Regards and best wishes,
Andrew Watson

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Structure, chemistry and origins of gypsum crusts in southern Tunisia and the central Namib Desert

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ABSTRACT

Gypsum crusts are broadly defined as accumulations at or within about 10 m of the land surface from 0·10 m to 5·0 m thick containing more than 15% by weight gypsum ($CaSO_4 \cdot 2H_2O$) and at least 5·0% by weight more gypsum than the underlying bedrock. The deposits are often, but not invariably, consolidated owing to cementation by gypsum. The crusts are found in many of the world's deserts where mean monthly potential evaporation exceeds mean monthly precipitation throughout the year.

Using structural, fabric and textural criteria, three main types of crust may be distinguished: (1) bedded crusts, found either at or beneath the land surface, which are made up of discrete horizontal strata up to 0·10 m thick, each showing a gradation in gypsum crystal size from less than 50 μm at the top to more than 0·50 mm at the base; (2) subsurface crusts, of which there are two forms, one made up of large, lenticular crystals (up to 0·50 m in diameter)—the desert rose crusts—and the other, a mesocrystalline form, with gypsum crystals up to about 1·0 mm in diameter; and (3) surface crusts, which are subdivided into columnar, powdery and cobble forms, all of which are made up of predominantly alabastrine gypsum (crystallites less than 50 μm in diameter).

In southern Tunisia and the central Namib Desert, bedded crusts are found around ephemeral lakes and lagoons. They are characterized by size-graded beds, gypsum contents of 50–80% by weight and comparatively high concentrations of sodium, potassium, magnesium and iron. They are interpreted as shallow-water evaporites which accumulate when saline pools evaporate to dryness. Desert rose crusts or *croûtes de nappe* generally contain 50–70% by weight gypsum, and have higher sodium concentrations than the second subsurface form. Texturally they are characterized by poikilitic inclusion of clastic material within large lenticular crystals. They are interpreted as hydromorphic accretions, which precipitate in host sediments at near-surface water tables through the evaporation of groundwater. The second form of subsurface crust—the mesocrystalline—often occurs in close association with the various surface forms. Unlike the hydromorphic crusts, they are not restricted to low-lying terrain. They are characterized by gypsum contents reaching 90% by weight, and have a close chemical and textural similarity to columnar surface crusts. This mesocrystalline form represents an illuvial accumulation; the surface forms—excluding the bedded crusts—are exhumed examples at various stages of solutional degradation. Subsurface precipitation of gypsum from meteoric waters containing salts leached from the surface, results in displacive gypsum accumulation in the soil zone. In southern Tunisia, the gypsum is derived from sand and dust deflated from evaporitic basins; in the central Namib, salts dissolved in fog water are the most likely source. Where other salts are present, differential leaching may form two-tiered crusts, calcrete—gypsum or gypsum—halite, if rainfall is sufficient to mobilize the less soluble salt yet insufficient to flush the more soluble. Gypsum crust genesis is restricted to arid environments, and if their susceptibility to post-depositional alteration is acknowledged, they can provide valuable palaeoclimatic indicators.

INTRODUCTION

Gypsum crusts have been reported from all the continents, including Antarctica. They are found in many arid regions, generally where throughout the year mean monthly potential evaporation exceeds mean monthly precipitation. Most of the major occurrences of the crusts are in regions where mean annual rainfall is less than about 250 mm, though there are some important exceptions. The gypsum accumulations are found at the land surface or within about 10 m of the surface. They may reach a thickness of 5 m and contain up to 95% by weight gypsum. There exists a great structural diversity among the deposits: laminar beds characterize many lacustrine and lagoonal environments; so-called desert rose crusts, composed of large, interlocking lenticular gypsum crystals, are commonly found in and around sabkhas and playas; and a wide variety of microcrystalline forms occur in areas where such close hydrological associations are not apparent.

The great variability in the structure and composition of the crusts necessitates a broad definition if all the types and forms are to be included. Here the following qualifications are employed: first, a minimum thickness of 0·1 m; second, a minimum gypsum content of about 15% by weight (D'Hoore, 1964); and, third, a gypsum content at least 5% greater than the underlying bedrock (Buringh, 1968). While the term gypsum *crust* suggests some consolidation of the deposit, weakly cemented or powdery gypsum accumulations are not excluded from this discussion since they can be intimately linked to the development of indurated varieties. In cases where cementation of host material is by agents in addition to gypsum—by calcite or halite for example—only those in which gypsum constitutes the principal cement will be considered gypsum crusts.

Using broad structural, fabric and textural criteria, three main types of crust may be differentiated (Watson, 1979, 1983).

(1) Horizontally bedded crusts—generally occurring at the surface—composed of 0·05–0·1 m thick strata, each showing a gradation from fine-grained alabastrine material to coarse (greater than 0·5 mm) crystals from top to bottom. In the study areas, thicknesses of such crusts can reach 4 m.
(2) Subsurface crusts, which are subdivided into two forms. First, a macrocrystalline desert rose form, composed of lenticular crystals up to 0·5 m in diameter; these crusts achieve thicknesses of 5 m. Second, a mesocrystalline form, characterized by lenticular crystals no more than about 1 mm in diameter. These crusts, which are usually less than 2 m thick, often have a columnar macrostructure.
(3) Non-bedded surface crusts, which are subdivided into three forms. First, an indurated microcrystalline form (crystals less than 50 μm in diameter) up to 2 m thick, which commonly has a columnar structure. Second, an unconsolidated, powdery form up to 2 m thick, and, third, an intermediate form comprising a powdery matrix with microcrystalline gypsum cobbles up to about 0·5 m in diameter studding the surface.

While it is likely that this physical diversity attests to different genetic processes, there is little detailed chemical or petrographic information available upon which to base a genetic classification. The purpose of this investigation was to characterize the various types of gypsum crusts in two areas—the Chott region of southern Tunisia and the coastal zone of the central Namib Desert. On the basis of these characterizations as well as stratigraphic and geomorphic criteria, genetic models are proposed for the main types of gypsum crust. While the processes involved in the development of bedded crusts and desert rose crusts have received considerable attention, the mesocrystalline subsurface form and the various surface forms are less well known and understood. The main goal of the following discussion is to elucidate the origins of these forms of gypsum crust.

ANALYTICAL PROCEDURES

Gypsum determinations were undertaken using t[he] gravimetric technique advocated by Coutinet (196[.] Standard conductimetric methods were not employ[ed] since their accuracy is in doubt in cases of hi[gh] gypsum content (Bower & Huss, 1948; Jackson, 19[.] Golkin *et al.*, 1960; Lagerwerff, Akin & Moses, 196[.] Calcium carbonate was determined by using a sim[ple] calcimeter (Allison & Moodie, 1965).

For the determination of the weight percentag[e] insoluble residue and both major and trace elem[ent] concentrations, 50 g of air-dried sample were crus[hed] and 0·5 g of this material was analysed. Insol[uble] residue values refer to the weight percentag[e] material not dissolved after boiling for 30 min i[n] hydrochloric acid. Elemental analyses were cond[ucted] on the filtrant therefore the results pertain to samples and not individual gypsum crysta[ls] crystallite aggregates. In effect, elemental conce[ntra]tions refer not only to ions co-precipitated gypsum but also ions incorporated on crystal between crystals and within host sediment.

Sodium and potassium were analysed by photometry. Strontium, magnesium and ca[lcium] concentrations were determined by atomic abso[rption] spectrophotometry (A.A.S) using an air/ace[tylene] flame—lanthanum chloride was added to the solutions to overcome response depression owing to the presence of aluminium (Whiteside, 1976). Calcium concentrations determined by A.A.S. were often 0·5–4% greater than those calculated on the basis of gypsum and calcium carbonate content. While this may result from overdetermination of calcium using A.A.S. (Walsh & Howie, 1967), there remains a possibility gypsum content is underestimated in samples containing more than 40% by weight gypsum (Watson, 1982, pp. 667–669). Total dissolved iron and total dissolved aluminium were also determined by A.A.S., the former using an air/acetylene flame, the latter using a nitrous oxide/acetylene flame.

Table 1 presents the mean chemical and mineralogical characteristics of the gypsum crusts of southern Tunisia and the central Namib Desert: 98 samples are from the former; 53 are from the latter.

The petrographic terminology employed in the study of gypsum crust micromorphology is drawn from both pedology and metamorphic petrology. However, here the established metamorphic nomenclature, derived from the study of gypsum/anhydrite ($CaSO_4$) deposits (Hammerschmidt, 1883; Bundy, 1956; Holliday, 1970), will be adopted.

FACTORS CONTROLLING GYPSUM CRUST DISTRIBUTION

Figure 1 presents a global map showing the broad patterns of gypsum crust distribution. Most of the boundaries of the areas of gypsum crusts are tentative owing to the absence of detailed soils/sediment maps. Also, many isolated occurrences of gypsum deposits are not represented. For the sake of brevity, the full bibliographic details upon which the map is based are not presented here. This information is available elsewhere (Watson, 1979, 1982, 1983) and an annotated, regional bibliography is available from the author.

Rainfall

Gypsum crusts are found in semi-arid and arid regions. Only rarely are extensive areas of crusts found in regions where mean annual rainfall exceeds 250 mm. The few exceptions, such as in Rajasthan where mean annual rainfall reaches 300 mm, may be explained by high temperatures which maintain potential evaporation levels above actual precipitation levels throughout the year. Should moisture availability exceed potential evaporation at any time, meteoric water will dissolve surface and near-surface gypsum accumulations and transport the material into the soil zone. If the soil-moisture storage capacity is exceeded, dissolved gypsum will be carried to the groundwater zone. If the infiltration capacity is exceeded, gypsum dissolved at the surface will be removed in surface runoff.

Sources of calcium sulphate

In addition to the climatic control on gypsum crust distribution, it is noteworthy that broad areas of the

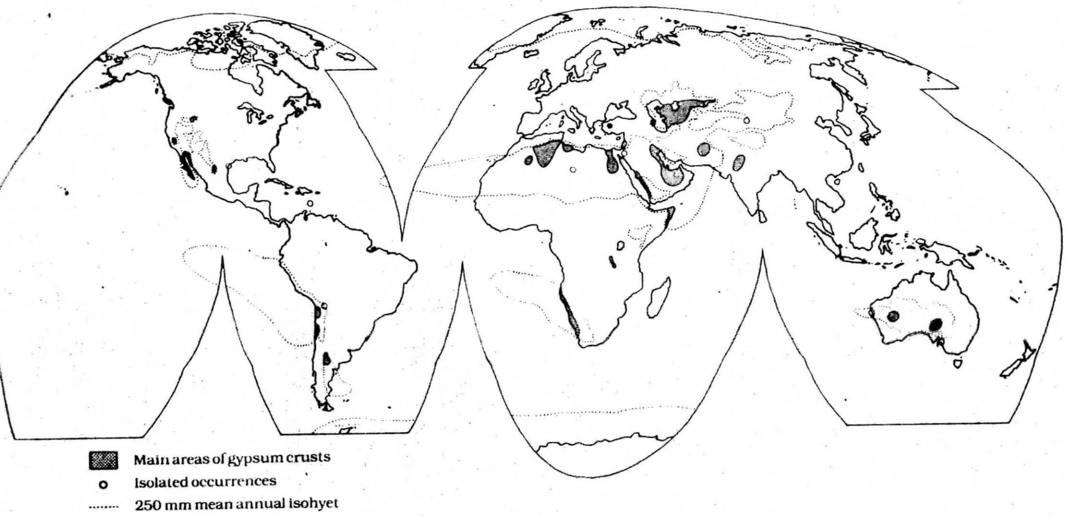

Fig. 1. Generalized distribution of surface gypsum accumulations excepting bedrock deposits.

Table 1. The mineralogical and chemical compositions of the different types and forms of gypsum crusts in southern Tunisia and the central Namib Desert (see Figs 2 and 3 for the major sampling locations). Standard deviations are in parentheses. Overall mean concentrations of strontium are omitted since in all the crust forms from the two study areas the levels consistently show a marked difference

		Insoluble residue wt%	Gypsum wt%	$CaCO_3$ wt%	Na^+ ‰	K^+ ‰	Sr^{++} ‰	Mg^{++} ‰	Fe (total) ‰	Al (total) ‰
Bedded crusts										
Tunisia	Range	2–4	64–84	1–6	1·50–11·20	0·06–1·00	1·00–5·00	0·50–11·00	0·35–0·75	0–1·00
Three samples	Mean	3 (0·7)	74 (7·4)	3 (2·2)	5·20 (4.30)	0·45 (0·40)	2·50 (1·80)	5·50 (5·90)	0·50 (0·15)	0·50 (0·40)
Namib	Range	1–11	49–66	0–31	2·00–15·00	0·10–25·00	0·20–0·50	1·40–16·00	0·60–9·80	0·50–4·60
Three samples	Mean	7 (4·2)	55 (7·8)	13 (13·3)	6·40 (6·10)	8·50 (11·70)	0·30 (0·15)	7·70 (6·10)	4·00 (4·10)	2·10 (1·80)
Overall mean		5 (2·6)	64 (12·4)	8 (10·7)	5·80 (5·30)	4·50 (9·20)	—	6·60 (5·30)	2·30 (3·40)	1·30 (1·50)
Desert rose crusts										
Tunisia	Range	9–29	49–83	1–12	1·10–5·80	0·25–1·10	0·40–11·00	1·20–7·00	0·60–5·00	0·40–5·30
11 samples	Mean	21 (7·9)	63 (14·5)	4 (3·2)	2·30 (1·50)	0·70 (0·25)	2·70 (2·90)	3·30 (1·80)	1·90 (1·20)	1·90 (1·30)
Namib	Range	6–29	57–83	0–19	1·50–9·00	0·15–1·20	0·20–1·90	0·40–23·00	0·60–3·50	0·50–6·30
10 samples	Mean	14 (6·2)	68 (7·5)	4 (5·6)	3·60 (2·20)	0·85 (0·25)	0·95 (0·65)	9·10 (6·60)	2·20 (0·85)	3·30 (2·50)
Overall mean		18 (7·9)	66 (8·6)	4 (4·5)	2·90 (2·00)	0·75 (0·25)	—	6·00 (5·60)	2·00 (1·10)	2·60 (1·60)
Mesocrystalline subsurface crusts										
Tunisia	Range	1–30	50–89	0–30	1·20–5·00	0·05–1·00	0·60–6·80	0·10–8·00	0–3·50	0·10–3·30
25 samples	Mean	9 (8·8)	70 (11·2)	6 (7·0)	1·90 (0·85)	0·35 (0·05)	2·40 (1·70)	2·30 (2·50)	0·85 (0·85)	1·00 (0·85)
Namib	Range	2–29	53–87	0–9	1·50–6·00	0·10–5·50	0·10–2·00	0·50–10·00	0·40–10·00	0·40–9·90
12 samples	Mean	14 (9·6)	62 (12·8)	2 (2·9)	3·00 (1·30)	1·00 (1·40)	0·55 (0·55)	4·30 (3·00)	3·00 (2·60)	2·20 (2·40)
Overall mean		11 (9·5)	67 (12·0)	5 (6·3)	2·20 (1·10)	0·55 (0·85)	—	2·90 (2·80)	1·50 (1·90)	1·40 (1·70)
Columnar surface crusts										
Tunisia	Range	1–24	56–95	0–11	1·20–2·80	0·10–1·50	0·50–8·90	0–6·40	0–3·00	0–2·70
22 samples	Mean	6 (5·8)	79 (8·5)	5 (3·2)	1·80 (0·40)	0·35 (0·30)	1·90 (1·80)	1·80 (1·90)	0·55 (0·50)	0·60 (0·60)
Namib	Range	1–15	67–86	0–6	1·60–6·40	0–1·20	0·20–1·90	0·20–23·00	0·10–2·40	0·10–5·00
Six samples	Mean	8 (5·6)	77 (7·6)	2 (2·0)	3·20 (1·50)	0·55 (0·45)	0·95 (0·70)	9·40 (8·50)	1·10 (0·85)	2·50 (2·20)
Overall mean		6 (6·3)	78 (8·2)	5 (3·1)	2·10 (0·95)	0·40 (0·40)	—	3·40 (5·30)	0·65 (0·80)	1·00 (1·40)
Cobbles										
Tunisia	Range	1–6	75–91	0–5	1·40–2·60	0·05–0·75	0·50–4·00	0–3·20	0·10–0·40	0·20–0·80
11 samples	Mean	3 (2·0)	83 (5·5)	3 (1·6)	1·70 (0·35)	0·20 (0·20)	1·40 (0·90)	0·70 (0·85)	0·25 (0·10)	0·45 (0·20)
Namib	Range	1–14	56–89	0–10	1·40–2·20	0–0·85	0·20–1·10	0·30–8·80	0·30–8·90	0·10–3·50
Eight samples	Mean	8 (4·3)	72 (12·7)	3 (8·5)	1·70 (0·35)	0·35 (0·25)	0·40 (0·30)	2·80 (2·60)	2·90 (3·10)	1·40 (1·00)
Overall mean		5 (4·1)	78 (10·9)	6 (10·2)	1·70 (0·35)	0·25 (0·25)	—	1·60 (2·10)	1·30 (2·40)	0·80 (0·80)
Powdery accumulations										
Tunisia	Range	3–72	17–85	0–15	0·70–4·00	0·20–3·20	0·20–3·30	0·20–48·00	0·20–7·10	0·20–6·00
26 samples	Mean	33 (21·1)	50 (21·4)	5 (3·6)	1·60 (0·80)	0·90 (0·70)	1·10 (0·80)	4·10 (9·10)	2·10 (1·60)	2·10 (1·40)
Namib	Range	3–37	25–86	0–64	1·30–6·20	0·10–2·10	0–1·80	0·90–6·30	0·50–9·00	0·10–5·40
14 samples	Mean	14 (9·8)	64 (16·2)	9 (16·3)	2·40 (1·60)	0·70 (0·65)	0·55 (0·55)	3·80 (1·40)	2·80 (2·60)	2·10 (1·70)
Overall mean		26 (20·6)	55 (20·4)	6 (10·2)	1·90 (1·20)	0·80 (0·70)	—	4·00 (7·40)	2·40 (2·00)	2·10 (1·50)

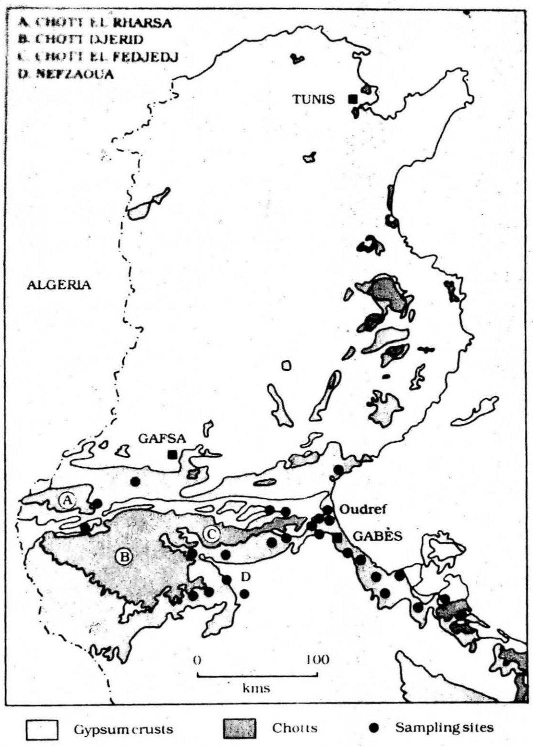

Fig. 2. Southern Tunisia showing gypsum crust distribution (after Cointepas & Gaddas, 1971) and locations of the main sites from which data are presented in Table 1.

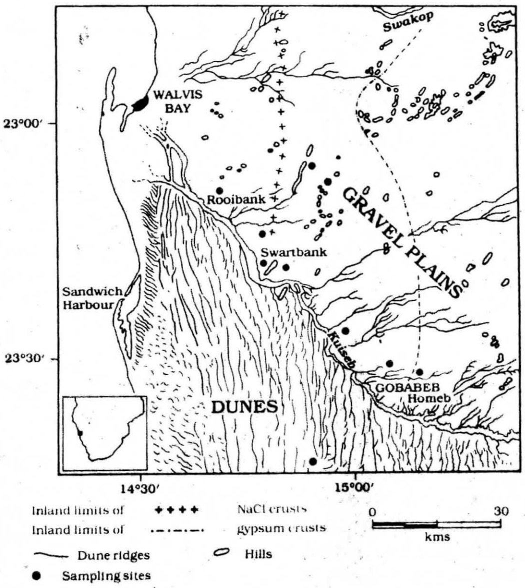

Fig. 3. The central Namib Desert showing distribution of crusts (after Martin, 1963; Scholz, 1963) and locations of the main sites from which data are presented in Table 1.

arid zone are devoid of the accumulations. A source of calcium sulphate ($CaSO_4 \cdot 2H_2O$)—whether in bedrock, surface or underground water, or the atmosphere—is essential. Examples of authigenic gypsum crusts, formed by bacterial (Rozanov, 1961) or chemical action (Martin, 1963) have been reported from Central Asia and from the Namib Desert but in both areas atmospheric deposition of gypsum has also been cited as a primary source (Shumakov & Mikhovich, 1960; Besler, 1972). In the two areas discussed here, the gypsum sources may be highly localized, resulting in complex distributional patterns. The distribution of gypsum crusts in southern Tunisia has been described by Cointepas & Gaddas (1971) and Watson (1979). Figure 2 shows the location of sampled sites within the area. In the central Namib Desert, the distribution of gypsum crusts is less well mapped though Martin (1963) and Scholz (1963) provided valuable data. Figure 3 shows the distribution of crusts based upon their work and upon information from the sampling sites shown.

In southern Tunisia, the main source of gypsum forming the crusts is the gypsiferous strata in Cretaceous limestones and clays. The precise mechanisms involved in its appearances at the surface are disputed. Some workers have suggested that the rise of groundwater (Dalloni, 1953; Pouget, 1968; Beckmann, Scharpenseel & Stephan, 1972; Schwenk, 1977) or soil moisture (Bureau & Roederer, 1961) carries dissolved gypsum to the surface where it precipitates upon evaporation of the water. Others have cited the deflation of evaporites from seasonally filled lake basins as the major vector (Coque, 1955a, b, 1962; Le Houérou, 1956, 1960). The surface crusts in southern Tunisia play an important geomorphic role in protecting pediment slopes (*glacis*) from erosion. The preservation of between three and five *glacis* in the vicinity of the Chotts el Fedjedj and Djerid has been attributed to the slopes' encrustation by gypsum accumulations (Coque, 1960). In the Nefzaoua, east of Chott Djerid, cementation of the surface of gypsiferous sand dunes has resulted in their stabilization and preservation beneath a 0·5–1 m thick carapace.

In the central Namib Desert, gypsum is not present in the bedrock, which comprises Precambrian micaschists and Palaeozoic granites. Here, an atmospheric source is most likely though again the exact processes involved in gypsum accumulation are uncertain (Martin, 1963; Besler, 1972; Carlisle *et al.*, 1978). The various forms of surface crust are not as widespread as they are in southern Tunisia. However, the same types and forms of crusts are represented. Relict beaches along the Atlantic coast are mantled by gypsum crusts (Rust & Wieneke, 1973, 1976; Wieneke & Rust, 1973a, b, 1975, 1976). Though currently exposed at the surface, these crusts have the structural characteristics of desert rose crusts. Similar relict crusts have been reported from the Tunisian Nefzaoua (Bureau & Roederer, 1961; Coque, 1962; Zimmermann, 1963). In the central Namib, hydromorphic crusts—both the bedded and desert rose types—form areas of positive relief following the deflation of unconsolidated sediments surrounding the depressions in which the crusts developed.

PHYSICAL CHARACTERISTICS

Bedded crusts

In the two study areas, horizontally bedded gypsum crusts are found peripheral to ephemeral lakes, such

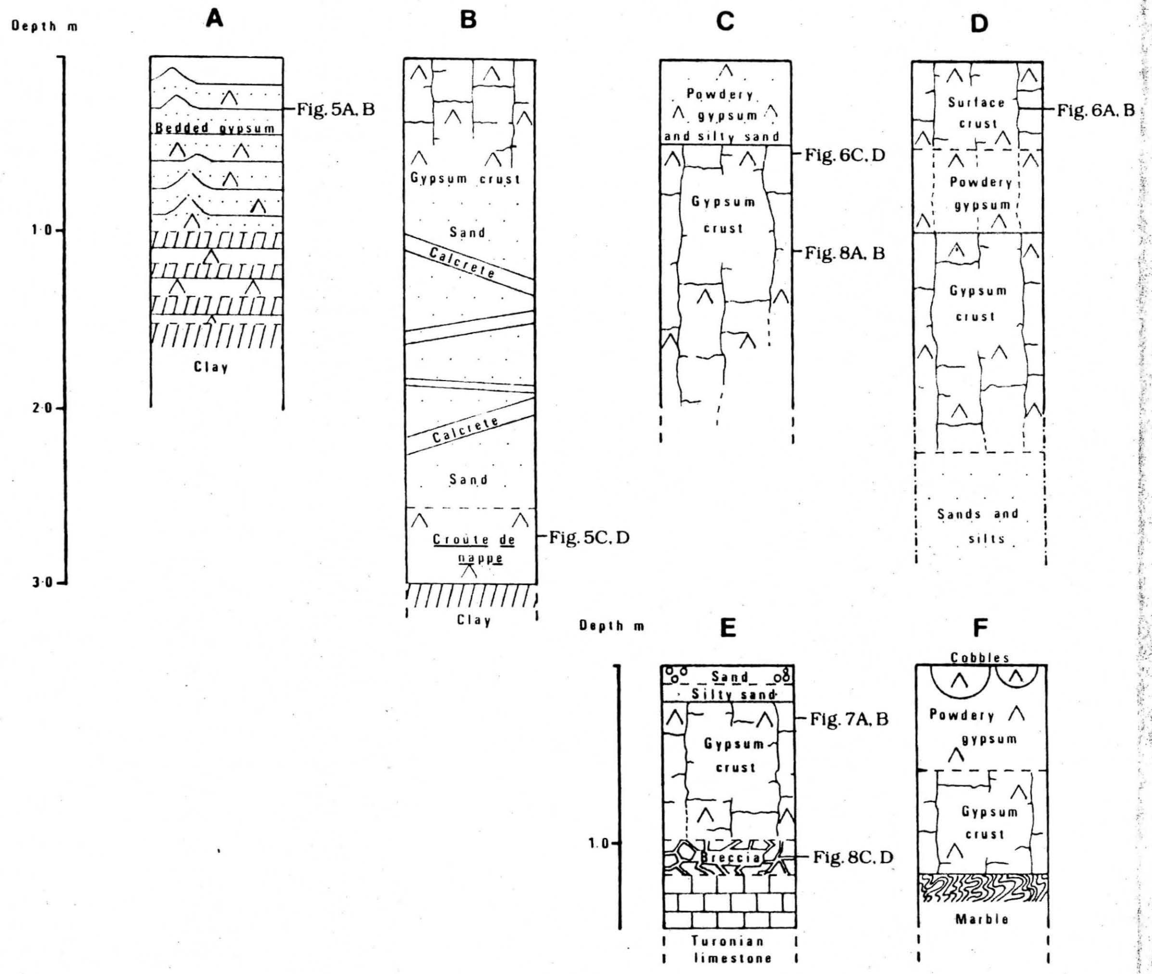

Fig. 4. Examples of profiles exhibiting various forms of gypsum crust. (A) Bedded crust from Chott el Rharsa, southern Tunisia, showing tepee structures. (B) Desert rose crust (*croûte de nappe*) beneath gypsum and calcrete encrusted dune sand east of Chott Djerid in the Tunisian Nefzaoua. (C) Mesocrystalline subsurface crust beneath a thin cover of unconsolidated material near Gabès, southern Tunisia. (D) Section exhibiting both a columnar surface crust and a mesocrystalline subsurface crust in southern Tunisia. (E) Columnar surface crust on limestone bedrock west of Gabès, southern Tunisia. (F) Gypsum cobbles set in a powdery gypsum matrix overlying a mesocrystalline subsurface crust on marble bedrock at Swartbank in the central Namib Desert. Typical fabrics and textures of the crusts are shown in Figs 5, 6, 7 and 8.

as Chott el Rharsa in southern Tunisia, and around coastal sabkhas. In both areas, these sabkhas have been interpreted as former lagoons now infilled by evaporite sedimentation (Busson & Perthuisot, 1977; Perthuisot, 1980; Gevers & Westhuyzen, 1931). The gypsum crusts are characterized by strata 0·05–0·1 m thick which may be disrupted by tepee structures at intervals of 0·5–2 m laterally (Fig. 4A). The upturned fractures are probably the product of desiccation at the surface and possibly are enhanced by upward movement of saline groundwater (cf. Bellair, 1957; Christiansen, 1963; Butzer & Hansen, 1968; Krinsley, 1970). Individual strata comprise microcrystalline or alabastrine (individual grain diameters commonly less than 50 μm) gypsum at the top, grading downwards to lenticular gypsum crystals up to 0·5 mm in diameter (Fig. 5A, B).

The gypsum content of crusts made up of accumulations of these strata is variable since horizons of sand and silt-sized clastic material occasionally occur between the laminae. The crusts commonly contain 50–80% gypsum by weight; in examples from the southern Tunisia and the central Namib, the additional constituents are principally quartz grains and calcium carbonate (Table 1).

Desert rose crusts

Subsurface crusts composed of large, interlocking lenticular gypsum crystals up to 0·5 m in diameter are usually confined to low-lying desert basins where they are encountered at or just above the water table (Fig. 4B). Relict examples are characterized by corroded crystals which, when exposed at the land surface, may decompose completely to form microcrystalline crusts. The term *croûte de nappe* has been adopted widely, the implication being that the crusts are the product of gypsum crystallization from saline groundwater. In areas which have experienced marked fluctuations in groundwater levels, thick *croûtes de nappe* can develop.

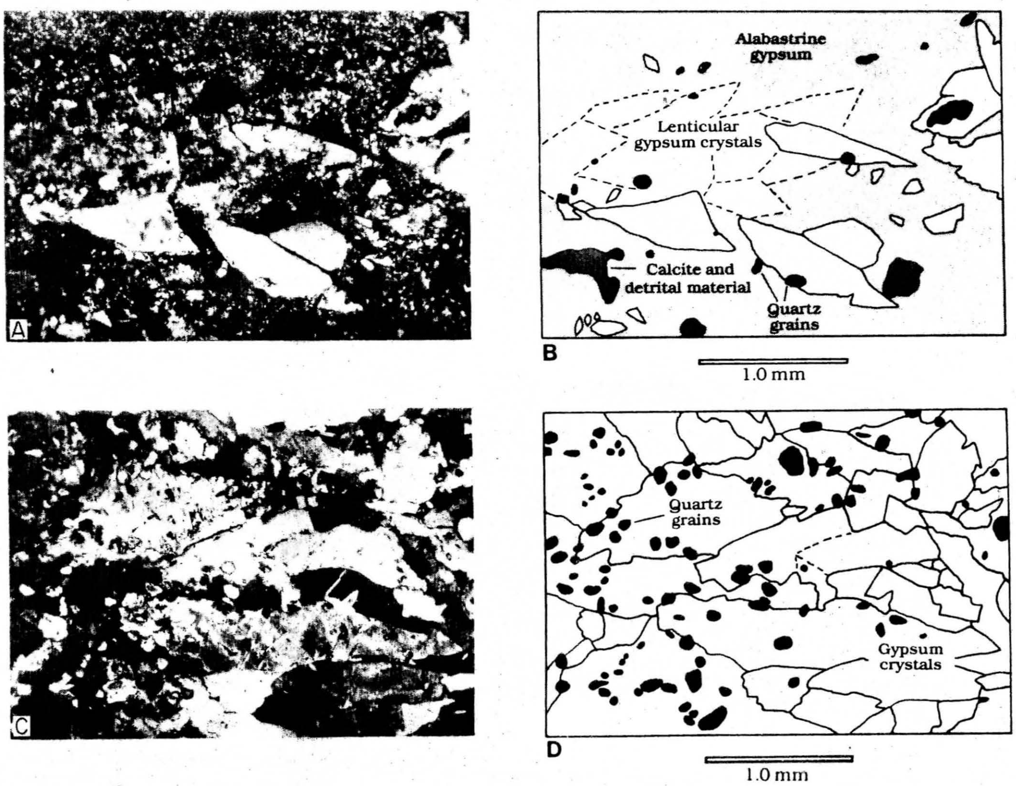

Fig. 5. Photomicrograph (A) and diagram (B) showing a bedded gypsum crust from Chott el Rharsa, southern Tunisia. Horizons of large, lozenge-shaped gypsum crystals are interbedded with bands of alabastrine gypsum. Crossed nicols.

Photomicrograph (C) and diagrams (D) showing poikilitic inclusions of quartz grains within large, lozenge-shaped to granular gypsum crystals in a desert rose crust. Crossed nicols.

Kulke (1974) reported examples 5 m thick in the Algerian Souf.

The desert rose crusts in the two study areas have significantly higher insoluble residue contents and correspondingly lower gypsum contents—generally 50–70% by weight—than the other types of gypsum crust (Table 1). The insoluble material, mainly quartz grains included poikilitically within the gypsum crystals (Fig. 5C, D), constitutes 20–30% by weight of the bulk sample. Poikilitic inclusions are rare in other types of gypsum crust even when large, porphyroblastic gypsum crystals are present.

Mesocrystalline subsurface crusts and surface gypsum crusts

Unlike the bedded crusts, which are confined to ephemeral lake basins or lagoons, and the desert rose crusts, which are restricted to areas with a near-surface water table, the mesocrystalline subsurface crusts (Fig. 4C), and the various surface forms (Fig. 4D, E, F) have diverse topographic distributions. Though frequently found around basins of inland drainage, such as Lake Eyre in Australia and the Chotts of Algeria and southern Tunisia, the terrain they underlie or mantle is very variable. Not only do they encrust extensive plains but also relict dunes, pediments inclined at 20° or more, hill crests and interfluves. These characteristics apply to both the surface and subsurface forms since often they occur together (Fig. 4D, F).

Structure

The most striking structural feature of the indurated surface gypsum crusts is their columnar conformation.

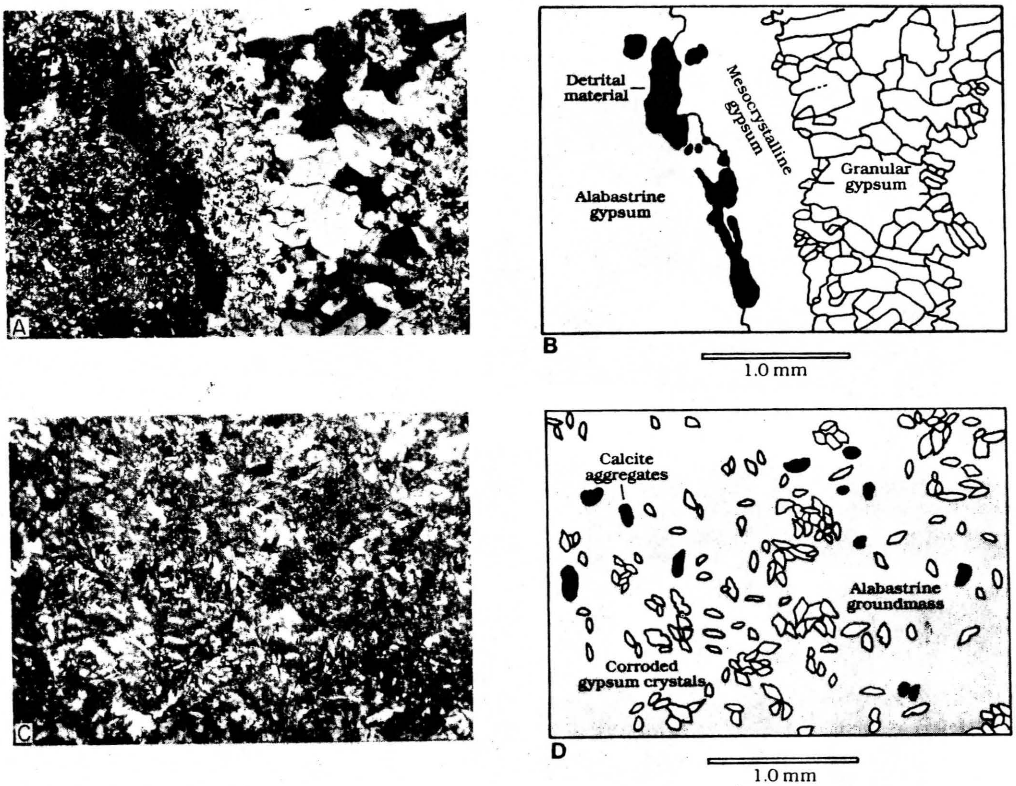

Fig. 6. Photomicrograph (A) and diagram (B) showing the wall of a column from a surface gypsum crust. Large granular gypsum crystals fill the zone between columns and grade laterally into mesocrystalline and alabastrine material. The marked zonation probably represents several phases of gypsum crystallization from water percolating through the fissures between columns. Crossed nicols.

Photomicrograph (C) and diagram (D) showing admixed mesocrystalline and alabastrine gypsum from the top of a subsurface crust. Lozenge-shaped crystals show evidence of solutional pitting. Crossed nicols.

Roughly hexagonal columns 0·25–0·75 m in diameter may extend vertically through the full thickness of the crust which is usually from 1 to 2 m. The surfaces and walls of the columns are more indurated than their interiors, being characterized by alabastrine crystal textures (Fig. 6A, B). This is probably the result of gypsum dissolution and rapid recrystallization under the influence of meteoric water moving downwards in the narrow fissures between the columns. The origin of the columniation is enigmatic. It may be the product of lateral displacement of host sediment during gypsum crystallization but little non-gypsic material is found between the columns. It is more likely that tensional stresses caused by desiccation (Tucker, 1978; Watson, 1980) or partial dehydration of gypsum to hemihydrate/bassanite ($CaSO_4 \cdot \frac{1}{2}H_2O$) (Chatterji & Jeffery, 1963; Hunt *et al.*, 1966) results in fissuring. Downward water movement preserves the cracks. Mesocrystalline subsurface crusts also exhibit columniation.

The two additional forms of surface gypsum accumulation are common in both southern Tunisia and the central Namib Desert. Unconsolidated, powdery accumulations have a very variable gypsum content, from 20 to 90% by weight. Occasionally, they are encountered overlying mesocrystalline subsurface crusts. The other surface form, consisting of gypsum cobbles studding the surface of powdery accumulations, also often overlies the subsurface crusts. The cobbles, which may be from 0·2 to 0·5 m in diameter, are conical when small with the apex on the underside; the flat upper surface is level with the land surface (Fig. 4F). The cobbles probably represent the remnants of former columnar crusts which have degraded by dissolution, the powdery sediment being residual material. Gypsum cobbles have the same superficial induration characteristic of the columns of surface crusts.

Micromorphology

In thin section mesocrystalline subsurface crusts are composed of lozenge-shaped gypsum crystals which are discoidal crystals in two dimensions. The lozenges are generally less than 1 mm in diameter and only rarely contain inclusions of host material. Peripheral dissolution features are rare (Fig. 6C, D). In contrast, indurated surface gypsum crusts are made up of alabastrine material. Larger, lozenge-shaped crystals occur as porphyroblasts and invariably show evidence of superficial dissolution (Fig. 7A, B). Porphyroblasts are absent from gypsum cobbles; this may reflect the gradual dissolution of large crystals near the surface by infiltrating meteoric water. Subsequent rapid evaporation of this water is most likely to result in multiple crystal nucleation, resulting in the precipitation of alabastrine material. Indurated surface crusts and the mesocrystalline subsurface form may also exhibit granular crystal textures. These masses of interlocking, irregularly-shaped crystals are confined to column walls and probably result from multiple nucleation and crystal growth under supersaturated conditions (Fig. 6A, B).

Two important crystal textures which are encountered mainly in the subsurface form of crust are the fibrous habit and calcite pseudomorphs after gypsum. Fibrous gypsum has been attributed to two processes: tensile strain crystallization (Shearman *et al.*, 1972; Phillips, 1974) and displacive crystallization (Aljubouri, 1971; Watts, 1978). While the second of these has most often been invoked under the high pressures associated with anhydrite hydration (Matsuura, 1925; Bundy, 1956; Holliday, 1970), Watts (1978) described fibrous calcite from near-surface calcretes. The fibrous gypsum crystals from subsurface mesocrystalline crusts exhibit uniform extinction even when they are curved; undulose extinction would be indicative of tensile strain crystallization (Phillips, 1974).

Lozenge-shaped calcite crystals or crystal aggregates, pseudomorphic after gypsum (Fig. 7C, D) have only rarely been reported from near-surface deposits (Warren, 1982). In samples where gypsum replacement has been only partial, the calcite crystals have grown into the gypsum crystal along cleavage planes, usually (010) (Fig. 8A, B). There is no sign of interstitial voids between the calcite crystals and the gypsum. The features are not therefore the product of solutional replacement but probably result from chemical alteration by sulphate reducing bacteria—a process occurring under aqueous, anaerobic conditions (Butlin, 1953).

Mineralogy

While the two forms of subsurface gypsum crust, the desert rose *croûte de nappe* and the mesocrystalline, may usually be differentiated on the basis of the higher clastic content of the former, this is not the case with the mesocrystalline form and the indurated surface crusts. The surface crusts contain slightly less insoluble residue and more gypsum than the subsurface crusts they frequently overlie (see Table 1). The gypsum content of either may be as high as 90% by weight, the remainder consisting of insoluble residue in the form

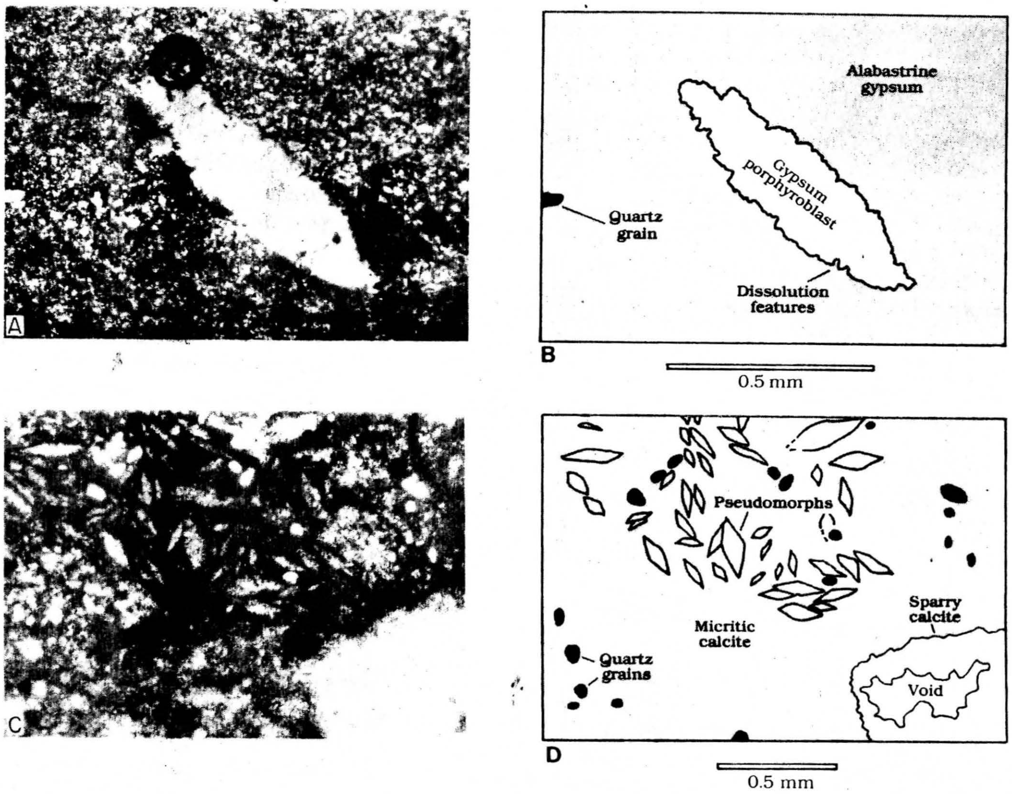

Fig. 7. Photomicrograph (A) and diagram (B) showing a gypsum porphyroblast, exhibiting peripheral dissolution features within an alabastrine groundmass. Crossed nicols.

Photomicrograph (C) and diagram (D) showing lozenge-shaped calcite crystal aggregates pseudomorphic after gypsum crystals in a calcrete from southern Tunisia. Plain light.

of quartz grains, and generally less than 5% calcium carbonate.

Powdery gypsum accumulations show a great diversity in their chemical compositions not only in their gypsum and insoluble residue contents but also the concentrations of the sodium, potassium, strontium, magnesium, iron and aluminium ions (Vieillefon, 1976). Gypsum cobbles have compositions very similar to indurated surface crusts, lending support to the view that they may represent remnants of surface crusts following degradation through dissolution. Their gypsum contents may reach nearly 90% by weight (Table 1).

GEOCHEMISTRY

While it is not the intention here to discuss in detail the geochemical distinctions among the various types and forms of gypsum crusts, some brief comments on the data presented in Table 1 are pertinent. It should be reiterated that the data refer to bulk samples and not to individual gypsum crystals or selected crystal aggregates.

In the case of the bedded crusts from the two study areas, concentrations of sodium, potassium, magnesium and iron are high in comparison with the other types of gypsum crust. Though high concentrations of ions co-precipitated with gypsum are to be expected under conditions of rapid crystal growth (Kushnir, 1981), the provenance of the cations identified here is unknown.

Similarly, the origin of the high concentrations of sodium and magnesium ions found in the desert rose crusts (Table 1) is uncertain. However, the gypsum crystals making up these crusts are also characterized by poikilitic inclusions, features which develop only when the crystal growth rate exceeds the maximum

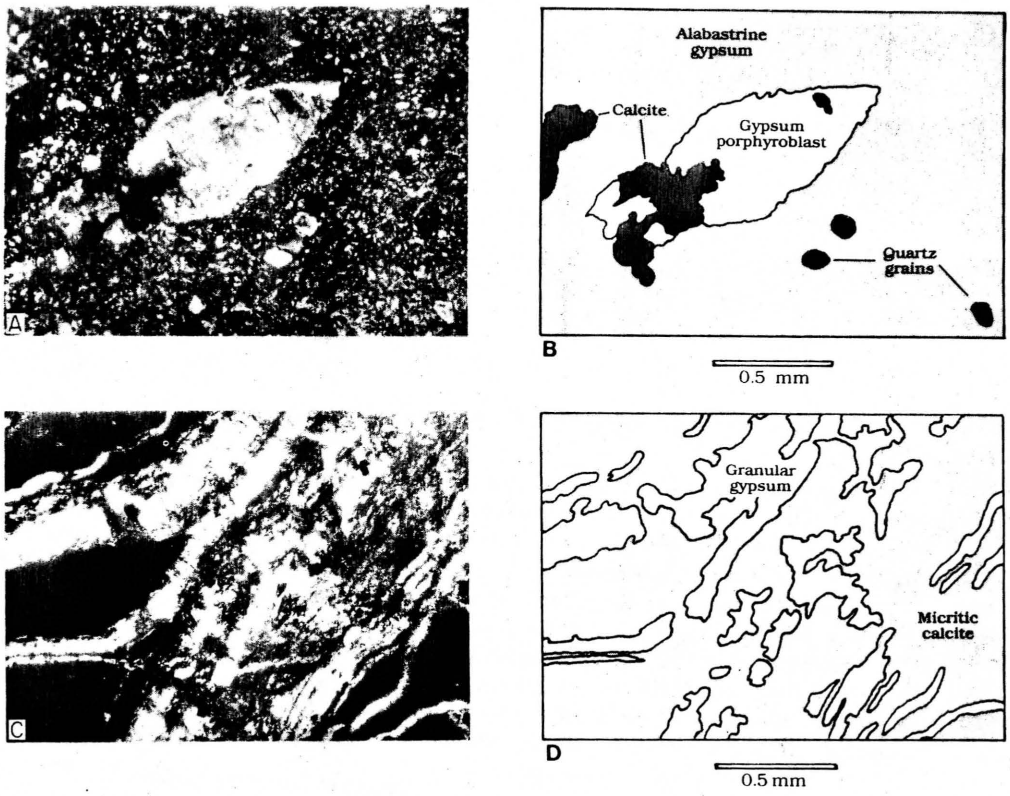

Fig. 8. Photomicrograph (A) and diagram (B) showing a large porphyroblastic gypsum lozenge within an alabastrine groundmass. Dark area within the crystal are zones of micritic calcite replacing gypsum along the (011) cleavage plane. Crossed nicols.

Photomicrograph (C) and diagram (D) showing granular gypsum crystals brecciating micritic limestone at the base of a surface gypsum crust west of Gabès, southern Tunisia. Crossed nicols.

rate of particle displacement (Kastner, 1970). Such conditions of rapid crystal growth are also conducive to the co-precipitation of additional ions (Kushnir, 1981).

Within the samples from mesocrystalline subsurface crusts and non-bedded surface forms, potassium, iron and aluminium are found in quantities roughly proportional to the insoluble residue content, probably being derived from coatings on sand grains. Sodium, strontium and magnesium tend to be more abundant in the subsurface crusts than the overlying gypsum accumulations (Fig. 9). It is unlikely that these cations are derived from the host sediment since the intermediate horizons between the crusts are depleted with respect to them. It is probable that the surface gypsum horizon has been leached by meteoric waters and the most soluble minerals translocated to the lower horizon. In the case of strontium salts, which are less soluble than gypsum, this process may involve the liberation of liquid inclusions in large gypsum crystals undergoing dissolution (Kushnir, 1980). Alternatively, recrystallization of gypsum within the surface crust following partial dissolution of crystals may be too rapid, or the crystals too immature, to allow strontium ions to fill gaps in the crystal lattice. Free strontium ions will be leached into the lower horizons during subsequent wetting.

DISCUSSION

Origins of bedded crusts

The size-grading of gypsum crystals from small at the top to large at the base of each of the strata forming the horizontally bedded crusts suggests that gypsum

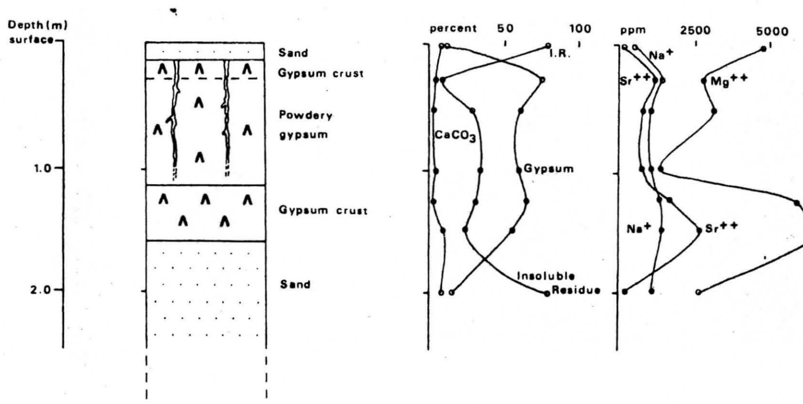

Fig. 9. Variation in mineral and cation content with depth through a double gypsum crust near Oudref, southern Tunisia (Fig. 2).

crystallization occurred in a shallow surface-water environment (Fig. 10B). Evaporation from a shallow body of water, rich in dissolved salts, will not produce the marked density stratification encountered in deep water. If the water is less than about 1 m deep, sulphate reducing bacteria are unable to effect the alteration of gypsum crystallites to calcite or aragonite as they sink from the surface (Abd-el-Malek & Rizk, 1963; Bodenheimer & Neev, 1963; Friedman, 1965). Hence the first gypsum crystals to precipitate will continue to grow on the bed as more ions migrate to the crystal faces (Kushnir, 1981; Warren, 1982). Late in the evaporative cycle, not only is the time available for crystal growth reduced, but dissolved salts more soluble than gypsum, especially sodium chloride and magnesium salts, may also hinder growth and eventually nucleation. Assuming that the water body evaporates to dryness, the final gypsum precipitates will form alabastrine material—presumably, with high co-precipitated ion concentrations.

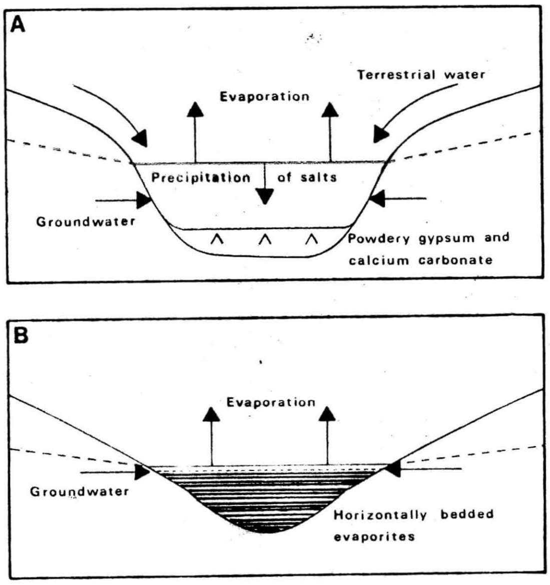

Fig. 10. Models of gypsum crust accretion in lacustrine environments. (A) Deep-water model (after Durand, 1963). (B) Accumulation of bedded crusts as a result of periodic flooding of a basin by rising groundwater, its subsequent evaporation and precipitation of dissolved salts.

Origins of desert rose crusts

Several mechanisms have been proposed to account for *croûte de nappe* genesis. Pouget (1968) discounted the role of evaporation in cases where the crusts occur at depths of 2 m or more. In fine-grained sands, a maximum depth of soil moisture and groundwater evaporation of about 1 m has been cited (Wipplinger, 1958; Stengel, 1968a, b). Pouget (1968) held that fluctuations in the amount of sodium chloride in the groundwater may cause periodic gypsum crystallization beneath the surface evaporation zone. The solubility of gypsum in pure water at 40°C is about 2·0 g $CaSO_4$ per litre, and in water containing 200 g NaCl it is about 8·0 g per litre (Hill, 1937; Zen, 1965). Hence, if the downward percolating meteoric water has a lower sodium chloride/calcium sulphate ratio than the groundwater, the solubility of gypsum may be reduced sufficiently to promote its crystallization. Zverev (1964) and Wigley (1973) showed that such a reaction can occur if waters containing calcium carbonates and sulphates are mixed, owing to the common ion effect. *Croûtes de nappe* generally have higher sodium levels than the other types of gypsum crust excepting some bedded, lagoonal evaporites (Table 1). Sodium probably stimulates the develop-

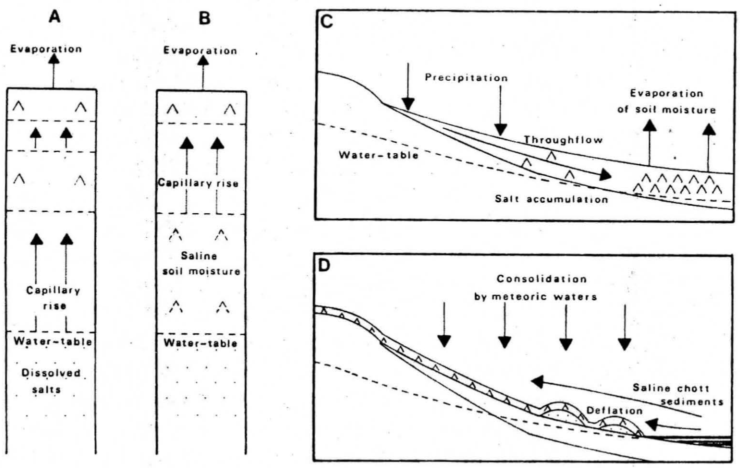

Fig. 11. Schematic representation of some models of gypsum crust formation. (A) Capillary rise of saline groundwater. (B) Capillary rise of soil moisture containing dissolved salts (after Bureau & Roederer, 1961). (C) Down-slope accumulation of gypsum as a result of leaching of the hillslope sediments by throughflowing water (after Conacher, 1975; Risacher, 1978). (D) Consolidation of aeolian deposits by meteoric water (after Coque, 1955a, b, 1958, 1962).

ment of the lenticular crystal habit by retarding growth of the (111) face at the expense of ($\bar{1}02$) (Masson, 1955; Edinger, 1973). However, Pouget's model does not allow for long-term stability in hydrochemical conditions and may therefore preclude the development of large crystals with poikilitic inclusions of host material. Since most *croûtes de nappe* in the study areas occur near the surface, gypsum crystallization through groundwater evaporation is the most likely genetic process.

Origins of mesocrystalline subsurface crusts and surface gypsum crusts

A number of models have been postulated to account for the development of surface gypsum crusts and the mesocrystalline subsurface form. Lacustrine sedimentation was advocated by Stainier (1912) and by Durand (1963) to account for many of the surface gypsum deposits of the Algerian Souf (see Fig. 10A, B). It may be discounted on the grounds of the structural distinctions between the surface crusts and hydromorphic forms as well as on topographic grounds. Many surface crusts occur on hill crests well above the zone of possible lacustrine transgression.

The topographic factor also precludes an origin related to groundwater influences. While gypsum *croûtes de nappe* may be altered structurally from aggregated, large lenticular crystals to alabastrine gypsum through solution and recrystallization at the land surface, the occurrence of surface crusts on steep slopes rules out the possibility that they are the product of evaporation at a near-surface water table. Moreover, it is unlikely that capillary rise of groundwater plays a significant role in their genesis; Keen (1936), for example, argued that the cellular structure of soil voids precludes significant upward movement of water by capillarity (Fig. 11A). Much empirical evidence supports this (Wipplinger, 1958; Stengel, 1968a, b) though Ali & West (1983) showed that capillary rise of saline moisture from a shallow water table plays an important role in the formation of gypsum nodules in some sabkhas. Tricart & Cailleux (1960, pp. 147–151) pointed out that in order for a 0·5 m thick gypsum crust to accrete under hydrostatic conditions, 200 m of water would have to evaporate—assuming maximum gypsum solubility, the figure would be 40 m. Without groundwater replenishment, the water from about 100 m of sediment would have to rise to the surface (Holmes, 1969).

Several alternatives have been proposed to overcome the shortcomings of the *per ascensum* models. Bureau & Roederer (1961) suggested that meteoric waters which replenish the moisture deficit in gypsiferous surface sediments are drawn to the surface by capillarity during subsequent dry periods, precipitating the dissolved gypsum at the surface (Fig. 11B). Risacher (1978) proposed that water moving laterally through the soil zone down slopes would become saturated with gypsum derived from soil materials. Subsequent evaporation of the water would result in gypsum crystallization and crust accretion on the lower slopes (Fig. 11C). While these processes occur in some instances (Conacher, 1975), they are not applicable in areas where gypsum is not present in the local bedrock or lower soil zone.

A number of workers have suggested that surface gypsum crusts represent surface aeolian or atmospheric deposits which have become consolidated under the influence of meteoric water (Fig. 11D). Coque (1955a, b, 1958, 1960, 1962), Le Houérou (1960) and Mensching (1964) held that the surface gypsum crusts around the Chotts of southern Tunisia are evaporitic deposits deflated from the lake basins following evaporation of lake waters at the end of cooler periods during the Pleistocene.

A similar model was proposed by Jessup (1960a, b, c) to account for gypsum crusts in South Australia. He suggested that subsurface gypsum crusts are deposits deflated from evaporitic pans, clays overlying the crusts apparently representing materials subsequently deflated from the same pans. If the model is valid, the structural and chemical distinctions between subsurface crusts in the same vertical section may result from different diagenetic processes. However, the aeolian models have several inconsistencies. Most significant of these is the frequent presence of lag gravels on top of surface crusts or above subsurface gypsum horizons. In many cases the deposition of these coarse-grained materials cannot post-date gypsum accumulation. Indeed, large bedrock fragments, showing no evidence of lateral transport, may overlie the crusts. The size of some of these boulders precludes the possibility that they were translocated upwards through surface sediments by cyclic wetting and drying causing volumetric changes in clay minerals or gypsum (Jessup, 1960a; Ollier, 1966; Cooke, 1970).

Per descensum accumulation of gypsum crusts

Models involving the subsurface accumulation of water soluble salts have been advocated to explain the genesis of calcretes (Brown, 1956; Ulrich *et al.*, 1959; Arkley, 1963, 1967; Gile, Peterson & Grossman, 1966). Page (1972) attributed the gypsum crusts in southern Tunisia to leaching of surface deposits of gypsum into the soil zone by rainwater. The water will replace the moisture lost during antecedent dry conditions, and subsequent evaporation—from the surface downwards—will result in the crystallization of salts dissolved in the water. Provided that the amount of infiltrating water does not exceed the soil moisture deficit—in other words that the field capacity of the soil is not exceeded—the soluble salts will not be flushed out of the soil zone. Under such conditions, accumulation of soluble salts will occur as long as they are available at the surface through aeolian or atmospheric deposition. In southern Tunisia this takes the form of gypsiferous sand and dust deflated from evaporative basins. In the central Namib Desert and parts of Soviet Central Asia, salts dissolved in fog moisture provide the principal source (Walter, 1936, 1937; Boss, 1941—in the central Namib; Shumakov & Mikhovich, 1960—in Central Asia).

This model is applicable to only the mesocrystalline subsurface crusts. Indurated surface gypsum crusts are attributed to the exhumation of subsurface crusts by deflation or other erosional processes (Akhvlediani, 1962; Tolchel'nikov, 1962). The structural differences between indurated surface crusts and the mesocrystalline subsurface form may be explained by diagenesis owing to repeated dissolution of lenticular crystals by rainwater and rapid recrystallization producing alabastrine material (Fig. 6C, D). Once exhumation has occurred, the exposed crust may act as a source of gypsum for another subsurface crust, provided that rainfall or diurnal variations in humidity are sufficient to induce leaching. Under such conditions, salts more soluble than gypsum, which were trapped in the subsurface accumulation zone, will quickly be leached out of the surface horizon. This would account for some of the chemical differences between the crust types (Fig. 9). Late in the cycle, the relict surface crust will consist of residual cobbles, remnants of the former columnar structures. While powdery gypsum accumulations may represent the final stage in the deterioration of an exhumed horizon, the great variability in their chemical composition suggests that some are primary atmospheric deposits.

Sources of gypsum in the study areas

The geomorphological significance of this model of gypsum crust genesis cannot be overstated. In southern Tunisia the geomorphic events which have produced the present features are as follows: first, deflation of gypsum from chotts and sabkhas where salts accumulate as a result of evaporation of 'groundwater' which floods the basins during the wetter winter months; second, the development of a subsurface crust as the aeolian deposits are leached into the soil zone; third, widespread exhumation of the subsurface crusts by deflation; and, fourth, the current phase of destruction of the surface crusts as the gypsum is again leached into the lower soil zone where it is forming a mesocrystalline subsurface crust.

At certain periods aeolian erosion is hindered by the presence of surface crusts; some lacustrine crusts south of Chott el Fedjedj have, however, eroded to form small yardangs (Besler, 1977). At other times the deposition of gypsiferous sand and dust, or the exhumation of a subsurface crust by erosion, will initiate the formation of a further generation of subsurface crusts. Such cycles are as much dependent on gypsum availability as on specific climatic events.

In the central Namib Desert, a primary marine origin of the gypsum may be discounted on topographic grounds—some crusts occur more than 200 m above present sea-level. An atmospheric origin is the most likely. In this area, hydrogen sulphide is derived from the release, by oceanic upwelling, of gases produced on the seabed by bacterial action. When dissolved in fog moisture it is oxidized to sulphur dioxide which in turn may be hydrolyzed and further oxidized in the presence of metal ion catalysts to sulphates (Holt, Cunningham & Engelkemier, 1978) (Fig. 12). It is also feasible that gaseous sulphur trioxide reacts with sodium chloride in solution to form sodium sulphate (Eriksson, 1958) or gypsum, if calcium ions are available. Near the coast, about 120 kg soluble salts^{-1} ha yr^{-1} are deposited from the atmosphere (Boss, 1941). Following their deposition on the land surface, the salts are leached into the soil zone by subsequent rainfall.

This mode of origin could account for the low strontium levels in these crusts compared with those in Tunisia, where gypsum is derived from deposits of primary marine origin. Isotopic studies of the water of crystallization of the gypsum making up the crusts of the central Namib provide a $\delta D/\delta^{18}O$ ratio which corresponds closely to that of meteoric water (Sofer, 1978). This probably reflects recrystallization of gypsum following its dissolution by rainwater. In contrast, sulphur isotope studies show a close similarity between the sulphur of the sulphate component of the gypsum crusts and fog water, but not seabed oozes off the coast. Carlisle *et al.*, (1978) found that basal crusts have $\delta^{34}S$ values of +12·9–+17·7‰ (with a mean of +15·9‰). These compare with values of +13·41‰ from a single fog water sample and −10·96 and −8·20‰ from two samples of seabed mud. If Jensen & Nakai's (1961) observation that $\delta^{34}S$ enrichment occurs when biogenic hydrogen sulphide undergoes oxidation is correct, fog water represents the most likely sulphate vector in the central Namib.

Displacive crystallization

This model of illuvial gypsum crust genesis provides a mechanism for the formation of crusts on hill crests and hill slopes and also explains the occurrences of lag gravels above the accumulations in some areas. However, a subsurface origin gives rise to the problem of accounting for the high gypsum contents of the crusts. The crusts of Algeria (Kulke, 1974) and southern Tunisia have volumetric porosities of between 30 and 45%, essentially the same as most host sediments. Hence their accretion does not involve the infilling of voids between host grains, but either displacement or replacement. There is little evidence of chemical replacement. In cases where the materials above and below the gypsum horizon are almost wholly quartz sand, the quartz grains incorporated within the crust only rarely show signs of solution. In contrast, displacive features are common. Pseudo-anticlines, the products of lateral displacement, are frequently encountered in subsurface crusts. They cannot, however, account for the 50–80% volumetric displacement to which the gypsum content of the crusts testify. Micromorphological features such as floating quartz grain textures, brecciation of large clasts (Fig. 8C, D) and fibrous crystals, are indicative of displacive crystallization.

Soil moisture containing calcium sulphate in solution will adhere to the surface of host grains owing to surface tension (Keen, 1936). Crystal growth during evaporation will be most pronounced at grain contacts where moisture tends to collect (Plet-Lajoux, Monnier

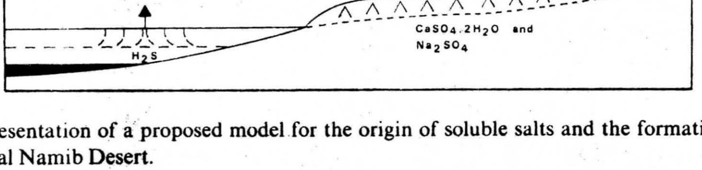

Fig. 12. Schematic representation of a proposed model for the origin of soluble salts and the formation of salt crusts in the coastal zone of the central Namib Desert.

& Pedro, 1971); the force of crystallization being sufficient to displace the host grains (Plet-Lajoux *et al.*, 1971). Depending on the nature of the host sediment, a decrease in volumetric porosity may occur as a result of infilling of voids by growing crystals. However, the amount of infilling and displacement required to account for crusts containing 80% or more gypsum by weight, necessitates additional mechanisms of crust accretion. Since major lateral displacement is limited by counteractive crystallization forces in the horizontal plane—hence the development of pseudo-anticlines—upward displacement is likely to predominate. The force required to achieve upward displacement of an overburden of 1 or 2 m is readily generated during unidirectional gypsum crystal growth (Goudie, Cooke & Evans, 1970).

Since crystal growth is limited by the availability of moisture, diagenetic overgrowths of alabastrine gypsum will be the norm in the upper soil zone. The ionic attraction of crystal faces will be greatly reduced once soil moisture has evaporated and subsequent crystallization will occur at the contacts between crystals, displacing them rather than increasing their size. This process may account for the higher gypsum content of residual cobbles (Table 1). These are undergoing dissolution, as is evidenced by solutional pitting on any residual lozenge-shaped gypsum crystals. However, rapid evaporation of moisture after wetting precipitates alabastrine material as overgrowths which displace clastic particles as well as existing gypsum crystals.

Differential leaching

In areas where at any time of the year rainfall exceeds the moisture storage capacity of the soil zone, subsurface accumulation of gypsum will be hindered by leaching of water-soluble salts into the groundwater zone. Moreover, in extremely arid regions insufficient moisture may be available to leach surface deposits of gypsum into the soil zone. It is in these areas peripheral to the main occurrences of illuvial gypsum crusts that two-tiered crusts may develop. Page (1972) attributed the superimposition of calcretes on gypsum crusts in southern Tunisia to the leaching of two distinct aeolian deposits at different times. Horta (1979, 1980) attributed the calcrete–gypsum crusts of Algeria to the same process. Similarly, in the central Namib Desert, Gevers & Westhuyzen (1937) held that halite horizons beneath gypsum accumulations represented two different phases of coastal evaporite sedimentation. In both regions the two soluble mineral horizons are clearly differentiated, there being little mixing of the salts. This would be unlikely if leaching and displacive accretion occurred at two periods.

In areas where calcium sulphate and calcium carbonate or calcium sulphate and sodium chloride are deposited at the surface, both will be leached into the soil zone if sufficient rainfall is available to mobilize the least soluble. Both will accumulate if rainfall is insufficient to flush the most soluble mineral out of the soil zone. Periodically, above average rainfall will cause leaching beyond the main horizon of crust accretion. At this time the salts will be removed to greater depths in quantities proportional to their solubilities (Drever & Smith, 1978). Chemical considerations come into play since gypsum solubility is reduced in the presence of calcium carbonate and enhanced by sodium chloride. However, the relative mobilities of the salts through the soil zone differ sufficiently to result in their accumulation within discrete horizons (Figs 13 and 14).

In the central Namib both calcrete–gypsum crusts and gypsum–halite crusts are encountered (Kaiser & Neumaier, 1932). The inland limits of halite crusts and gypsum crusts are shown on Fig. 3. Halite crusts do not extend further inland than the 25 mm mean annual isohyet, and gypsum crusts predominate between the coast and the 40 or 50 mm mean annual isohyet. Figure 13 shows a section near Gobabeb (Fig. 3) where calcrete overlies a subsurface gypsum crust. Figure 14 shows a section at Rooibank (Fig. 3) near the coast, where a gypsum crust overlies a halite accumulation. In the latter section, the calcium carbonate peak at a depth of 0·3 m is enigmatic. Since there are calcrete pebbles in the lower horizons, the carbonates may represent remnants of an older calcrete which has been described by Martin (1963) in this area. Since the inland limit of gypsum crusts corresponds roughly with the most easterly extent of the coastal fog belt, two factors control the distribution of the crusts. First, further inland increased rainfall promotes leaching of gypsum through the soil zone. Secondly, since evaporite minerals are absent from bedrock and groundwater, the most likely sources of soluble salts are fog moisture and aerosols which have a limited inland distribution (Yaalon, 1964, 1971; Yaalon & Lomas, 1970).

CONCLUSIONS

Gypsum crusts may be subdivided into three main types on the basis of structural and textural criteria.

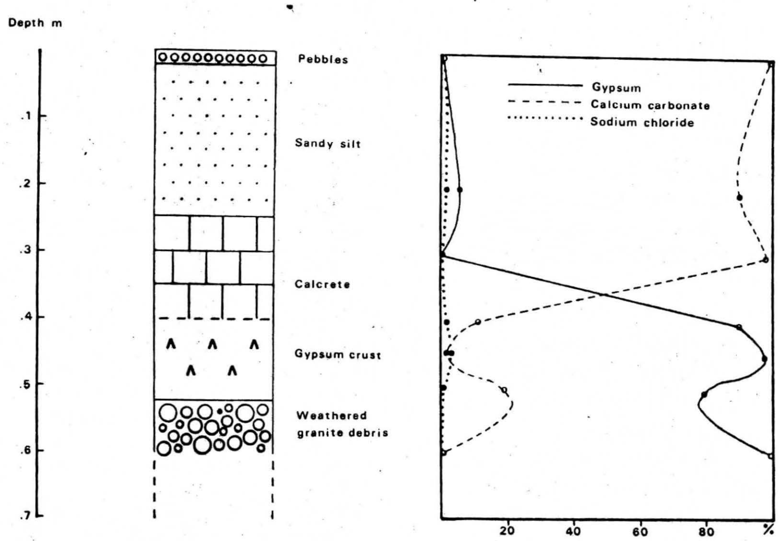

Fig. 13. Two-tiered (calcrete–gypsum) crust near Gobabeb, central Namib Desert (Fig. 3), showing the variation in mineral content with depth. Gypsum, calcium carbonate and halite (determined from the concentration of sodium) are plotted as percentages of the total acid-soluble portion of the samples. The amount of insoluble residue ranges from 13% in the basal sample, to 29% in that from the surface.

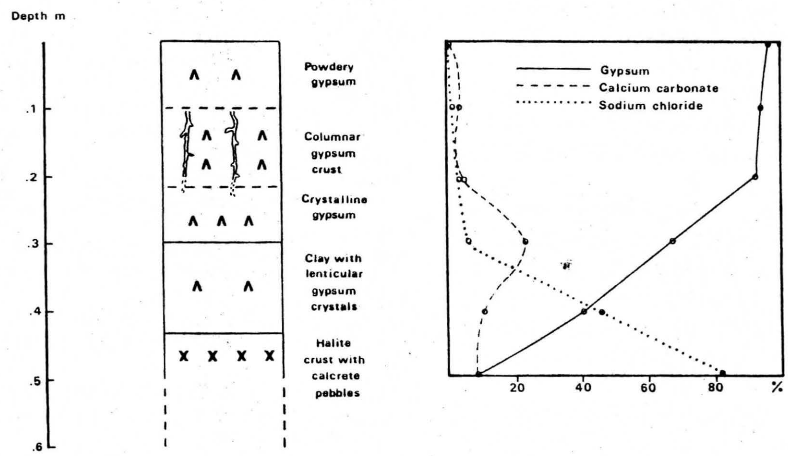

Fig. 14. Two-tiered (gypsum–halite) crust, Rooibank, central Namib Desert (Fig. 3), showing the variation in mineral content with depth. Gypsum, calcium carbonate and halite (determined from the concentration of sodium) are plotted as percentages of the total acid-soluble portion of the samples. The amount of insoluble residue ranges from 13% in the surface sample, to 62% in that from the base of the section.

Those formed by evaporation of shallow surface water bodies in lacustrine and lagoonal environments are characterized by horizontal, size-graded beds. Those which develop through evaporation at a near-surface water table, termed desert rose crusts or *croûtes de nappe*, are composed of large, interlocking lenticular gypsum crystals which enclose particles of host material poikilitically. The bedded crusts and desert rose crusts generally have higher concentrations of sodium, potassium, magnesium and iron than the mesocrystalline subsurface form. In part this may result from the incorporation of larger quantities of detrital or host material, and a greater abundance of ions co-precipitated with gypsum in the hydromorphic crusts. The surface crusts have a variety of forms but all are the result of exhumation and degradation of subsurface accumulations. These subsurface, illuvial crusts are derived from surface gypsum deposits which have various origins. In southern Tunisia, gypsum-rich sand and dust deflated from seasonally-flooded basins are the main source. In the central Namib Desert, salts dissolved in fog moisture are probably the immediate source. Elsewhere, gypsiferous fluvial, colluvial and aeolian sediments have also been identified.

With the exception of bedded and desert rose crusts, gypsum crust genesis occurs when meteoric water, which contains gypsum dissolved at the surface, is held in the soil zone until subsequent evaporation precipitates the soluble salts. Crystallization at host grain contacts, and occasionally as fibrous gypsum, results in displacive accretion. Exhumation of the illuvial horizons exposes indurated columnar crusts. If sufficient rainfall is available to induce leaching, these crusts degrade to form gypsum cobbles and powdery accumulations with a comparatively low gypsum content. The dissolution of the surface crust may provide the gypsum necessary for the formation of another subsurface accumulation. Two-tiered illuvial crusts, usually either calcium carbonate–gypsum or gypsum–halite, form when two salts with different solubilities are mobilized from the surface into the soil zone. Differential accumulation occurs if rainfall is insufficient to leach the more soluble salt out of the system.

While gypsum crusts are found only in semi-arid and arid regions of the world, being the products of specific hydrological or pedogenic processes, great care must be exercised when employing these features as palaeoenvironmental indicators. The susceptibility of gypsum to dissolution and reprecipitation can result in marked chemical and textural changes following burial or exhumation of a crust. Moreover, the illuvial origin of some forms of crust, combined with an atmospheric and/or aeolian origin of the gypsum, can result in the mantling of old landforms and landscapes with comparatively recent crusts. Nevertheless, by bearing these caveats in mind, relict gypsum crusts can provide valuable indicators of past hydrological, climatic and pedogenic events in many arid environments.

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