Facies Associated with Primary Gypsum Nodules of Northern Egyptian Sabkhas

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ABSTRACT

Modern sabkha and lagoonal, evaporitic environments are well developed in the Mediterranean coastal zone of Egypt between Alexandria and El Alamein. It is a semi-arid region with an annual rainfall of about 19 cm. Landward of the modern, ooid beach-ridge is a narrow depression. This is occupied by partially-vegetated sabkhas of desert-loess and some small lagoons. Those which are moderately hypersaline contain the cockle, Cardium glaucum; very hypersaline lagoons are precipitating gypsum.

The sabkhas are usually underlain by the following sequence of Holocene sediments. At the base are lagoonal shelly silts, locally with Cardium. Lagoonal gypsum follows. Then comes desert-loess, within which gypsum nodules are developing by precipitation from capillary water. These sabkha deposits are being gradually covered by ooid sand. The present marine transgression should ultimately produce a sequence in which an oolitic limestone is overlain by a cockle bed, followed by laminated gypsum, overlain, in turn, by a red bed siltstone with gypsum nodules. This would be capped by oolitic limestone. Ancient strata resembling certain of these facies include cockle beds associated with evaporites in British, late-Jurassic strata. The facies association of desert-loess with gypsum nodules, halite, caliche, palygorskite and scorpions can be matched in the British Trias.

INTRODUCTION

Primary gypsum nodules have been reported in sabkhas of the Mediterranean coast of Egypt (West, Ali and Hilmy, 1979). The present paper is a brief review of the facies of the sabkha sequence in which they occur and also of the lagoonal deposits with which they are closely associated. Emphasis is on features relevant to the recognition and interpretation of ancient analogues. Details of the relationship of the nodules to the compositions of interstitial brines are given elsewhere (Ali and West, 1983).

Although calcium sulfate nodules are common features of ancient evaporites (e.g. Withington, 1961; West, 1965; Shearman, 1966), their original mineral composition remains disputable. Shearman (1966) and Kinsman (1966) suggested primary anhydrite; others have argued for primary gypsum subsequently replaced by anhydrite (Kerr and Thomson, 1963; Murray, 1964; West, 1965; Tucker, 1976).

The possible environments in which they can originate are also controversial. Modern calcium sulfate nodules of the Trucial Coast (Shearman, 1966; Kinsman, 1969; Butler, 1970) indicate an origin in supratidal-sabkha sediments usually overlying intertidal and lagoonal deposits. Some authors (e.g. Dean, Davies and Anderson, 1975; Dean and Anderson, 1982) consider that nodules can form in subaqueous environments. Schreiber, Roth and Helman (1982) have suggested that some subaqueous gypsum deposits may be converted to nodular gypsum by later subjection to a sabkha environment ("sabkha-ized"). The northern Egyptian sabkhas and lagoons are important in providing new evidence for the origin of calcium sulfate nodules and associated facies.

Setting of Evaporitic Environments of Northern Egypt

Most of northern Egypt is extremely arid with less than 13 cm average annual rainfall. A number of hypersaline lakes occur in the desert regions away from the coast

(Figure 1). Most of these either deposit halite at present or have deposited it in the past. Their surfaces are usually below sea level.

The northern coastal zone is less arid and is vegetated to various extents. In the vicinity of the Nile Delta it can be divided broadly into three main regions (Figure 2). The Delta consists of clastics, including volcanic detritus from distant sources. East of the Delta is a region of siliciclastic sand derived from it by eolian action and longshore drift. West of the Delta are former beach-ridges of Pleistocene limestone with depressions between them (Figure 2). This area is discussed in more detail below.

Gypsum is, or has been, deposited in several lagoons of the coastal zone (Figure 1). These are close to sea level. Ca^{2+} and SO_4^{2-} ions are derived from the sea and Na^+ and Cl^- ions are returned to it. In the east, gypsum occurs at the margins of Bardawil Lagoon and Lake Manzala (Levy, 1974; Said, 1962). At El Alamein, west of the Nile Delta, some smaller lagoons are depositing gypsum at present.

Gypsum is also precipitated as nodules within the soil profiles of sabkhas which are adjacent either to the coast or to coastal lagoons (Figure 1). The nodules are abundant west of the Nile Delta between Sidi Kreir (near Alexandria) and El Alamein, and have been investigated in detail here

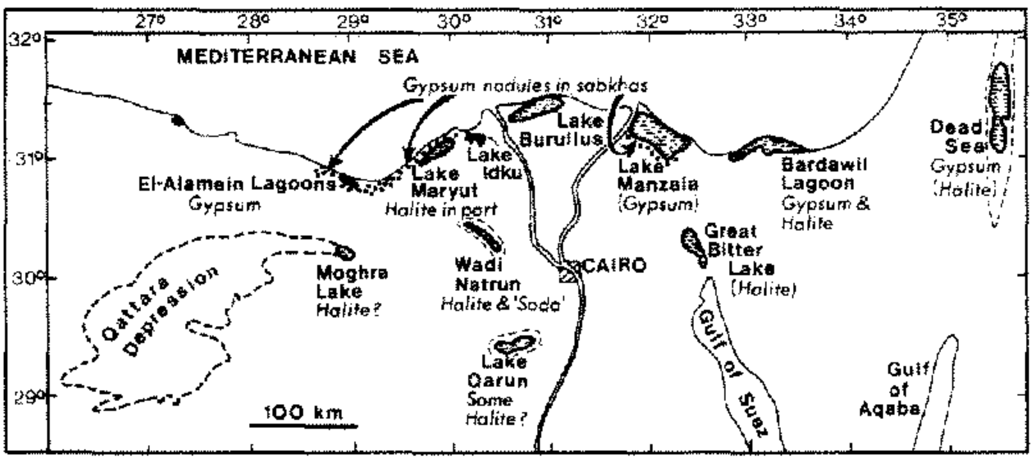


Figure 1. Simplified location map showing areas with modern gypsum nodules and the main hypersaline lagoons and lakes of northeastern Egypt and adjacent region. The major evaporites of the lakes and lagoons are given. Those in brackets are evaporites that were formerly, but are no longer, precipitated. Broken lines indicate large areas below sea level.

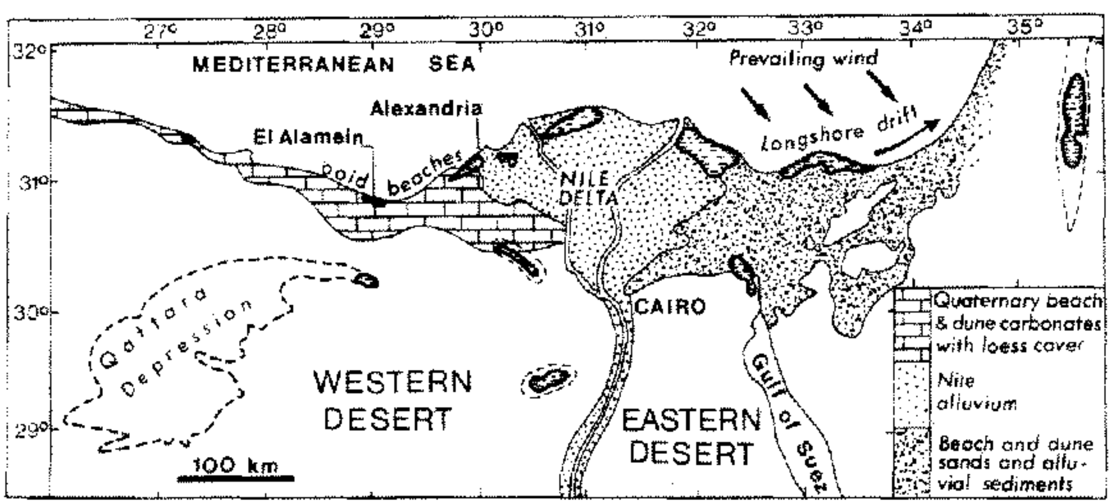


Figure 2. Much simplified geological map of Quaternary sediments of the coast of northeastern Egypt and adjacent region. Based mainly on Said (1962) and Shata (1969). Siliciclastic sands are transported eastward from the Nile Delta by wind and longshore drift (Pomeranceblum, 1966; Levy, 1974). West of the Delta the coastal zone consists mainly of ridges of Pleistocene limestone parallel to the coast. Between the ridges are depressions which contain desert-loess overlying limestone.

(West, Ali and Hilmy, 1979; Ali and West, 1983). Gypsum nodules also occur around Lake Manzala, a rather more arid area (Fathi *et al.*, 1972; Ali and West, 1983), and near Haifa in Israel (Magaritz and Kafri, 1979).

Coastal Zone—Climate and Physiography

The climate of the coastal zone west of the Nile Delta is moderated by proximity to the sea, and there is rapid increase in aridity from the coast southward to the Western Desert. Detailed climatic data is available for Alexandria. Maximum monthly average air temperature is 30°C. Rainfall is very variable from year to year but averages about 19 cm. It usually falls only from September to May (Hume and Hughes, 1921) and is sufficient for scrubby vegetation. Annual evaporation is about 10 times the rainfall.

The parallel limestone ridges of the coastal zone (Figure 3) were formerly beach and dune ridges of carbonate sand (Butzer, 1960). They have developed as the coast has, in general, prograded northwards during the Pleistocene. The modern beach and dune ridge, the Coastal Ridge, is about 20 m high. It consists of white, aragonitic, ooid sand (Hilmy, 1951) and is part of the extensive coastal ooid deposits of the eastern Mediterranean between Alexandria and the Gulf of Gabes, Tunisia (Emelyanov, 1972; Fabricius and Schmidt-Thomé, 1972). In spite of the general Quaternary regression, there is at present a transgression (Butzer, 1960) and the ridge is retreating landward.

South of the Coastal Ridge is the long, narrow (½ km wide) First Depression. It consists mainly of semi-vegetated sabkhas of saline, desert-loess, the surfaces of which are near to sea level. Both the sabkhas with gypsum nodules and the lagoons discussed in this paper are developed within this depression.

The second ridge, that on the south side of the depression, is the Abu Sir Ridge. It is about 30 m high, of Pleistocene age and well-lithified. It consists of white limestone, a grainstone with skeletal and algal debris. Low-Mg calcite is dominant near the surface. Caliche in the upper part contains authigenic palygorskite (Hassouba and Shaw, 1980). The ridge is flanked on both sides by alluvial fans of loam with land snails. Farther south is the Second Depression, a 2-km-wide sabkha of loess with halophyte plants but without large gypsum nodules. A large lagoon formerly occupied this depression (De Cosson, 1935), but now there are only shallow salt lakes in places (Figure 3). To the south is the third ridge of Pleistocene limestone. The third depression, the Wadi-El-Gypse, contains Pleistocene gypsum (Hume, 1912), and also palygorskite in associated marls (Hassouba and Shaw, 1980). Other ridges exist farther south.

First Depression—Environments and Groundwater

The sabkhas of the depression are characterised by numerous nebkhas, small mounds or dunes, about 1 or 2 m in diameter, of blown silt (desert-loess) developed around small halophytic shrubs, particularly the saltbush *Halocnemum*. The sabkhas resemble in some respects the dikaka environments of Glennie and Evamy (1968). The flat surface of silt between the mounds has a thin, firm crust bound by halite and gypsum. Footprints of herbivores, including those of gazelles and camels, are commonly preserved in this. Ostriches would also have left footprints prior to their extinction in this area in historic times. Insects, including grasshoppers and dragonflies, are common and scorpions are present. Land snails are conspicuously absent on the saline sabkhas but are abundant on the ridges. Lizards and snakes occur.

The saltbush environment is uncultivated, in contrast to some of the adjacent higher ground, and indicates areas where the water table is within about 1.5 m of the surface (i.e., where the surface is within the capillary fringe). Trees

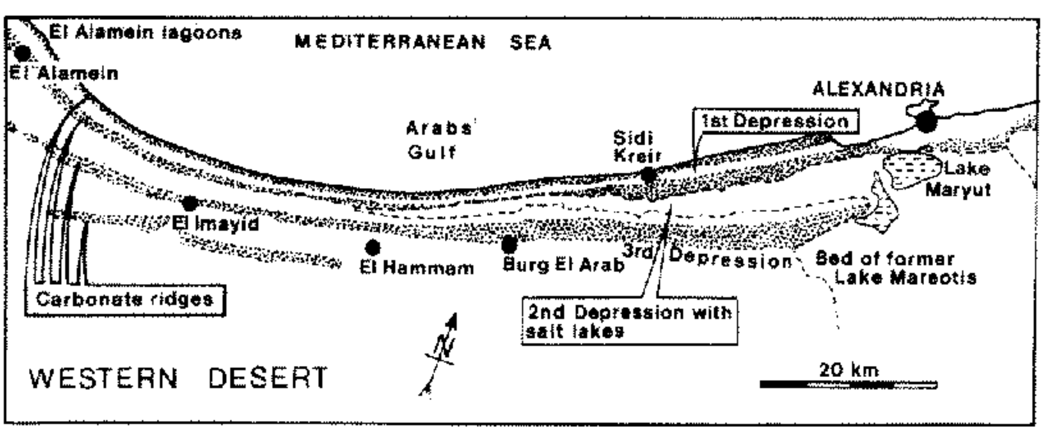


Figure 3. The major features of the coastal zone west of the Nile Delta. The First Depression lies between the modern Coastal Ridge of ooid sand and the parallel Abu Sir Ridge of Pleistocene limestone. Gypsum nodules occur in the desert-loess of this depression.

are absent from the sabkha except at the foot of the Coastal Ridge, which holds some low-salinity water from the winter rains.

The groundwater beneath the water table is hypersaline. Total dissolved solids range from about 41 g/l near the El Hamman to 79 g/l at El Alamein. The First Depression slopes gently northward toward the Coastal Ridge, adjacent to which the water table is closest to the surface. The composition of the groundwater brines indicates derivation mainly from the sea through this ridge (Ali and West, 1983). A similar process has been recognised in Libya (Rouse and Sherif, 1980).

Near El Alamein there is a series of lagoons in the First Depression. The Coastal Ridge is lower here. These lagoons probably also receive seawater mainly by seepage through the ridge, as in the case of some South Australian coastal lagoons (Warren, 1982, figure 3). Those situated immediately northeast of El Alamein British military cemetery are most saline (168 g/l in September, 1980) and are saturated or nearly saturated for gypsum. The environment is a little more arid here than in other parts of the First Depression (Shata, 1969). Other lagoons a few kilometers to the east are of lower salinities. None of the lagoons is sufficiently hypersaline to precipitate significant quantities of halite.

SEQUENCE OF SEDIMENTS

The Holocene sequence of sediments beneath the sabkhas of the First Depression is similar at most places. It can be divided into a series of "zones" based on particular mineralogical characteristics (Figures 8 and 9). There is a systematic pattern of brine compositions. Carbonate sediments, like those of the limestone ridges underlie the depressions (Ball, 1939) and locally project through the sabkha sediments to the surface (although mainly in the Second Depression).

The lowest sediments studied (zone I) consist of silt with fragments of limestone, aragonitic ooids, glauconite grains and algal-bored bivalves. These deposits have been seen at only a few places because of difficulties of coring and digging below the water table. Material excavated during the construction of a canal at El Alamein includes silt with shells of *Cardium* and cerithid gastropods which seems to have come from this unit. Zone I probably represents lagoonal sediments, the deposition of which preceded that of the main loess sequence.

The typical desert-loess, a type of sediment discussed in more detail below, commences with zone II. It is a laminated, unfossiliferous, calcareous, quartz silt. The zone II loess contains small gypsum crystals and probably originated during the filling of hypersaline lagoons. Zones I and II now lie below the water table in contact with hypersaline groundwater. Zone III contains nodules and ruckled bands of coarse, lenticular to tabular gypsum crystals. Zone IV contains white, fine-grained gypsum nodules in light brown loess.

The uppermost zone (V) consists of moist, laminated silt with plant roots and some dispersed halite and gypsum. The upper part of this saline soil is usually in dark gray, reduced condition (Figure 8).

The more distinctive facies are now considered in more detail.

HYPERSALINE LAGOONAL COCKLE FACIES

Description

Lagoonal deposits with cockle (*Cardium*) shells are common on the North African coasts. The occurrence of these bivalves in sequences of sediment with gypsum, as at El-Alamein and also at the Bardawil Lagoon (Levy, 1977), is of special interest.

Cockles are the European and Mediterranean edible bivalves of estuaries and lagoons which belong to the closely related species *Cardium edule* Linné and *Cardium glaucum* Poiret ("*C. lamarcki*"). Distinction is not easy (Nossier, 1980) and in old accounts both are given as "*C. edule*." All or almost all of the Mediterranean cockles probably belong to *Cardium glaucum* (Rygg, 1970; Gaillard and Testud, 1980). The Egyptian examples usually show the greater asymmetry characterising this species. *C. glaucum* probably originated in the conditions of isolation and variable (and often high) salinities of the desiccated Mediterranean during the Messinian (Rygg, 1970).

The presence of *Cardium glaucum* in Quaternary and older sediments can provide evidence regarding salinity. It is euryhaline to a remarkable extent and can tolerate 3‰ to 60‰ salinity (Rygg, 1970; Nossier, 1980; Gaillard and Testud, 1980). Thus a low-diversity (i.e., non-marine) fauna with abundant *Cardium glaucum* suggests either brackish (hyposaline) or hypersaline conditions. Presumably, a cockle deposit of brackish water origin would be more likely to be associated with "freshwater" (limnic or oligohaline) mollusc and charophyte-bearing beds, fluvial-type sediments and much plant debris. A hypersaline cockle deposit would be more likely to be associated with evaporites, celestite, stromatolites, blown silt or sand or unfossiliferous laminated dolomites or limestones.

Modern brackish environments with the bivalve include the lagoons of the Nile Delta (Hume, 1912). *Cardium* shells, together with remains of *Corbicula*, *Ostrea* and *Pirenella*, are abundant in the sediments beneath Lake Maryut and its former westward extension in the Second Depression (Hume and Hughes, 1921).

A modern, moderately hypersaline environment with *Cardium glaucum* is a lagoon (AL.1) east of El Alamein. The brine is of approximately 55‰ salinity in summer. There are other, similar lagoons nearby. The bivalves here are dwarfed (Figure 4), with a mean length of 12.6 mm,

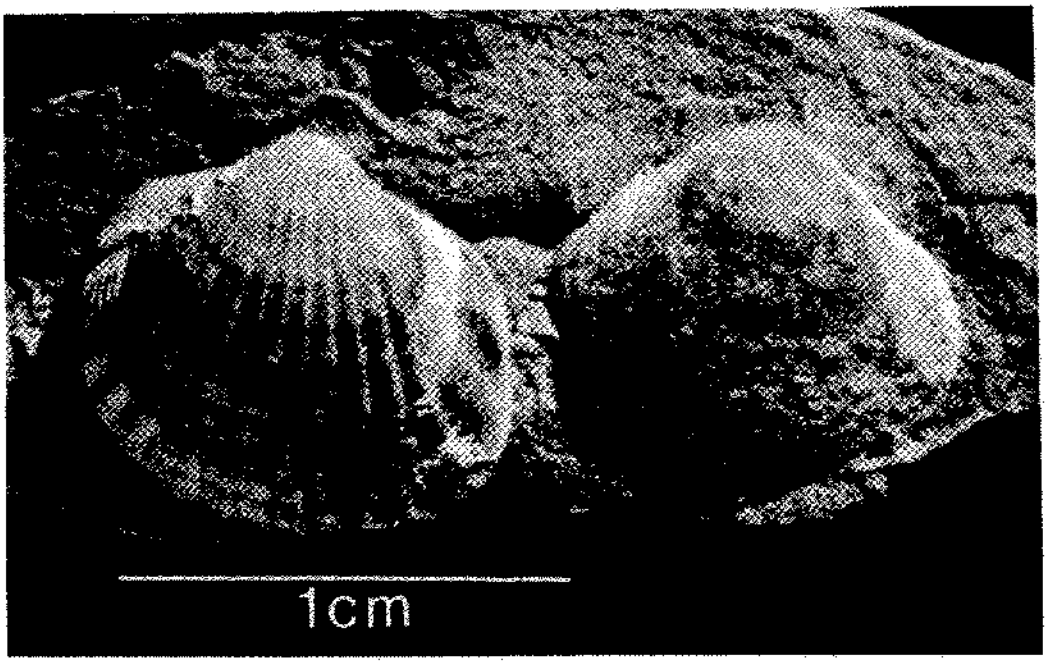


Figure 4. A stunted cockle shell (*Cardium glaucum*) from the easternmost (A.L.1) of the El Alamein lagoons is on the left. A comparable fossil cockle (*Protocardia purbeckensis*) on the right is from lagoonal strata with gypsum of the Purbeck Formation (Late Jurassic-Early Cretaceous) of southern England.

and are associated with turreted gastropods. Elsewhere, *Cardium glaucum* occurs in hypersaline lagoons of the south of France and of the Sea of Azov (Rygg, 1970). The abundant *Fragum* (Cardiaceae) of hypersaline Shark Bay, Western Australia (Hagan and Logan, 1974) may be analogous.

It is thus probable that the sediments with cockles in the Holocene sequence with gypsum at El-Alamein are of hypersaline origin, particularly since there is no significant source of low-salinity water here. The Bardawil deposits may be of similar origin but require further investigation.

Ancient Analogues

A Pleistocene analogue is present in the Egyptian coastal zone. The gypsum of the Third Depression is of laminated lagoonal type (Hume, 1912; Hassan, 1977), rather than nodular sabkha type. It alternates with *Cardium* limestone and this probably represents the cockle-rich sediments of former hypersaline lagoons.

Perhaps the best-known examples of ancient "cockle beds" with evaporites are in the lagoonal Lower Purbeck Formation (Upper Jurassic-Lower Cretaceous) of southern England (Arkell, 1947). The "cockles" are bivalves of the species *Protocardia purbeckensis* (Figure 4). They occur in members known as the "Hard Cockle Beds" and the overlying "Soft Cockle Beds" (Bristow and Forbes *in* Damon, 1884; Clements, 1969; Ali, 1981). In the Soft Cockle Member there is secondary gypsum that has replaced anhydrite, which in turn is a replacement of primary gypsum (West, 1964). It contains well-developed nodules and enterolithic veins (West, 1965). Calcitized gypsum occurs in the Hard Cockle Member. The usual association of the small cockle *Protocardia purbeckensis* with evaporites suggests that the species was tolerant of hypersaline conditions. Comparison with the modern analogues suggests that it might have been able to live in brine of up to about 60‰ salinity. The lack of desert sediments, the presence of coniferous forests, and the characters of the insect, molluscan and ostracod faunas is evidence, however, for a climate that was semi-arid and of Mediterranean type (West, 1975; 1979; Francis, 1983). This is confirmed by the palaeolatitude of about 37°N (Smith and Briden, 1977).

Sabkha cycles are present in these cockle beds. Shearman (1966) and Holliday and Shephard-Thorn (1974) have described sabkha cycles with calcium sulfate nodules in another part (the basal strata) of the Purbeck Formation and compared them to modern sequences of the very arid Trucial Coast. The sequences are similar in many respects and the nodules are strikingly similar.

The best of the sabkha cycles (H.C.2 or bed 36 of Clements, 1969) in the Hard and Soft Cockle Members includes the "Lower Insect Bed" of Durlston Bay. The cycles are not always complete but an idealised sequence based on several cycles is as follows:

5. (at the top). Erosion-surface, in some cases with some plant debris (*origin*—sabkha surface, sometimes with vegetated land nearby)
4. Nodules of gypsum, in some cases dissolved so as to

leave moulds, in pelletoid limestone (*origin*—supratidal sabkha)

3. Laminated lenticular gypsum (*origin*—lagoon "intertidal" flats)
2. Laminated argillaceous limestones with "cockles," pseudomorphs after halite, and insect and plant debris. These are usually compacted pelmicrites with graded laminae of quartz silt. Calcispheres, ostracods and foraminifers may be present (*origin*—very shallow, hypersaline lagoon sometimes desiccated, sometimes subjected to floods which washed in silt and debris of plants and insects)
1. (at the base). Argillaceous limestone with abundant "cockle" shells (*Protocardia purbeckensis*) and mudclasts (*origin*—a lagoonal shell-beach with ripped-up clasts of dried carbonate mud).

LAGOONAL GYPSUM FACIES

Description and Origin

In the "intertidal" zone of a hypersaline lagoon at El Alamein, northeast of the British military cemetary, tabular to sublenticular gypsum crystals up to about 3 cm in length are developed (Figures 6a and b). These crystals differ from most lenticular to sub-lenticular crystals in possessing (010) faces. They show zoning, perhaps of seasonal origin. They lie flat (with c-axes approximately vertical), scattered over the wet flats. The large size is presumably because crystal growth is slow in lagoon water which is just saturated for gypsum.

Small mounds or domes of gypsum, about 10 cm high and from about 15 to 50 cm wide have formed at the margins of the gypsum-saturated lagoons adjacent to El Alamein (Figure 5). The domes are particularly well-developed where small waves break in a few centimeters of water, but they also occur to a depth of at least a meter. In plan-view many of the mounds have roughly lunate forms which are convex toward the lagoon. The domes are aggregates of tabular to blocky gypsum crystals, mostly of a few millimeters in length. In some cases the upper parts have developed aggregates of large tabular to sub-lenticular crystals (Figure 6c). They resemble the isolated crystals of the "intertidal" flats but are thicker in the c-direction and firmly cemented together. Comparable gypsum domes have been described from Quaternary gypsum deposits of South Australia (Warren, 1982).

Algal-stromatolite heads occur at the margins of some lagoons. These are small, of about 10 cm diameter, and less conspicuous. Some consist of algal filaments and fibro-radiating aragonite. Others are of algal-laminae alternating with small gypsum crystals. Laminar algal mats are also common and older Holocene algal-mats are present in sediment that has been excavated from beneath the lagoons.

The top of a laminated gypsum deposit of lagoonal type is present at about 5 to 10 cm beneath the "intertidal" flats of the lagoons near El Alamein (Hume and Hughes, 1921)

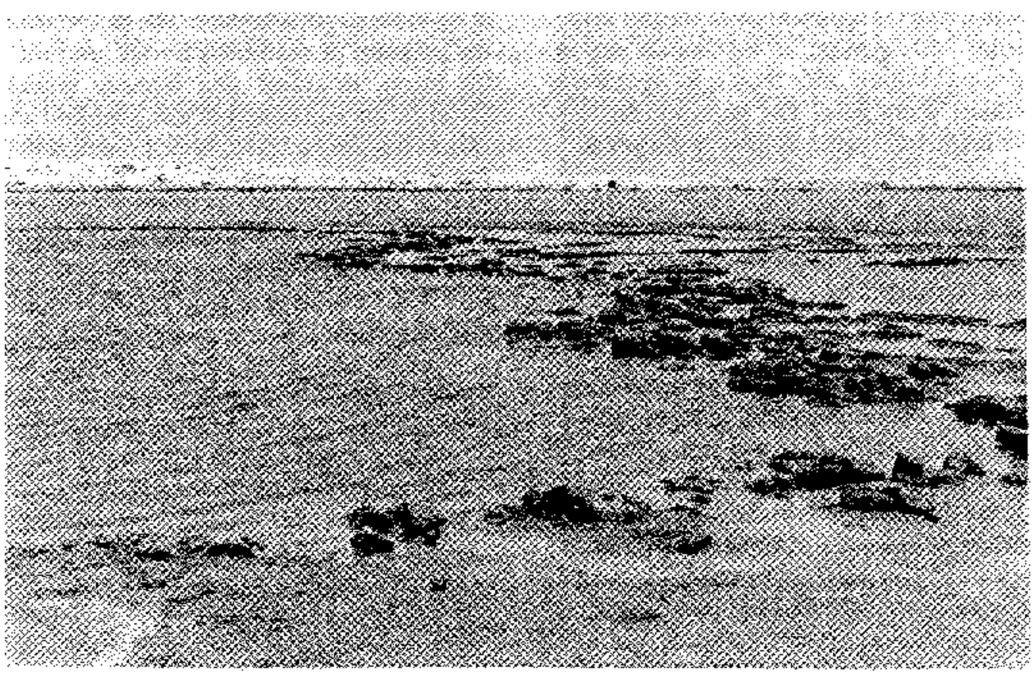
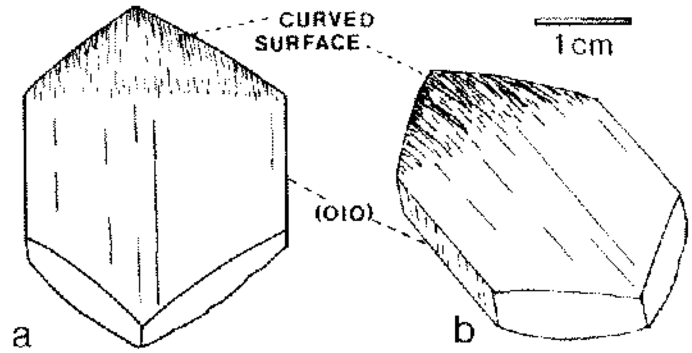


Figure 5. Small domes of gypsum crystals at the margin of the hypersaline lagoon at El Alamein. The domes range up to about 50 cm in width.



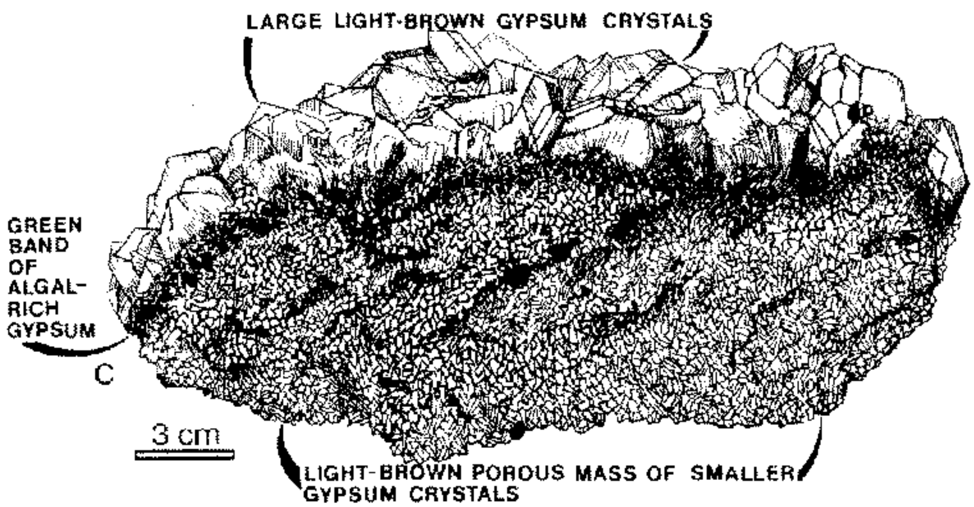


Figure 6. Gypsum crystals from a hypersaline lagoon in the First Depression at El Alamein north of the British military cemetary. a, b—a typical large platy crystal of the "intertidal" zone. c—part of a gypsum dome from the lagoon margin, broken through to show structure.

and the upper part of this was observed in trial pits. Large artificial excavations have brought much gypsum to the surface. This includes crystals of up to 11 cm in length, developed at right-angles to bedding and containing growth laminations.

Peculiar small ponds of about 1.5 m depth and with steep or overhanging sides occur at the margin of the broad, gently-shelving lagoon, north-east of the El Alamein military cemetery. The unusual morphology of these ponds is explained by local dissolution of the gypsum bed. The gypsum domes are best-developed at the margins of these karstic ponds (Figure 5).

The El Alamein gypsum bed is not quarried and therefore, unfortunately, is not well exposed. Similar laminated gypsum, also apparently of Holocene age, occurs at the southeastern margin of a Nile Delta lagoon, Lake Manzala. This is worked commercially at El Ballah, near Ismailia, and features exposed include ripple-marked gypsum and small tepee-like structures.

Ancient Analogues

The lagoonal origin of the Pleistocene gypsum of the Wadi-El-Gypse has already been mentioned. It presumably originated in lagoons similar to those at El Alamein and, similarly, behind a carbonate barrier beach (the third ridge).

Fabrics of modern and ancient gypsum deposits of lagoonal origin have been described by Shearman (1978) and Schreiber, Roth and Helman (1982). The Egyptian evaporites show similar features. Some Miocene evaporites of the Mediterranean may have originated in environments like those of the modern Mediterranean lagoonal evaporites. Ripple marks, for example, are present (Schreiber, Roth and Helman, 1982) as at El Ballah. Large tabular to sublenticular crystals almost identical to those of the El Alamein "intertidal" zone (Figures 6a and b) occur in the Sannoisian (Oligocene) evaporites of Paris (Lacroix, 1962, figure 20). They probably originated in a similar environment.

Stromatolites originally in contact with gypsum, and thus resembling those at El Alamein, occur in the Purbeck Formation of southern England (West, 1975). Stromatolites largely of gypsum are present in the Palaeogene evaporites of southeastern France (Truc, 1978).

LOESS-SABKHA FACIES WITH GYPSUM NODULES

Desert-Loess

Most modern environments with gypsum nodules in Egypt and elsewhere are semi-vegetated sabkhas with halophyte plants and nebkhas. They occur where the surface is within the capillary fringe and are usually about 0.5 m above the water table. The sediment consists predominantly of silt (69% is of particle size 2–63 μm, for 11 samples) which is light brown, friable and calcareous. It consists of about 38% quartz, 32% calcite, 21% feldspar and 10% dolomite (means for 3 samples). Deposition of similar silt takes place on roads and buildings when strong winds are blowing. S.E.M. studies confirm field observations that this material is desert-loess (Ali and West, 1983). Some blown gypsum also occurs. It forms small dunes in the sabkha adjacent to gypsum-depositing lagoons at El Alamein.

Gypsum Nodules—Description

Zone IV contains white, soft and friable gypsum nodules. They are spherical or elliptical, up to 4 cm in diameter and displace the host sediment (Figure 7). They are composed of minute (50 μm), lenticular to tabular crystals of gypsum. This silt-sized gypsum is similar to the South Australian gypsite, as defined by Warren (1982), a material that is similarly developed in soil profiles above the water table. The nodules in Zone III, beneath, are of larger yellowish gypsum crystals that are mostly cemented to each other.

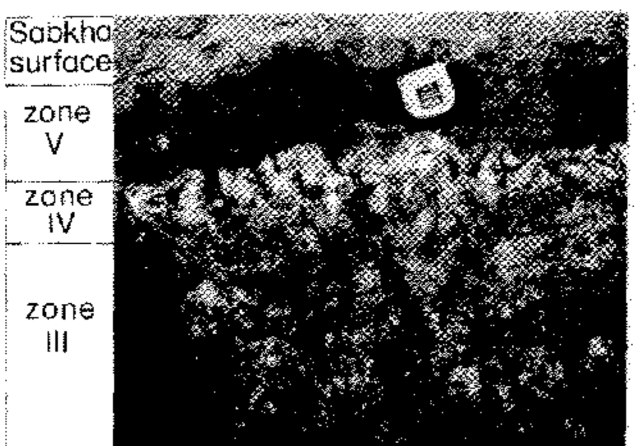


Figure 7. Desert-loess of the First Depression with white gypsum nodules (zone IV) overlying coarser gypsum nodules (zone III). Loess at the top contains no nodules but has interstitial waters of high salinity and saturated for halite. Scale is given by the tape measure holder, 5 cm wide.

Gypsum Nodules—Origin

Evidence that the gypsum is primary and not a replacement of anhydrite includes: (1) lack of Recent anhydrite in the region, (2) the friable, porous character of the upper (gypsite) nodules, and (3) the relationship between crystal size and distance from the sabkha surface. Changes in composition of the interstitial brines in the various zones indicates that precipitation of calcium sulfate is occurring at present.

The salinities of the phreatic groundwater vary from about 40‰ to about 80‰ and most ions are in proportions appropriate for concentrated seawater. Ca^{2+} and SO_4^{2-} ions are in excess, however, and the groundwaters are near to saturation for gypsum. Groundwater brines are largely derived by seepage of seawater through the very permeable sediments under the Coastal Ridge. They have probably been modified by dissolving some of the lagoonal gypsum under the sabkha (Ali, 1981).

The upward increase in salinity (Figure 8) and the details of brine chemistry (Ali and West, 1983) show that there is upward movement of brine by capillarity (the "per ascensum" mechanism) with evaporation at the surface

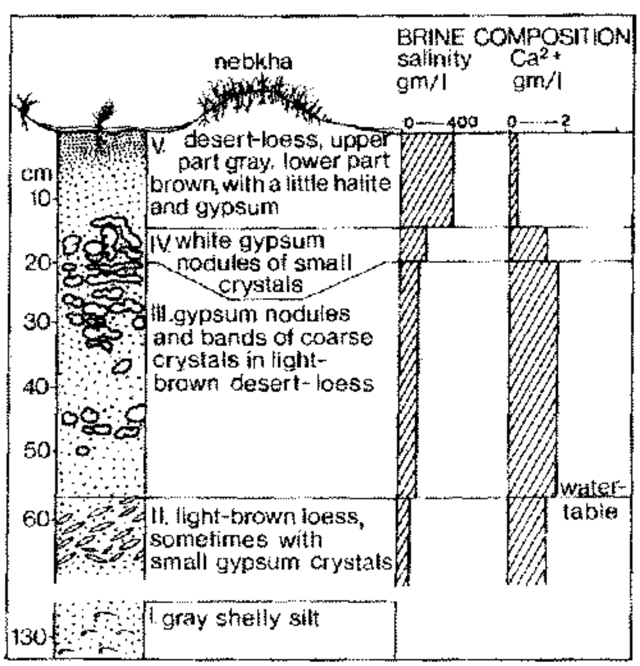


Figure 8. A typical profile (A.D.2 pit) through sabkha loess with nodules divided into a number of "zones." Brine composition as shown in the mean for each zone based on a series of profiles, details of which are in Ali (1981). The interstitial brine increases upward in salinity, given here as total dissolved solids in g/l. Ca^{2-} is lost from the interstitial brine in zone IV. Nebkhas are not to scale.

(Watson, 1979). The upward-moving brine becomes supersaturated for calcium sulfate and loses Ca^{+} in the zone IV sediments (Figures 8 and 9) by precipitating displacive gypsum nodules. The small crystal size of the gypsum probably results from the high salinities of interstitial brines and the rapidity of precipitation in summer.

The gypsum would be precipitated as a thick crust at the surface if Na^{+} and Cl^{-} ions were not present. The existence, however, of the very high salinity zone, with halite, at the top of the sabkha profile displaces downward the zone of gypsum supersaturation. Thus the gypsum is precipitated within the sediments and is displacive.

The development of gypsum nodules involves limited recycling of calcium sulfate by dissolution of some gypsum beneath the water table and concurrent precipitation as nodules nearer the surface. This is "sabkha-ization" of Schreiber, Roth and Helman (1982). The major process, however, is probably the development of nodular gypsum from ions derived from seawater. The surprisingly small proportion of halite in the sediments undoubtedly results from annual dissolution by the winter rains; the less soluble gypsum remains.

Modern Analogues

The gypsum nodules are strikingly similar in morphology, displacive features and purity to the classic anhydrite nodules of the sabkhas of Abu Dhabi and Kuwait of the Arabian Gulf (e.g., Shearman, 1966; Butler, 1969; Gunatilaka, Saleh and Al-Temeemi, 1980). Apart from traces in Algeria and Tunisia (Bellair, 1954; Durand, 1959), anhydrite appears to be absent on the North African coasts (Perthuisot, 1977). Relatively low groundwater salinities and temperatures are probably responsible. Cl^{-} averages only 66 gm/l in zone IV of the northern Egyptian sabkhas where calcium sulfate is precipitated. This is insufficient at the prevailing temperatures (mean air temperature 19°C) for stability of anhydrite (cf. Kinsman, 1974).

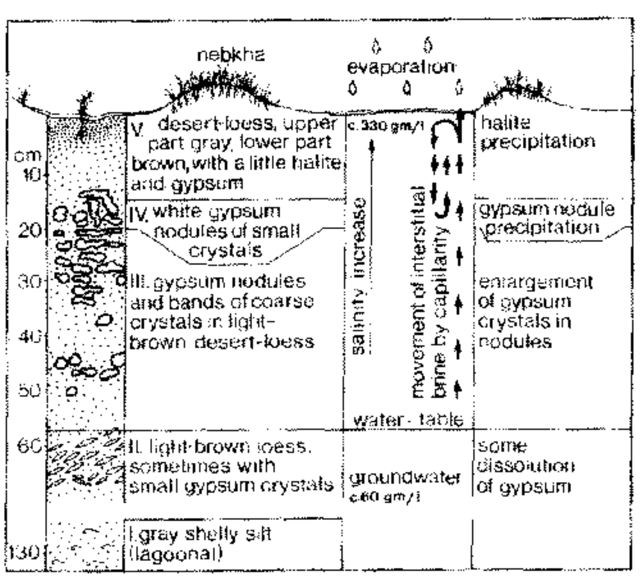


Figure 9. "Per ascensum" mechanism of precipitation of gypsum as nodules in zone IV. Precipitation at this level explains the loss of Ca^{2+} shown in Figure 8. Nebkhas are not to scale.

Much of the Arabian Gulf anhydrite has been shown to be secondary replacements of gypsum (Butler, 1969; 1970; Cuff, 1969; Bush, 1973; Perthuisot, 1977; Gunatilaka, Saleh and Al-Temeemi, 1980). It might all have originated as primary displacive gypsum nodules. Shearman (1966) and Bush (1973), however, have produced evidence for displacive growth of anhydrite. The differences in mineral composition, in spite of the similarities of the large-scale features of the calcium sulfate nodules of the two regions, remain an unresolved problem.

Ancient Analogues

The loess with gypsum occurs in proximity to sediments with palygorskite. The brown, iron-oxide-stained silt would presumably become a "red bed" siltstone with time. It thus provides a model for the formation of some ancient red bed facies. The British Mercia Mudstone, of Triassic age, although usually finer-grained than the Egyptian sediments, contains loess-like sediments with gypsum nodules and some palygorskite (Wills, 1970; Jeans 1978). This and associated Triassic strata exhibit, amongst other features, calcretes, desiccation cracks, footprints, dolomite, halite deposits, stromatolites, lake (or lagoon) beach deposits, erosion of pre-existing limestone and scorpion remains (Tucker, 1978; Wills, 1947). All of these are present in the modern Egyptian coastal zone in either the First or the Second Depression. Although Tucker (1978) argued for river transport of the fine-grained sediment of the Mercia Mudstone, other authors (e.g., Sherlock, 1947; Taylor, Price and Trotter, 1963) have considered that this is largely of wind-blown loess origin. Thus, the British Triassic sediments resemble the Egyptian desert-margin deposits, except that the former lack associated marine sediments.

CONCLUSIONS

The lagoonal and sabkha evaporites of the northern Egypt coastal zone between Alexandria and El Alamein are of semi-arid, desert-margin type. They probably represent a small relic of a type of evaporite and lagoonal facies that was widespread in the Mediterranean during the Messinian.

The general history of this region during the Pleistocene has been one of regression and progradation of carbonate sediments northward. The Holocene, however, has mainly been characterised by a slow transgression. A shallow sea presumably flooded the Pleistocene carbonates on the site of the First Depression (Figure 10a). The shallow marine environment would have been the natural precursor to the

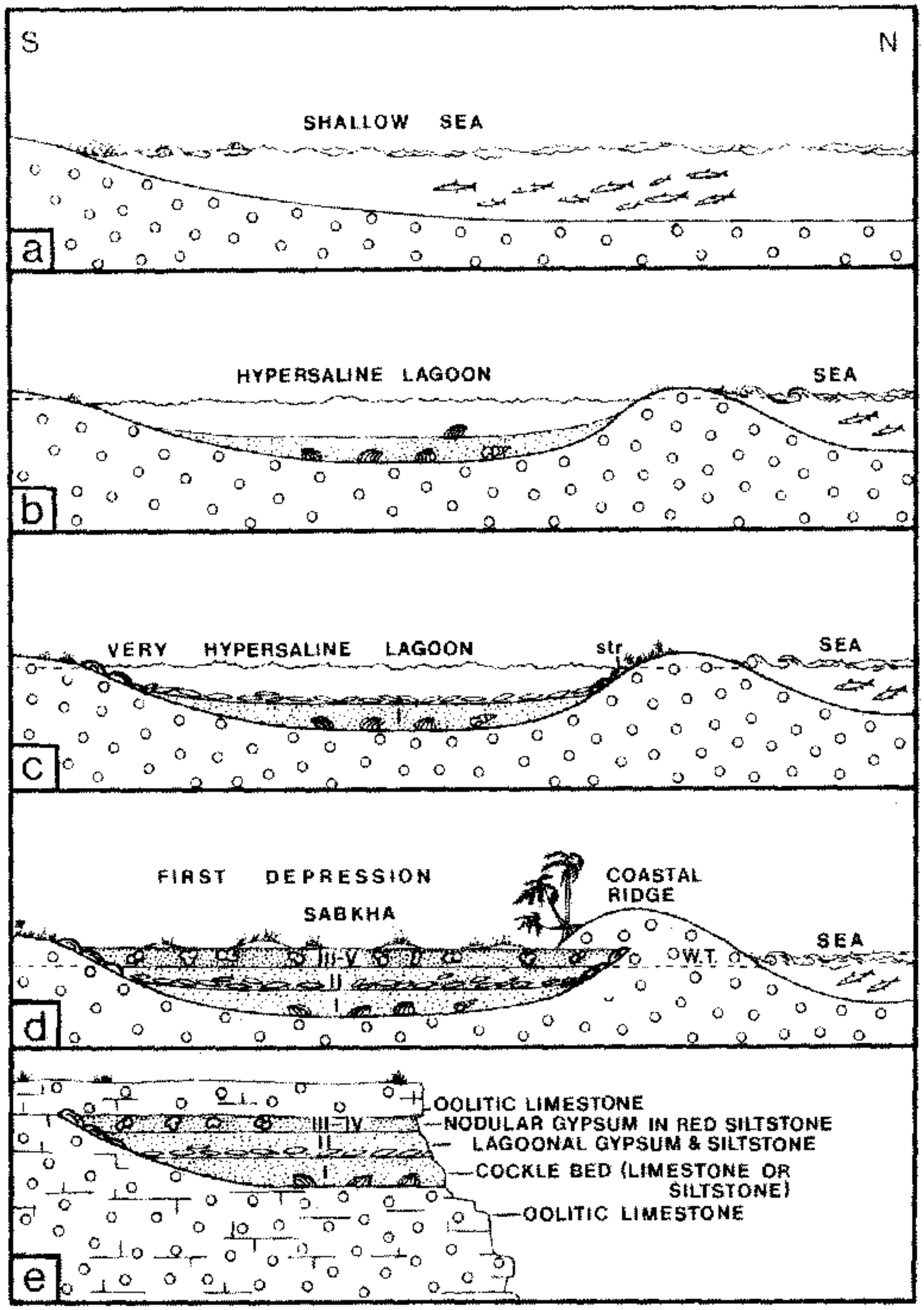


Figure 10. Hypothetical development of a rock sequence by continued sedimentation of the carbonate and loess deposits of the First Depression, followed by lithification:

a. Ooid sands form in a shallow sea (salinity 40‰).
b. Sedimentation in restricted lagoons, in some cases with *Cardium* bivalves and cerithid gastropods (salinity in dry season 60‰).
c. Precipitation of gypsum in a very restricted lagoon (salinity in dry season 120‰). Stromatolites (str.) may develop at the margins.
d. Present stage of development in most of the First Depression, shown schematically. Gypsum nodules are forming in sabkhas of desert-loess. *Cardium* shells may be present in zone I sediments at the base in some but not all parts. The Coastal Ridge is moving landwards because of the action of wind and sea.
e. A rock sequence that could result, assuming that the present slow transgression continued. Ooid sediments would cover the desert-loess by continuation of landward movement of the Coastal Ridge over the sabkha.

lagoons, which would have been created by the growth of the Coastal Ridge. At first this would have been a low, narrow and incomplete barrier (Figure 10b). At this stage, seawater and lagoon brines would have readily penetrated it so that the lagoons on the south side were at first only moderately hypersaline. Their sediments include cockle shells and cerithid gastropods. With greater restriction, next, there was precipitation of gypsum in the lagoons. Blown silt eventually filled most of the lagoons, and sabkhas were developed. Evaporation of capillary brines is now taking place at the surface of these. The desert-loess is sufficiently permeable for capillarity and, thus, nodules of gypsum are precipitated by the "per ascensum" mechanism. Salinities increase upwards and an uppermost zone with much Na^+ and Cl^- causes gypsum precipitation to take place beneath it. Anhydrite is absent.

If the present slow transgression continues, the ooid sand of the Coastal Ridge will continue to be driven landward, partly by wind action and partly by marine action (Figure 10d). It will in time cover the First Depression. Thus, the following sequence, from bottom to top, will be eventually developed: oolitic limestone, lagoonal cockle bed, lagoonal gypsum, desert-loess siltstone with gypsum nodules, erosion surface with plant debris and oolitic limestone (Figure 10e). If, however, a regression were to occur after the filling of the lagoon, a similar sequence would develop, except that it would be capped by more desert-loess rather than by oolitic limestone. Thus, a red bed siltstone would overlie the evaporitic sequence and, perhaps, a sandstone of desert wind-blown origin would follow. The Purbeck sabkha sequence described above resembles part of the sequence, that from the cockle bed to gypsum nodule bed, but has a carbonate rather than loess matrix. Sequences more closely resembling those in northern Egypt, however, are likely to be recognised in other formations of semi-arid origin, particularly those of red bed type.

ACKNOWLEDGMENTS

The authors particularly thank Professor Louis F. Dellwig for making it possible for this paper to be given at the Symposium. Professor Hussein and the Board of the Department of Geology, Ain Shams University provided generous support for field work in Egypt, without which this work would have been impossible. Mrs. L. Emery typed the paper and Mrs. A. Dunkley redrew the diagrams.

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