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A review of the origin and setting of tepees and their associated fabrics

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ABSTRACT

Carbonate hardgrounds often occur at the surface of shallow subtidal to supratidal, lacustrine, and subaerial carbonate shelf sediments. These are commonly disrupted and brecciated when the surface area of these crusts increases. In the subtidal environment, megapolygons form when cementation of the matrix causes the surface area of the hardgrounds to expand. Similar megapolygons form in the supratidal, lacustrine and subaerial settings when repeated incremental fracturing and fracture fill by sediment and/or cement also causes the area of the hardgrounds to expand. The arched up antiform margins of expansion megapolygons are known as tepees.

The types of tepees found in the geological record include:

(1) *Submarine tepees* which form in shallow carbonate-saturated waters where fractured and bedded marine grainstones are bound by isopachous marine-phreatic acicular and micritic cements. The surfaces of these brecciated crusts have undergone diagenesis and are bored. Unlike tepees listed below they contain no vadose pisolites or gravity cements;

(2) *Peritidal and lacustrine* tepees are formed of crusts characterized by fenestral, pisolitic and laminar algal fabrics. This similarity in fabric makes these tepees of different origins difficult to separate.

Peritidal tepees occur where the marine phreatic lens is close to the sediment surface and the climate is tropical. They are associated with fractured and bedded tidal flat carbonates. Their fracture fills contain geopetal asymmetric travertines of marine-vadose origin and/or marine phreatic travertines and/or Terra rossa sediments. The senile form of these peritidal tepees are cut by labyrinthic dissolution cavities filled by the same material.

Lacustrine tepees form in the margins of shallow salinas where periodic groundwater resurgence is common. They include groundwater tepees which form over evaporitic 'boxwork' carbonates, and extrusion tepees which also form where periodic groundwater resurgence occurs at the margins of shallow salinas, but the dominant sediment type is carbonate mud. These latter tepee crusts are coated and crosscut by laminated micrite; the laminae extend from the fractures downward into the underlying dolomitic micrite below the crust.

Both peritidal and lacustrine tepees form where crusts experience alternating phreatic and vadose conditions, in time intervals of days to years. Cement morphologies reflect this and the crusts often contain gravitational, meniscus vadose cements as well as phreatic isopachous cement rinds.

(3) *Caliche tepees* which are developed within soil profiles in a continental setting. They are formed by laminar crusts which contain pisolites, and fractures filled by micritic laminae, microspar, spar and Terra rossa. Most of the cements are gravitational and/or meniscoid.

In ancient carbonates, when their cementation and diagenetic fabric can be interpreted, tepee structures can be used as environmental indicators. They can also be used to trace the evolution of the depositional and hydrological setting.

INTRODUCTION

This paper describes the disrupted surface and near-surface carbonate crusts of shallow carbonate shelves in settings ranging from subtidal to supratidal to lacustrine environments. It emphasizes how, in environmentally distinct settings, these crusts expand. In the subtidal this expansion is probably a response to the force of crystallization of the cements that form the matrix of the crust. In contrast, supratidal lacustrine or subaerial setting expansion is caused by repeated cycles of fracturing, fracture fill and/or cementation. In both cases as the surface area of the crusts grows, they crumple to form a pattern of megapolygons with upturned antiform margins. These antiforms are known as tepees (Adams & Frenzel, 1950).

Penencontemporaneous cementation of the surface sediments of carbonate environments is common and frequently can result in crusts that exhibit the local disruption just described. The setting in which carbonate cementation and crust development occurs varies. It may be in the deep waters surrounding isolated carbonate platforms like those of Pacific atolls or the Bahama banks (Schlager & James, 1978; McIlreath & James, 1979; Mullins & Neumann, 1979; Mullins, Neumann & Wilbur, 1980; Cook & Mullins, 1983). It may occur in the platform rim (Kendall & Schlager, 1981; James, 1983), or in the shallow-water shelf sediments capping the platform. The latter include the subtidal zone (Shinn, 1969; Harris, 1978; Dravis, 1979; Halley, Harris & Hine, 1983; Wilson & Jordan, 1983), the intertidal, and supratidal zone (Illing, 1954; Shinn, Ward & Ginsburg, 1969; Shinn, 1983) or coastal lakes (Warren, 1982; Warren, Lock & Granger, 1984).

This paper concentrates on some of the effects of cementation in these shallow-shelf sediments. Some of the most spectacular examples of the rapidity of this cementation of Holocene carbonates can be seen in beachrocks. In the Pacific, for instance, some beachrocks even contain World War II artifacts and human skeletons (Milliman, 1974). Others, when quarried for building stone, are quickly replaced by the rapid formation of new beachrock (Moresby, 1835). Similarly in the Arabian (Persian) Gulf subaqueous crusts from seafloor contain modern glass bottles and pottery (Shinn, 1969). Wherever they occur, these cemented surface sediments, or hardgrounds, usually form planar or undulatory surfaces which conform to the morphology of the adjacent uncemented sediments. Where the cemented surface undergoes expansion, it crumples and can locally form tepee breccias.

CLASSIFICATION AND GENESIS OF DISRUPTED CRUSTS AND TEPEES

In their simplest form, tepees are early diagenetic features associated with carbonate crusts which occur in four different depositional settings; shallow subtidal, intertidal, supratidal and continental. Tepees from each of these four settings have associations of texture and fabric which, when recognized, can allow environmental interpretations to be made (Table 1). No matter what the setting, tepee formation involves three processes:

(1) early cementation of the surface sediments;
(2) fracturing of the resulting crust and;
(3) infilling of these fractures with sediment and cement.

This paper classifies tepees on the basis of their various depositonal settings and then considers each form of tepee in terms of how the three listed processes operate in each depositional setting.

In modern settings, several mechanisms cause crusts to expand and crumple into tepee structures (Table 2) and any one of these may dominate in a particular depositional setting. Most mechanisms, particularly where the crusts are at intervals exposed to subaerial and subaqueous conditions, involve fracturing of the crusts (sometimes in response to thermal expansion and contraction, sometimes in response to the buoyancy effects of a fluctuating water table) and the resulting cracks are filled with sediment or cement or both. Often one mechanism may dominate in an early stage of crust and tepee formation, only to be replaced at a later stage by another mechanism, that may involve part or all of the sedimentary section associated with tepee development.

In ancient carbonate successions where tepee fabrics and their associated sediments can be related to the processes that were active during crust and tepee formation, they can be used as palaeoenvironmental indicators. These mechanisms evolve over time in response to changes in the depositional and hydrological setting.

It is because tepees may be confused with collapse and other breccias that we propose that the word tepee be used as a non-genetic, purely geometric term to describe bowed-up carbonate crusts that are sometimes overthrust and which, in two dimensions, resemble an inverted 'V'. The two key observations

Table 1. Characteristics of modern carbonate crusts

Feature	Subtidal	Intertidal	Supratidal	Lacustrine	Continental
Dominant lithology	Bioclastic grainstone	Bioclastic, ooids & grapestones	Pelletal & intraclastic wackestone	Pelletal & intraclastic wackestone	Pelletal & intraclastic wackestone
Dominant cements	Aragonite & high Mg calcite	Aragonite & high Mg calcite	Aragonite & high Mg calcite	Low Mg calcite, & dolomite	Low Mg calcite
Cement type	Acicular (aragonite), equigranular to fibrous (Mg Calcite) bladed to Micritic	Acicular (aragonite), equigranular to fibrous (Mg Calcite) Micritic	Acicular (aragonite), equigranular to fibrous (Mg Calcite) Micritic	Micritic or acicular aragonite or spar (dependant on chemistry of inflow water)	Micrite & microspar
Gravity cements	No	Rare	Common	Common	Common
Laminar crusts	No	Yes (coniatolites, stromatolites)	Yes (coniatolites, stromatolites)	Yes (stromatolites)	Yes (caliche hardpan)
"Vadose" pisolites	No	No	No	Yes	No (caliche instead of pisolites)
Oncolites	Yes	No	No	Yes	No
Crosscutting/ borings	Yes	Unknown	Uncommon	Uncommon/ occasionally common	Rare
Leaching	No	No	Yes	Yes	Yes
Laminar fenestrae	No	Yes	Yes	Yes	Uncommon
Associated with evaporites	No	Yes	Yes	Yes	Uncommon
Associated with dolomite	Uncommon (need drawdown)	Uncommon	Yes	Yes	Yes
Open marine shell fragments	Yes	No Restricted marine	No Restricted marine	Yes/No (dependent presence surface marine connection)	No
Plant root (Rhizo-concretions)	No	No	Uncommon	Uncommon	Yes
pore water	Marine	Marine	Marine, mixed occasional meteoric	Marine/meteoric	Meteoric
Embayed, blackened intraclast	No	No	Uncommon	Uncommon	Yes
Boxwork	No	No	No	Yes	No

germane to this definition are 'bowed up' and 'inverted V shape', but neither observation defines the setting of tepee formation. The latter can only be recognized by using: (1) features associated with the tepees that formed in response to both the expansion mechanisms; and (2) the processes acting in the depositional setting of the associated sediments (Tables 1 and 2). Using this approach, submarine tepees, peritidal tepees, lacustrine tepees (groundwater and extrusion), and caliche tepees can be distinguished (Table 2). Each type is based on well-defined examples in the Holocene record. This two-part classification leads to a more precise determination of tepee type which in turn may carry with it important palaeoenvironmental information.

Submarine tepees and hardgrounds

Submarine tepees are associated with submarine cementation, though we emphasize that not all submarine hardgrounds contain these features. Cements binding the various marine hardgrounds are

Table 2. Interpretation of tepees: processes of formation and setting

I. Submarine Tepees: (Shinn, 1969, modified)	Expansion by pressure of crystallization in the sediment matrix and possibly in fractures in submarine crusts. Indicates a hardground in shallow, carbonate-saturated waters.
II. Peritidal Tepees: (Assereto & Kendall, 1971)	Major expansion caused by fill by cement and sediment of fractures formed by minor expansion by force of crystallization of thermal contraction and expansion of cement fill of cracks. Indicative of shallow water table and climatic extremes about the margin of a shallow water body. A strandline indicator.
III. Lacustrine Tepees:	
A. Groundwater Tepees: (Warren 1982, 1983)	Major expansion caused by fill by cement and sediment of fractures formed by thermal contraction and expansion. Minor expansion caused by fluctuations of pore pressures in porous box-work sediments below the tepee-affected crust. Indicates periodic groundwater resurgence about margins of shallow water body. A strandline indicator.
B. Extrusion Tepees: (Muir *et al.*, 1980)	Major expansion caused by fill cement of fractures formed by thermal contractions and expansion. Minor expansion by swelling and contraction of unconsolidated muds beneath tepee structures. Indicative of groundwater resurgence about margins of nearshore salinas. A strandline indicator.
IV. Caliche Tepees: (Klappa, 1980b)	Expansion by a combination of the force of crystallization, wetting and drying, and rhizobrecciation. Indicative of an exposure surface (paleosol) in a continental environment.

aragonite and/or high magnesium calcite (Taft *et al.*, 1968; Shinn, 1969; Harris, 1978; Dravis, 1979; Bathurst, 1982). The aragonite may be micritic or fibrous. The aragonitic micrite cements are more common at or just below the water–sediment boundary, while fibrous cements are found within the interior of these submarine crusts and, where grapestones occur, within the interiors of these grain aggregates. The high-magnesium calcites may be micritic or bladed; again the micritic cements are more common as coatings on near-surface grains and crusts, while the blades are more common in intraskeletal pores. Sedimentary textures still reflect the depositional setting in which the sediments were deposited despite being modified by subsequent diagenesis. In consequence, shallow water grainstones, be they oolites, grapestones, or nearshore subaqueous bioclastic sands, usually exhibit cross bedding. If the exterior of these crusts are not buried by sediment they become bored and eroded by organisms which inhabit this surface (Fig. 2).

In Holocene shallow-water settings, submarine cementation is best developed in grapestone sediments. Particularly good examples can be seen in the Bahamas where oolites and/or grapestones on the seafloor are cemented into thick crusts hundreds of millimetres thick which stack up through the Holocene succession (Taft *et al.*, 1968; Harris, 1978; Dravis, 1979; Shinn, 1983), but here no tepees have been reported. Similarly, Holocene cementation of oolites in the coastal terraces of Hamlin Pool, Shark Bay is equally dramatic (Logan, 1981), but again, no tepees have been observed. However, on the seafloor of the Arabian Gulf off Qatar (Shinn, 1969; Assereto & Kendall, 1971) similarly cemented crusts expand and override themselves, forming compressional submarine tepees in response to the force of crystallization of the cements within the hardgrounds. It may also be that fracturing and fill, which is central to our interpretation of tepee formation in the intertidal to subaerial environment, is even at work in this submarine setting but further research needs to be done to establish this. Submarine tepees occur on a gigantic scale marking the margins of saucer-like expansion megapolygons up to 40 m across (Fig. 1). The cements associated with the matrix of the subaqueous bioclastic sands of the Arabian Gulf have similar fabrics and mineralogy to those binding the hardgrounds of oolites, grapestones and hardened pellets of the Bahamas and Shark Bay; however, it is the cement forming in fractures that exerts a pressure of crystallization that causes the overthrusting in these submarine tepees. This cement-fill of fractures in the submarine-cemented hardgrounds is thought to be incremental and accompanied by sediment fill. Today this form of tepee occurs in areas of the shallow sea-

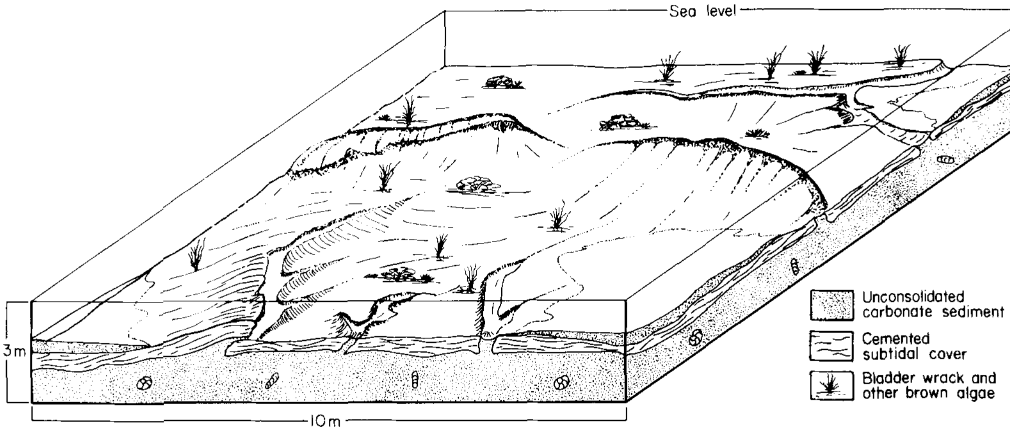

Fig. 1. Submarine megapolygons in the open marine waters of the Arabian Gulf near Abu Dhabi. The crusts are characterized by an open marine biota and borings which crosscut both grains and cements.

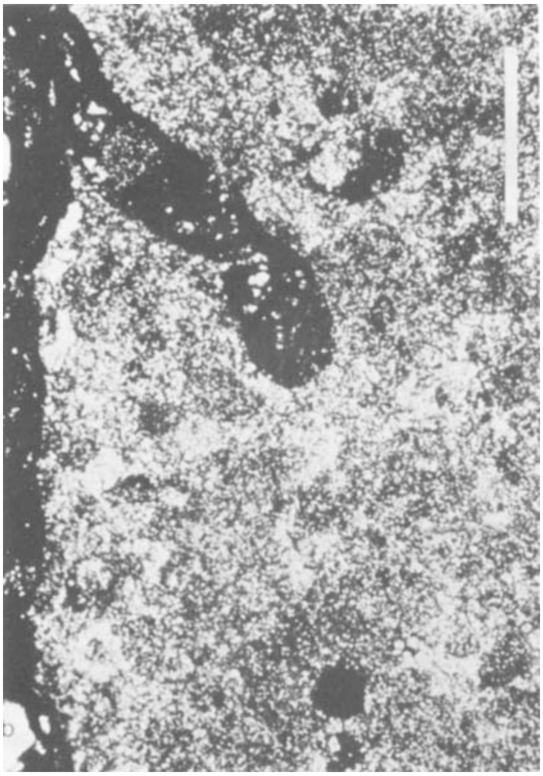

Fig. 2. Thin section photomicrograph of bored marine hardground from the Middle Devonian of Western Canada. Scale bar is 0·5 mm (Courtesy of Jack Wendte).

floor where pore waters are saturated with respect to calcium carbonate (Shinn, 1969). It is possible that the initial fracturing in the Arabian Gulf was caused by earthquakes just as the Devonian platform margin and marginal-slope carbonates of the Canning Basin were disrupted. These Devonian cemented and fractured sediment crusts occur in the deeper waters beyond the margin of the Canning Basin (Playford *et al.*, 1984). They contain near-horizontal, and some vertical, sheet cracks filled by laminated marine cements and sediments (Fig. 4). These fractures are probably a response to gravitational sliding of the crust triggered by earthquakes (Playford, Keraus & Hurley, 1984) rather than expansion. While these submarine features from the Canning Basin are not tepees, it is clear that they have properties and fabrics in common with the submarine tepees of the Arabian Gulf; namely, their association with hardgrounds, the occurrence of sheet and vertical fractures, and the presence of marine cements in fractures. However, it should be noted that laminations in the Arabian Gulf submarine crusts are thought to be rare or absent (Shinn, 1969) and unlike the Canning Basin example the crusts contain skeletal grains associated with a relatively unstressed shallow-shelf marine biota.

In the rock record, submarine tepees and the associated crusts or hardgrounds may be distinguished from peritidal and subaerial tepees by the recognition of the presence of abundant subtidal borings that cut through the open-marine sediments and their associated marine cements (Fig. 2) (Purser, 1969). That the borings are subtidal can be determined from the fact that the sediments that overlie, fill and are incorpo-

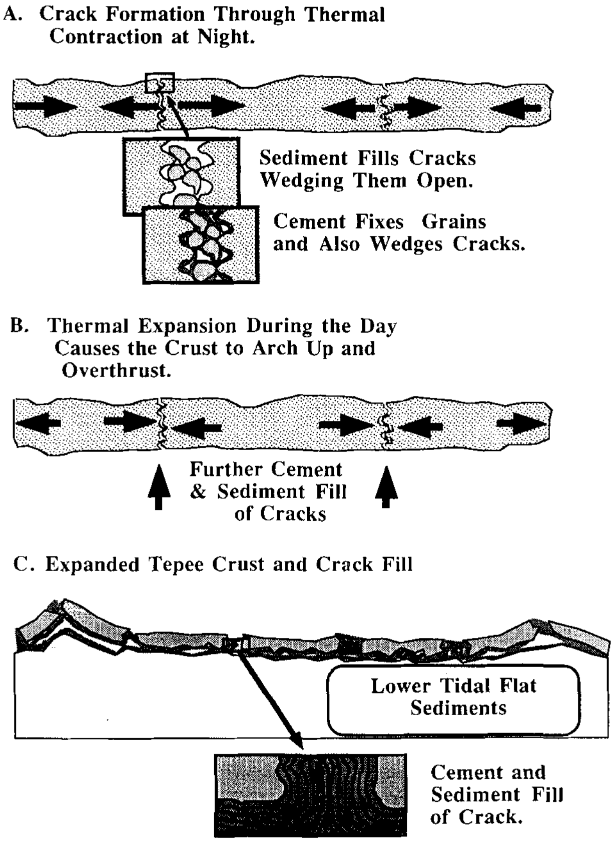

Fig. 3. Cartoon of veneer crusts' cement fill and expansion forming tepees.

rated in the borings are subtidal. Also the associated cements tend to occur as isopachous rims that presumably were precipitated in voids which were always filled by seawater.

Examples of ancient submarine tepees occur in the Jurassic of the Paris Basin (Purser, 1969; Fursich & Palmer, 1979). However, here differential compaction may have played a major role in the formation of these submarine tepees because these Jurassic hardgrounds appear draped over cemented sponge reefs (Fursich & Palmer, 1979). Other submarine tepees are believed to occur in the Ordovician of Scandinavia (Lindstrom, 1963).

Peritidal tepees, their crusts, their cements and related diagenesis

All the crusts described in this section show some textural evidence for subaerial exposure, including gravitational cements, fenestrae, and desiccation cracks. These laminar crusts, which are common in both the upper intertidal and supratidal environments, are frequently cemented stromatolites. Examples occur in the Holocene of Southern Australia (Warren, 1982), Shark Bay, Western Australia (Fig. 5) (Read, 1974), the Arabian Gulf (Kendall & Skipwith, 1969), and the Bahamas (Fig. 6) (Shinn, Ginsburg & Lloyd, 1965). Most of these supertidal crusts contain a restricted marine biota, such as the cerithid gastropods found associated with those of the Arabian Gulf. Some of these crusts of the Arabian Gulf are formed by laminar marine aragonite flowstones (the coniatolites of Loreau & Purser, 1973). Other crusts from the Bahamas exhibit a palisade structure caused by the cementation of the tufted blue-green algae, *Scytonema* (Hardie, 1977).

The cementation of the intertidal and supratidal crusts that subsequently deform into tepee structures in the Bahamas and the Arabian Gulf (Fig. 7) is

Fig. 4. Mounded carbonate mud layer transected by arched horizontal fractures filled by marine cement (neptunian sill) in the Devonian Virgin Hills Formation (forereef), Canning Basin, Western Australia. Geological hammer for scale.

induced by capillary evaporation (Assereto & Kendall, 1971, 1977). Cementation is often restricted to specific locations in the intertidal zones of carbonate depositional environments, but when it occurs, it is locally widespread. Cemented horizons are common in tropical carbonate beaches and are called beach rocks (Bathurst, 1971; Milliman, 1974).

In Shark Bay, early-lithified crusts occur in tidal-flat carbonates. These intertidal veneers exhibit local tepee structures (Read, 1974) (Fig. 5). Similar cemented crusts form intertidal tepees at the margin of the Khor al Bazam Lagoon, Abu Dhabi (Fig. 7 and 8) (Assereto & Kendall, 1977). The cements in these various crusts probably grow in response to evapora-

Fig. 5. Holocene veneer crusts broken by fractures. Irregular surface contains small tepees from the intertidal to lower supratidal of Depuch Loop, Western Australia. Paul Hoffman for scale.

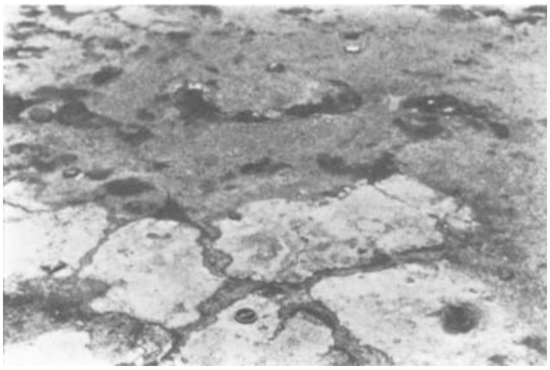

Fig. 6. Expanding supratidal capillary crust with fracture fill, which contains tepee structures at other locations on the west side of Andros Island, Bahamas. Lens cap is 30 mm in diameter.

tion of water trapped by surface tension within the sediment at low tide. Cementation is most rapid in the intertidal zone of coastal flats and beaches; both are zones of groundwater resurgence (Moore, 1973, 1977; Hanor, 1978). Early cements in intertidal crusts may be micritic, bladed, or fibrous, and may be composed of aragonite, high-magnesium calcite, low-magnesium calcite, or dolomite. The high-magnesium calcite and aragonite cements appear related to marine water tables (Hanor, 1978). In contrast, the low-magnesium calcite and dolomite cements seem to be related to the influx of meteoric water, either from rainfall or from seaward-flowing groundwaters (Folk, 1974). These meteoric waters enter the shoreline when beach sediments are subaerially exposed at low tide (Land, 1973; Hanor, 1978) or during progradation of the beach (Strasser & Davaud, 1986).

Fig. 7. Intertidal tepees in and about the edge of the Khor al Bazam Lagoon, Abu Dhabi. Crust is composed of cerithid gastropod wackestone/grainstone containing restricted lagoonal biota (Fig. 8). The underlying sediments are unconsolidated wackestones/mudstones deposited in a restricted lagoonal setting. Prograding sabkha sediments will later cover this crust with an evaporitic supratidal sequence (Scale; Abdul Al Sharan).

In the supratidal zone behind quiet water lagoons and at the edges of saline coastal lakes in geographic locales where evaporation is high and the seawater has higher salinities, cements locally bind the surface sediments of the tidal flats. The cemented crusts that form may be tens to several hundreds of millimetres thick. The crusts sometimes show evidence of early dolomitization caused by the evaporation of chemically altered seawater and/or meteoric waters which flow to the surface at times of low water levels (Shinn *et al.*, 1965; Bathurst, 1971; Muir, Lock & Von der Borch, 1980, p. 535; Eriksson & Warren, 1983).

Supratidal crusts often show evidence of fractures infilled with sediments and cements (Assereto & Kendall, 1977). These supratidal and peritidal tepees form by repeated episodes of crustal cracking caused by both thermal expansion and changes in the position of the water table. While the fractures are still open, cementation and sediment infiltration gradually fills the cracks in the crust and increase its volume. Subsequent contraction episodes related to desiccation do not exert enough force to return the crust back to its original position. Instead the crust expands by the addition of small increments of sediment and cement at the fracture margins. Eventually a crust becomes broken into overthrust compressional tepee ridges which surround polygonal shaped saucers of the same indurated limestone crust (Fig. 3). We term these structures peritidal tepees or, in some cases where they are associated with supratidal evaporites, sabkha tepees. In Holocene sediments the diameters of the polygonal saucers varies from as small as 0·1 to 0·2 m to as much as 2–4 m. The polygonal shape seems to be related to an optimal pressure distribution on a horizontal surface. Thus, non-orthogonal (120°) polygonal patterns are a response to expansion in a homogenous stress field while orthogonal (90° intersection) are a response to an inhomogeneous stress field (Warren, 1982). Expanding surface halite and anhydrite also form polygons (Butler, Kendall & Harris, 1982).

Areas where this type of cemented crust has been observed in the Holocene and is associated with the supratidal zone of tidal flats include the southwestern Arabian Gulf (Illing, Wells & Taylor, 1965; Evamy, 1973, Assereto & Kendall, 1977), Shark Bay (Davies, 1970; Read, 1974) and the Bahamas (Fig. 6) (Shinn *et al.*, 1965).

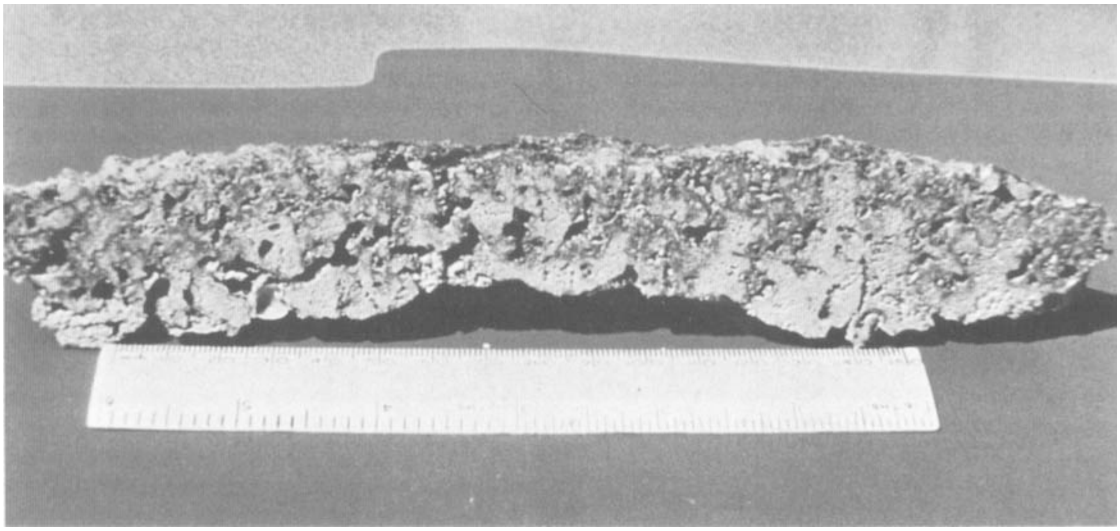

Fig. 8. Crust from the tepee-affected north-east margin of the Khor al Bazam Lagoon adjacent to Abu al Abyad, Abu Dhabi. The crust is composed of a highly burrowed cerithid gastropod grainstone cemented by acicular aragonite.

Assereto & Kendall (1977) described how the tepee structures in many ancient prograded peritidal and hypersaline sequences exhibit an evolution from (1) immature tepees composed of thin (0·01–0·20 m) crusts with little cement-fill which are interbedded with tidal flat carbonates and formed in a marine to near-marine setting to (2) mature tepees formed by thicker (0·20–1 m), more altered crusts whose fractures are filled by abundant sediment and cement (Figs 9 and 10) to (3) senile tepees formed of highly karstified, dissolved and reprecipitated carbonate later in the depositional cycle in a more landward setting (Fig. 11). The senile tepees tend to have formed when the mature peritidal tepees were covered by soil horizons and were subject to extensive dissolution and fill by carbonate sediment and cement (Assereto & Kendall, 1977). Such progradational sequences where tepees are abundant occur in the Triassic Calcare Rosso of Lombardy, Italy (Assereto & Folk, 1980).

Examples of ancient peritidal tepees and saucers with greater dimensions than those so far identified in Holocene sediments are common. These include those of the Jurassic of Morocco (Fig. 9) (Burri, DuDresnay & Wagner, 1973), the Triassic of the Italian Alps (Assereto & Kendall, 1977), the Permian of the Guadalupe Mountains in the United States (Fig. 10) (Assereto & Kendall, 1977) and the Lower Proterozoic Rocknest Dolomite of Northwest Canada (Grotzinger & Read, 1983). Associated saucers may be as much as 15 m in diameter, and the tepee ridges may crumple and brecciate as much as 3–5 m of lithified sediment. Deformation increases downward and is probably related to both the annual seasonal fluctuation of the water table (Warren, 1983a) and longer term cycles of periodic exposure and drowning. This interpretation is based on the oxygen isotope data from the Guadalupes (Rosenblum, 1985) and Rocknest area tepees (Grotzinger, 1985) and the fact that Holocene tepee crusts in South Australia can be seen to change their orientation in response to a fluctuating water table (Warren, 1983a). In addition to normal seasonal water-table fluctuations, this downward increase in disruption could also be interpreted to have been caused by either eustasy and/or unusual storm events.

We believe that in the case of the tepees of the Carslbad Group of the Guadalupe Mountains, as the succession matured, both tidal and eustatic sea-level events first buoyed up and then let the cemented and fractured sediment settle, so disrupting it further. The pore waters in this near-surface setting were initially marine but were displaced by meteoric waters as the sequence built up and outward. Previous reconstructions of these Guadalupian barrier island sequences during tepee formation (Handford *et al.*, 1983 & 1984; Rosenblum, 1985) have dealt with the hydrology in a two-dimensional dip-parallel section showing a major groundwater flow component running at right angles to the regional strike. In contrast, we consider the

Fig. 9. Bedding plane showing mature Jurassic megapolygons, with tepee margins Gorge du Todra, Morocco. Ian Evans for scale.

hydrology to have a lateral component of flow along the direction of the depositional strike of these barrier islands. Our analogy is the beach dune ridges of the Coorong region of South Australia where meteoric waters flow is along this trend, atop marine and hypersaline pore waters (Von der Borch, Lock & Schwebel, 1975). If so, then the major source of water for cementation would be marine, seasonally diluted by meteoric waters thus explaining the abundance of aragonite cements in these tepees. Similar aragonite cements are growing today in the tepees of the gypsum salinas of South Australia (Warren, 1982). These tepees probably developed while the barrier islands at the crest of the Delaware Basin shelf margin were accreting or 'catching up' by vertical aggradation following the 'start-up' phase of a relative sea-level

Fig. 10. Cross section of a mature tepee from Dark Canyon, in the Carlsbad Group (back side of Permian barrier-island facies) in the Guadalupe Mountains, New Mexico.

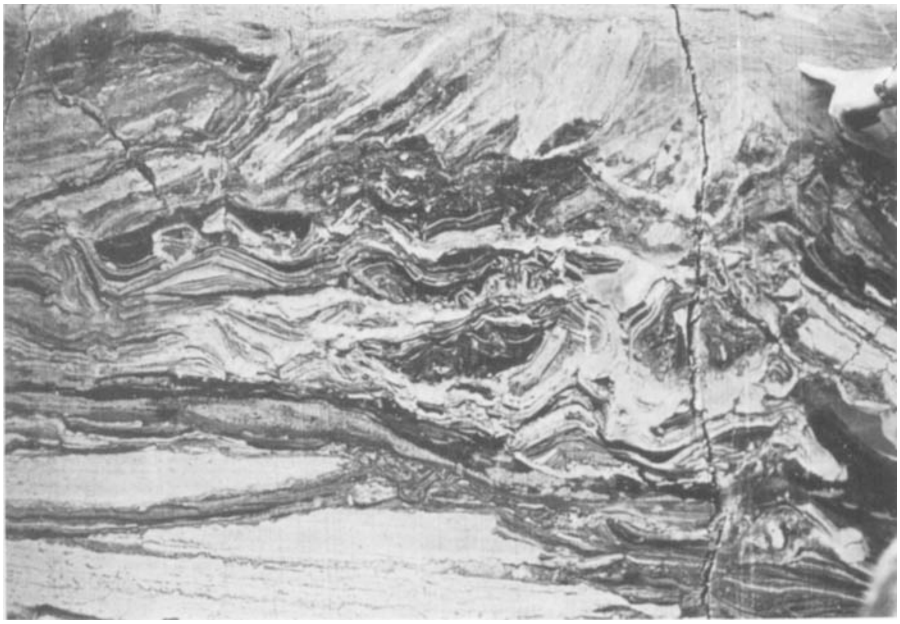

Fig. 11. Senile tepees that were exposed to diagenetic fluids of marine and meteoric origins, Triassic of Val Brembana, northern Italy. Note the cave roof of original fenestral pisolitic material, arched into a tepee, adjacent to Riccardo Assereto's finger. Below are numerous cross-cutting phases of cave-fill overlying horizontal and original fenestral pisolitic material.

rise (Kendall & Schlager, 1981). This faster sediment accumulation occurred on the seaward edge of a broad, restricted saline lagoon facies mosaic. The rate of lagoonal sediment fill lagged behind island build-up but eventually caught up with relatively high sea-level position. This again supports our suggestion that most of the early cementation in the tepees is predominantly tied to the influx of seawater rather than continental water. This 'catch up' ridge development followed by lagoonal fill (Kendall & Schlager, 1981) appears to be a common response on ancient depositional carbonate shelves subjected to a relatively rapid sea-level rise.

Whatever their origin, envelopes of marine aragonitic-travertine, or cement coating of both phreatic and vadose origins were common in the supratidal and intertidal crusts associated with ancient arid environments (Fig. 12). These crusts formed at the depositional surface and apparently continued accumulating during early burial. Examples of these cements can be seen in the Lower Proterozoic Wopney Orogen, Canada (Grotzinger & Read, 1983), the Devonian of the Canning basin, Western Australia (Playford, private communication), the Permian of the Guadalupe Mountains (Kendall, 1969; Assereto & Kendall, 1977; Warren 1983a; Rosenblum, 1985), the Triassic of the Italian Alps (Assereto & Kendall, 1977) and the Jurassic of the Moroccan High Atlas Mountains (Burri *et al.*, 1973; Assereto & Kendall, 1977). Such marine-vadose and marine-phreatic travertines frequently fill the fractures and cavities in the deformed compressional ridges found in these crusts, and these deformed crusts are commonly composed of coated grains and/or pisolites (Fig. 13). Such grains and/or pisolites formed and collected in the splash zone and in the soil horizons of the high intertidal and supratidal, often in zones of groundwater resurgence (Estaban & Pray, 1977; Ward, Kendall & Harris, 1986).

The early stages of this process occur today in the southwest Arabian Gulf where similar coated grains and pisolites are forming on the lee of beach ridges in the vicinity of Jebel Dhana in Abu Dhabi (Loreau & Purser, 1973), on the edges of Lake MacLeod (Handford *et al.*, 1983 & 1984), at Marion Lake (Warren, 1982), and Fisherman Bay (Ferguson, Burne & Chambers, 1982) in Australia.

In the Alpine Triassic of the Burgamasc Alps, senile tepees occur (Assereto & Kendall, 1977). The de-

Fig. 12. Vadose and phreatic marine and freshwater travertines enveloping a tepee breccia from Alpine Triassic of Val Brembana, northern Italy. The original tepee-affected crust makes up less than 20% of the rock. Riccardo Assereto's hand for scale.

formed travertine-coated crusts which are associated with these tepees are riddled by a labyrinth of small penecontemporaneous vugs and caves filled by a subsequent generation of marine sediment, travertine, terra rossa, and associated freshwater cements (Fig. 11). These senile tepees reflect alternating episodes of marine and meteoric diagenesis. The seawater is transported into these sediments by (1) storm surges across barrier islands and (2) upwelling associated with deflation flats, like that of Lake MacLeod in Western Australia (Handford *et al.*, 1983, 1984). The fresh water comes from influxes of continental groundwaters similar to those of the Guadalupe Mountains (Rosenblum, 1985). The mixed character of the senile tepee cements, which includes cements from vadose to phreatic zones and from marine to fresh water, reflects the repeated rise and fall of the sea, as documented by Grotzinger (1985) in the Proterozoic Rocknest Formation.

LACUSTRINE TEPEES

Carbonate crusts (Fig. 14) that occur within coastal dune fields of Australia grow around the edges of sea-marginal evaporative lakes which are located on deflation flats close to the sea. The lakes are below sea-level and are sometimes subjected to marine influences (Muir *et al.*, 1980; Ferguson *et al.*, 1982; Warren 1982, 1983a; Handford *et al.*, 1983 & 1984). The crusts usually form in areas fed by marine-derived and/or meteoric groundwaters. However, the aragonite crusts associated with these lakes form at or near the top of the water table of the seasonally exposed deflation flats, usually in saline lacustrine areas where marine groundwaters are returning to the surface (Warren & Kendall, 1985; Handford *et al.*, 1983). One of the most dramatic examples of this influx of seawater can be seen at Lake MacLeod north of Shark Bay where 'vadose pisolites' are growing today in voids immediately below the surface of the crusts (Handford *et al.* 1983). If any of these crusts were found in ancient carbonates, a lack of other data might lead a geologist to classify their setting as peritidal, not lacustrine.

Overthrust carbonate crusts that form by the evaporation of meteoric water are found around the edges of playas in the continental interior, as in the Great Salt Lake of Utah (personal observation), or the Salt Flat Playa in West Texas (Warren & Hussain,

Fig. 13. Pisolitic material and marine travertine from the Carlsbad Group behind the Permian barrier island in Walnut Canyon, Guadalupe Mountains, New Mexico. Note the multiple episodes of cementation.

Fig. 14. Groundwater tepee in the strandline crust of Deep Lake, South Australia. Note the surrounding breccia, tepee is about 0·4 m tall.

1984). In some near-coastal ephemeral saline lakes where resurgence of continental groundwater occurs, carbonate crusts composed of well ordered dolomitic micrite are often developed. In the Coorong region, capillary crusts composed of well ordered dolomite are forming about the strandline of many carbonate lakes. Most of the Holocene dolomite lakes are found a few 100's of metres from the sea, although Holocene dolomitic lakes can be found up to 120 kilometres from the coast (Warren, 1985).

Groundwater tepees (Figs 14, 15)

In the shoreline areas of some southern Australian salinas where gypsum and aragonite precipitate, the tepee expansion mechanism is driven by the lacustrine hydrology. Partially confined upwelling groundwater disrupts and fractures the aragonite-cemented aquitard crust (Fig. 15). Subsequent cementation, fractures, and replacement of primary aragonitic sediment with neomorphic aragonite within the expanded surface crust may cause a slight increase in the volume of the crust. Seasonal increments of extra volume create large overthrust polygons whose tepee margins are up to 0·8 m tall and megapolygon saucers up to 60 m across (Warren, 1982). Such tepees can be distinguished from other tepees and recognized in the ancient by remnants of an underlying boxwork limestone or palaeoaquifer (Fig. 16) or stromatolite/oncolites sitting atop tepee sutures (Warren, 1983a). These tepees are defined as groundwater or boxwork tepees.

Extrusion tepees (Figs 17, 18)

In South Australia, the ephemeral magnesian-carbonate lakes of the Coorong Region occur some 120 km west of the salinas where the groundwater tepees just described are forming. There are two types of tepee

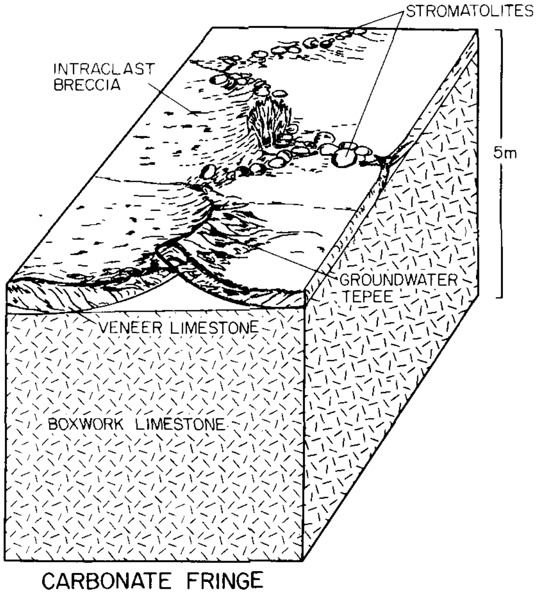

Fig. 15. Groundwater tepees from the Holocene strandline carbonates in southern Australian salinas. Resurging marine-derived groundwater flows up into the gypsum-depositing lake through the carbonates of the lake margin. The tepee sutures act as conduits for groundwater after passing through the underlying boxwork limestone. For this reason many tepees are capped by millimetre-laminated stromatolites.

structures within the shoreline of these lakes, and their expansion mechanisms are slightly different.

In Coorong Lakes with an early Holocene marine connection, tepee crusts occur which were formed in skeletal grainstone units containing a relatively open marine shelly fauna cemented by acicular aragonite (Warren *et al.*, 1984). Such aragonite-cemented crusts are often underlain by a marine skeletal packstone/grainstone unit. These crusts and the underlying shoreline facies record an earlier time when these lakes were the shoreline segments of early Holocene marine embayments. The crusts are best interpreted as marine supratidal hardgrounds in which peritidal tepees formed. The cracks in these crusts were probably initiated by thermal expansion and contraction.

Actively forming tepees occur in the same lakes further out into the lake, away from the high water shoreline (Figs 16, 17). These tepees formed as a result of overthrusting of a cracked dolomitic micrite crust. These dolomite crusts record a time when the same ephemeral lakes were cut off from the sea by beach ridge accretion across the former lake-chain entrance (Warren *et al.*, 1984). The mechanism of crust induration is believed to be related to carbonate precipitation from evaporating capillary waters that supply ions to these surface sediments. The cracks that usually occur in them were initiated as desiccation sutures which filled with mud and then hardened.

Fig. 16. Modern boxwork limestone beneath a tepee-affected limestone crust from Marion Lake, South Australia (Warren, 1982).

Fig. 17. Extrusion tepees in a dolomitic crust about the strandline of an ephemeral lake in the Coorong National Park, South Australia. Note the successful matching cements on either side of the infilled crack (Fig. 18). The end result of this process is overthrusting (tepees) of the capillary crust.

These crusts were and are periodically enveloped in a yogurt-like carbonate mud gel. This mud infill was and is bathed by resurging brackish to hypersaline continental waters (Muir *et al.*, 1980; Eriksson & Warren, 1983). Successive episodes of crack-infill and drying cause the crust to expand and overthrust as the crack widens. In such carbonate-mud dominated settings, far removed from a surface connection with seawater, the mechanisms of crust and tepee formation differs from the earlier, slightly more landward zone of Holocene supratidal marine hardgrounds which can be sometimes found in the same lake but in a more marginward position.

At times of lowered water levels in the lake (which are related to a mixed marine and meteoric water-table), groundwater resurges onto the lake floor through the underlying muds, up through the crack sutures, and out into the overlying sediments and the lake water column. Due to the extremely fine grain-size of unconsolidated Coorong muds (microns), this escaping water carries some of the underlying mud up into the cracks. This covers the wall of the crack fracture with another thin layer of mud. Subsequent evaporative lowering of the lake waters exposes the crust and the crack to the capillary or vadose zone. Mud enveloping the crust dries and contracts, reopening the previously mud-lined crack. Mud can now be blown or washed into the cracks from above. Subsequent evaporation dries the sediment and precipitates cements that bind the mud lining onto the walls of the crack. Today, successive layers of mud can be seen coating cracks in the crust (Fig. 18). Over time, the accretion of cemented mud linings causes the volume of the crust to increase to a point where it arches, crumples and sometimes overthrusts into a series of brecciated tepee structures. The extruded mud lining the cracks gives a characteristic near-vertical lamination, paralleling the cracks marking the position at which mud appears to have been squirted into from below or in some cases has washed into the cracks from above (Fig. 18). We call tepees dominated by this mechanism extrusion tepees due to the soft sediment deformation of the mud linings.

The successive laminae infilling the fractures associated with this type of tepee can be traced below the crust where the cracks open out into the underlying muds. This characteristic opening out of the laminae below the crust can be used to distinguish the mechanism of expansion from that of crusts where mud infiltration is from above as it is in the Arabian Gulf and Bahamian crusts. Dolomitic extrusion tepees can also be seen in the tepee crusts of the Salt Flat Playa of West Texas (Warren & Hussain, 1984). The best ordered dolomites of the Coorong and this playa occur in the crusts disrupted by tepees rather than in the adjacent unconsolidated muds.

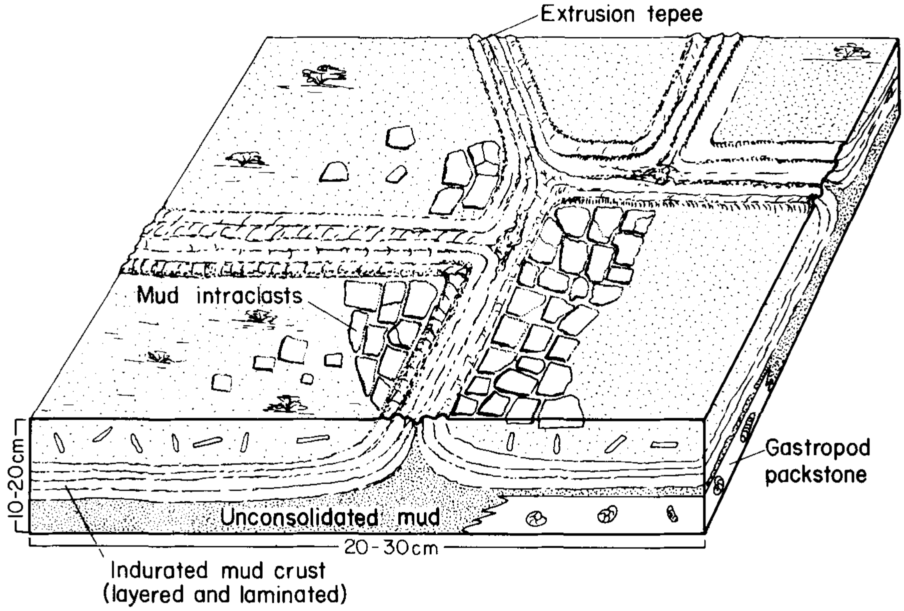

Fig. 18. Extrusion structures in the capillary crusts of the Coorong ephemeral lakes. Note the successive cemented laminae beneath the cemented capillary crusts of the strandline. The expansion process is independent of mineralogy, and crusts can be composed of dolomite, aragonite, hydromagnesite, magnesite and Mg-calcite.

CALICHE CRUST TEPEES

Caliche crusts (calcretes) are continental limestones which are well documented as forming in vadose, capillary and phreatic environments (Netterberg, 1980). They also contain tepees (Klappa, 1980a & b; and Fig. 19). The bulk of modern calcrete crusts are pedogenic horizons forming in arid to semiarid areas of the world in which the annual rainfall is between 300 mm and 500 mm (Reeves, 1976). It is beyond the scope of this paper to present more than a few of the more important characteristics of caliche (Table 1); however, more complete descriptions can be found in excellent papers by Reeves (1976), Netterberg (1980), and Esteban & Klappa (1983).

A caliche develops through several stages (Esteban & Klappa, 1983; Warren, 1983b). First isolated nodules and glaebules (Brewer, 1964) form, usually in an older host rock which may or may not be a limestone. These features often form in conjunction with rhizoconcretions. The buildup of glaebules and micrite eventually plugs the growing caliche profile. An indurated hardpan layer grows above the plugged layer and caps the whole caliche profile. This plugged layer usually contains laminar structures and caliche pisolites. The dominant carbonate mineral in a caliche is low Mg calcite occurring as micrite and occasionally as microsparite. In some places the micrite is replacive while in others it forms a true cement. Radiocarbon dating by Gile & Hawley (1969) suggests that thick plugged caliche profiles take at least 10 000 yrs to form. Caliche crusts appear to take much longer to form than any of the other crust types described in this paper which are all less than 6000 yrs old. A complete caliche profile is often more than 3–4 m thick, but most of it is powdery and unconsolidated. Only the well-cemented carbonate hardpan contains tepees (Fig. 19), but this horizon is usually less than 0·5 m thick. Caliche zones disrupted into tepees often contain laminar crusts (Klappa, 1979, 1980a & b; Netterberg, 1980).

There are two types of tepee structures associated with caliche profiles. One type occurs in the hardpan portion of the caliche where the indurated hardpan layer is brecciated and overthrust. The other type of caliche tepee forms when a calcrete grows in a pre-existing shale sequence. This second type of caliche tepee does not require induration to form the tepee pseudo-anticlines. They grow as powdery calcretes in shale hosts causing extension and crumpling, as in the Dwyka shale of South Africa (Watts, 1977).

Mechanisms forming tepees in indurated continen-

Fig. 19. Modern caliche tepee capping Pleistocene dune sands from Southern Yorke Peninsula, Australia. Note the abundant surrounding breccia. Lens cap for scale.

tal crusts or caliches have not been well studied. Assereto & Kendall (1977) suggest that the force of calcite crystallization within the plugged hardpan layers of a mature calcrete creates caliche tepees. Similarly, Watts (1977, 1978) suggests caliche tepees are due to the growth of displacive micrite within the profile. In contrast, because caliche tepees are usually surficial and associated with breccias Klappa (1980a & b), and Esteban & Klappa (1983) suggest that caliche tepees are actually associated with zones of caliche reworking. They further suggest that it is the pressure of the growing of near-surface tree roots which forces apart tepee blocks which we see in mature hardpan calcretes. It is our contention that in mature caliche profiles, force of crystallization and 'rhizobrecciation' are both active.

Tepees in caliche hardpans are relatively rare. When they do form, they grow as a result of the breakdown and dissolution of this hardpan, or by emplacement of micrite which increases the volume of the hardpan layer. Often, plant roots grow into the hardpan, forcing the indurated hardpan into the inverted 'V' shapes of tepees (Klappa, 1980a; Esteban & Klappa, 1983). Examples of Holocene caliche tepees can be seen in coastal dunes lining the carbonate shelf shorelines of Spain and southern Australia (Klappa 1980a; Warren 1983b) (Fig. 19) while ancient caliche tepees have been found in carbonate shelf sediments where sea-level lowering has exposed them. An example of this is the Carboniferous Newman Limestone of Kentucky (Fig. 20) (Ferm *et al.*, 1971; Inden & Moore, 1983). As in the Bathonian of Normandy, some of these Carboniferous tepees are formed above cemented carbonate mounds by the compaction of the sediment adjacent to mounds and the brecciation of the overlying laminated soil horizon (personal observation).

CONCLUSIONS

In many ancient shelf carbonates, if their depositional setting is to be determined, it is often important to define the trend of the strand line. Tepees can be used to do this, though if an ancient crust is disrupted to form these features, these tepees alone are not an indicator of a nearby shoreline.

Three types of tepees occur in cemented carbonate crusts in shoreline and near-shoreline positions, namely the peritidal tepees, the groundwater tepees and the extrusion tepees. Two of these types, groundwater and extrusion tepees, are associated with active groundwater flow in Holocene salinas of the older limestone areas behind the zone of active tepee formation (Warren, 1982; Eriksson & Warren, 1983). That is, groundwater tepees and extrusion tepees both

Fig. 20. Tepees in a caliche profile which caps a beach-barrier lagoonal sequence in the Newman Limestone (Carboniferous) in Kentucky. Geological hammer for scale.

need substantial groundwater heads in order to grow. Zones of tepee formation are affected by a great deal of active meteoric (and in some cases marine) groundwaters and so are often locations of active carbonate diagenesis, dissolution and secondary porosity development. Potentially porous strata which occur in association with groundwater and extrusion tepees are to be found not only in the porous sediments immediately below groundwater tepees (boxwork limestones and other palaeoaquifers), but will also occur in the topographically higher positions in the adjacent hinterland.

Modern groundwater and extrusion tepees are forming in the strandline zone of relatively quiet, shallow water evaporitic lakes and lagoons where there are no porous high-energy facies basinward of the shoreline. This is not the case with peritidal tepees found along the shore of the present Arabian Gulf (Warren & Kendall, 1985). There, these tepees are forming landward of a high-energy oolite and reef margin shoreline. The tepees are sandwiched between an overlying, prograding, anhydrite-cemented supratidal unit with algal peat and an underlying prograding subtidal/intertidal carbonate sand (a potential hydrocarbon reservoir, especially if dolomitized).

Tepees forming in a caliche profile mark unconformities in a continental setting. Caliche zones below the tepees are usually impermeable and form a carapace which hinders erosion and encourages preservation of the paleosol. However, caliche tepees are often associated with zones of underlying and adjacent karst which are sites of extensive meteoric diagenesis (Esteban & Klappa, 1983; Inden & Moore, 1983; Warren, 1983b).

In palaeogeographic reconstructions, it is important to be able to distinguish caliche tepees from shoreline/strandline associated tepees. However, examples of caliche tepees developed on marine carbonates following a lowering of relative sea-level as, for instance, the Mississippian Newman Limestone of Kentucky (Ferm *et al.*, 1971; Inden & Moore, 1983), indicate that caution must be used in interpreting these features.

Submarine crusts which form tepees, like caliche tepees, do not record the effects of specific environmental conditions; rather they form as cemented layers and hardgrounds in grainstone and packstone units in waters with depths of up to 30 m. As such, they are passive layers which do not reflect any particular shelf facies. For instance in the Devonian of the Canning Basin the deformed sediments are laminated basin margin micrites (Fig. 4) (Playford *et al.*, 1984). In contrast, some ancient Jurassic submarine tepees in the Bathonian of Normandy are in shelf carbonates and the tepees grew by the preferential compaction of submarine hardgrounds over cemented sponge reefs (Fursich & Palmer, 1979).

Tepee-affected crusts often contain cements which are specific to the environment of formation. When first formed, cements associated with the marine crusts tend to be composed of aragonite or high Mg calcite. The aragonite cements are usually composed of acicular crystals, while the high Mg calcite is often micritic but can range from equigranular to bladed. Cements in caliche tepees are mainly composed of low-magnesian calcite precipitated from meteoric waters (Folk & Land, 1975). Dolomite cements are also found in continental environments, especially in areas with schizohaline continental waters or marine-meteoric mixing zones (Muir *et al.*, 1980; Eriksson & Warren, 1983). The fabrics and textures in the tepee-affected crust, along with the presence or absence of the following: 'vadose pisolites', solution collapse boxwork limestones after evaporites (Fig. 16), the restricted versus open nature of the enclosed skeletal grains, and the other factors listed in Table 1, allow a determination of the setting of crust formation. It is from the fabrics preserved in the crusts that the first level environmental determination comes; not the actual presence of tepee structures. Once the general setting has been determined, the tepees give a fine tuning to this model since their presence can be used to determine areas of groundwater resurgence, shorelines, strandlines, and unconformities (Table 2).

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