

The Arabian Gulf: A Modern Carbonate-evaporite factory; a review

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RESUMEN

El Golfo Pérsico es una cuenca «foreland» situada entre la placa árabe al SO y el cinturón plegado de los Zagros al NE. Se trata de una cuenca marina somera con profundidad generalmente inferior a los 100 m. Es una cuenca marina marcadamente asimétrica con la mayor profundidad localizada cerca de la costa NE actual de Irán, al pie del cinturón plegado de los Zagros y con una profundidad decreciente hacia el SO, hacia la plataforma de Arabia. Es, pues, un mar marginal del Océano Índico. Las altas temperaturas y las pocas lluvias en la zona han producido un ambiente marino con un reducido aporte de agua dulce, altas temperaturas y salinidad. Está colonizado por abundante fauna y flora de poca diversidad procedente del Océano Índico. La producción biológica del material que constituye el almacén de los sedimentos unido a la precipitación química ha producido una amplia variedad de sedimentos carbonáticos. La evaporación en la vecina plataforma árabe ha provocado la precipitación de sedimentos evaporíticos. La reacción entre carbonatos de origen biológico y aguas subterráneas salinas ha favorecido los procesos de dolomitización.

El aporte de sedimentos terrígenos alóctonos debido a procesos eólicos y fluviales es claramente asimétrico, siendo más acusado en los márgenes NO y NE del Golfo y estando prácticamente ausentes de la costa SO de la plataforma árabe. El modelo actual de *facies* refleja la localiza-

ción geológica, llegada asimétrica de aportes terrígenos y el clima. Una serie de cinturones de *facies* paralelos al Golfo y a la disposición tectónica de la línea de costa desde el NE al SO son: margas neríticas de la cuenca, carbonatos costeros de barrera-lagoon y evaporitas de plataforma costera. Las últimas pasan hacia el S a las dunas de arena de origen eólico y a las gravas de los abanicos aluviales de Arabia. Hacia el NO, y rellenando longitudinalmente, se encuentra el delta del Eúfrates-Tigris, que se dispone paralelo a la directriz tectónica antes citada.

El modelo de sedimentación actual del Golfo Árábigo demuestra ser útil para la diferenciación de sedimentación a escala global, pero particularmente en los depósitos permo-triásicos del NO de Europa.

Palabras clave: Golfo Árábigo, sabkha, dolomía, yeso, modelos evaporíticos.

ABSTRACT

The Arabian Gulf is a foreland basin lying between the Arabian Shield to the southwest and the Zagros fold belt to the northeast. It is a shallow marine basin with depths generally < 100 m. It has a marked asymmetry with the deepest water close to the northeast Iranian shore at the foot of the Zagros fold mountains and the depths decrease to the southwest towards the Arabian Shield. The area is a marginal sea of the Indian Ocean. High temperatures and low rainfall have produced a marine environment with a low influx of fresh water and high temperatures and salinity. It is colonised by an abundant but low diversity Indian Ocean flora and fauna. Biological production of skeletal material, together with chemical precipitation, have produced a wide variety of carbonate sediments. Evaporation in the adjacent coastal plains of Arabia has caused precipitation of evaporite sediments and reaction between biologically produced carbonate and saline ground waters has resulted in dolomitization. The supply of terrigenous allochthonous sediment by aeolian and fluvial processes is markedly asymmetric and is restricted to the northwestern and northeastern sides of the Gulf and is virtually absent along the southwestern Arabian shoreline. The modern *facies* pattern reflects the geological setting, asymmetric supply of terrigenous material and the climate. A series of *facies* belts parallel the Gulf and the causative tectonic trend and are, from northeast to southwest: neritic basinal marls; Arabian neritic shelf carbonates; coastal barrier-lagoonal carbonates; and coastal plain evaporites. The latter pass southwestwards into the aeolian dune sands and alluvial-fan gravels of Arabia. In the northwest, filling the

basin longitudinally and parallel to the tectonic trend is the Tigris-Euphrates delta. The pattern of sedimentation of the modern Arabian Gulf has proved to be a useful model for the elucidation of carbonate-evaporite sedimentation in various parts of the geologic column, but particularly for the Permo-Triassic deposits of northwestern Europe.

Key words: Arabian Gulf, sabkha, dolomite, gypsum, evaporite models.

INTRODUCTION

The Arabian Gulf (earlier known as the Persian Gulf), is a foreland basin lying between the Arabian Shield to the southwest and the Zagros fold mountain belt to the northeast (Fig. 1). It is a small remnant of the northwest-southeast Tethyan trough in which a thick series of oil rich deposits accumulated, often in environments very similar to those found today (Falcon, 1967; Murriss, 1980).

The physiography and geology of the region are the results of the interaction of the African and Asiatic plates (Sengör, 1985). This movement continues today to cause underthrusting along the Zagros line and earthquakes and volcanoes in Iran (Norwozi, 1971; Page *et al.*, 1957) (Fig. 1). Adjustment in the basement has resulted in a complicated pattern of structures in the modern Gulf, due to interaction of north-south orientated structures of the Arabian Shield and the northwest-southeast structures of the Zagros trend (Kassler, 1973). In addition, complications have arisen by movement of thick, deep-seated evaporites of Cambrian age escaping to regions of lesser stress (Falcon, 1967).

THE BATHYMETRY AND OCEANOGRAPHY

The modern Gulf is a neritic, marine basin infilled in the northwest by the delta of the Tigris-Euphrates rivers to form the plains of Mesopotamia: it is rarely deeper than 100 m except for a few isolated bathymetric depressions inside the entrance; and it has no sill (Fig. 2).

The deepest waterdepth is along the Iranian side, where it is bordered by a narrow shelf. In contrast, there is a broad platform on the Arabian side «The Great Pearl Bank», usually 30 m in depth, which is particularly well developed in the south between the Straits of Hormuz and the Qatar peninsula.

Numerous shoals, banks and islands occur throughout the area: most

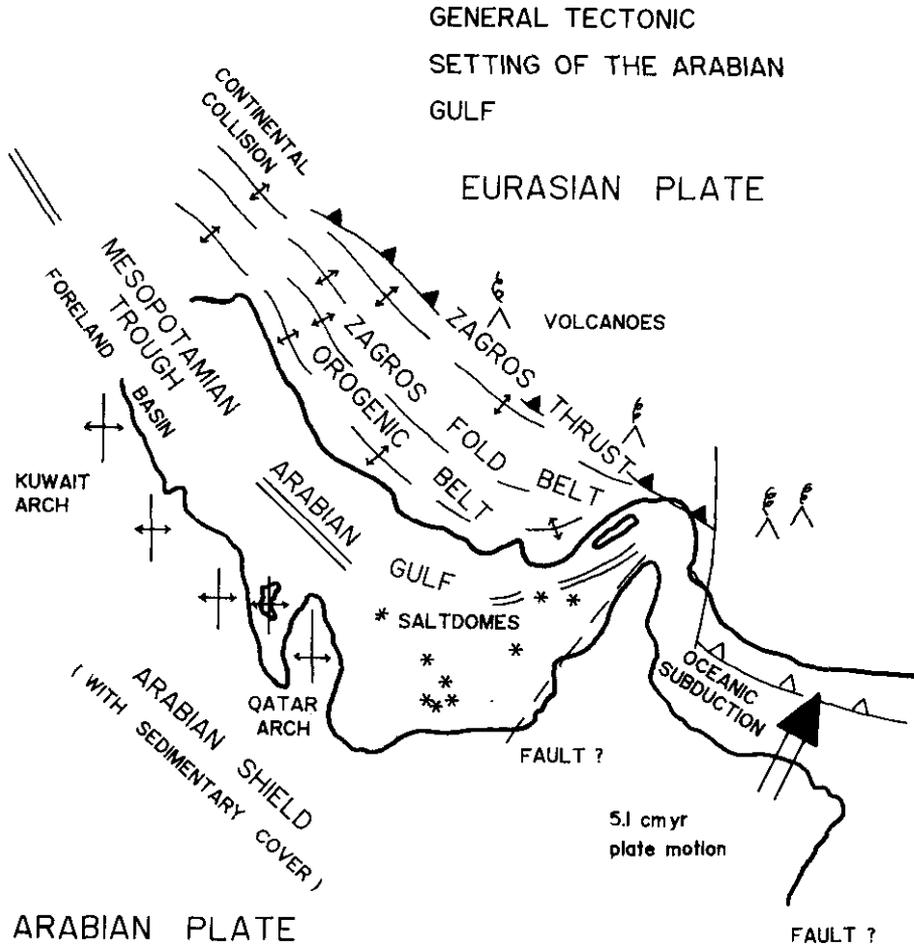


Fig. 1.—General tectonic setting of the Arabian Gulf.
Fig. 1.—Esquema tectónico general del Golfo Árabe.

are structurally controlled, some being diapiric, whilst others are probably depositional features built by sedimentation during the final phases of the Flandrian transgression (Kassler, 1973; Purser, 1973).

The waters of this marginal basin of the Indian Ocean have high temperatures (23-33° C) and salinities (37-38%) at the entrance with wider ranging values (16-32° C and 38-41%) in the northwest. Higher temperatures (20-37° C) and salinities (50-75%) occur in the coastal waters. The

Gulf is mesotidal in the extreme northwest and southeast and microtidal around the Qatar peninsula. There is a general anti-clockwise circulation of the surface waters: Indian Ocean waters on entering the Gulf become concentrated by evaporation and sink, to return as a salty plume into the adjacent ocean.

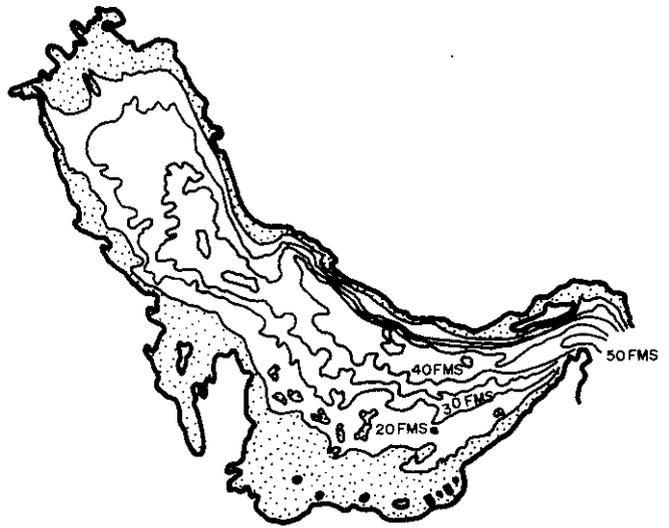
THE SOURCE OF THE SEDIMENT

The area is essentially one of autochthonous carbonate-evaporite production diluted by allochthonous, terrigenous sediment (Sugden, 1963a,b). The allochthonous supply is asymmetric being confined to the northwest and northeast (Emery, 1956). The Tigris-Euphrates, together with small streams along the Iranian coast, are the main conduits of carbonate-rich rock (calcite and dolomite) fluvial terrigenous detritus (Fig. 3). Virtually no sediment is transported to the Arabian shoreline by fluvial processes. Also, the Gulf is unusual in that it receives vast quantities of aeolian terrigenous sediment carried mainly by the northwest Shamal wind, but also by more local winds. The aeolian terrigenous sediment is generally composed of fine sand silt and clay, with high contents of carbonate (calcite and dolomite) (Khalaf, et al., 1979; Foda, Khalaf & Al-Kriadi, 1985). Elsewhere, on parts of the Arabian coast, quartzose dune sands are driven into the coastal waters (Shinn, 1973; Fryberger, Al-Sari & Clisham, 1983).

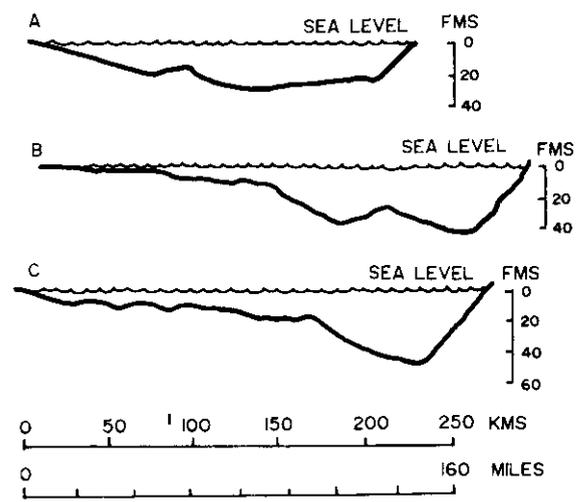
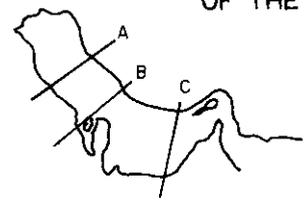
The Gulf contains an impoverished *ie* low diversity, but abundant Indian Ocean fauna and flora (Hughes-Clarke & Keij, 1973; Basson et al., 1977; Jones, 1985). Skeletal production by benthonic organisms and its subsequent comminution dominates sedimentation over the Arabian Shelf area. Remains of planktonic organisms are of less importance and are only noticeable in the sediment of the outer areas adjacent to the Indian Ocean (Fig. 3). However, planktonic molluscs –pteropods– are found over the whole area. (Hoefs & Sarnthein, 1971; Hughes-Clarke & Keij, 1973). In contrast to the previously held view that the Gulf is a region of low phytoplankton production the remains of these are common (Bedford, 1975; Al-Kais, 1976). Diatoms and dinoflagellates are found throughout the area and diatom blooms appear to be responsible for carbonate precipitation (Wells & Illing, 1963). Coccoliths are also found in muddy sediments, but have not been studied in detail.

Evaporation dominates the Arabian margins of this marginal sea (Fig. 3). Chemical precipitation leads to production of oolitic sediments, forming

BATHYMETRY OF THE ARABIAN GULF



SOME GENERALIZED BATHYMETRIC PROFILES OF THE ARABIAN GULF



an important element of the barrier coastline (Evans et al., 1973; Purser & Loreau, 1973); and is probably responsible for the precipitation of some carbonate mud in the lagoons as well as the development of the cement of carbonate crusts. Evaporation and reaction between biologically produced sediment and highly saline groundwaters has resulted in precipitation of an interesting suite of evaporitic minerals.

Large (but as yet unknown quantities) of chemicals are transferred to the Gulf by subsurface groundwater flow from Arabia (and possibly Iran) (Fig. 3). This regional gulfward flow can be detected in the reactions in the coastal plains (Paterson & Kinsman, 1977) and even offshore, where subaqueous springs have long been used by pearl-divers to replenish their drinking water.

THE MODERN SEDIMENTARY FACIES

A wide variety of sedimentary facies are developed in the Arabian Gulf and its adjacent land areas (Fig. 4). Although some useful general discussions have been presented on the Iranian coastline (Baltzer & Purser, 1990), little detailed study has been undertaken in this region [although the narrow shelves and adjacent deeper water are fairly well-known (Siebold et al., 1973)] and will not be discussed.

ARABIAN NERITIC BASIN

Marls dominate the deeper water of the northeastern parts of the Gulf (Siebold et al., 1973) (Fig. 4). Skeletal debris, consists of: benthonic molluscs and foraminifera, echinoids, polyzoa, serpulids and solitary corals are common. Planktonic molluscs are common throughout the area and have been proven to be living in the surface waters (Hoef & Sarnthein, 1971). Diatom and dinoflagellates are common, but planktonic foraminiferal remains are restricted, in the main to southeast of the Qatar peninsula towards the open Indian Ocean (Evans, 1966; Hughes-Clarke & Kreij, 1973). Authigenic pyrite is common but never abundant and small amounts of glauconite occur in the sediment. Organic carbon may reach values up to 1.5% in these deposits.

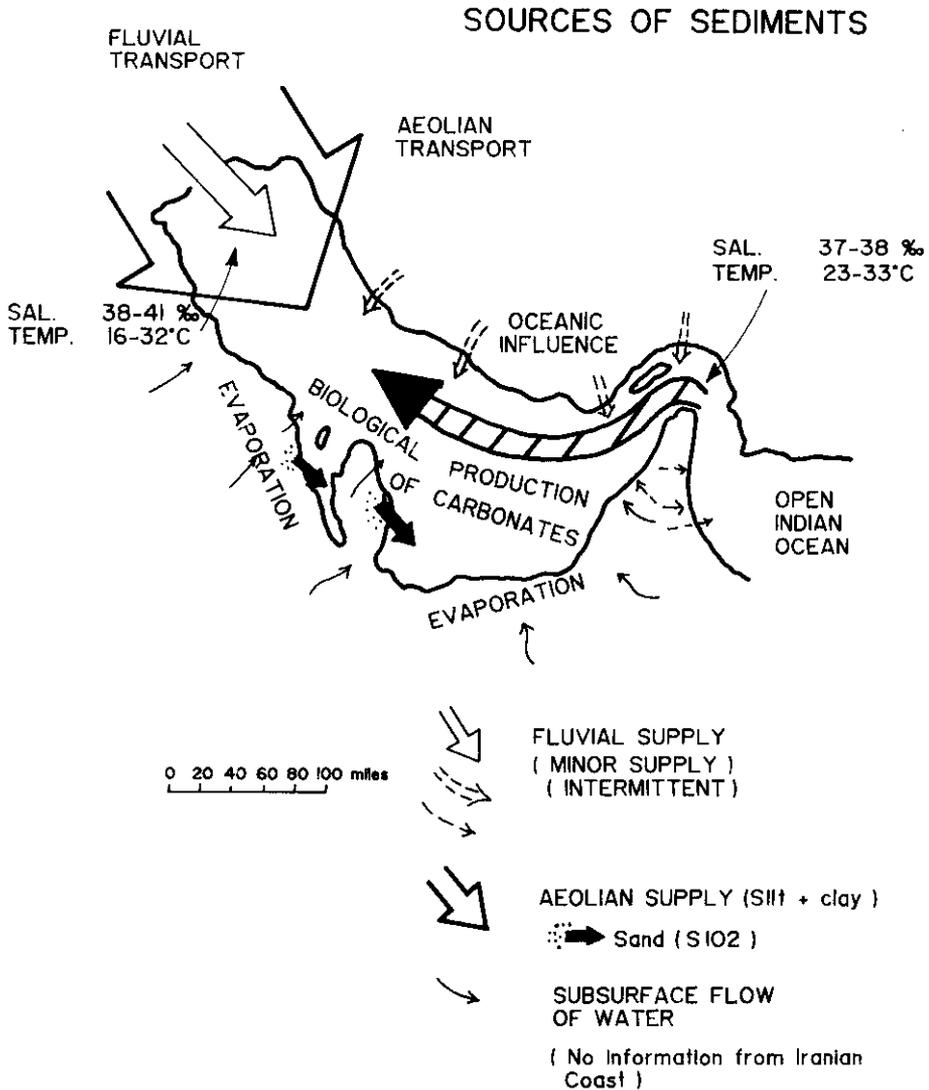


Fig. 3.—Sources of sediments.

Fig. 3.—Origen de los sedimentos.

The fine grained fraction of the sediments is rich in carbonate, partly of modern organic origin (aragonite), but most is terrigenous (calcite and dolomite) being derived from the hinterland where large areas of carbonate rocks are exposed (Pilkey & Nobel, 1966). The basinal marls are

often thin and form merely a veneer over shallow water sediments. Sometimes, shallow water oolitic and skeletal sands are exposed and are mixed with modern mud to form palimpsestic sediments (Evans, 1966; Sarnthein, 1972; Stoffers & Ross, 1979).

THE ARABIAN SHELF

The marls of the deeper water neritic basin are succeeded to the southwest, as the water shallows, by coarser and more calcareous sediment of the shallow water platform, which borders the Arabian coastline (Fig. 4). This platform has an irregular bathymetry and numerous shoals and islands inherited from subaerial erosion of tectonic features (some of which are diapiric), during the low levels of the Quaternary. This has resulted in a patchwork of sediments (Wagner & Van Der Togt, 1973). However, where the topography is less complicated, there is a gradual coarsening towards the shoreline (Houbolt, 1957) (Fig. 5). Skeletal carbonate sands and muddy sands (skeletal grainstones and packstones) cloak the surface, with muddy sands and muds. (Skeletal wackestones and mudstones) in the bathymetric depressions and in the lee of islands or banks sheltered from the waves generated by the northwest shamal. Stirring by waves and currents is constantly winnowing the sediment and transferring the fines to the depressions. Ultimately, when these are filled, the shelf will be covered by a blanket of slightly muddy skeletal sands (skeletal packstones) which will merge into cleaner carbonate sands (skeletal grainstones and reefal boundstones) in shallow water around bathymetric highs and the mainland coast.

The sediment consists of molluscan debris, benthonic foraminifera, echinoid plates and spines, polyzoa, serpulid, worm tubes with rare sponge spines and fish remains. Peloids, composite grains and some non-carbonate grains (mainly quartz and occasional glauconite) are also present. The sediments usually contain 0.5% organic carbon. This sediment is produced by *in situ* breakdown of skeletal material partly by physical and biological processes. Although waves and tidal currents are especially important during shamal winds, it is probable that much of the comminution is biological, being achieved by bottom feeding fish and other biota. Also, the grains become infested with borings of endolithic cyanobacteria and fungi, which weaken the shell structure and make them more prone to breakdown. Current studies suggest that there may be a distinct depth controlled zonation of various species (Al Thukair, Pers. Com.) and, if so,



Fig. 4.—General facies pattern of Arabian Gulf area and surrounding area.

Fig. 4.—Distribución general de facies en el Golfo Árabe y áreas adyacentes.

this may prove to be a valuable palaeo-depth indicator in ancient rocks where these borings are so abundant (Al Thukair & Golubic, 1991a, b). The change from skeletal sands to rounded skeletal sands around Qatar (Houbolt, 1957), may be due not to increased physical activity, but due to

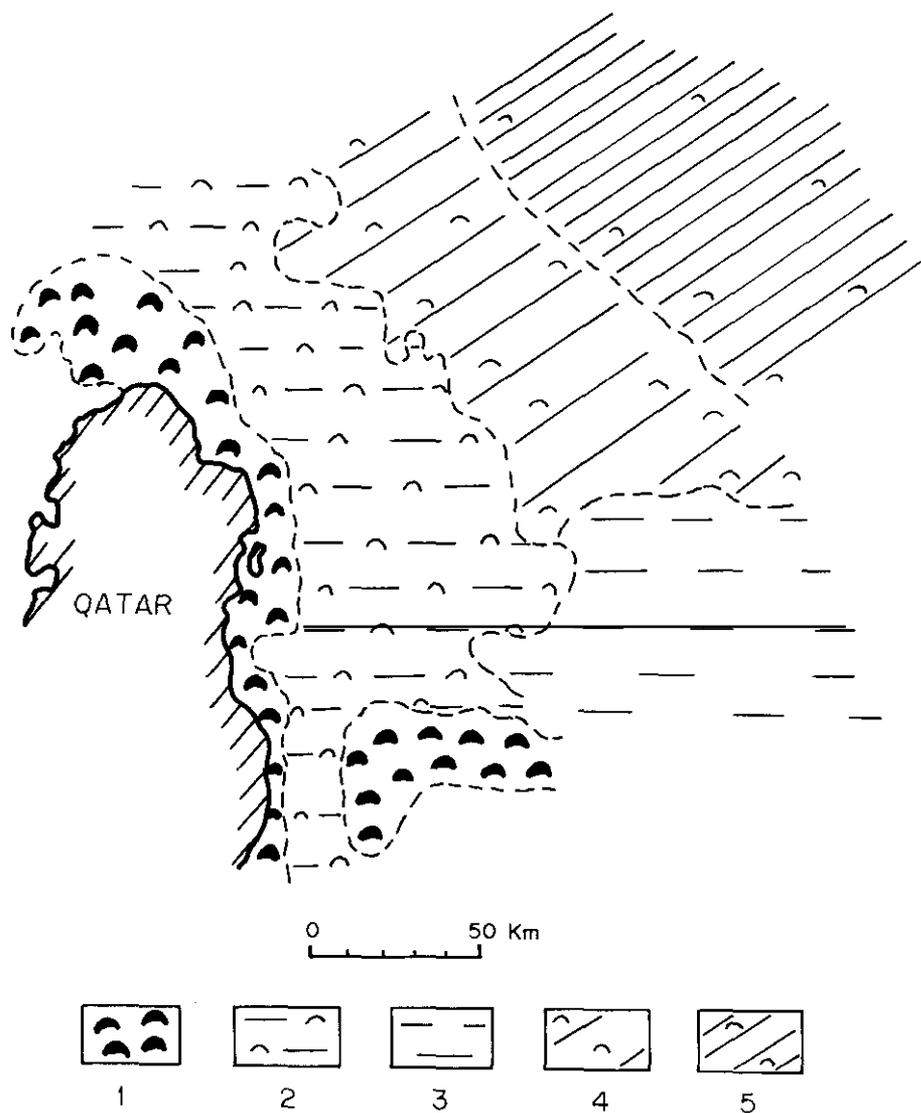


Fig. 5.—Sediment distribution NE of Qatar Peninsula. 1. Skeletal calcarenites with rounded grains. 2. Skeletal calcarenites with appreciable calcilutite, including sediments rich in *Heterostegina*. 3. Very calcilutitic calcarenites. 4. Very marly/marly calcarenites. 5. Calcarenitic marl/marl. (modified after Houbolt 1958, with additional data).

Fig. 5.—Distribución de sedimentos al NE de la Península de Qatar. 1. Calcarenitas esqueléticas con granos bien redondeados. 2. Calcarenitas esqueléticas con bastante calcilutita, incluyendo sedimentos ricos en *Heterostegina*. 3. Calcarenitas muy calcilutíticas. 4. Calcarenitas margosas/muy margosas. 5. Margas/Margas calcareníticas.

such increased endolithic cyanobacterial activity. Alternatively, more rounded grains may be inherited from coastal beach-dune complexes drowned during the final phases of the Flandrian transgression.

Mud grade carbonate is undoubtedly being produced by skeletal comminution. However, clouds of muddy water, with no contact with the sea floor have been observed to develop in the shallow waters of the Arabian shelf. These so called «whitings» are composed of aragonite mud which appears to have been produced by diatom blooms (Wells & Illing, 1964). A problem still exists as to the exact mechanism and the efficacy of this mechanism to produce precipitated carbonate mud (De Groot, 1965). Notwithstanding the problems, the clouds clearly differ from those produced by stirring of sediment on shoals and banks by storm waves.

Widespread subaqueous cementation (aragonite and high magnesium calcite) is taking place on the sea floor to produce crusts which are bored and support an epifauna. Radio-carbon dating, the presence of enclosed human artifacts and the similarity of the fauna of the cemented sediment to that of the enclosing sediment, as well as isotopic analyses, all confirm that this process is taking place under prevailing oceanographic conditions and that these crusts are not subaerially cemented layers which have been subsequently drowned (Shinn, 1969). The crusts hinder bottom coring and also shallow-geophysical surveys due to the high reflectivity of the hard surface. The cementation appears to occur when the sea floor is relatively stable (*ie* non or slow sedimentation) for a considerable period when supersaturated interstitial waters precipitate the cement. Similar crusts are developed at all depths: on nearshore oolitic tidal deltas, in lagoons as well as in the intertidal zone. They are all the equivalent of a diastem in the rock record. The widespread development of these crusts in the shelf is important: it allows the development of an epifauna over wide areas to produce a pattern of sediments and faunas which contrasts with areas such as the Bahamas (Shinn, 1969).

The shallow banks and islands which abound in this shelf have an important effect on sedimentation in their vicinity. The dominance of the northwesterly Shamal wind and wave attack produces a marked asymmetry around these features (Fig. 6) (Houbolt, 1957; Purser, 1973). Coral-algal reefs are often best, or sometimes only, developed on their windward side. They are occasionally backed by beach complexes on the bank tops, enclosing semi-protected areas in which fine grained sediment can accumulate. Trails of detritus, derived from the shallow water of the bank tops, extends down-wind for up to 15 km (Houbolt, 1957). If these

were preserved in the geological column they would be important indicators of the proximity of a shallow water (tectonic?) high.

THE ARABIAN COASTAL BARRIER

The Arabian shoreline, although variable, consists essentially of a coastal beach-dune barrier (Fig. 7). This may abut directly on the mainly coastline but in many places encloses lagoons (Evans & Bush, 1970; Evans et al., 1973; Purser & Evans, 1973). A few leeward shores are exceptional where quartzose dune-sand builds into the nearshore waters (Shinn, 1973). Generally, it appears that the barriers have been produced by accretion around remnants of aeolian dune complexes inundated during the final phase of the Flandrian rise of sea level (Evans & Purser, 1973).

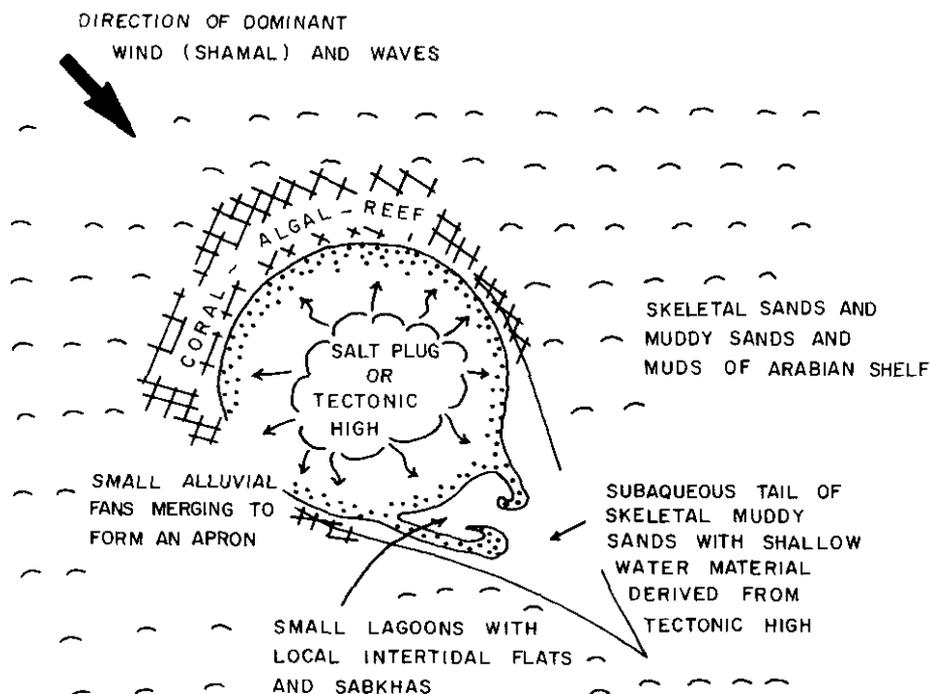


Fig. 6.—Shallow bank and carbonate sedimentation dominated by the NW Shamal wind (Modified after Houbolt, 1957 and Purser, 1973).

Fig. 6.—Bajo y sedimentación carbonatada asociada dominada por el viento NW (Shamal) (modificado de Houbolt, 1957 y Purser, 1973).

Where the beach-dune coastal barriers enclose lagoons, wide tidal deltas form at the mouths of the tidal inlets (Fig. 7). These shallow platforms are very turbulent (due to high wave and tidal action) and this, combined with the high temperatures and salinities, results in the production of oolites. They are indeed «oolite factories». The oolitic sands (oolitic grainstones) are fashioned into bedforms: breaker-point bars, large and small scale ripples and contain a limited macro-fauna of molluscs, echinoids and burrowing crustaceans. Sometimes, cemented crusts (aragonite and high magnesium calcite) are developed and these are bored and coated with weed and an epifauna. Some of the oolitic sand spills seaward, down the face of the deltas to produce a sharp contact with the nearshore skeletal sands (skeletal grainstones and packstones). The sands are also driven landwards by wave action to form beach dune complexes. High aeolian dunes develop adjacent to the tidal delta «oolite factories» with lower dunes in the intervening areas. The beaches of oolitic sands are narrow with steep beach faces (seaward dipping, planar-bedded oolitic grainstones) and berms (landward inclined oolitic grainstones) with concentrates of skeletal debris (skeletal grainstones) and crustacean burrows. Beachrock cementation is common. The dunes are composed of landward inclined crossbedded oolitic sands (oolitic grainstones) with abundant abraded skeletal debris and microfauna and sparse rhizomes of dune plants and terrestrial animal burrows. These sands are migrating inland «an aeolian transgression» to cloak intertidal and infilled lagoonal sediments and, elsewhere, where the barrier abuts directly against the shoreline, to dilute quartzose desert dune sands. Between the tidal deltas are coral-algal reefs formed of an impoverished Indian Ocean fauna (Kinsman, 1964) (coral-algal boundstones) and in some parts of the coast they form the main barrier with a capping of barrier islands (Kendall & Skipwith, 1969). In the lee of the reefs are sandy, sandy-mud or muds (skeletal wackestones and mudstones).

Tidal channels extend from the tidal inlets into the lagoons and gradually bifurcate and shallow landwards near the mainland shoreline (Fig. 6). They are bordered by narrow terraces which broaden along the mainland shoreline. There are many small islands on the banks and shoals between the channels which are fringed by narrow beaches enclosing mangrove swamps and cyanobacterial mats.

Here, the temperatures and salinities are higher and more variable than those of the adjacent shelf and increase inland (Edwards, Bush & Evans, 1986) (Fig. 7). There is an abundant but low diversity macro and microfauna with a great abundance of cerithid gasteropods in the inner

parts (Evans et al., 1973). Coral only extends into the outer parts of the lagoons where it fringes some of the banks. Similarly, echinoids die out in the lagoons although asteroids and, more particularly, ophiuroids extend further landwards in the lagoons.

Green algae are not abundant but *Jania* sp and *Acetabularia* sp are found and, although they disarticulate to produce carbonate mud, are not sufficiently abundant to explain all of this component (Evans et al., 1973), much of which is comminuted skeletal debris as well as possible being partly directly precipitated (Kinsman, 1969a, b). The channels are floored with skeletal and peloidal sands fashioned into dm-m sized bedforms with various flood and ebb orientations in different channels (crossbedded skeletal/pelletal grainstones); they contain more mud and in the inner part are sandy muds (peloidal/skeletal packstones and wackestones). Cemented aeolian sands sometimes crop-out on the channel floors and are overlain by a lag of coarse shell and intraclasts. Whereas oolitic sands may occur on the outer terraces, they never extend far into the lagoon. The terraces are covered with pelletal sands sometimes with a muddy matrix (peloidal grainstones and packstones) with a variable content of skeletal remains—particularly those of cerethid gastropods and some bivalves. The sediments are burrowed by crustaceans and worms. Grasses form dense carpets in parts of the terraces and in the channels. Their films of cyanobacteria cloak the grains and in places grapestone-type grains are present. Elsewhere they bind the surface over large areas. Also cemented crusts cover large areas of the lagoon floor (aragonite and high magnesium calcite cements). These are bored and support a restricted epifauna —*Brachiodontes* is common— and in many places the expansion of the crusts during cementation has produced m-sized tepee structures. Waves drive terrace sediments shorewards to form narrow sandy beaches (peloidal and skeletal grainstones) which show bankward cross-stratification and the sediments are heavily bioturbated by crustaceans. The narrow beach-barriers enclose mangrove swamps containing densely bioturbated mud, with many plant rhizomes and elsewhere cyanobacterial mats with cemented crusts and small amounts of replacive dolomite. Along the mainland shore there is a wide intertidal flat covered by rippled peloidal sands and muddy sands (peloidal grainstones and packstones) with a dense population of grazing cerethid gastropods. The bare flats pass shorewards into a broad (100s m wide) cyanobacterial mat which in places may be decimetres thick. Sediment driven shorewards by storm waves and tides are quickly coated with cyanobacterial filaments and similar successive events have built up the intertidal zone. The mats

show a wide variety of growth forms and during period of extended low water become cracked and dessicated (Kendall & Skipwith, 1968a,b; Kinsman & Park, 1976). The resulting sediments consist essentially of laminated mud-cracked, in part cavernous, crypt-algal bedded peloidal muddy sands (peloidal packstones) with lenses of peloids and skeletal debris-mainly gastropods. Gypsum occurs beneath and within the mats. In exposed areas these are replaced by narrow beach ridges composed of coarse skeletal gravel and sand (skeletal grainstones).

Generally, the sediments of the coastal barrier contain only moderate quantities of organic matter (Evans & Bush, 1970; Evans et al., 1973). However, some later authors have claimed that the sediments are rich in this material and have a potential as source rocks. (Ferguson & Ibe, 1981) but this has been disputed (Kenning et al., 1989). On the other hand, the cyanobacterial mats are rich in hydrocarbons, as are some of the other organic rich sediments (mangrove peats *etc.*) (Kenning et al., 1989). They seem to be good potential source rock material but only if rather special sequences of events allow their preservation in the geologic record [Evans, 1989; and see Warren (1986) for general discussion].

THE COASTAL SABKHA

The lagoons are bordered to landward by a low coastal plain just above sea level with a salt encrusted surface-the sabkha, which during periods of high tide and strong onshore winds may be partly inundated by lagoonal water. Coastal sabkhas have many origins (Tricart, 1954; Purser, 1985). The seemingly monotonous salt encrusted surface is often of multiple origin and usually shows many old strand-line features, such as beach ridges and infilled tidal creeks on its outer surface and, elsewhere, particularly on its inner parts, superb surfaces of truncated cross-stratified aeolian deposits. (Evans, Kendall & Skipwith, 1964).

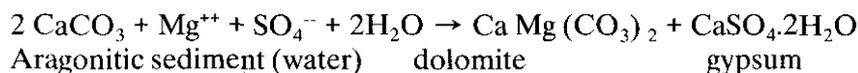
The sabkha shows its optimum development in the UAE in the southern Arabian Gulf. Here the Flandrian rise of sea level led to the inundation of the outer aeolian dunefields of the Arabian desert. Indeed, such dune sands are known to be present beneath the waters of various parts of the Arabian Gulf (particularly in the Gulf of Salwa), where they once linked those of Saudi Arabia, Bahrain and Qatar (Al-Hinai, Moore & Bush, 1987; Darwish & Conley, 1989) and are probably elsewhere more extensive beneath contemporary marine deposits but are as yet unproven.

The rising sea truncated the aeolian dunes by marine erosion and in-

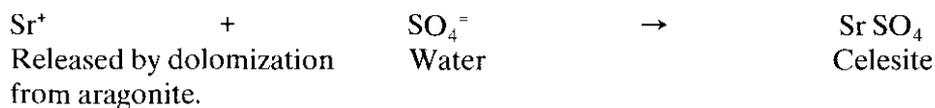
land they were deflated by the wind due to the drowning of the up-wind sand sources by the marine waters. This inundation appears to have reached its maximum level about 4000 years BP and a prominent beach-ridge of skeletal sand (skeletal grainstone) marks the maximum extent of this event (Evans et al., 1969; Kinsman & Paterson, 1982). As the lagoons became increasingly sheltered by the growth of the oolitic beach-dune and reefal barriers to seaward, they became infilled with skeletal peloidal sands and muds. The surface of these deposits were cemented to produce hardcrusts as are found in the adjacent lagoons today. Although sediment continued to be produced it was swept shoreward by waves and currents to form (as it continues to do today) extensive intertidal flats, which were quickly colonized by cyanobacterial mats. The inner lagoonal coastline has accreted at a rate of 1-2 km per thousand years over the deposits of the infilled lagoon to produce a progradational coastal plain underlain by a wedge of carbonate lagoonal and intertidal flat sediments. (Fig. 8). Off-shore winds cloaked the emerging intertidal flat with a blanket of sand and silt and locally ephemeral streams supplied sediment; this process continues today. Exceptional storms which can raise local sea level 1-2 m above normal lead to inundation of the outer sabkha by lagoonal waters and these deposit a veneer of marine sediment over its outer parts. Finally, evaporation has led to deposition of evaporite minerals which have aided in the accretion. As well as leading to deposition, the encroaching storm waters are sometimes turbulent and truncate the surface. In addition, winds are constantly trimming the accreting surface. It is this interplay of the various processes of deposition and erosion which have produced the monotonous equilibrium surface of the sabkha (Figs. 9a, b). The groundwaters of the sabkha are of both continental and marine origin (Fig. 10): waters are swept over the surface during storm periods some; some water, but probably very insignificant amounts, percolates into the sabkha from the adjacent lagoons; water moves up into the sediments, from the underlying aquifers; and occasional overland floods and precipitation supply small amounts of water to the groundwater system. Whereas the outer sabkha is underlain by marine derived groundwater and the inner sabkha by continental derived groundwater; in the intermediate area is a zone of mixed origins. As the sabkha progrades seaward, similarly the zone of mixed and continental derived waters move seawards (Paterson & Kinsman, 1977, 1981). The groundwaters of the outer sabkha undergo a cyclical pattern of changes: flooding of the surface by storm-driven lagoon waters [so called «flood recharge» (Butler, 1969)]; evaporation of the water from the saturated near surface sediments, «ca-

pillary evaporation»; and finally, (and this is the «normal» situation on the sabkha) draw-up of water from the underlying lagoonal and aeolian sediments, «evaporative pumping» (Hsü & Schneider, 1973; McKenzie et al., 1980). The results is precipitation of evaporites and the production of diagenetic minerals due to reaction between the carbonate sediment at the progradational wedge and the evaporating saline ground water.

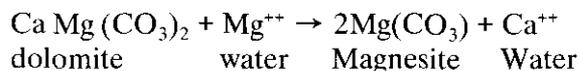
Evaporation produces gypsum (CaSO₄·2H₂O) firstly beneath and within the cyanobacterial mats and later a mush of gypsum above the mats. Reaction between the concentrated ground waters and the aragonitic peloidal and skeletal sands and muddy sands of the prograding intertidal flat sediments has led to the production of fine-grained diagenetic calcium-rich dolomite and further gypsum is produced, as large crystals, as a byproduct of this reaction



(Wells, 1962; Curtis et al., 1963; Illing, Wells & Taylor, 1965; Kinsman, 1969a, b; McKenzie, 1981; Paterson & Kinsman, 1982; Illing & Taylor, 1993). Also small amounts of celestite (Sr SO₄) are produced, probably due to the inability of the replacive dolomite lattice to accommodate the strontium ions (Evans & Shearman, 1964)

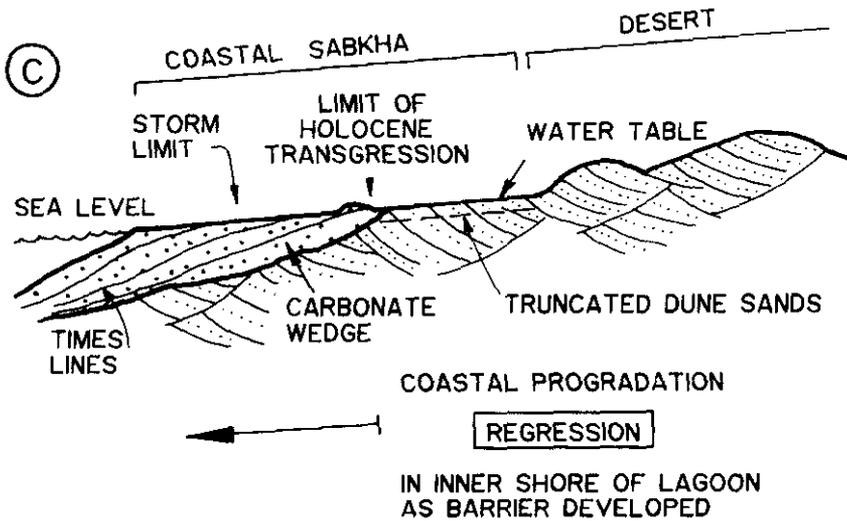
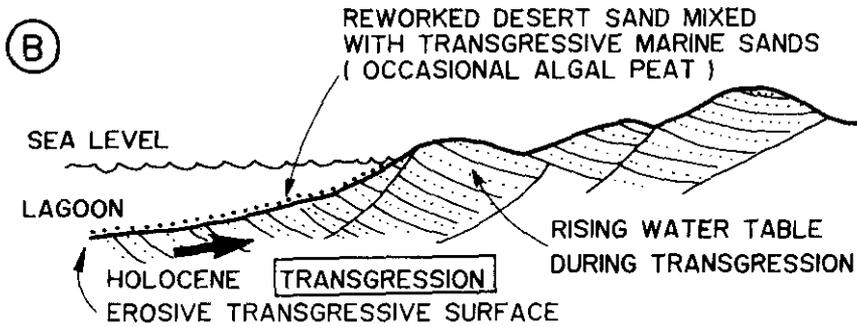
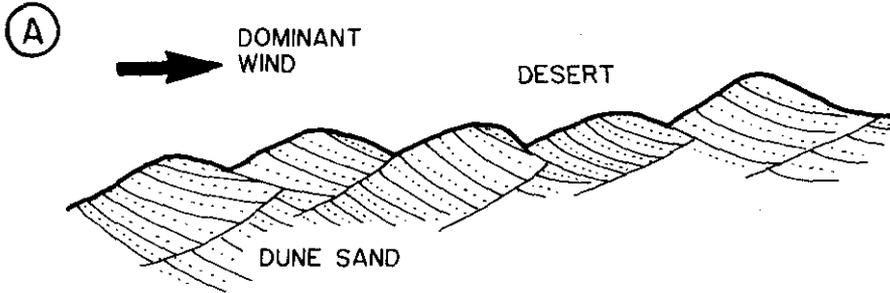


Dolomite replaces fine aragonite mud and pelleted mud but hardly affects the stouter skeletal grains. The result is a dolomitic pelloidal packstone and wackestone, often with ghosts of the original peloidal texture. Although some dolomitization of subtidal sediments occurs in the sabkha plain sediments, and even subaqueous dolomite has been reported from Kuwait (Gunatilaka et al., 1984, 1986), it is mainly concentrated in the intertidal sediments. In parts of the prograded carbonate wedge the process has proceeded further and magnesite has resulted from the reaction between dolomite and interstitial basins (Bush, 1973)



Temperatures and salinities are sufficiently high in the supratidal sediments-largely of aeolian origin-overlying the intertidal sediments with their cyanobacterial mats-for anhydrite (CaSO₄) to be the stable sulphate

EVOLUTION OF COASTAL SABKHAS



phase. This mineral first appears as a paste amongst the gypsum mush above the mats. The early anhydrite is after gypsum and pseudomorphs are present (Kinsman, 1969a, b; Bush, 1973). However, much of the anhydrite shows no evidence of a gypsum precursor and appears to be primary. The anhydrite is extensively developed in the aeolian supratidal sediment where it forms scattered blebs, nodules and discontinuous courses, with striking pygmatic structures and diapiric masses. Where it becomes dominant, nodules have impinged to produce the typical «chicken-wire texture» with thin films of brown aeolian sediment defining the pattern (Shearman, 1966). The volume of anhydrite is considerable and it has an important effect in raising the level of the sabkha surface. In the inner parts of the sabkha plain anhydrite is less abundant and reaction with groundwaters has led to its conversion to gypsum (Butler, 1969).

There are no significant concentrations of halite, largely due to the high humidity of the area. Much of the sodium chloride which is deposited is either blown inland by winds or is redissolved by flood waters and returned in the subsurface seaward flow of groundwaters (Kinsman, 1976). Other minerals have been described from the sabkha sediments but these are often ephemeral and of minor importance (Kinsman, 1969a, b; Gunatilaka et al., 1985).

Whereas gypsum is very common in the sabkha sediments it is generally absent in sub-aqueous sediments. However, it has been reported to have precipitated from shallow ephemeral brine pools in the sabkha at Qatar (Illing, Wells & Taylor, 1969) and Kuwait. In the latter case, it forms a laminar «balatino-type» deposit but of very limited areal extent (Gunatilaka & Shearman, 1988). Interestingly, artificial brine filled pools on the sabkhas of Abu Dhabi are often lined with beautiful crusts of prismatic gypsum.

Although anhydrite has been found on the sabkhas of Abu Dhabi (UAE) (Curtis et al., 1963), Saudi Arabia (Fryberger, Al-Sari & Clisham, 1983), Bahrain (Evans, Bush & Temple, 1980) and Kuwait (Gunatilaka, Saleh & Al-Temeemi, 1980; Gunatilaka & Mwango, 1987 and Gunatilaka, 1990) curiously, it is very sparse in the sediments of Qatar where only small inclusions have been found in gypsum crystals (Illing, Wells & Taylor, 1965) and as an alteration of gypsum (Perthuisot, 1977). It appears that southern Kuwait is the northern limit of contemporaneous an-

Fig. 8.—Evolution of coastal sabkhas. A. Sand desert, B. Holocene transgression, C. Coastal progradation and deposition of a carbonate wedge.

Fig. 8.—Evolución de las sabkhas costeras. A. Desierto arenoso, B. Transgresión holocena, C. Progradación costera y sedimentación de una cuña de carbonatos.

hydrite formation and the limits of its latitudinal extent may be useful in paleogeographic reconstructions (Gunatilaka, 1989).

THE ARABIAN DESERT

Inland of the coastal barrier with its associated lagoons and sabkha plains are the extensive deserts of Arabia (Figs. 1 and 11) (Holm 1960;

PROCESSES OF EROSION AND DEPOSITION ON COASTAL SABKHAS

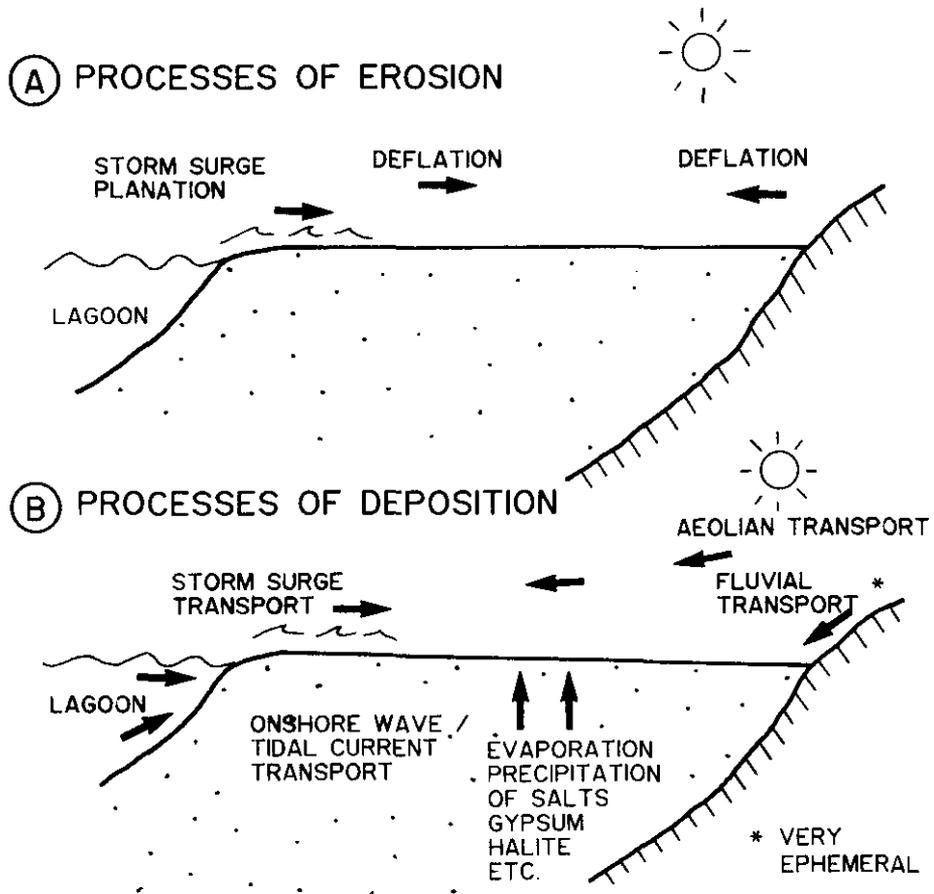


Fig. 9.—Processes of erosion and deposition on coastal sabkhas.
Fig. 9.—Procesos de erosión y sedimentación en sabkhas costeras.

Glennie, 1970). Huge volumes of quartzose dune sands (quartz-arenites) form a complex of dunes, often up to 100 m high, of diverse and multiple origin.

The sand originates from the crystalline rocks of the Arabian shield and its cover rocks and the fringe of the alluvial fans. This sand is being driven southwards from the Nafud through the Dhana and coastal deserts of the Hejaz into the great depression of the Rub al Khali.

In some locations *eg* Saudi Arabia (Fryberger, Al-Sari & Lisham, 1983), Qatar (Shinn, 1969), dune sands are being driven into the sea to mix with the nearshore sediments. Elsewhere, along the UAE and other coasts, where the coastal barriers abut directly onto the coast, without intervening lagoons, the quartzose dune sands are being diluted with carbonate sands.

Inland sabkhas, often very extensive, have developed in some areas and are the sites of extensive sulphate deposits (Glennie, 1970). Elsewhere, where the gulfward moving groundwater intersects the surface *eg* parts of Saudi Arabia, shallow lakes with reed beds develop between the dunes.

The dune sands pass landwards, along the desert rim into a belt of extensive alluvial fans (Fig. 10). These have complex histories and probably are largely of Pleistocene age, but are still active in many parts today. They are composed of thick conglomerates, sandy conglomerates and sands. Conglomerate clasts exhibit beautiful desert varnish and ventifacts are common on the surface.

In the extreme southeast of Arabia, the fans reach the coast to interfinger with the coastal barrier-lagoon and sabkha deposits (Purser & Evans, 1973). In some areas, the fan-gravels interfinger with sabkha and coastal barrier-lagoonal deposits without appreciable amounts of intervening dunes. In such areas, due to the influx of brackish water from the fans, the adjacent sabkhas have little or no evaporite-usually so characteristic of coastal sabkhas elsewhere.

THE TIGRIS-EUPHRATES DELTA

The northwestern extremity of this shallow marine basin is infilled with the sediments of the Tigris-Euphrates delta. It is a typical A-zone delta (Audley Charles, Curray & Evans, 1977) and is unusual in that as it is building into a very saline sea (Gunatilaka, 1986; Baltzer & Purser, 1990). This delta is also unusual in that the aeolian sediment supply con-

WATER MOVEMENT IN SABKHAS

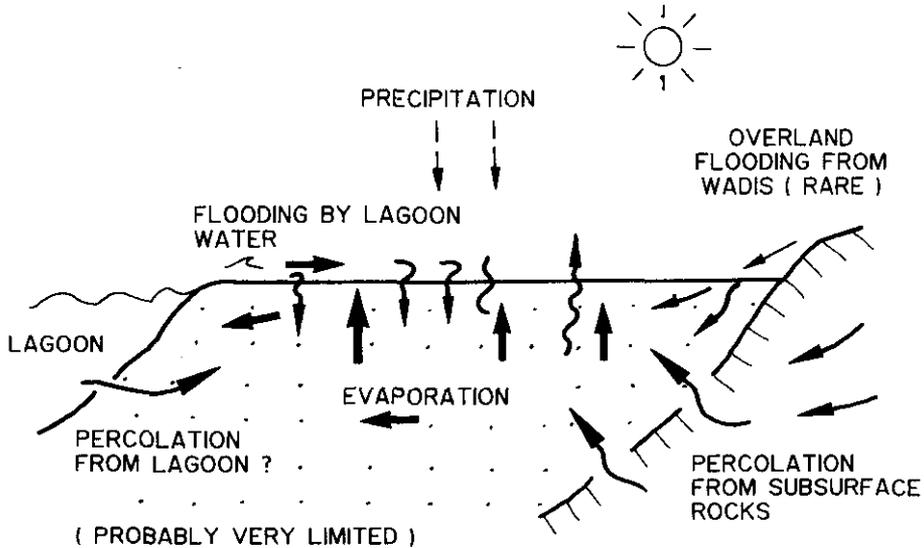
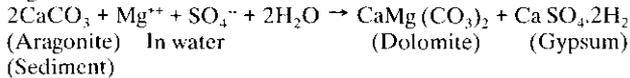
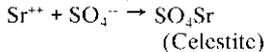


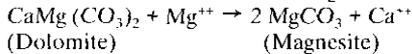
Fig. 10.—Water movement in sabkhas. Reaction between sediment and water:



Sr^{++} held in aragonite lattice is released during dolomitization (it is not taken up by dolomite, but released) and combines with sulphate in sea water to form *celestite*:

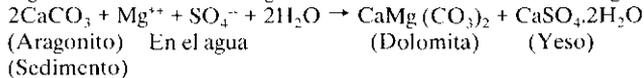


Also, further reaction between Mg^{++} rich brines and dolomitic sediment produces *magnesite*:

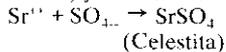


(After Evans 1986).

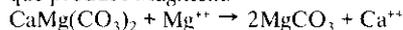
Fig. 10.—Movimiento del agua en las sabkhas. Reacción entre agua y sedimento:



El Sr^{++} en la red del aragonito se libera durante la dolomitización (no entra en la red de la dolomita) y se combina con el sulfato en el agua del mar formando *celestita*



También se produce otra reacción entre las salmueras ricas en Mg^{++} y el sedimento dolomítico que produce *Magnesita*



(Según Evans, 1986).

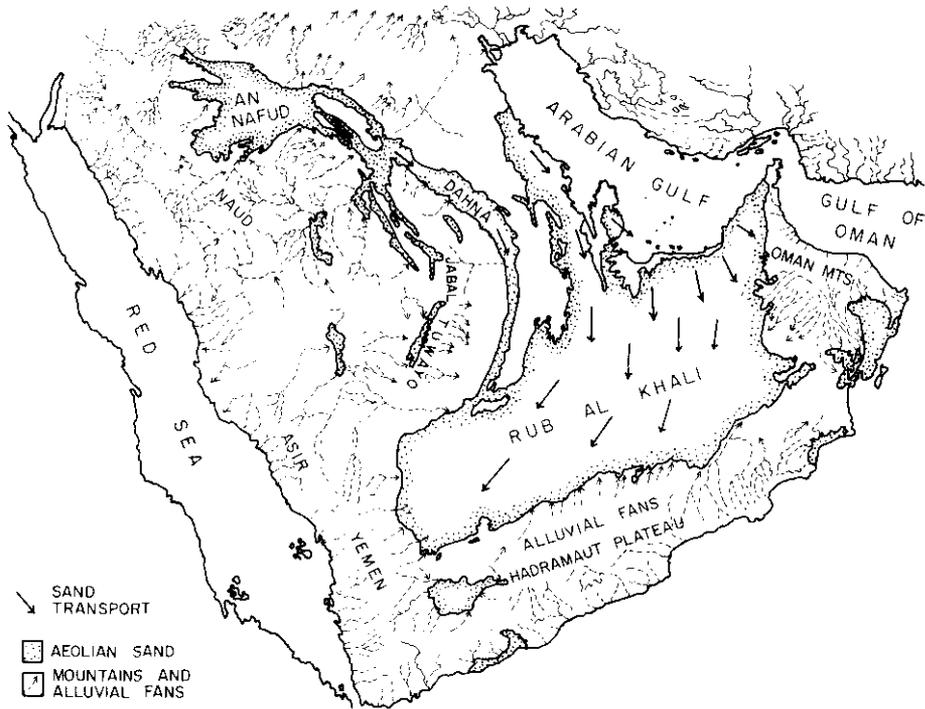


Fig. 11.—Sand and stone deserts in Arabia and prevalent wind and sand transport directions.

Fig. 11.—Desiertos arenosos y pétreos en Arabia y viento dominante y sentido del transporte de la arena.

tributed, particularly by the northwest shamal, is very significant and may equal the fluvial supply. It has been claimed that aeolian sediment accumulates at a rate of 0.8 mm/yr on the land surface of neighbouring Kuwait (Foda, Khalaf & Al-Khadi, 1985).

The fluvial channels which merge downstream to form the funnel-shaped estuarine channel of the Shatt-el-Arab are bordered by broad levees (Fig. 12). In places, crevasse splays spread from the channels into the interchannel areas which, in the lower deltaic plain, are dominated by shallow fresh-brackish water lakes and dense surrounding marshes of thick high reed beds of *Phragmites* sp and *Typha* sp, locally known as «Ahwar» (Aqrabi & Evans, 1994). These are flooded in spring and early summer when snow melts in the headwaters of the rivers. Elsewhere, remote from the river channels, are saline fluvial plains and sabkhas occur along the coastal areas (Fig. 12). The sediments of the levees and cre-

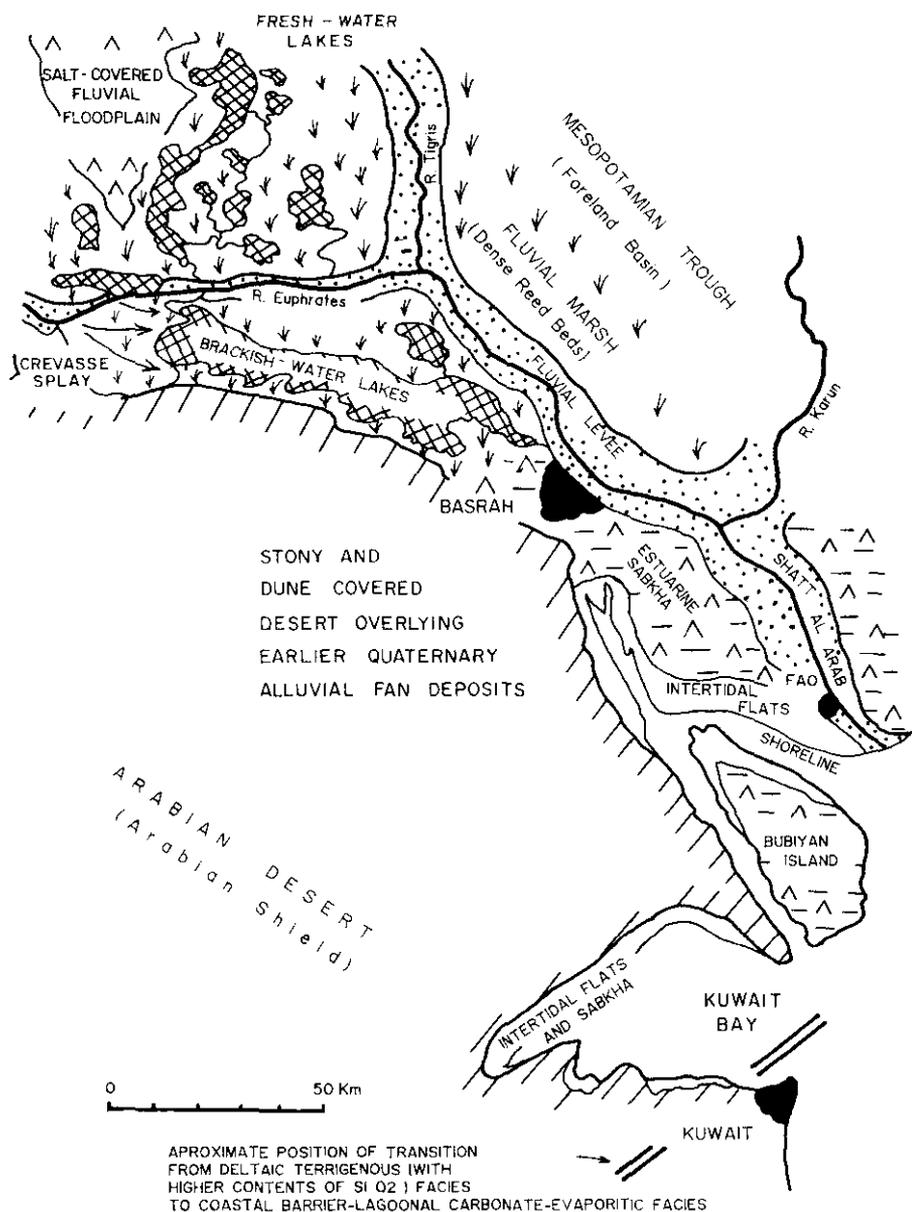


Fig. 12.—Schematic sketch of the Eastern part of the Tigris-Euphrates-Karun delta, showing the various sedimentary environments (Modified from Aqrawi and Evans, 1994, and Baltzer and Purser, 1990).

Fig. 12.—Diagrama esquemático de la parte oriental del delta del Tigris-Eufrates-Karun y sus diversos medios de sedimentación (Modificado de Aqrawi y Evans, 1994, y Baltzer y Purser, 1990).

vasses are well stratified sandy silts and muds, whilst those of the lakes and surrounding marshes are bioturbated sandy silts and clayey silts with abundant plant roots (Aqrawi & Evans, 1994) and a varied brackish water fauna of molluscs.

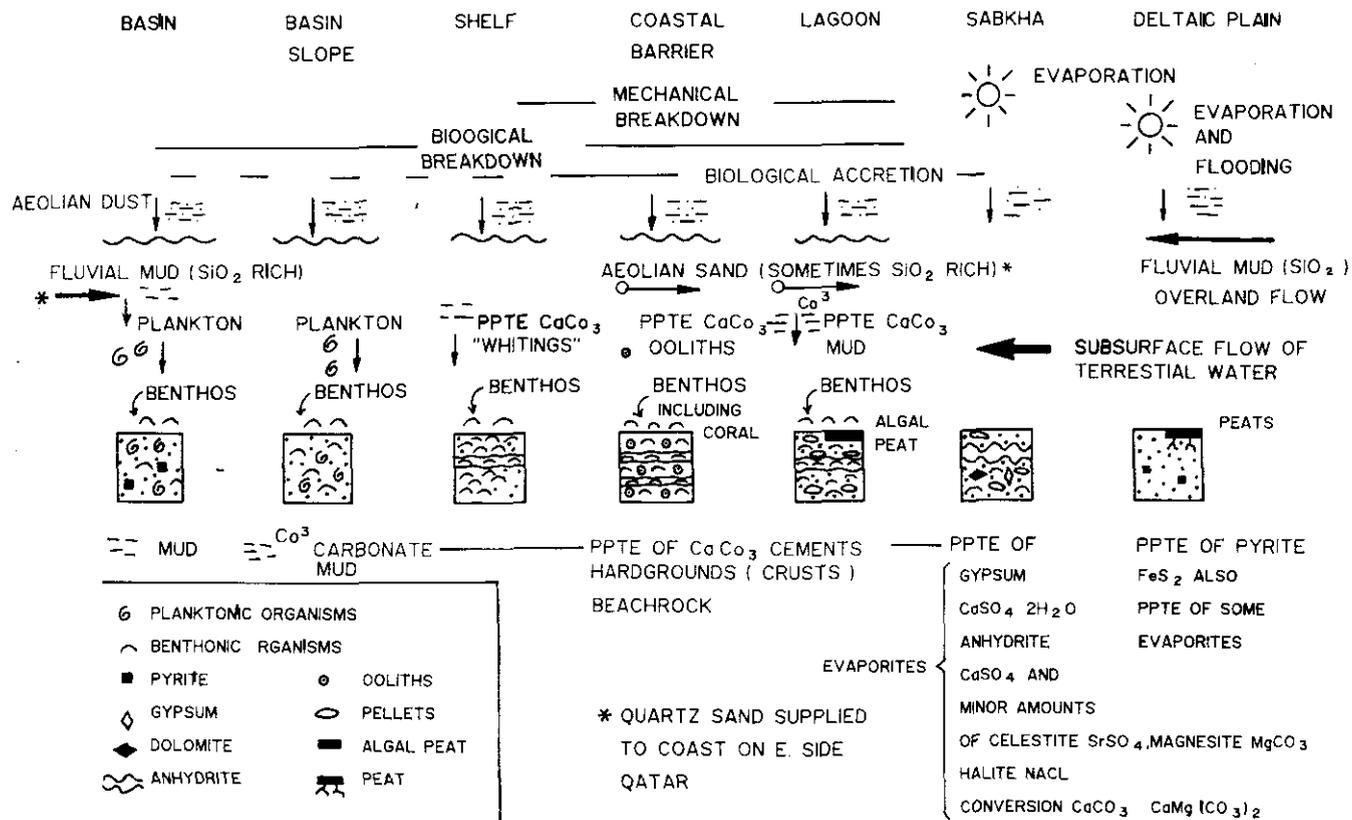
The aeolian and fluvial sediment supply are very similar in composition; and, because of the vast quantities of carbonate rocks in the hinterland, are rich in detrital carbonate. Consequently, the Ahwar sediments are rich in allochthonous carbonate. However, in addition, authigenic high magnesium calcite, calcite, calcium-dolomite, gypsum and pyrite develop in the sediments. Authigenic palygorskite forms in the sediments as well as being allochthonous (Aqrawi, 1993).

Peat beds are present in the Holocene and although it has not been proven are probably forming today in some of the Mesopotamian marshes further inland. In the Ahwar sediments, the organic carbon ranges from 0-20% with the highest amounts in the freshwater lake and marsh sediments. Generally, it appears that much of the abundant organic debris produced by reed growth is being very efficiently decomposed; perhaps because of the high temperatures and abundant sunlight (Aqrawi & Evans, 1994).

Although there are some spectacular evidences of local recent tectonic movements - such as the warping of historic canals (Lees & Falcon, 1952), the area appears to have been relatively stable during the Holocene (Larsen & Evans, 1978). Infilling of the foreland basin between the Arabian Shield and the Zagros fold mountain belt of Iran has been complicated by the damming effect of the large Quaternary Wadi-Al-Batin and Karun alluvial fans. These enclosed a depression which had to be infilled before the delta could prograde into the waters of the open Gulf (Rzoska, 1980; Baltzer & Purser, 1990) (similar to the way that the Mississippi has to infill the Atchafalaya lakes before it can commence its next phase of progradation into the Gulf of Mexico on the west of its present deltaic plain). Marine influences certainly extended as far as 200 km from the present coastline in the Holocene (Larsen & Evans, 1978; McFayden & Vita-Finzi, 1978).

The exact seaward limit of the deltaic influence is not known although brackish surface water has been traced south of Kuwait; but probably extends to about 100 km from the shoreline (Evans, 1966; Siebold et al., 1973). Shallow water sands in the nearshore waters outside the main fresh water outflow, Shatt-el-Arab, are fashioned into a complex of elongate tidal bars (Off, 1963). These pass seawards into prodeltaic marls which enclose the reef capped Kharg Island off the Iranian coast and

ORIGIN OF THE MAIN SEDIMENT TYPES



merge into the sediments of the neritic basin. The delta has a curious mixture of sediments and is similar to the Nile delta in many ways, with an association of sabkhas (evaporitic sediments) and lakes where dense reed beds develop (organic rich sediments) (West, Ali & Hilmy, 1979; Evans, 1989). The association of fluvial channels and brackish lakes where reed beds develop are in many ways reminiscent of the Wealden deposits of Europe. Today, there is a marked change from the terrigenous deltaic deposits of the delta with the carbonate- evaporitic *facies* of the Arabian shoreline in Kuwait Bay (Gunatilaka, 1986; Evans, 1989).

CONCLUSIONS

The Arabian Gulf with its wide variety of sediments (Fig. 13) has attracted a great deal of attention since the early description of its Holocene sediment cover by Emery (1956) and the very perceptive studies of Sugden (1963a, b). It has helped Ahr (1973) in his formulation of the concept of a «carbonate ramp» in contrast to the «shallow shelf» model derived from the Bahamas. Differing from the latter because of the gentle slope from basin to shoreline without a sharp slope-break between basin and shelf and its related banks or protective shelf-edge reefs. This «carbonate-ramp» model as exemplified by the present Arabian Gulf, is often more appropriate to the interpretation of many ancient carbonate sequences.

The extent of formation of penecontemporaneous dolomite and the proof of its replacive, not primary, character by the reactions as predicted by Klement, (1894, 1895), has aided the understanding of dolomitic carbonate sequences and their diagenetic history (Illing & Taylor, 1993). The discovery of widespread contemporaneous cementation and the replacement of early aragonite by high magnesium calcite cements; particularly its development under shelf waters convinced workers of the reality of contemporaneous subaqueous cementation and the lack of the need to invoke uplift or deep burial to initiate sedimentation (Shinn, 1969; Taylor & Illing, 1969). Furthermore, it has furthered understanding of hardgrounds and their associated faunas in the geologic record. Although the direct precipitation of aragonite from marine waters was suspected for a long time; this process was only unambiguously witnessed in the waters of the Arabian Gulf (Wells & Illing, 1963; De Groot, 1965).

Fig. 13.—Origin of the main sediment types.

Fig. 13.—Origen de los principales tipos de sedimentos.

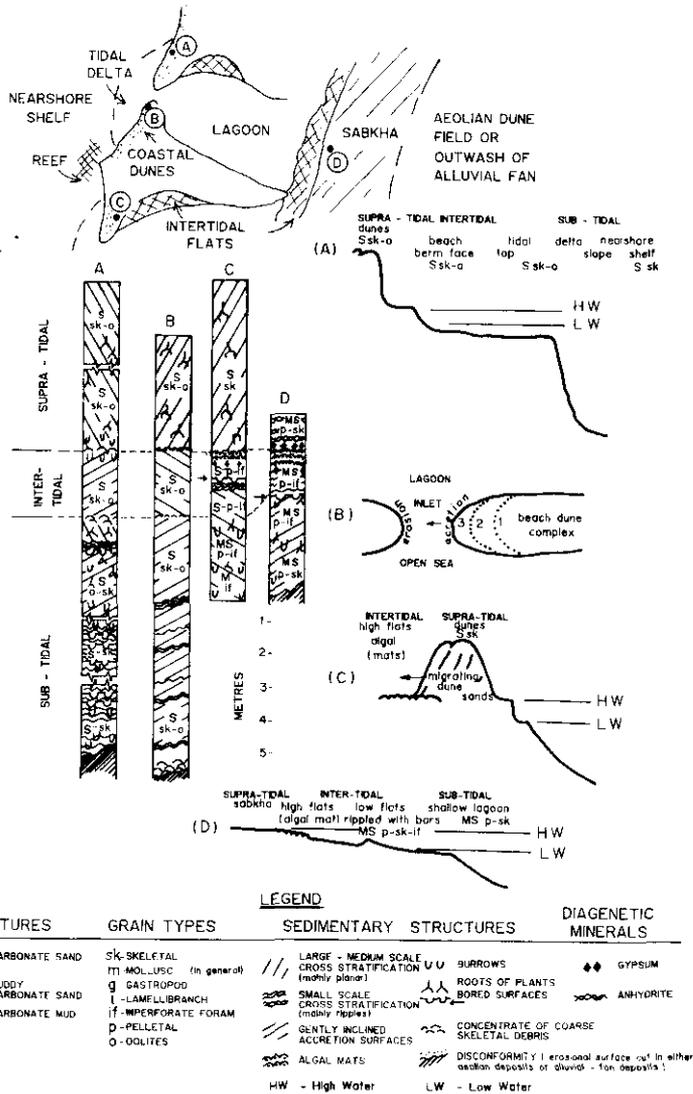


Fig. 14.—Vertical sequences produced by accretion at various locations in barrier-lagoon complex (NB direction of cross bedding profile is drawn assuming land is at the left). A. Prograding barrier island tidal delta complex. B. Laterally accreting beach dune complex due to inlet migration. C. Landward migrating dunes capping intertidal and lagoonal sediments. D. Prograding landward margin of lagoon.

Fig. 14.—Secuencias verticales producidas por acreción en diversas posiciones de un complejo barrera-lagoon (la dirección de la estratificación cruzada ha sido dibujada suponiendo que la tierra firme está a la izquierda). A. Complejo Isla barrera-delta mareal. B. Complejo playa-duna con crecimiento lateral causado por la migración de la bocana mareal. C. Dunas que migran hacia tierra sobre sedimentos de lagoon e intermareales. D. Orilla de lagoon que migra hacia tierra.

The discovery of modern anhydrite in the sabkhas of the Trucial Coast UAE (Curtis et al., 1963) has led to the enthusiastic (and later often ill-judged) application of the sabkha model to evaporitic sequences. Early perceptive studies of Shearman (1966), initiated a revolution in their interpretation and of the evolution of evaporitic basins. Furthermore, the juxtaposition of the coastal barrier and evaporitic sabkha plains with the aeolian dune fields and alluvial fan gravels of the Arabian peninsula, provided a timely model for the study of the Permian deposits of the evolving North Sea oil province (Glennie, 1972).

Although much has been learned from this interesting marginal sea and adjacent areas many problems remain. There are still unsolved problems about the precipitation of aragonite in the open waters of the Gulf; the reasons for the fluctuating sediment supply and periods of stability of the sea floor which allows the development of cemented layers are not clearly understood; the exact mechanism for oolitic growth and the attachment of the cortices of aragonite to the cores is still unclear. Regionally, a great deal remains to be learned about: the Saudi Arabian coast (a region hardly studied); the Iranian coast and interior basins; the *facies* and evolution of the Tigris-Euphrates delta; and the three dimensional relationship and the response of sediments to the complicated eustatic and tectonic changes in the area. It is possible that further studies in this interesting area may aid as much the understanding of the rocks of the geologic column as those now completed appear to have already done.

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