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Desert gypsum crusts as palaeoenvironmental indicators: A micropetrographic study of crusts from southern Tunisia and the central Namib Desert

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Desert gypsum crusts are of three main types: shallow-water evaporites, which are characterized by size-graded beds; subsurface crusts, which are either macrocrystalline groundwater evaporites, or mesocrystalline illuvial accretions; and surface crusts—excluding the bedded type—which are exhumed illuvial crusts. Pedogenic processes involving the leaching of gypsum-rich surface deposits and subsequent displacive gypsum crystallization in the lower soil zone account for the formation of the illuvial crusts. The various forms of surface gypsum crust—columnar, powdery, and cobble—represent different stages in the degradation of exhumed crusts. Dissolution and leaching of gypsum transform columnar crusts to cobbles which deteriorate leaving a powdery residuum.

Examination of thin sections of gypsum crusts from southern Tunisia and the central Namib Desert reveals that the exposure and degradation of illuvial, pedogenic crusts are characterized by distinct diagenetic features. The subsurface, illuvial crusts are composed predominantly of mesocrystalline (50 μm to 1·0 mm in diameter), lenticular gypsum. Crystals larger than 1·0 mm sometimes have poikilitic inclusions, though these features are more common in the macrocrystalline groundwater crusts. Rarely, fibrous gypsum crystals—indicative of displacive crystallization—are found in the illuvial crusts. Syndepositional and early diagenetic features include biogenic structures and calcite pseudomorphs after lenticular gypsum. Columnar surface crusts are composed predominantly of albastrine gypsum (crystallites less than 50 μm in diameter). This texture develops through rapid gypsum crystallization following partial dissolution of lenticular crystals by infiltrating meteoric water. When large crystals occur as isolated remnants (porphyroblasts) in the surface crusts, they typically exhibit dissolution features and, occasionally, alabastrine overgrowths.

The recognition of these characteristic structural and textural features in relict gypsum crusts can provide detailed information about the geomorphic history and palaeoenvironments of many arid regions. Radiometric dating of gypsum palaeosols is problematic because of their illuvial origin. Nevertheless, evidence suggests that the gypsum crusts of southern Tunisia developed in the early Holocene following desiccation of the chotts which had been inundated during the late Pleistocene. Evaporation of the lake waters precipitated gypsum which was then deflated and redeposited on the surrounding landscape. From here it was leached into the lower soil zone and illuvial gypsum crusts accreted. Subsequently, these pedogenic crusts were exhumed and the gypsum is currently being leached into the lower soil zone once again. In the central Namib Desert, the ages of the gypsum crusts are uncertain. Notwithstanding the difficulty in obtaining radiometric dates, studies of the gypsum's isotopic composition have

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provided valuable information on palaeoenvironments, and are a promising area of future research. Some of these studies have suggested that the crusts in the Namib are recent features. However, several 14C dates and also calculations of the theoretical rates of accretion indicate that the crusts may have formed during the late Pleistocene. If this is the case, their preservation supports the view that the Namib Desert has remained arid throughout the late Pleistocene and Holocene.

Introduction

Gypsum accumulations are found at or near the land surface in parts of all the earth's desert regions (Watson, 1983). They are usually confined to warm deserts where mean annual rainfall is less than about 250 mm (Watson, 1985). However, in cooler arid regions, such as the Namib Desert of south-west Africa, the upper rainfall limit may be as low as 50 mm/year. Generally, the accumulations are found in areas where gypsum is deposited on the land surface by atmospheric processes or by the evaporation of surface waters. The accretion of crusts within the regolith—usually no more than 10 m beneath the surface—is most commonly attributable to either groundwater influences or pedogenic processes. Relict crusts occurring at the surface or within the soil zone have been employed to reconstruct past climates and environments. In some instances, crusts have been interpreted as evidence of former high sea-levels (Wieneke & Rust, 1976) or higher water tables (Srivastava, 1969; Kulke, 1974) and lake levels (Tolchl'nikov, 1962; Coque & Jauzein, 1967; Horta, 1979, 1980). In other cases, pedogenic crusts have been attributed to phases of climatic transition when climates become more arid as a result of either higher temperatures or reduced rainfall (Coque, 1955*a*,*b*, 1958, 1962: pp. 99–101; Page, 1972). In southern Tunisia, where surface crusts are widespread, Coque (1962: p. 98) held that 'les croûtes ne sont plus que les constructions mortes'.

Gypsum crusts and soils may be broadly defined as surficial and penesurficial accumulations containing at least 15% gypsum by weight (D'Hoore, 1964) and at least 5·0% more total gypsum than underlying bedrock (Buringh, 1968). A number of types have been distinguished (Coque & Jauzein, 1967; Vieillefon, 1976); some reach thicknesses of more than 4·0 m (Goudie, 1972; Kulke, 1974) and some contain over 90% gypsum (Page, 1972; Warren, 1982). Using structural and stratigraphic criteria, three main types of gypsum crust have been identified (Watson, 1979, 1983, 1985). Their characteristics are here briefly outlined.

1. Horizontally-bedded crusts, found at or beneath the land surface, are often made up of discrete strata up to about 0·10 m thick. Each stratum exhibits graded bedding of gypsum crystals from microcrystalline material (crystallites less than 50 μm in diameter) at the top, to large lenticular crystals (greater than 50 mm in diameter) at the base. Tepee structures (Warren, 1983) at intervals from 0·50 to 2·0 m laterally are a common feature of these crusts.
2. Subsurface crusts, generally found more than 0·50 m beneath the land surface, are divided into two distinct forms. The first is made up mainly of large, lenticular crystals up to 0·50 m in diameter; these are termed desert rose crusts. The second is a mesocrystalline form composed of lenticular or prismatic crystals up to about 1·0 mm in length. This form often exhibits weakly developed columnar structures essentially the same as those encountered in some surface crusts.
3. Surface crusts, other than the bedded type, are subdivided into three forms. The first comprises indurated, columnar crusts made up of roughly hexagonal columns from 0·25 to 0·75 m in diameter which extend through the full thickness of the crust, generally 1·0 to 2·0 m (Fig. 1). These columnar crusts are composed predominantly of microcrystalline gypsum (crystallites less than 50 μm in diameter). The second form consists of powdery accumulations. These have a great variability in their gypsum contents. The third is an intermediate form which consists of cobble and boulder-size

Figure 1. Columnar, surface gypsum crust developed on Neocomian clays south of Chott el Fedjedj, southern Tunisia (Fig. 3, site EH).

masses of microcrystalline gypsum (Fig. 2). The flat, upper surfaces of the cobbles are flush with the land surface and the undersides are set in accumulations of powdery, gypsiferous material.

While these constitute the most common types of desert gypsum crusts, a number of other forms have been reported. These include bedded crusts composed of large, prismatic selenite crystals (Bellair, 1954; Warren, 1982) and nodular accumulations (Fathi *et al.*, 1973; Ali & West, 1982). It has also been suggested that since atmospheric deposition is often the main source of gypsum in the crusts, some surface forms may be aeolian sediments which have been cemented *in situ* (Coque, 1955*a*,*b*, 1958, 1960, 1962; Tucker, 1978; Warren, 1982). Most of the surface crusts described here, however, have a scatter of pebbles or rock cobbles at the surface (Fig. 2). These often occur on hilltops or on broad plains where the gravelly materials could not have been deposited by fluvial processes or mass wasting. It is possible that pebbles and cobbles migrate upwards through surficial materials as a result of volumetric changes in the deposits during wetting and drying cycles (Jessup, 1960; Ollier, 1966; Cooke, 1970). However, these processes

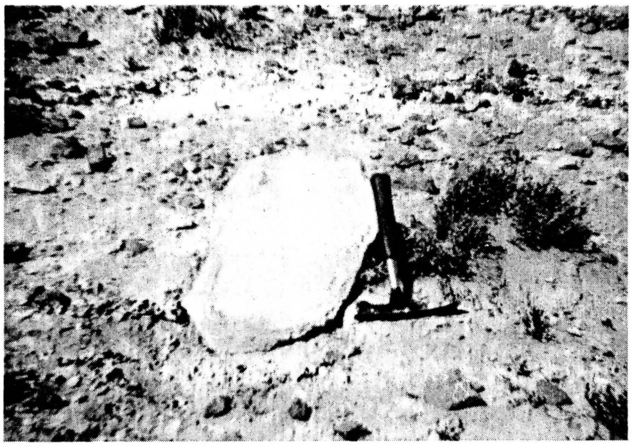

Figure 2. Large gypsum cobble set in a powdery gypsum accumulation, southern Tunisia (Fig. 3, site LI). Note the lag deposit of pebbles and cobbles of Turonian limestone upon the surrounding, encrusted surface.

usually occur in materials containing expansive clay minerals, especially smectites. Since these are uncommon in the gypsum crusts described here (Watson, 1980), it is likely that the surficial gravels are lag deposits which remain following erosion of finer materials.

Previous work (Watson, 1983, 1985) suggested that the mesocrystalline subsurface crusts and the various surface forms have a similar origin. The purpose here is to examine the micromorphology of the non-bedded varieties of gypsum crusts, to elucidate the relationships between the various forms, and to characterize the processes involved in their evolution and diagenesis. Earlier work has provided a detailed genetic classification of the different types of crusts based upon their structure and chemistry (Watson, 1985). It is now appropriate to present a model of gypsum crust evolution based upon petrographic criteria; criteria which may be readily employed in the field and laboratory without resorting to complex chemical analyses.

This discussion will rely upon petrographic data from gypsum crusts in southern Tunisia (Fig. 3) and the central Namib Desert (Fig. 4) for which geochemical and mineralogical information has been presented elsewhere (Watson, 1985). The crusts of Tunisia and neighbouring parts of Algeria have been widely employed in palaeoenvironmental reconstructions (Stainier, 1912; Agafonoff, 1936; Coque, 1951, 1955*a*,*b*, 1958; Le Houérou, 1960; Zimmerman, 1963; Page, 1972). In contrast, relatively little work has been undertaken on the significance of gypsum crusts in the Namib (Ward *et al.*, 1983; Ward, 1984) though they are widespread (Martin, 1963; Scholz, 1963, 1968, 1972). In studies by Rust & Wieneke (1973, 1976), Wieneke & Rust (1973*a*,*b*, 1975, 1976), and Rust (1975), these crusts were interpreted as important indicators of periods of aridity and geomorphic inactivity during the late Pleistocene and Holocene. However, little information is available on the types of gypsum crusts which were examined; such information is a prerequisite to their use as palaeoenvironmental indicators.

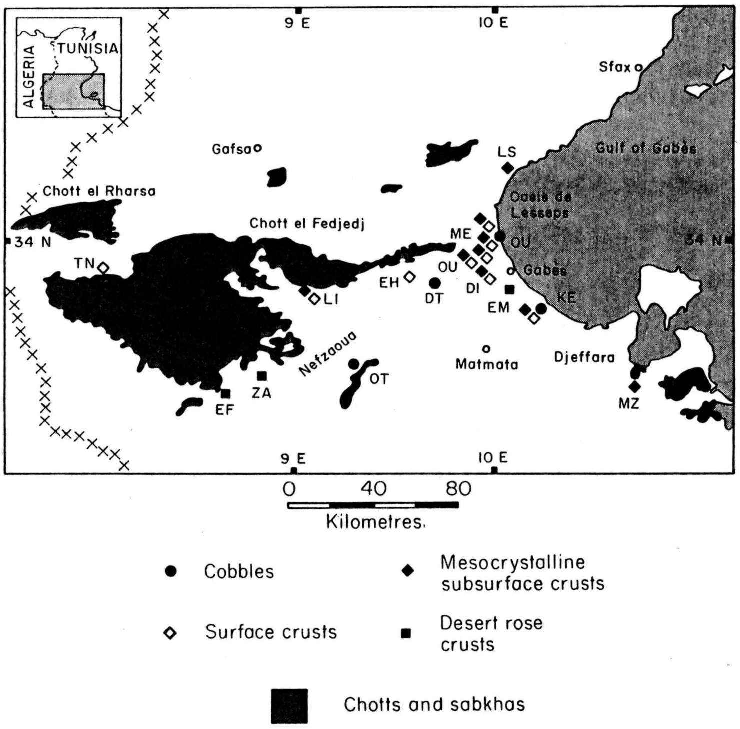

Figure 3. Southern Tunisia showing location of sampling sites.

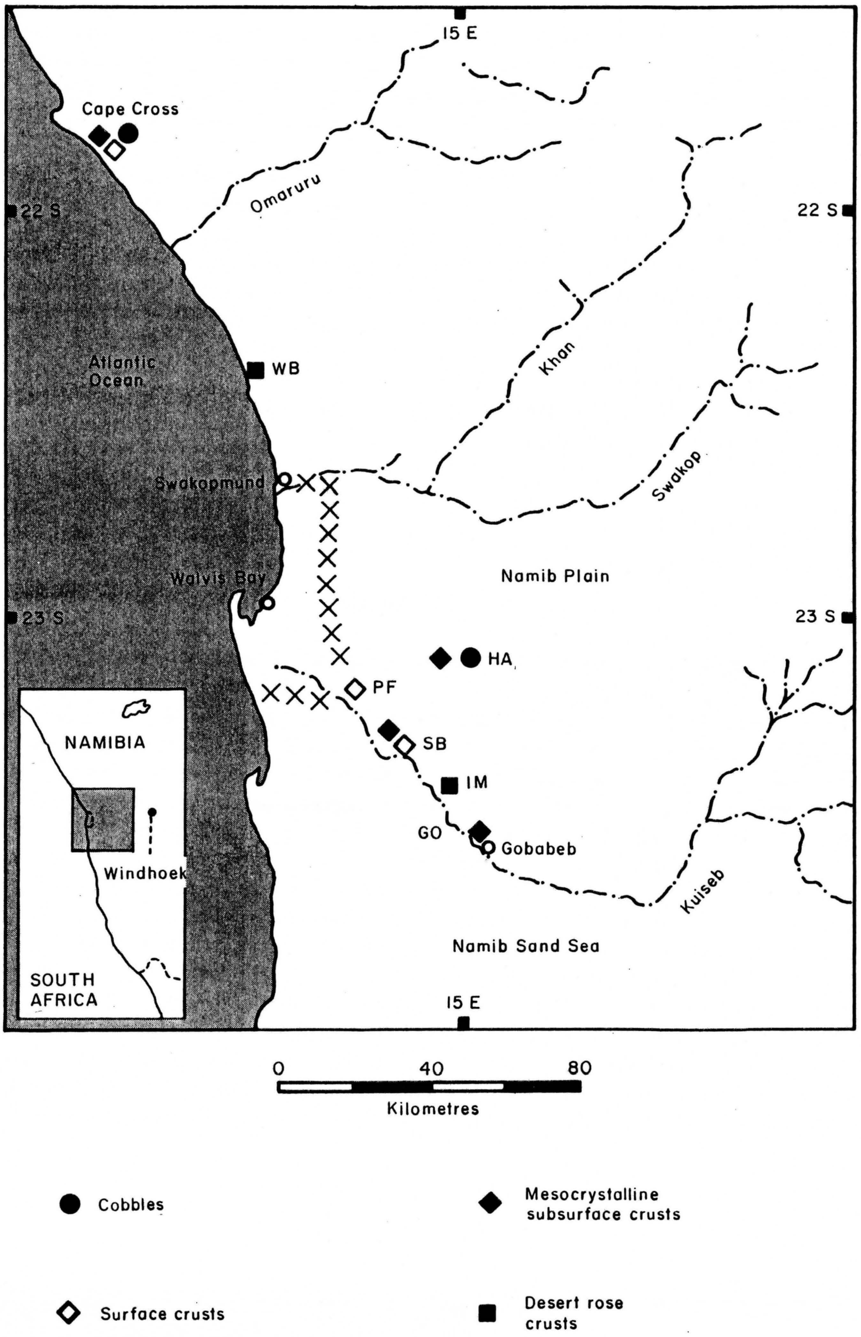

Figure 4. The central Namib Desert showing location of sampling sites.

Field areas

In southern Tunisia (Fig. 3), gypsum crusts are found around seasonally flooded basins, called chotts or sabkhas. Gypsum in Cretaceous bedrock is dissolved in groundwater which floods the basins in the cooler winter months; gypsum precipitates when the waters evaporate. Subsequent deflation redistributes the gypsum on the surrounding terrain, a process which was apparently more prevalent at the end of wetter periods during the Pleistocene (Coque, 1958, 1962: pp. 99–101). The gypsiferous, aeolian deposits undergo dissolution and leaching by meteoric water; gypsum reprecipitates in the soil zone forming illuvial, mesocrystalline crusts (Page, 1972). This same model has been invoked to explain calcrete formation (Brown, 1956; Ulrich *et al.*, 1959; Arkley, 1963, 1967; Gile *et al.*, 1966).

In the central Namib Desert, gypsum is not present in the bedrock. Here an atmospheric origin is most likely. Hydrogen sulphide, formed on the sea-floor by bacterial action, is released into the atmosphere and dissolves in fog moisture. Hydrolysis and oxidation in the presence of metal ion catalysts (Holt *et al.*, 1978) form sulphates which are precipitated on the land surface. About 120 kg soluble salts/ha/year may be deposited (Boss, 1941). While only a small portion of this may be calcium sulphate, other sulphates may form gypsum through cation exchange in the soil adsorption complex (Krupkin, 1963). Again, leaching and recrystallization produce illuvial, mesocrystalline gypsum crusts.

Provided that rainfall is insufficient to flush the soil zone, carrying water-soluble salts to the water table, and provided that soluble salts are available at the land surface, thick illuvial crusts can accrete. The various surface crust forms are attributed to the exhumation of the mesocrystalline subsurface form through the erosion of unconsolidated surficial material by wind or slope processes (Akhvlediani, 1962). In this respect, the surface forms are indeed relict features as Coque (1962: p. 98) suggested. Exposure of the crust promotes degradation as a result of dissolution by meteoric water moving through the upper soil zone. Columnar crusts degrade to cobbles; these gradually decrease in size leaving an unconsolidated residue. The same types and forms of subsurface and surface crusts are represented in the two field areas.

Methods

A total of 70 samples of non-bedded varieties of gypsum crusts were thin-sectioned. These comprised: 12 gypsum cobbles (10 from Tunisia and 2 from the Namib); 19 columnar surface crusts (15 from Tunisia and 4 from the Namib); 27 mesocrystalline subsurface crusts (21 from Tunisia and 6 from the Namib); and, for comparative purposes, 12 desert rose crusts (5 from Tunisia and 7 from the Namib).

Thin sections were prepared in the absence of water to prevent excessive dissolution of water-soluble minerals. The thin sections were ground under acetone to prevent dehydration of gypsum to hemihydrate (bassanite).

A number of terminologies have been employed to describe the microstructural and microtextural features found in gypsum rocks. Some have been adopted exclusively in the study of penesurficial, pedogenic and evaporitic gypsum lithofacies (Stoops, 1978; Arakel & McConchie, 1982; Warren, 1982). However, since the textural terminology employed in the study of gypsum bedrock is more familiar (Hammerschmidt, 1883; Bundy, 1956; Holliday, 1970; Mossop & Shearman, 1973; Schreiber & Hsü, 1980), it will be used here. It should be pointed out that some of the textural terms have genetic connotations associated with the metamorphic processes which occur when anhydrite bedrock hydrates to gypsum. Here, however, these terms are used solely in their descriptive senses.

Results

Gypsum crystals have a variety of forms. In thin section, they most commonly appear as rhombic (lozenge-shape) crystals which represent cross-sections of lenticular (discoidal) crystals. For the purposes of this examination, the textures which prevail when these lenticular crystals occur *en masse* are divided into those made up of crystals greater than 1·0 mm in diameter (Fig. 5) and those less than 1·0 mm but more than 50 μm (Fig. 6). This lower limit is arbitrary but generally marks the size below which crystal shape becomes indistinct. Aggregates of gypsum crystals with diameters of less than about 50 μm and cryptocrystalline masses create alabastrine textures (Holliday, 1970) (Fig. 7).

Less common than the lenticular and alabastrine textures, are masses of granular gypsum. These consist of irregularly shaped, interlocking crystals (Fig. 8) which may grade into alabastrine textures when crystal size falls below about 50 μm. Porphyroblastic gypsum crystals generally have a lenticular habit and occur within alabastrine groundmasses (Fig. 9). These isolated crystals are usually from 0·50 to 5·0 mm in diameter. As in

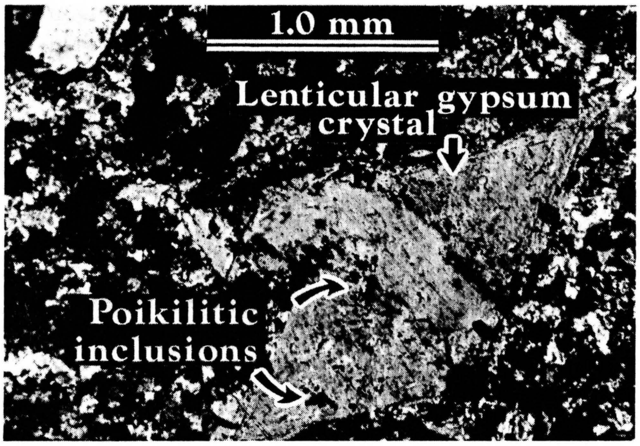

Figure 5. Photomicrograph (crossed nicols) showing large, lenticular gypsum crystals with poikilitic quartz-grain inclusions, Cape Cross, central Namib Desert (Fig. 4).

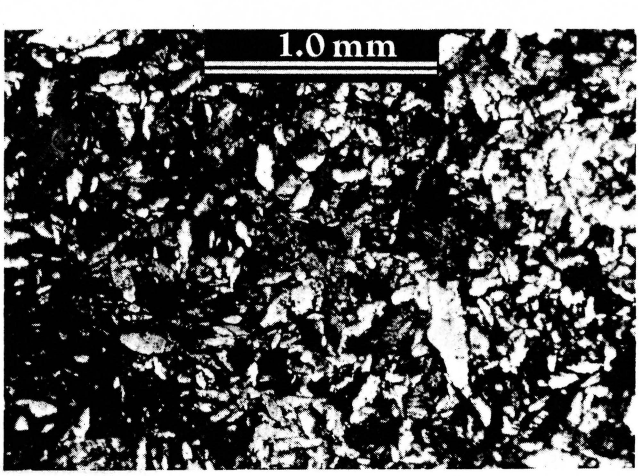

Figure 6. Photomicrograph (crossed nicols) showing a typical groundmass of lenticular, mesocrystalline gypsum.

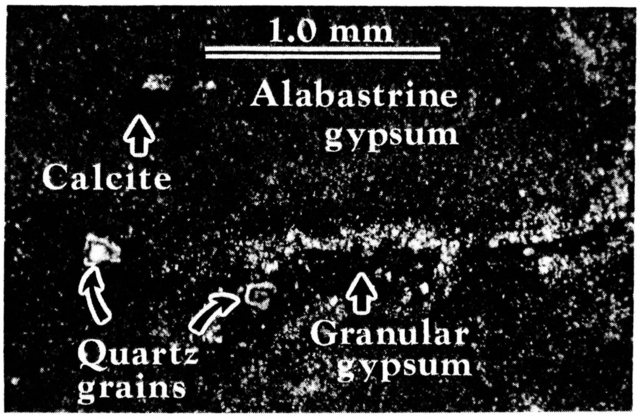

Figure 7. Photomicrograph (crossed nicols) showing an alabastrine gypsum groundmass from a subsurface crust in southern Tunisia (Fig. 3, site LS) Note isolated quartz grains and void-filling mesocrystalline to granular gypsum.

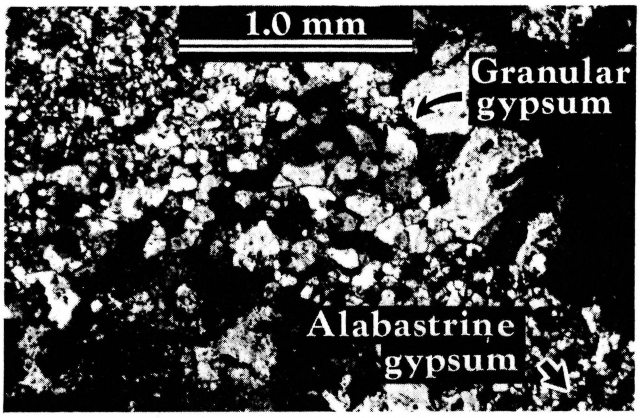

Figure 8. Photomicrograph (crossed nicols) showing a groundmass of granular gypsum crystals grading to alabastrine material. Cape Cross, central Namib Desert (Fig. 4).

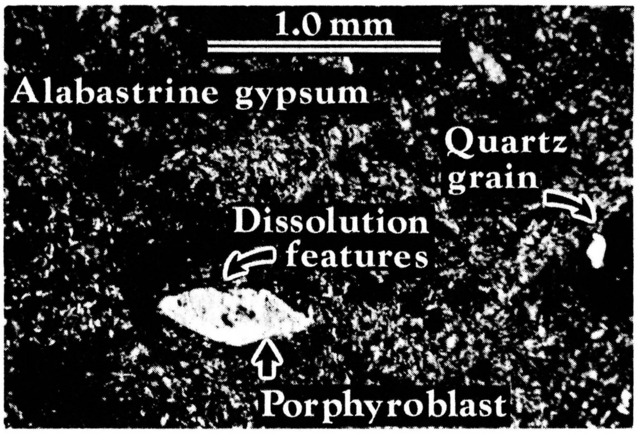

Figure 9. Photomicrograph (crossed nicols) of a lenticular gypsum porphyroblast in an alabastrine groundmass; note the peripheral dissolution features. Sample is from a columnar surface crust in southern Tunisia (Fig. 3, site LI).

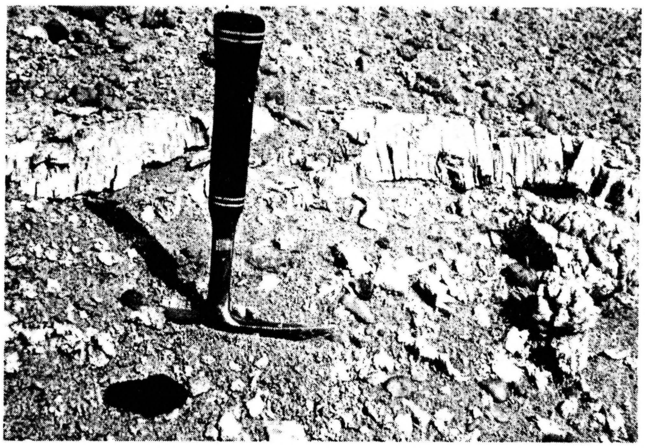

Figure 10. Zone of fibrous gypsum crystals within a surface crust in the central Namib Desert (Fig. 4, site PF).

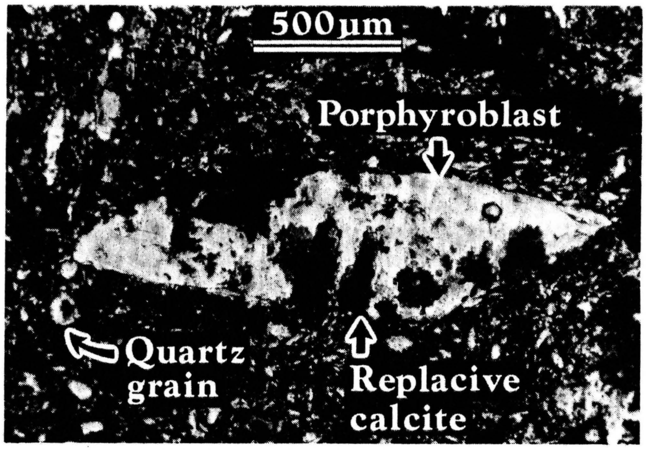

Figure 11. Photomicrograph (crossed nicols) of a large, lenticular gypsum crystal in an alabastrine groundmass; note the dark zones of micritic to sparry calcite which replaced the gypsum along the crystal's cleavage plane (011). Sample is from a subsurface crust at Oasis de Lesseps, southern Tunisia (Fig. 3).

the case of porphyroblasts in some metamorphic rocks (Misch, 1971), those in gypsum rocks and desert crusts may be relics (Holliday, 1970), detrital inclusions, or replacive or displacive crystal growths. The final gypsum texture which is recorded here is the fibrous crystal habit (Fig. 10). Though rarely encountered in these deposits, its occurrence is significant because Watts (1978) suggested that fibrous crystals may be indicative of displacive crystallization.

The description of calcite textures in the gypsum crusts is limited to their subdivision into sparry and micritic forms, aggregates of crystals less than about 100 µm in diameter are classified as micrite. A distinct calcite fabric comprising either sparry or micritic aggregates pseudomorphic after lenticular gypsum occurs in some crusts (Fig. 11).

Clastic quartz grains occur in the gypsum crusts usually as isolated grains within a mesocrystalline or alabastrine groundmass, creating a floating texture. In crusts made up of lenticular crystals greater than 1·0 mm in diameter, and occasionally in those exhibiting

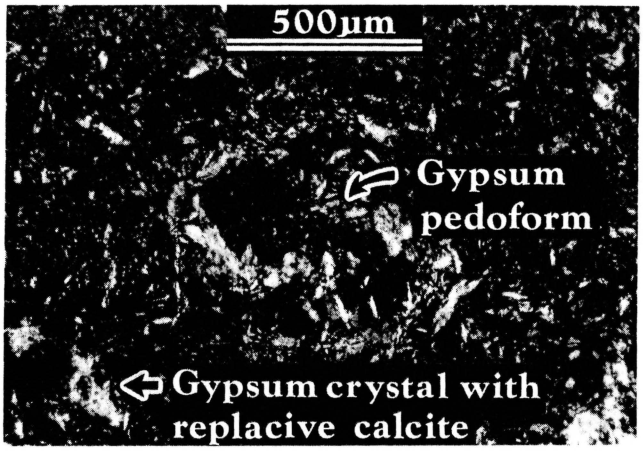

Figure 12. Photomicrograph (crossed nicols) showing pedoforms composed of mesocrystalline gypsum around a core of alabastrine gypsum; the groundmass is of alabastrine and mesocrystalline gypsum. Note the partial replacement of a gypsum crystal by calcite, lower left. Sample is from a mesocrystalline subsurface crust in southern Tunisia (Fig. 3, site OD).

porphyroblastic gypsum crystals, quartz grains may be included poikilitically within the crystals (Fig. 5).

Two final crystalline fabrics common in many gypsum crusts are here collectively termed pedoforms. Consisting of concentric and linear arrangements of either gypsum (Fig. 12) or micritic calcite crystals, the structures are probably biogenic. They may represent infilled burrows of small organisms or root channels.

The micromorphological information from the thin sections of the various crust forms is presented in Figs 13 and 14. In Fig. 13, the data from two sites where more than one crust form is represented in a vertical section are shown to facilitate direct comparison of the micromorphological characteristics.

Discussion

To obtain a general impression of the micromorphological features which typify each of the crust forms, the overall characteristics are shown graphically in Fig. 15. Mean values for the occurrence of the various features have been calculated by ascribing nominal values to their frequencies: 0, if absent; 1, if present; 2, if abundant; and 3, if dominant (see Fig. 13 for the definition of these frequencies). It should be noted that the data presented in Figs 13 and 14 reflect some differences between the crusts in the two field areas. Most noteworthy of these are the absence of fibrous textures in the crusts from southern Tunisia and the virtual absence of pedoforms from the Namib crusts. Both characteristics may reflect the significantly lower mean annual rainfall in the coastal Namib, less than 50 mm compared with about 150 to 200 mm in southern Tunisia. Aridity limits the vegetation cover, so root-fill structures are scarce in the crusts from the Namib. Fibrous gypsum is only very rarely found in modern, surficial deposits. Though it has been reported from southern Tunisia (Gruet, 1954), it does not occur in any of the gypsum crusts described here. Its presence in crusts from the Namib is enigmatic; the extreme aridity and the limited effect of leaching of water-soluble salts near the surface, may account for the preservation of the fibrous gypsum.

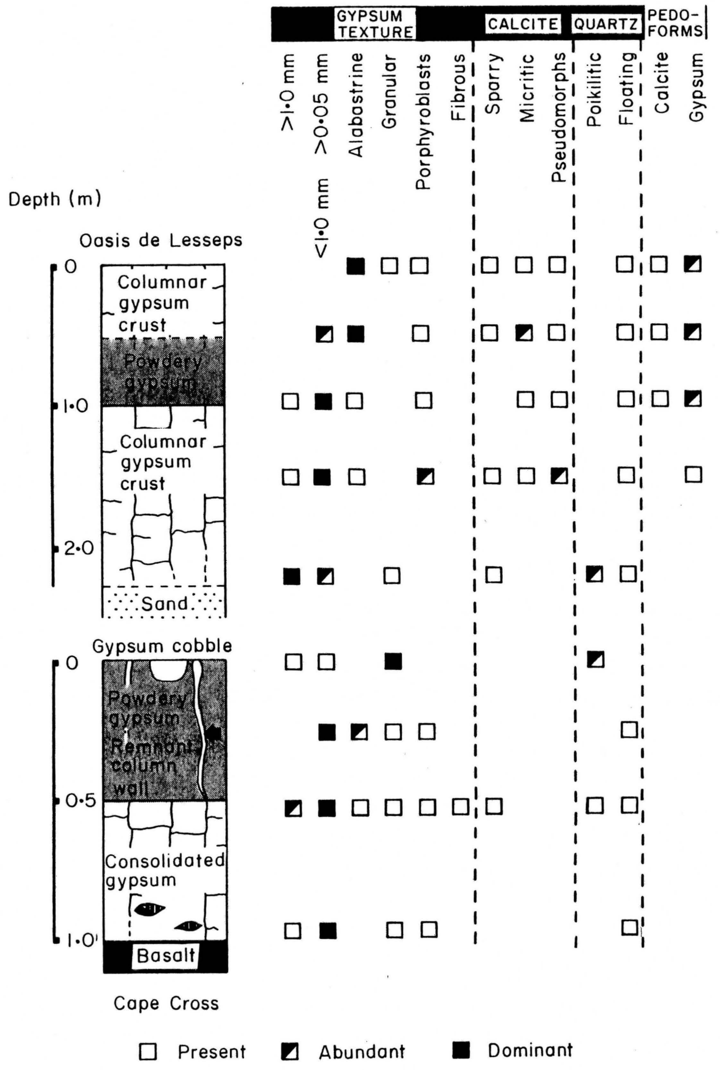

Figure 13. Variation in the frequency of micromorphological features with depth through two sections exhibiting more than one crust form. Lenticular, alabastrine and granular gypsum, and calcite textures are described as *abundant* if they make up more than 20% of the area of the thin section; and *dominant* if they comprise more than 50%. Fibrous textures are described as abundant if they make up more than 10% of the area. In the case of isolated features (porphyroblasts, pseudomorphs, and pedoforms), abundance is defined as one or more in 25 mm^2. An average of more than 5 quartz grains/mm^2 constitutes abundance, and represents about 10% by weight of the bulk sample. A dominance of quartz grains indicates a grain-supported fabric—a rare feature in the crusts described here.

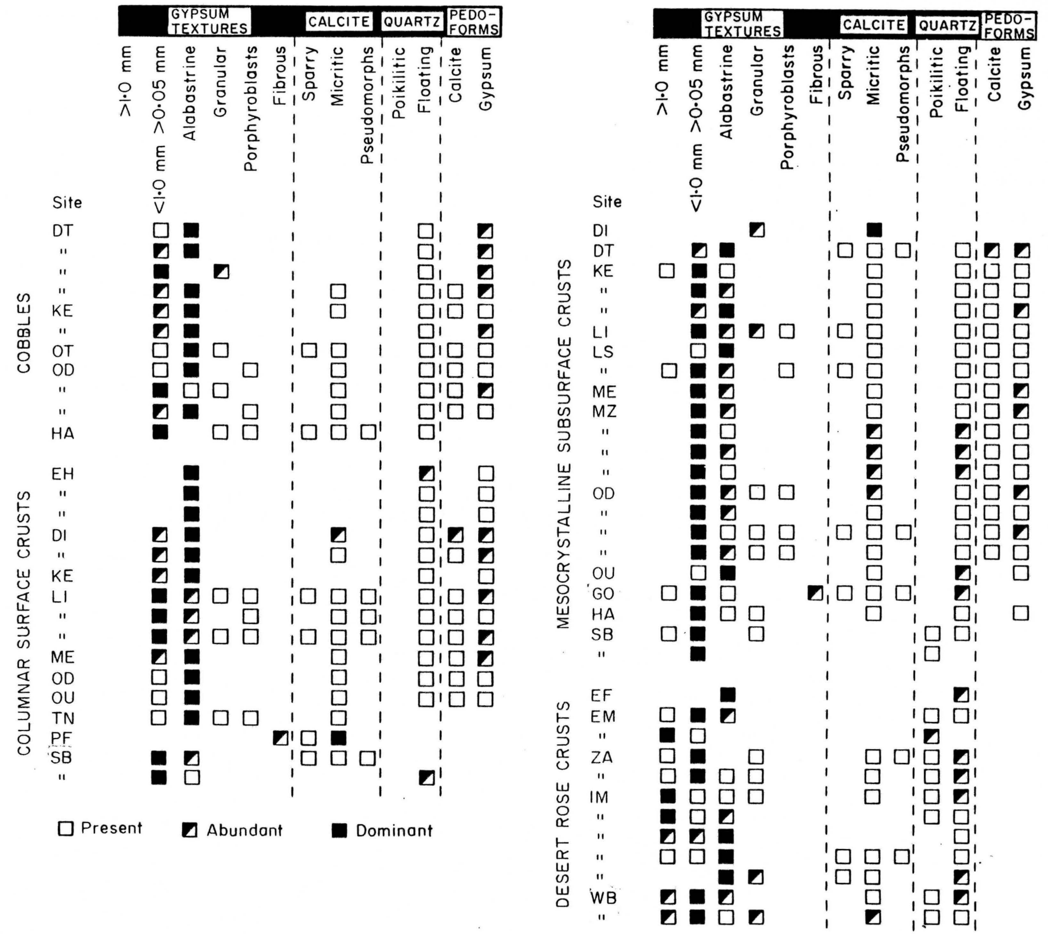

Figure 14. Micromorphological characteristics of the various forms of gypsum crusts in southern Tunisia and the central Namib Desert. Site locations are shown on Figs 3 and 4.

While Fig. 15 is not intended to provide a rigorous, quantitative comparison of the crust forms, it does suggest several broad patterns.

1. While the mesocrystalline subsurface form, columnar surface form, and cobbles are broadly similar in their micromorphological characteristics, the desert rose crusts are distinct. The lenticular crystals (greater than 1·0 mm in diameter) exhibit poikilitic quartz-grain inclusions which are rare in the other crusts. Generally, these crusts contain about 20% clastic material compared with about 10% in the other forms (Watson, 1985). Though mesocrystalline and alabastrine fabrics are common, the overall coarser texture of these crusts results in an absence of porphyroblasts and pedoforms, features which can occur only within fine-grained groundmasses.
2. In mesocrystalline subsurface crusts (characterized by a predominance of crystals from 50 μm to 1·0 mm in diameter), larger crystals may occur towards the base and often contain poikilitic inclusions (Fig. 13, sample from below 2·0 m at Oasis de Lesseps). These are rare in the surface crust forms.
3. Columnar surface crusts differ from the mesocrystalline subsurface form mainly in terms of the prevalence of alabastrine rather than mesocrystalline textures and the

absence of large crystals. Other noteworthy trends are the decrease in the occurrence of micritic calcite and an increase in the frequency of gypsum pedoforms.

4. These last two trends continue in gypsum cobbles. In the case of the pedoforms, this probably reflects the greater abundance of plant roots nearer the land surface. Other than this, surface cobbles generally have the same micromorphological characteristics as columnar crusts, though an increase in the abundance of granular textures is evident.

Petrographic features of subsurface crusts

Both forms of subsurface crust accrete through displacive crystallization of gypsum. In the case of desert rose crusts, this occurs at a near-surface water table; and in the case of mesocrystalline subsurface crusts, it is within the lower soil zone. Poikilitic inclusions within large gypsum crystals attest to displacive crystallization of the desert rose crusts. These features are also found in the deepest horizons of some mesocrystalline crusts (Fig. 13). It is likely that at depth, soil moisture is less frequently depleted than nearer the surface; this permits uninterrupted crystal growth and the poikilitic inclusion of host material (Kastner, 1970). In places where soil-water salinity increases with depth, owing

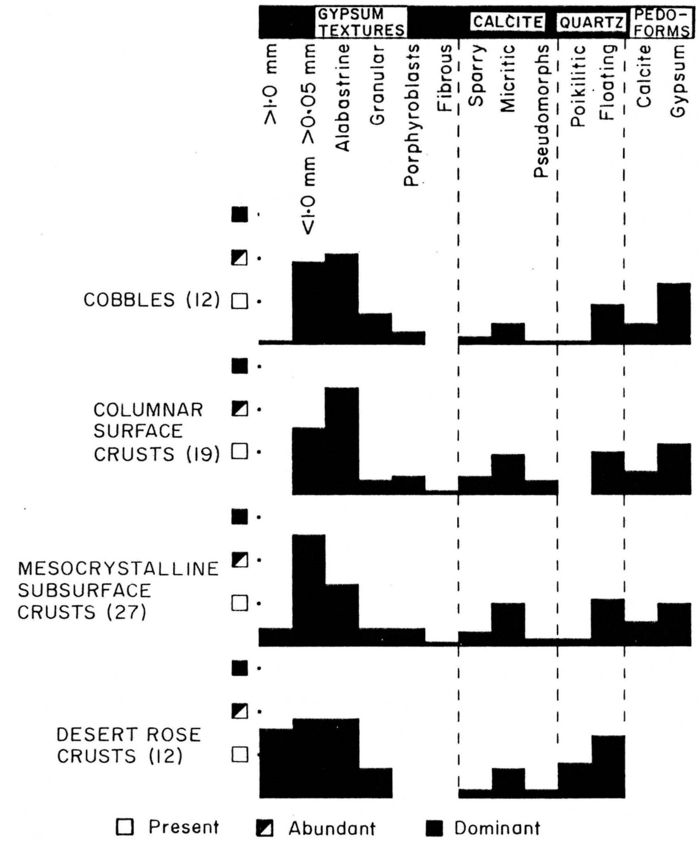

Figure 15. Mean frequencies of the occurrences of micromorphological features in the different forms of gypsum crust in southern Tunisia and the central Namib Desert. Numbers of samples are in parentheses.

to the concentration of leached sodium chloride, gypsum solubility is enhanced (Hill, 1937; Zen, 1965; Pouget, 1968) and the development of the lenticular crystal habit may be stimulated (Masson, 1955; Edinger, 1973). In the Namib Desert, these crusts occasionally exhibit fibrous crystal fabrics (Fig. 10). Such textures have been attributed to tensile strain crystallization under the high pressures associated with the hydration of anhydrite rock (Shearman *et al.*, 1972; Phillips, 1974); viewed under crossed nicols, these crystals typically exhibit undulose extinction. The fibrous crystals found in gypsum crusts exhibit uniform extinction, even when curved, and show evidence of antitaxial growth (outward from the walls of a fissure). Both characteristics are indicative of displacive crystallization (Aljubouri, 1971; Watts, 1978).

These subsurface crusts are generally actively accreting in the two field areas. In southern Tunisia, studies of the levels of tritium in the water of crystallization of gypsum forming the crusts indicate that while the subsurface crusts are accreting, the surface forms are not experiencing crystallization of gypsum from modern meteoric water (Vieillefon, 1980). Syndepositional and early diagenetic features found in the subsurface crusts include pseudomorphic fabrics—lenticular aggregates of calcite crystals, and ghosts of lenticular crystals in calcite masses (Fig. 11). When gypsum crystals show signs of partial replacement by sparry calcite, there are no interstitial voids. This argues that the calcite does not infill voids created by dissolution of gypsum, rather, direct alteration occurs. Such a replacement could be affected by sulphate reducing bacteria (Butlin, 1953) under aqueous, anaerobic conditions. If this is the case, these diagenetic features can originate only in the water-saturated environment wherein the subsurface crusts accrete.

Diagenetic features of surface crusts

Exposure of the illuvial crusts through erosion of the overlying materials brings the gypsum crusts into the upper soil zone, which is leached by downward-moving meteoric water. While this process may eventually destroy the exhumed crust, though the dissolved gypsum may recrystallize in the lower soil zone, a number of micromorphological features characterize this degradation.

The development of columnar structures in the crusts probably originates during illuvial accretion since incipient columniation is evident in many examples which have not been exhumed. The structures may form as a result of volumetric shrinkage during desiccation (Tucker, 1978; Watson, 1980), or thermal contraction (Kocurek & Hunter, 1986), or perhaps partial chemical dehydration (Hunt *et al.*, 1966). Upon exposure, the fissures become the primary paths of water seepage from the surface. This produces characteristic crystalline fabrics on the walls of the columns (Fig. 16). Granular crystal textures are common, probably resulting from rapid crystallization from water supersaturated with gypsum. Since these granular zones are less porous than the alabastrine and mesocrystalline portions, they are less susceptible to dissolution and can persist at the land surface (Fig. 13, Cape Cross). This may account for the greater frequency of these textures in surface cobbles than in the columnar surface and illuvial subsurface forms.

The predominance of alabastrine textures in the surface crusts and cobbles is the main micromorphological characteristic of their evolution from mesocrystalline, illuvial crusts. The development of these textures is associated with the dissolution of lenticular crystals by downward-moving meteoric water, and subsequent rapid recrystallization when soil moisture evaporates. Dissolution predominates over recrystallization and remnant porphyroblastic crystals typically exhibit surficial dissolution features (Fig. 9). During the evaporation of saline soil moisture, ionic migration to gypsum nucleation sites is limited; hence, alabastrine crystallites and sub-crystals form. The effects of this process are well represented in exposed desert rose crusts. Examples from raised beaches—which are probably exposed sabkha facies—along the central Namib coast (Fig. 4, site WB) show diagenetic overgrowths of alabastrine material on large, lenticular crystals (Fig. 17).

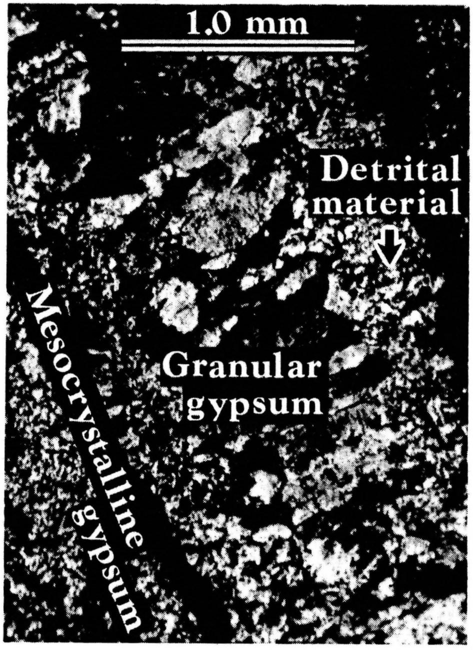

Figure 16. Photomicrograph (crossed nicols) showing granular gypsum textures from the wall of a columnar structure in a subsurface crust in southern Tunisia (Fig. 3, site LI). Note dark bands of micritic calcite and detrital material, and also zone of displacive (?), mesocrystalline gypsum between the detrital and granular material.

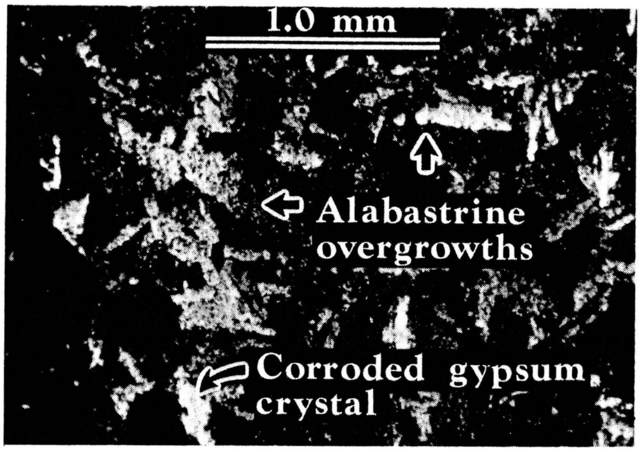

Figure 17. Photomicrograph (crossed nicols) showing alabastrine overgrowths on corroded, lenticular gypsum crytals in an exposed desert rose crust in the central Namib Desert (Fig. 4, site WB).

This micromorphological diagenesis also influences gypsum crust chemistry. Surface crusts and cobbles have lower bulk concentrations of sodium, potassium, strontium, iron, and aluminium ions that illuvial subsurface crusts (Watson, 1985). In part, this reflects smaller quantities of clastic material in the surface forms. However, it is likely that minimal gypsum crystal growth following nucleation limits the coprecipitation of ions (Kushnir, 1980, 1981), residual salts being subsequently leached into the lower soil zone.

The higher average gypsum content of surface crusts and cobbles relative to subsurface crusts may reflect continuing displacive crystallization of alabastrine material (Plet-Lajoux *et al.*, 1971) during diagenesis.

The criteria for identifying the specific type and form of a gypsum crust can be based upon these petrographic characteristics. Desert rose crusts are composed of large lenticular crystals which often contain poikilitic inclusions of clastic host material. Even when the crystals are corroded or exhibit diagenetic overgrowths of alabastrine material, their size and form are diagnostic of a hydromorphic origin. Mesocrystalline subsurface crusts are made up predominantly of lenticular crystals less than 1·0 mm in diameter. Generally, the crystals do not show signs of dissolution, though the occurrence of calcite pseudomorphs after gypsum attests to diagenesis. Occasionally, these pedogenic crusts contain fibrous gypsum crystals which are indicative of accretion through displacive crystallization in the lower soil zone. The various forms of surface crust are exhumed illuvial crusts at different stages of degradation through gypsum dissolution and leaching by meteoric water. They are composed mainly of alabastrine gypsum; any large, lenticular crystals occurring as isolated porphyroblasts usually exhibit surficial dissolution features. A columnar construction is characteristic of the exposed crusts; often the walls of the columns are made up of granular gypsum crystals. Further degradation leads to the formation of individual cobbles composed of alabastrine and granular gypsum, and eventually, upon their dissolution, only unconsolidated material remains.

Palaeoenvironmental implications

In southern Tunisia, the presence of gypsum crusts on pediment slopes (*glacis*) of different ages prompted Coque (1958, 1962: pp. 99–101) to suggest that crusts formed at several periods during the Pleistocene. He felt that each *glacis* formed under conditions of higher rainfall; at which times, the large chotts were perennially flooded. Subsequent aridity caused the lakes to evaporate, precipitating gypsum in the basins. Deflation of the evaporite beds redistributed the gypsum on the surrounding *glacis*; consolidation of the deposits then protected the relict landscape from erosion as the climate became more arid. In the chott region of southern Tunisia, there are usually four generations of *glacis*; the oldest being the highest, and subsequent surfaces being progressively lower. The upper three are mantled by gypsum crusts. Le Houérou (1960) held that the oldest crusts date from the early Pleistocene and that the most recent encrusted *glacis* dates from prior to the last prolonged inundation of the chotts during the Last Glacial. However, evidence of several periods of high lake levels is equivocal (Zimmerman, 1963). Moreover, since the gypsum crusts mantle the breaks-in-slope between the *glacis*, the crusts may date from one phase of chott deflation. Dalloni (1953) and Bureau & Roederer (1961) argued that this occurred before the Last Glacial. Page (1972), however, held that the last phase of chott desiccation and deflation was during the early Holocene, though older crusts dating from before the Last Glacial may be preserved locally, as at La Skhirra (Fig. 3, site LS; Fig. 7).

Based upon the presence in some crusts of stone artefacts of Mousterian typology, Page (1972) felt that the oldest surviving crusts formed more than 28,000 years ago. Two factors make this date questionable; first, the precise age of the Mousterian is debatable; and, second, since the crusts are of illuvial origin, material incorporated within them may be much older. This second point also applies to 14C dates of crusts based upon the dating of material included within them. Hence, the 14C date of 9,500 to 8,000 years B.P. obtained from a bone within a gypsum crust in southern Tunisia (Page, 1972) may not be representative of the age of the crust. Nevertheless, the crust cannot be older than this date and, therefore, must be of Holocene age.

The petrographic data presented here indicate that the forms of surface crust found in southern Tunisia are undergoing dissolution by meteoric water with the gypsum being leached into the lower soil zone. However, rainfall is insufficient to flush the soil zone, and recrystallization of gypsum from evaporating soil moisture is causing the accretion of subsurface, illuvial crusts. This interpretation is supported by studies of tritium levels in the water of crystallization of gypsum forming the different types of crust (Vieillefon, 1980). It is likely that most of the surface and mesocrystalline subsurface crusts date from the early Holocene when conditions drier than during the late Pleistocene were re-established.

Subsurface gypsum crusts, both the desert rose and mesocrystalline varieties, may persist as relict forms if sedimentation prevents their exposure (Pouget, 1968). However, diagenesis following exhumation is a prerequisite for the development of the structural, textural and geochemical characteristics of the surface forms. Hence, their preservation as palaeosols necessitates a transition from surficial erosion to sedimentation. Very few examples of buried gypsum crusts exhibiting the features of surface forms have been described. They may occur in areas where dunes advance over older dunes fossilized by gypsum encrustation (Coque & Jauzein, 1967). Near La Skhirra in southern Tunisia (Fig. 3, site LS; Fig. 7), a thick gypsum crust exhibiting the structural and textural characteristics of a columnar surface crust occurs beneath a true surface form (Page, 1972). In this case, the lower horizon is a former surface crust which was buried by the deposition of gypsiferous dust. The upper gypsum crust probably developed as an illuvial horizon before being exhumed.

Having been exposed, a crust will protect the land surface from further erosion. Phases of exhumation and leaching may be cyclic events unrelated to all but major changes in climate. Nevertheless, in southern Tunisia, the exposure of the present surface crusts may attest to a period of greater aridity than today, at some time following the formation of illuvial crusts in the early Holocene. The current phase of dissolution of surface crusts, accompanied by accretion of subsurface, mesocrystalline crusts, may be a response to conditions wetter than those prevailing at the time of exhumation of the present surface forms.

Most data on climatic fluctuations in the Namib during the Quaternary suggest that 'the current desert regime . . . dates from the late Tertiary, with the Quaternary climatic and eustatic fluctuations superimposed on a dominant, and possibly progressive, aridifying trend' (Ward *et al.*, 1983: p. 181). It has been suggested that gypsum crusts formed during the arid periods following brief, wet interludes in this progressive desiccation (Rust & Wieneke, 1973, 1976; Wieneke & Rust, 1973*a*,*b*, 1975, 1976). However, owing to the difficulties involved in determining the ages of gypsum crusts, the precise chronology of climatic changes in the region is uncertain. Fourteenth century dates from materials incorporated in gypsum crusts on raised shorelines near Walvis Bay (Fig. 4) suggest an age of about 36,000 years B.P. (Hv 5231) for a beach about 17 m above present mean sea level, and about 26,000 years B.P. (Hv 5957 and Hv 5958) for a beach 2·0 m above m.s.l. (Wieneke & Rust, 1976). As has been pointed out, such dates can provide an estimate of only the maximum possible age of the crusts in which the dated material is found. Similar crusts on a raised shoreline 17 m above present sea level at Wlotzkas Baken (Fig. 4, site WB) have undergone micromorphological modification (Fig. 17). The preservation of these relict, hydromorphic gypsum crusts argues that the present phase of aridity has lasted since the crusts formed, perhaps 36,000 years ago, because under wetter conditions, their degradation would be more pronounced. Most other palaeoclimatic evidence supports this view that the Namib was extremely arid during the late Pleistocene (Marker & Mueller, 1979; Ward *et al.*, 1983; Ward, 1984).

The occurrence of gypsiferous playa deposits in some dry pans in the central Namib (Watson, 1985) indicates that there were episodes in the past which were wetter than today. These evaporites can be preserved at the surface only under arid conditions; this same logic applies to relict, pedogenic calcretes (Yaalon & Ward, 1982). However, the age of the gypsum crusts and, hence, the continuity of the current arid phase are difficult to ascertain. It is possible to estimate the age of illuvial, pedogenic crusts from their thickness and theoretical rate of accretion (Goudie, 1973). An accurate estimate requires that surface deposits are the sole source of gypsum (or whatever material the crust is composed of), that deposition rates are constant, and that gypsum is not flushed from the soil zone. The rate of accretion can be determined as:

$$\mathrm{Ct} = \frac{\mathrm{I}}{\mathrm{Cg}} \times \frac{\mathrm{D\,gyp}}{\mathrm{C\,gyp}}$$

where: Ct is the accretion rate in mm/1,000 years;
I is the rate of surface deposition of salts in $g/m^2/year$;
Cg is the specific gravity of the crust;
D gyp is the percentage of gypsum in the surface salt deposit; and
C gyp is the percentage of gypsum in the crust.

A crust containing 80% gypsum and 20% quartz by weight, and having a volumetric porosity of 40%, has a specific gravity of 1.422. With a salt deposition rate of 120 kg/ha/year and a mean chloride/sulphur trioxide ratio of 7.1 (Boss, 1941; Eriksson, 1958), and assuming all chloride combines with sodium and all sulphur trioxide forms gypsum, the surficial salt deposits are 18·37% gypsum. Using these figures, the calculated rate of gypsum crust accretion is only 20 mm/10,000 years. Even assuming the higher salt deposition rates measured by Walter (1937), atmospheric inputs can account for only 0·20 m of crust accretion during the Holocene. Owing to the number of assumptions which must be made using very limited empirical data, such calculations are necessarily rough estimates. However, they suggest that some gypsum crusts in the Namib which are over 3·0 m thick (Knetsch, 1937; Martin, 1963; Goudie, 1972; Rust & Wieneke, 1973, 1976) may have required 100,000 years or more to accrete.

In contradiction to these observations, some studies of the $\delta\,^{34}S$ levels in the sulphate component of gypsum making up the crusts in the central Namib indicate that their ages are similar (Carlisle *et al.*, 1978). If markedly older crusts were present, isotopic fractionation over time would result in a broader range of $\delta\,^{34}S$ levels. It is possible that dissolution of gypsum accumulations in the soil zone followed by recrystallization along with gypsum leached from the surface more recently, gradually equilibrates $\delta\,^{34}S$ levels over time. However, the levels are similar to those in sulphates dissolved in fog moisture; which again suggests that the crusts are recent features. Notwithstanding some potential difficulties in interpreting the data, isotopic studies can provide valuable insights into the origins of gypsum crusts. In the central Namib, data suggest that while sulphur ions are derived from hydrogen sulphide released from sea-floor sediments (Carlisle *et al.*, 1978; Sofer, 1978), $\delta\,^{34}S$ enrichment may occur as the sulphides are oxidized (Jensen & Nakai, 1961) when they are carried inland in fog moisture. This may help differentiate crusts of pedogenic origin from relict sabkha evaporites even after characteristic genetic features (Castens-Seidell, 1984; Warren & Kendall, 1985) are obscured by subsequent diagenesis.

Summary and conclusions

Desert gypsum crusts originate either as shallow-water evaporites, groundwater precipitates, or pedogenic accumulations. In southern Tunisia and the central Namib Desert, pedogenic crusts are most widespread. They develop as mesocrystalline subsurface accretions through displacive crystallization from evaporating soil moisture which contains gypsum leached from the surface or upper soil zone. In southern Tunisia, evaporites deflated from periodically flooded chotts are the main source of gypsum. In the central Namib, fog moisture is probably the principal source of sulphates. The various forms of surface gypsum crust—columnar, cobble, and powdery—represent different stages in the degradation of exhumed illuvial crusts.

Each of the types and forms of desert gypsum crust is characterized by distinct petrographic features. Shallow-water evaporites and groundwater precipitates are readily differentiated from the pedogenic forms using macrostructural criteria. The surface evaporites are often bedded, and the subsurface hydromorphic crusts are composed of large, lenticular crystals, hence the term desert rose crusts. Notwithstanding the common origin of the pedogenic crusts, these may also be differentiated using petrographic criteria. Subsurface illuvial horizons are composed of lenticular crystals between about 50 μm and 1·0 mm in diameter which do not exhibit dissolution features. Other important characteristics include the occurrence of calcite pseudomorphs after gypsum and, occasionally, fibrous gypsum crystals.

During the exhumation of a subsurface crust through the erosion of overlying material, micromorphological changes occur. As the land surface is lowered, the illuvial crust enters the horizons which are leached by meteoric water seeping through the soil zone. This results in the dissolution of lenticular gypsum crystals, though subsequent evaporation of residual soil moisture precipitates alabastrine gypsum as overgrowths on remnant crystals. This in turn produces modifications in the chemistry of the crusts. Granular gypsum fabrics form along fissures through which meteoric water seeps; this enhances the columnar macrostructure of the crusts. Columniation persists until the final stages of degradation when residual cobbles set in a powdery matrix are all that remain. Eventually, even the cobbles disappear leaving only a powdery residuum.

This model of gypsum crust development has far-reaching implications. Not the least of these is the extent of surface erosion that the presence of exhumed crusts implies. A surface crust will restrict erosion until leaching and subsurface, illuvial accretion relocate the gypsiferous horizon. Nevertheless, by bearing in mind the structural and diagenetic features which characterize the different types of crusts and stages of their evolution, relict crusts can be valuable palaeoenvironmental indicators.

In southern Tunisia, the widespread occurrence of columnar surface crusts and gypsum cobbles attests to a period of exhumation of illuvial crusts; these probably developed in the early Holocene following the evaporation of lake waters which flooded the chotts during the late Pleistocene. The present phase of leaching of the exposed crusts is accompanied by accretion of another generation of illuvial gypsum crusts in the sub-soil. In some parts of southern Tunisia, the presence of former surface crusts now buried beneath more recent pedogenic crusts, suggests that gypsum crusts also formed prior to the Last Glacial, possibly as a response to earlier cycles of inundation and evaporation of the chotts.

In the central Namib Desert, the palaeoenvironmental significance of the gypsum crusts is equivocal. Data from isotopic analyses of a few crusts suggest that they formed in recent times. However, 14C dates from raised beaches along the coast suggest that some relict desert rose crusts may be up to 36,000 years old. The limited availability of gypsum for crust formation indicates that some pedogenic crusts may be even older. If this is the case, their preservation provides support for the opinion that an arid climate has prevailed in the central Namib throughout the late Pleistocene and Holocene (Ward *et al.*, 1983; Van Zinderen Bakker & Mercer, 1986). Further studies are required before these conflicting findings can be reconciled. Certainly, more studies of the isotopic composition (Carlisle *et al.*, 1978; Sofer, 1978; Vieillefon, 1980) and geochemistry (Kushnir, 1982) of desert gypsum crusts are warranted since they offer great promise for future palaeoenvironmental research in many arid regions.

Sedimentologists have only rarely considered the possibility that ancient gypsum deposits (perhaps converted to anhydrite during deep burial) are other than aqueous evaporites, sabkha sediments, or lithified dune sand. However, pedogenic gypsum crusts are common in many arid regions and their presence in the geological record may have been overlooked. Certain facies of the Dewey Lake Formation of the Permo-Triassic Ochoa Series of New Mexico (Page & Adams, 1940) and of the Upper Eocene Ledian of the Paris Basin (Termier & Termier, 1963: p. 317), have some of the micromorphological characteristics of pedogenic gypsum crusts. Similar facies are important bounding surfaces (Talbot, 1985) and stratigraphic traps for petroleum in ancient aeolian sandstones. The implications of their possible origin as pedogenic crusts should be considered.

Since this paper was accepted for publication, a valuable study of gypsum soils in Wyoming has appeared (Reheis, 1987). Illuvial horizons containing up to 60% gypsum develop through leaching of surficial aeolian deposits and subsurface reprecipitation at the maximum depth of wetting. Based upon current rates of atmospheric deposition, Reheis (1987) estimates that gypsum accumulation has occurred over 600,000 years. Similar calculations by Dan *et al.*, (1982) suggest that some gypsum soils in Sinai have formed over several hundred thousand years. It is also interesting to note that this model of subsurface accretion of eluviated surficial deposits has recently been invoked to explain the formation of desert pavements (McFadden *et al.*, 1987).

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