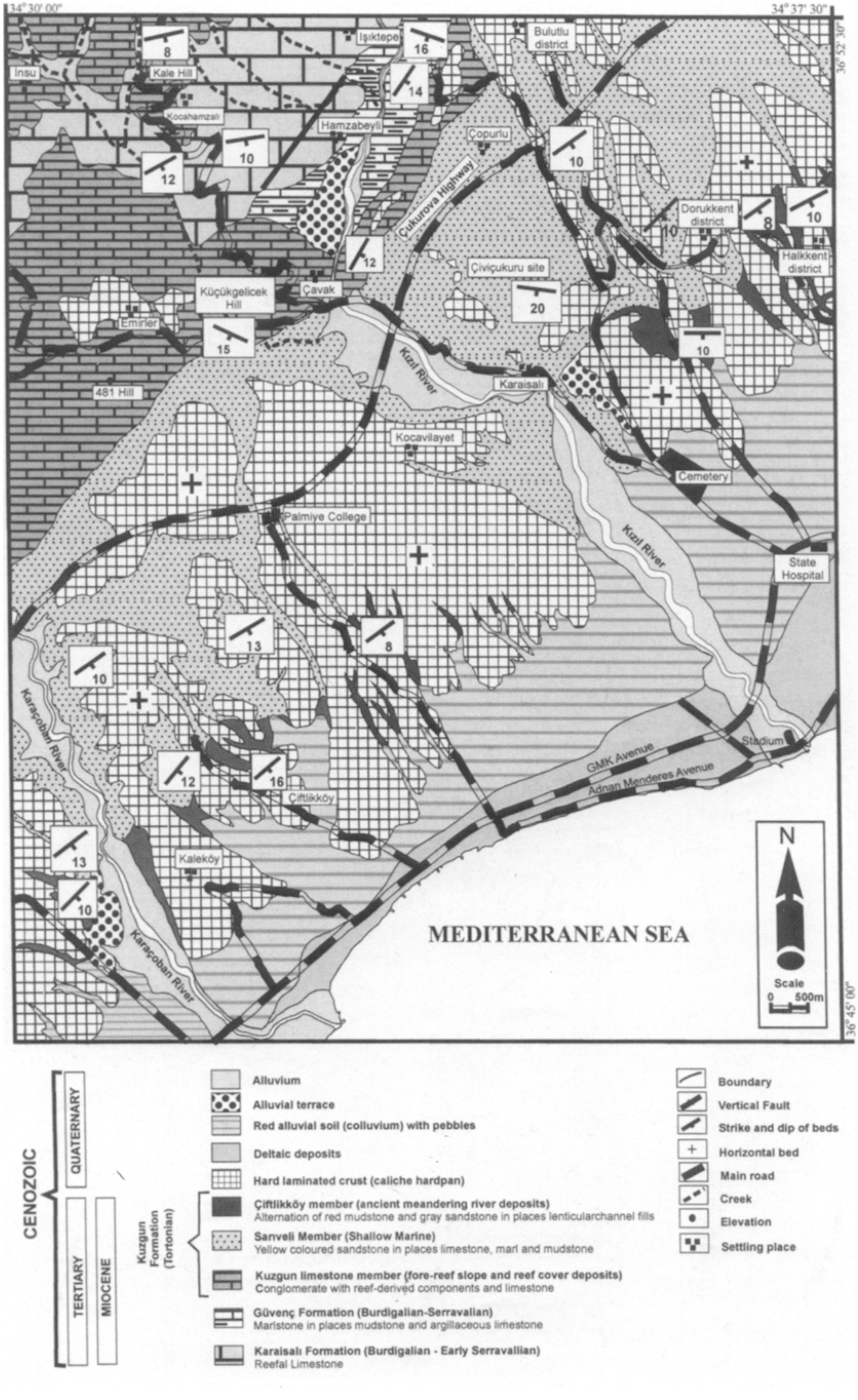

Figure 2. Geological map of the study area.

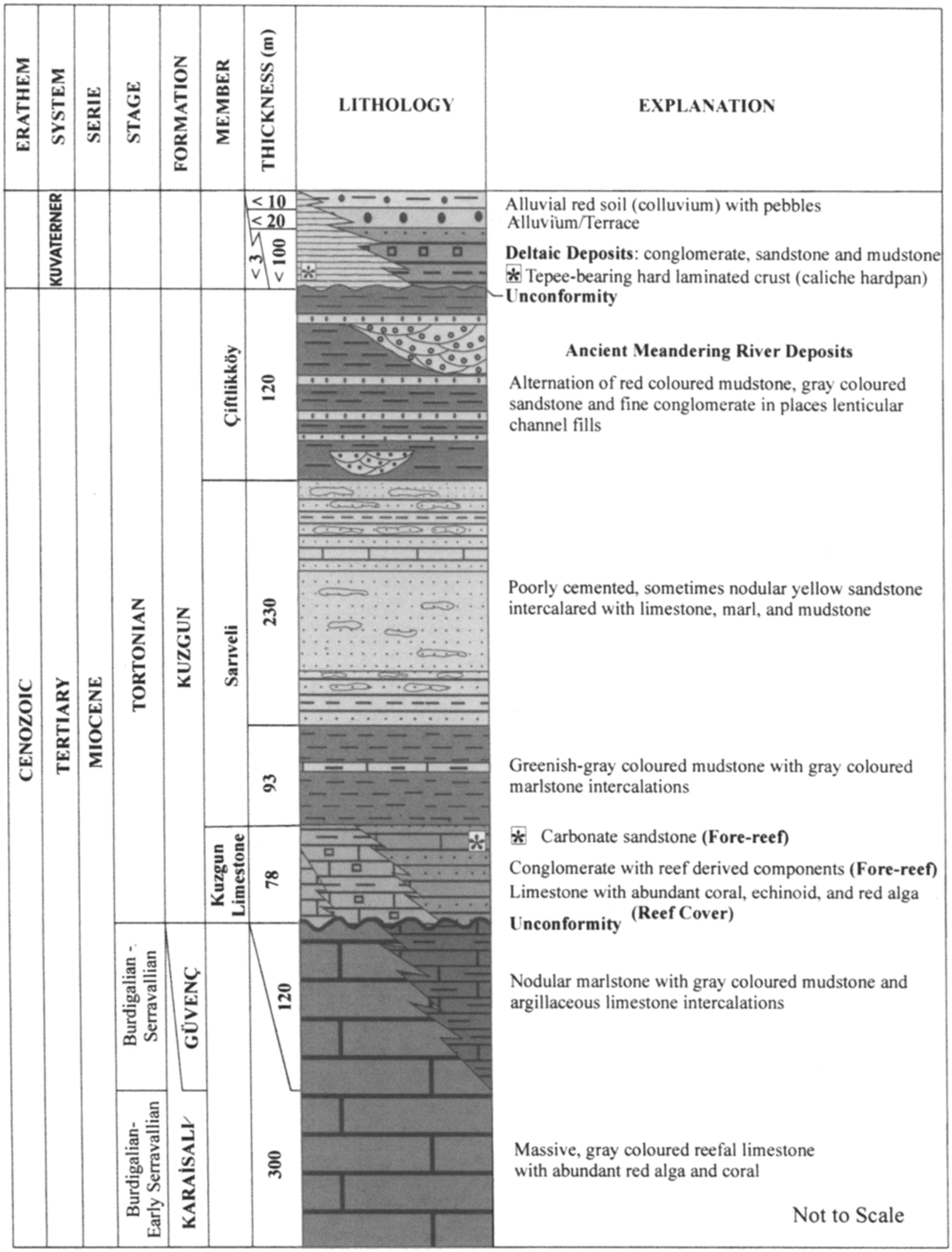

Figure 3. Generalized stratigraphic column for the study area.

with mudstone units. The formation contains various microfossils such as *Planorbulina* sp., *Quinqueloculina* sp., *Textularia* sp., *Amphistegina* sp., *Globigerina* sp., and *Globigerinatheka* sp. The benthic forms disappear in the middle and upper parts of the formation in contrast to planktic forms. The fossil content of the formation indicates deposition in relatively deep marine environment between the topographic highs. Therefore, the Karaisalı Formation represents a vertical and horizontal transition to the Güvenç Formation. The Kuzgun Formation is subdivided into three members; the Kuzgun limestone member comprising fore-reef slope deposits and reef cover sediments (coral-echinoid-red alga-bearing limestone), the Sarıveli member consisting of green coloured mudstone at the bottom then predominantly yellow coloured sandstone with yellow coloured mudstone units bearing marine fossils, and the Çiftlikköy member consisting of red coloured dominantly meandering river deposits. The Quaternary units are made of by hard laminated crust (hardpan calcrete), deltaic deposits, pebbly alluvial red soils (colluvium) and recent alluvium/terrace. Calcrete formation is widespread in and over the Kuzgun Formation and in the alluvial red soil.

CALCRETE TEPEES AND ASSOCIATED LITHOLOGY

Field Description

In the study area, tepees are associated with the hard laminated crust (hardpan calcrete) which occupies large areas (Fig. 2) and appears as a wavy crust on the small ridges and highs, forming a terrace-like morphology at a topographic height of 20 to 250 m. The hardpan calcrete covers the lithologically different beds of the Kuzgun Formation (Fig. 2) and also remains of alluvial materials in erosional troughs. It is typically a cream coloured, evenly discontinuous laminated, indurated, wavy horizon of calcium carbonate with an average thickness of 1 to 1.5 m. The carbonate crust has a sharp upper surface and gradational lower surface, passing down into isolotaded calcrete horizon. The upper surface commonly shows a dome-like morphology interpreted as a tepee structure or pseudo-anticline and wider troughs between the domes. Karstic surface structures such as rillenkarren, kamenitze and other karren forms are often seen on the dome-like morphologies.

The upper surface of the hardpan calcrete is composed of numerous dome-like or slightly elongated dome-like morphologies, called tepee structure in this study, which are clearly visible in the field (Fig. 4). Ridge-like tepee-morphologies are also present. In plan view, these antiformal

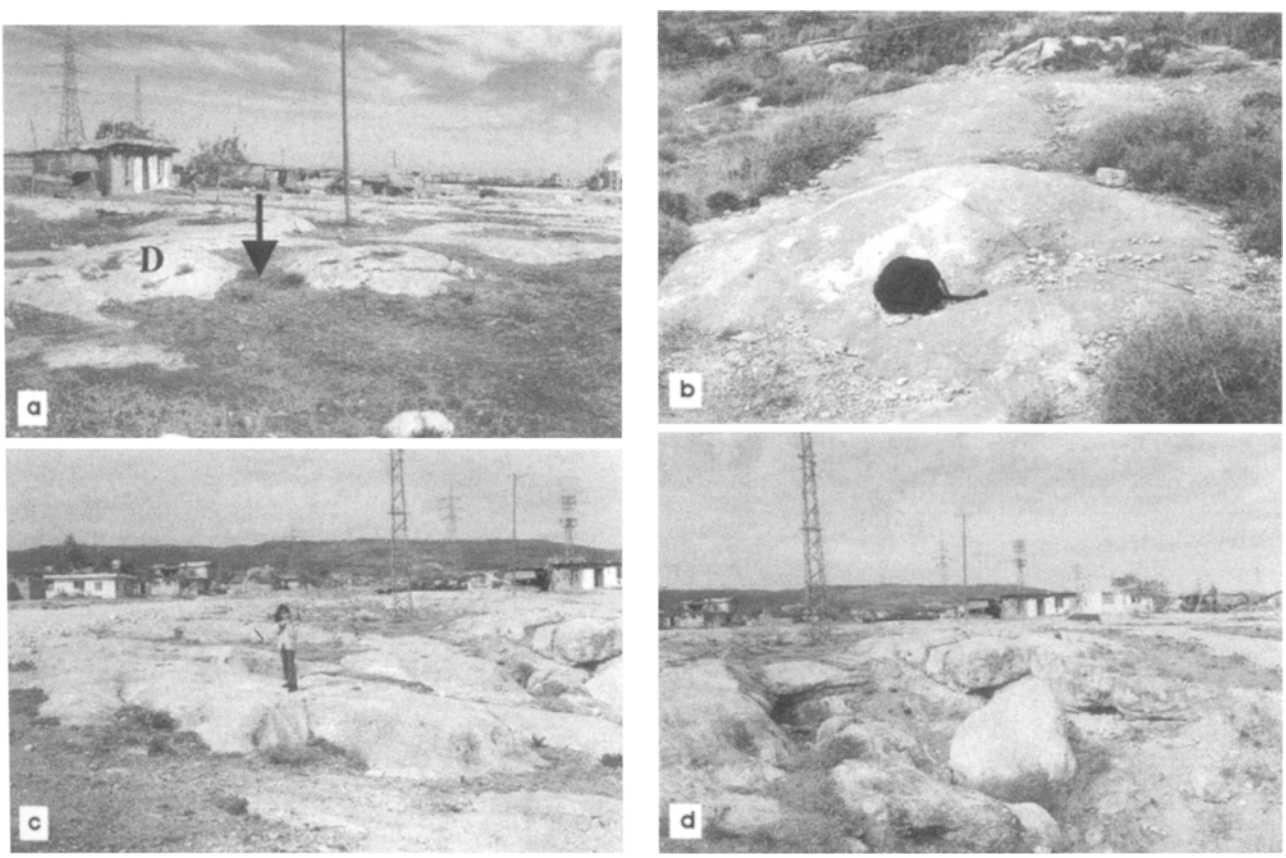

Figure 4. Field photographs of the calcrete tepees. a) Upper surface of the hard laminated crust (hardpan) showing dome-like morphologies (D) of tepees and troughs among them covered with red soil (arrow). b) Close view of dome-like morphologies. c) Dome-like morphology with flat-crest (child) and its roughly polygonal shape. d) Polygonal breakage of the antiform structures.

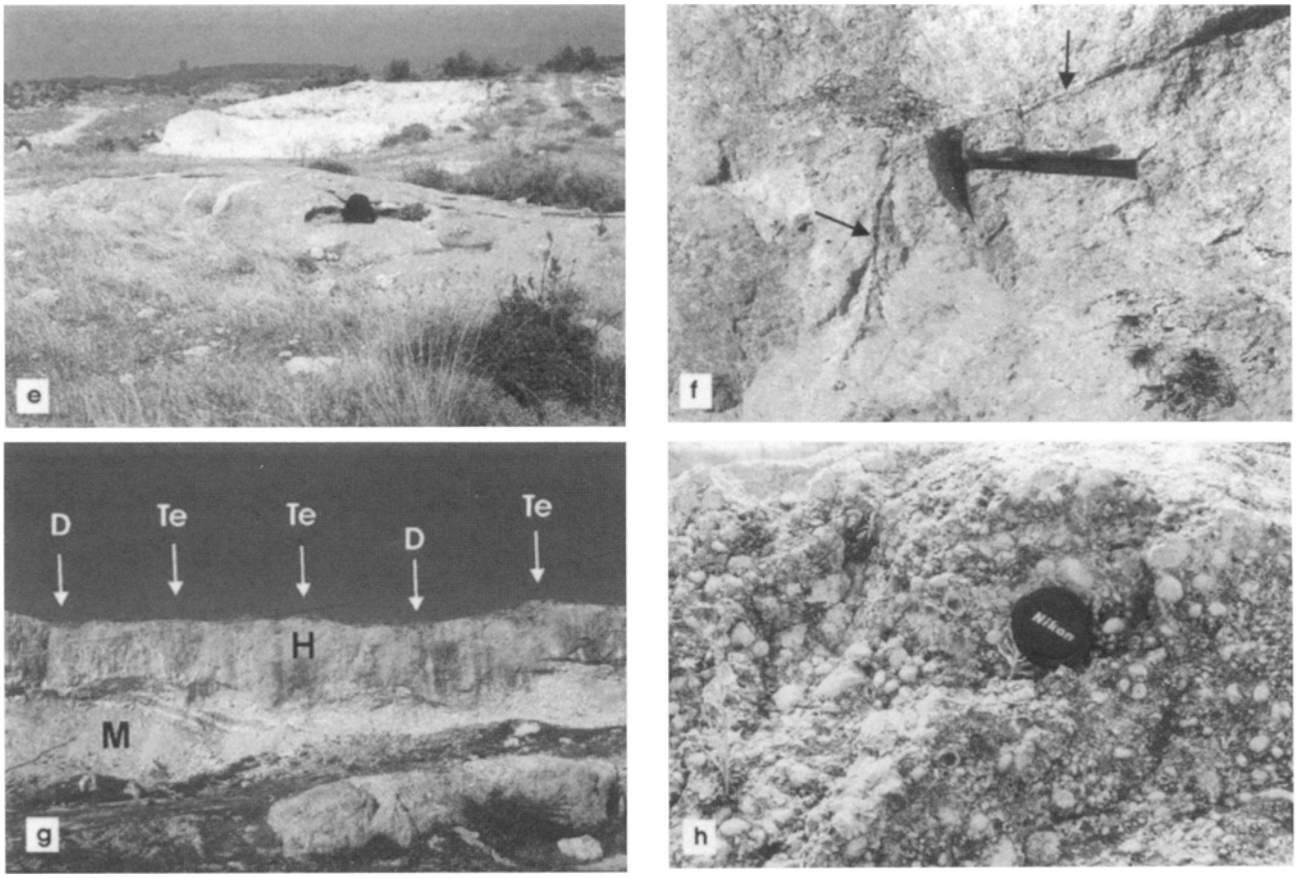

Figure 4 (continued). Field photographs of the calcrete tepees. e) Ridge-like morphology of the tepee-structure associated kamenitze (black bag). f) Polygonal fractures (arrows) with detrital sediment infill. g) Cross-sections of the dome-like morphologies showing an upward calcrete crust buckling (Te) and troughs (D) among them. H: hard laminated crust with wavy appearance; M: reddish to brown coloured mudstone (overbank deposits) including isolated caliche nodules (white mottlings). h) Poorly sorted and inversely graded pisolites in the pisolitic crust filling the a depresional area among the tepees.

structures show an irregular or roughly polygonal pattern and polygonal breakage. Some antiformal structures have flat crest. Uppermost parts of dome structures are usually eroded or have been disturbed by human activities such as agriculture, dwellings. The tepees have variable dimensions, but are mostly from 2 to 5 m in width, 3 to 8 m in length and 30 to 70 cm in height (Fig. 5). Their length to width ratio is rougly equal to 1 to1.5. The ridge-like morphologies are up to 27 m in length. The elongated morphologies do not show any orientation. Between the dome-like morphologies wider depressional areas are present. At the Taşlıseki site, a pisolitic crust occurs within the troughs between the domes. In these troughs, vertical or subvertical fractures are rarely observed within the polygonal pattern, and are infilled by either oxidized calcite or sediment.

In cross-section, the hard laminated crust has a wavy appearance due to tepee formation. The tepees appear as an upward buckled crust or surface undulations, and troughs occur between them (Fig. 4 g). Beneath the troughs, vertical or subvertical fractures are rarely observed. Buckling cracks (horizontal cracks) and thrusts are rare. Some antiform structures grade downwards into the nodular to tubular calcrete horizon below.

Petrography

Petrographic and SEM data reveal that the the hard laminated crust (hardpan) consists predominantly of micrite and microsparite. The hardpan exhibits typical and diagnostic calcrete features such as wavy lamination, floating grains, circum-granular cracks, clotted texture, rhizoliths, alveolar texture, calcite needles, calcified filaments, spherulite-like microcodium, and vadose calcrete pisoliths (vadoids) (Fig. 6).

Geochemistry

The XRD analysis indicates that the tepee-bearing calcrete unit is mainly composed of calcite, associated with minor smectite and palygorskite, and also accessory quartz, feldspar, illite and dolomite. The ICP-AES analysis (Table

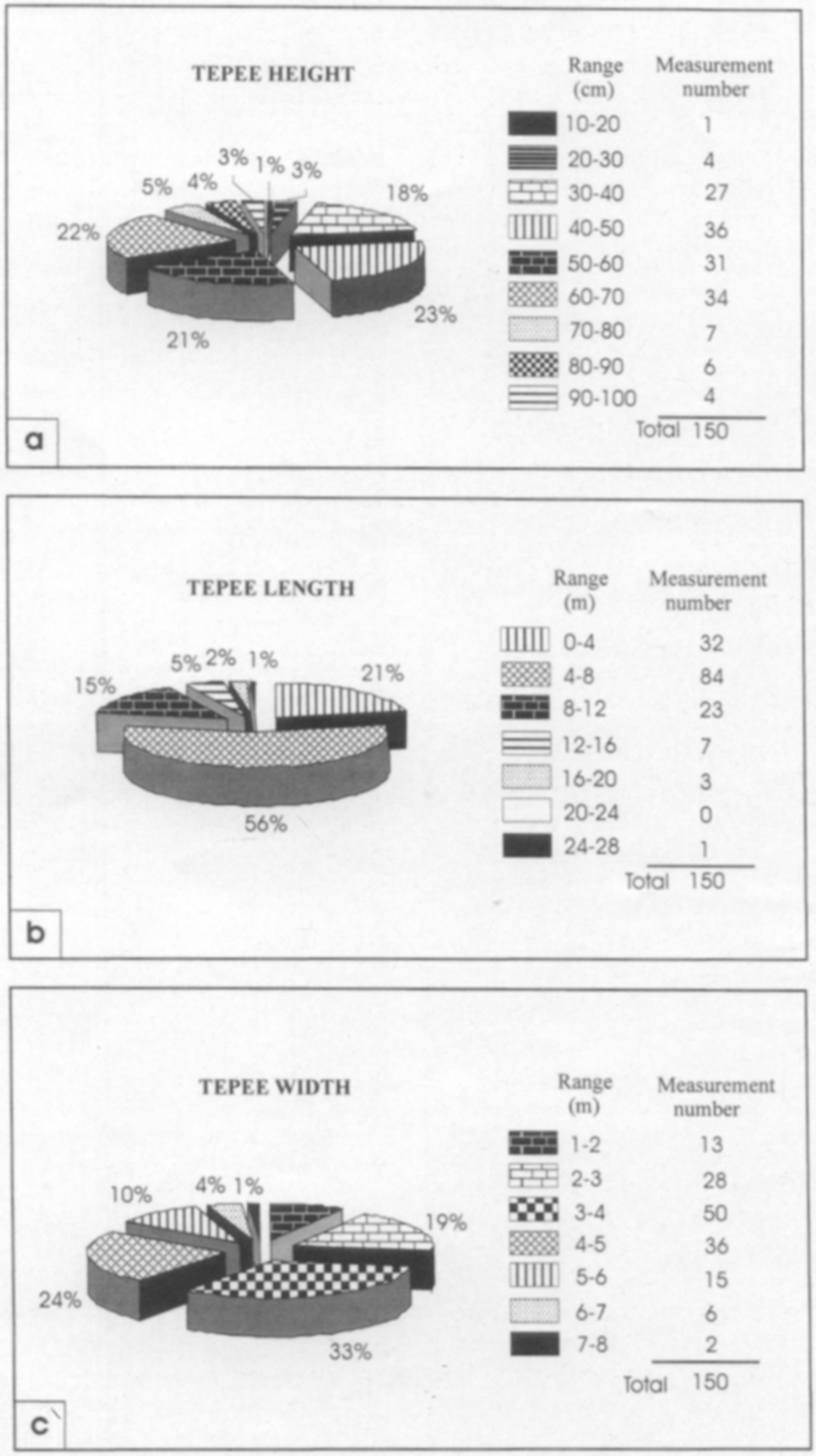

Figure 5. Pie diagrams representing tepee-size variations: (a) height, (b) length, and (c) width.

1) confirms the XRD results with high CaO content and small amounts of SiO_2 and Al_2O_3. Stable isotope analyses of calcrete samples show $\delta^{18}O$ and $\delta^{13}C$ values ranging – 4.89 to – 5.84 and - 8.49 to – 9.07 ‰ PDB, respectively (Table 2).

INTERPRETATION

Tepee structures are common in the hardpan calcrete which occupies large areas in the region and has a thickness of 1 to 1.5 m. XRD and ICP-AES analyses reveal that the tepee-bearing calcrete unit is composed mainly of calcite. The petrographic data indicate that the calcite is predominantly micrite and also microsparite. The $\delta^{18}O$ and $\delta^{13}C$ values are within the range of those commonly seen in pedogenic calcretes which differ from non-pedogenic calcretes with more negative $\delta^{13}C$ values (Fig. 7) (Manze and Brunnacker 1977; Salomons et al. 1978; Talma and Netterberg 1983; Purvis and Wright 1991; Strong et al. 1992; Achyuthan 2003; Alonso-Zarza and Arenas 2004). The $\delta^{18}O$ values reflect influence of meteoric water, and the more negative $\delta^{13}C$ values are indicative of strong addition of light CO_2 from soil-zone. The pedogenic origin is also confirmed by the presence of the biogenic structures (β fabric constituents) such as rhizoliths, alveolar texture, calcite needles, calcified filaments, spherulite-like microcodium, and vadose calcrete pisoliths. The petrographic data such as circum-granular cracks, alveolar texture, calcite needles and calcrete vadose pisoliths indicate formation in vadose zone for the hardpan calcrete and so also for the tepees. Tepees have mostly

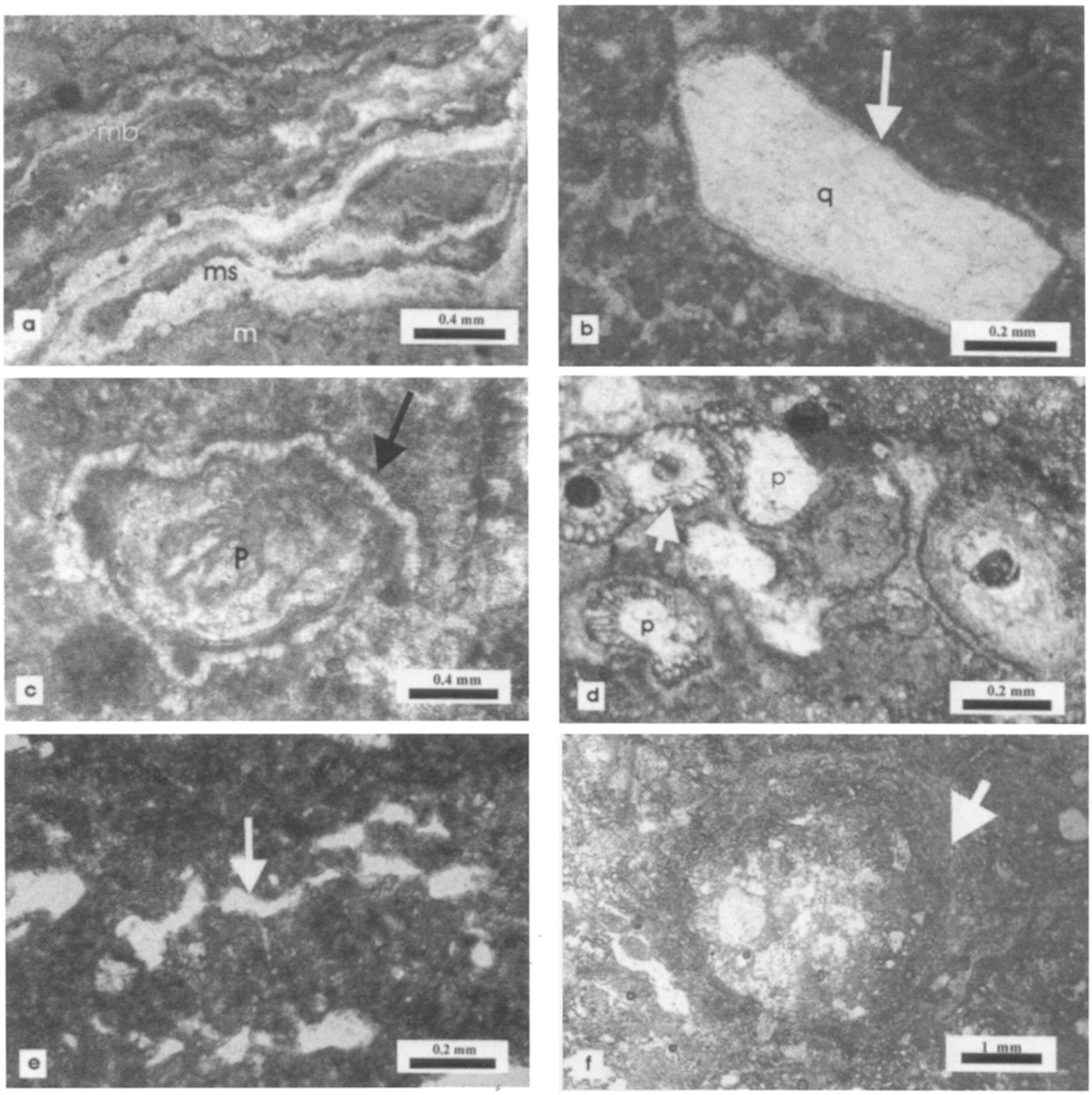

Figure 6. Micromorphological features of the caliche crust. a) Lamination in the hard laminated crust consisting of wavy micrite (m), microsparite/sparite (ms), and microbial (mb) laminae. b) Floating detrital grain (q) with microsparitic rim (arrow) in the pelletized micritic matrix. c) Circumgranular crack with sparry calcite infill (arrow) surrounding caliche pisolith (p). d) Rhizoliths (root-petrifaction) with cellular cortex structure (arrow) in an alveolar texture. p: pore. e) Fenestral cavities (arrow) in pelletized micritic matrix (clotted texture). f) Calcrete (vadose) pisolite (arrow) showing poorly laminated, microbial coatings and downward growing (pendant; right side).

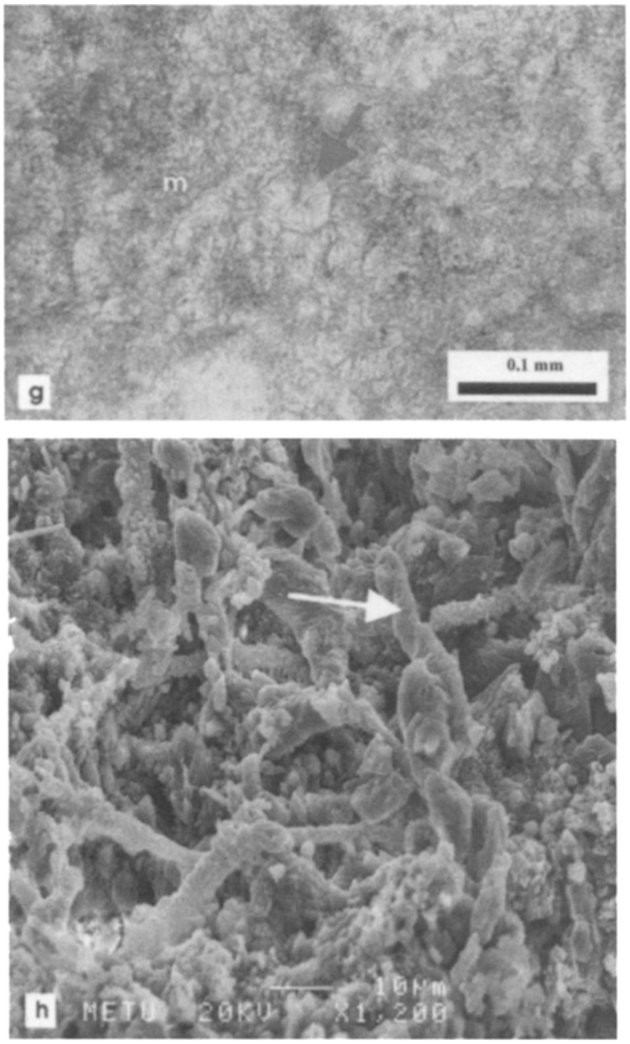

Figure 6 (continued). Micromorphological features of the caliche crust. g) Spherulite-like microcodium (arrow) consisting of radiating calcite prisms. Hard laminated crust. h) SEM image showing an irregular network of calcified filaments (arrow).

dome-like or slightly elongated dome-like morphologies in a metre-scale, and exhibit irregular to polygonal shapes and polygonal breakage. Their cross-sections indicate an upward buckling and rare thickening of the carbonate crust. The calcrete tepees in the region differ from those in peritidal carbonates in not exhibiting a network of saucer-like megapolygons with buckled margins (Burri et al. 1973; Assereto and Kendall 1977; Kendall and Warren 1987), whereas, calcrete tepees have a more inverted saucer-like form (see also Assereto and Kendall 1977, p. 191). The rough polygonal pattern is described by the outer boundary of the dome-like morphology which corresponds the troughs around the tepees, their breakage, and rare polygonal fractures. More convincing tepee structures with ideal triangular-shapes are not observed in the study area, and are extremely rare in the Adana region. The absence or scarcity of ideal tepee-forms, thrust structures and sheet cracks are due to the thickness of the deformed unit and

Table 1. Chemical composition of hard laminated crust samples.

sample no	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %	MnO %	Cr_2O_3 %	Ba ppm	Cu ppm	Zn ppm	Ni ppm	Co ppm	Sr ppm	Zr ppm	Ce ppm	Y ppm	Nb ppm	Sc ppm	Ta ppm	LOI %	SUM %
N-1	1.02	.05	.04	.35	54.17	<.01	<.02	<.01	.02	<.01	.002	67	<20	<20	<20	<20	150	<10	<20	<10	<10	<1	<20	44.2	99.88
N-3	15.44	.59	.30	.70	44.34	.03	.07	.03	.01	<.01	.003	107	<20	<20	<20	<20	202	<10	<20	<10	<10	1	<20	38.4	99.97
N-5	7.84	.87	.28	.32	49.56	.08	.17	.04	<.01	.01	.010	63	<20	<20	<20	<20	125	15	<20	<10	<10	1	<20	40.7	99.91
N-8	2.82	.70	.39	.36	52.30	.03	.06	.03	<.01	.01	.004	36	<20	<20	22	<20	75	<10	<20	<10	<10	1	<20	43.2	99.93
N-10	5.36	.89	.39	.50	50.74	.08	.15	.04	<.01	.01	.009	62	<20	<20	38	<20	260	<10	<20	<10	<10	1	<20	41.8	100.02
H-1	1.72	.49	.26	.29	53.35	<.01	.06	.02	<.01	<.01	.002	34	<20	<20	<20	<20	121	<10	<20	<10	<10	1	<20	43.7	99.93
H-3	3.62	.59	.26	.33	52.17	.03	.13	.03	<.01	<.01	.006	47	<20	<20	<20	<20	121	<10	<20	<10	<10	1	<20	42.8	99.99
H-4	5.16	.80	.33	.39	50.89	.08	.19	.04	.02	<.01	.008	65	<20	<20	<20	<20	141	20	<20	<10	<10	1	<20	42.1	100.04
H-5	3.50	.58	.24	.28	52.18	.04	.13	.03	.01	<.01	.004	53	<20	<20	<20	<20	95	<10	<20	<10	<10	1	<20	42.9	99.92
H-8	1.03	.24	.12	.32	54.22	.02	.04	<.01	<.01	<.01	.001	53	<20	<20	<20	<20	128	20	<20	<10	<10	<1	<20	43.9	99.93
H-9	3.01	.77	.39	.39	52.10	.02	.11	.04	<.01	.01	.003	58	<20	<20	<20	<20	110	<10	<20	<10	<10	1	<20	43.1	99.97
E-4	7.06	.77	.19	.34	50.09	.07	.22	.03	<.01	<.01	.007	72	<20	<20	<20	<20	194	10	<20	<10	<10	<1	<20	41.2	100.02
E-13	10.21	.86	.18	.35	48.42	.12	.28	.05	<.01	.01	.027	125	<20	<20	<20	<20	174	37	<20	<10	<10	<1	<20	39.5	100.05
E-66	10.40	.59	.17	.37	48.72	.03	.13	.02	<.01	.01	.006	78	<20	<20	<20	<20	163	<10	<20	<10	<10	<1	<20	39.6	100.07

Table 2. Stable isotope composition of hard laminated crust samples.

sample	$\delta^{18}O$	$\delta^{13}C$
H-1	-5.26	-9.00
H-3	-4.92	-8.89
H-4	-4.89	-8.66
H-5	-4.97	-9.03
H-8	-5.25	-9.07
H-9	-5.25	-8.90
E-4	-5.47	-8.49
E-13	-5.84	-8.91
E-66	-5.31	-8.56

degree of expansion, respectively. Most authors agree that tepees or pseudo-anticlines associated with calcretes are expansion structures caused by (i) alternating swelling of shale associated with calcretes (Price 1925); (ii) calcrete occurrence in pre-existing rocks (Jennings and Sweeting 1961; Watts 1977 for displacive growth); (iii) hydration of anhydrite (Blank and Tynes 1965); (iv) fracture-filling (Reeves 1970); and (v) a combination of crystallization, wetting and drying, and rhizobrecciation (Klappa 1980). Furthermore, Assereto and Kendall (1977) and Kendall and Warren (1987) discussed the driving mechanisms for all antiform structures in detail. Assereto and Kendall (1977) suggested that the force of crystallization of calcium carbonate in the plugged horizon is the most important mechanism for calcrete tepees. Except for wetting and drying, the other mechanisms seem to be unsatisfactory to explain formation of calcrete-related tepees or antiform

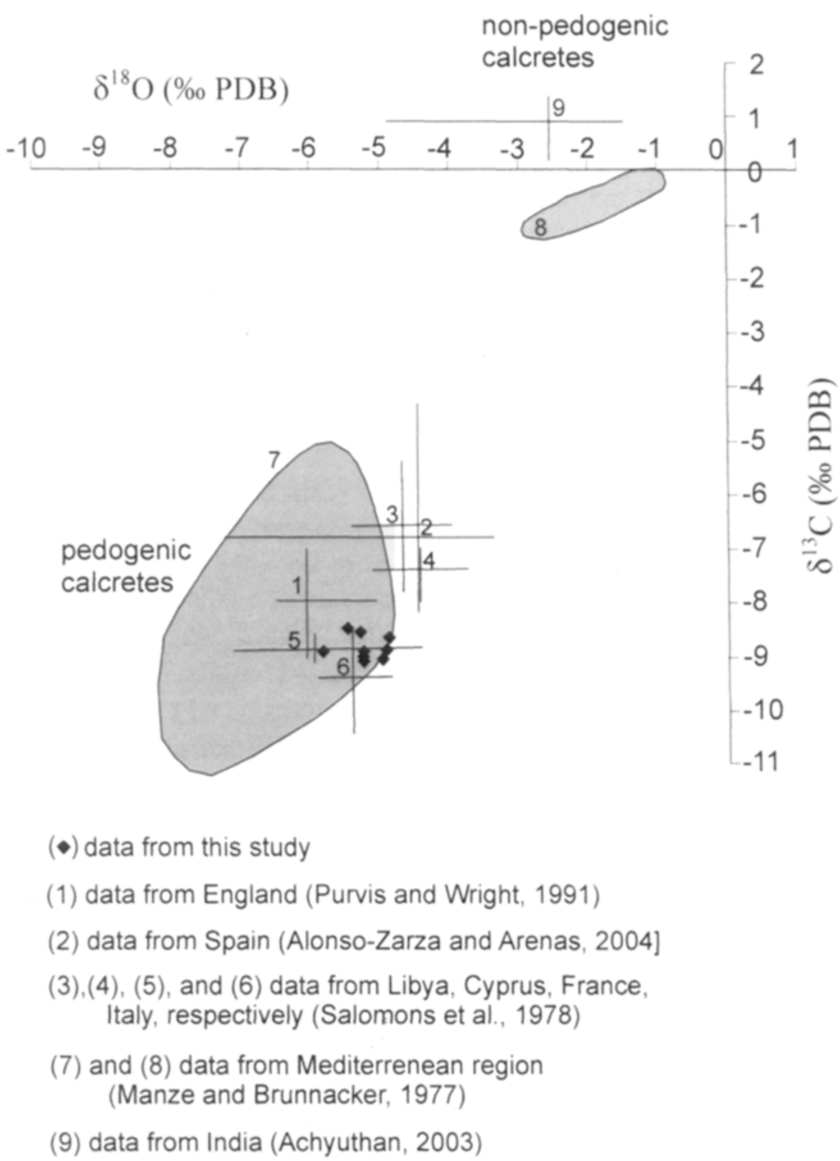

Figure 7. Cross plot of stable isotope values of the studied calcretes and their comparison with others from literature. The separation is due to pedogenic and non-pedogenic calcrete origins.

structures because of: (1) widespread occurrence of dome-like morphologies where caliche crust overlies different lithologies, predominantly yellow- coloured carbonate sandstones and red-coloured mudstones (overbank deposits) displaying well-developed isolated calcrete forms (plugged horizon); (2) an absence of evaporitic minerals; (3) scarcity of rhizobrecciation and fracturing which cause local deformation; and (4) crystallization is a progressive phenomenon that requires partial crust deformation or tepee formation at varying levels within the calcrete crust, whereas tepee deformation affects the whole crust, suggesting an occurrence during later stages of calcification. All features, as mentioned above, suggest that thermal and moisture-related expansion and contraction are the main deforming mechanism. Price (1925) stressed that semi-aridity of the climatic conditions are favourable for the development of calcrete tepees (pseudo-anticlines), high temperatures are also considered as necessary. Heating causes the calcrete crust to expand, and cooling results in contraction. However Assereto and Kendall (1977) noted that the thermal effect is insufficient to form widespread tepees because of an extremely low thermal expansion coefficient. The thermal expansion coefficient for limestones is roughly equal to $6 * 10^{-6}/^{o}C$ (Skinner 1966; FHWA 2002). Salmon et al. (2002) suggested that moisture significantly increases (> 30 %) thermal conductivity. Therefore, wetting and drying is also important for expansion as well as for calcrete formation itself (Revees 1970). The daily and/or seasonal combined effect of moisture and temperature causes expansion in the calcrete crust resulting in a buckling upward, dome-like surface morphology and/or local thickening of the crust. Cooling on the other hand, causes contraction, result in tensional stresses beneath the troughs, so leading to crust thinning and rock failure.

CONCLUSIONS

In the study area, tepee structures are widespread in the hard laminated crust (hardpan calcrete), indicating formation in vadose zone under meteoric water conditions. The tepees are characterized by dome-like or slightly elongated dome-like, and rarely ridge-like morphologies in plan view and an upward buckled crust or a surface undulation in cross-section. They mostly form on the scale of a few to several metres across, and 30 to 70 cm in height, showing irregular or roughly polygonal shapes and breakage. Thermal and moisture related expansion and contraction seem to be the most likely mechanism for formation of the calcrete tepees. Thermal expansion becomes more effective with moisture to produce dome-like morphologies and crust buckling, and the contraction by cooling results in troughs between them and tensional fractures.

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