Geologische Rundschau **78/2** | 525–536 | Stuttgart 1989

Fossil cyclic calcrete in the Kuwait Group clastic deposits (Mio-Pleistocene) of Kuwait, Arabian Gulf

By F. I. KHALAF and M. I. EL-SAYED, Kuwait*)

With 11 figures and 1 table

Zusammenfassung

Eine Untersuchung der klastischen Sequenz der oberen Kuwait-Gruppe, die entlang der Jal Az-Zor Zone in Nordkuwait aufgeschlossen ist, ergab mehrere Horizonte fossilen Kalksinters. Geländebeobachtungen und texturelle Charakteristik der Sequenz deuten an, daß der fossile Kalksinter in Zyklen eines feinkörnigen fluviatilen Sandsteines eingebettet ist und diagenetisch während interfluviatilen Stadien gebildet wurde. Merkmale der Ablagerungsverhältnisse und der Giagenese des verkalkten fluviatilen Sandsteines sprechen dafür, daß jeder Zyklus mit der Sedimentation des Sandsteines unter humiden Klimabedingungen begann. Auf dieses Stadium folgte eine Phase semiariden Klimas, während dessen sich die Kalksinterprofile entwickelten. Der obere Teil der Kalksinterabschnitte verwitterte in Regenzeiten, dabei bildeten sich »terra rosa«-Böden. Während des folgenden rauhen ariden Klimas wurden wüstenähnliche äolische Sande sedimentiert. Den fossilen knotigen Kalksinter findet man nur innerhalb des fluviatilen Sandsteines. Die Lithifizierung der Sandsteine erfolgte in zwei diagenetischen Phasen: In der frühen Phase wurde auhigener, mikrokristalliner Calcit und die Kalksinterknoten gebildet. Während der späteren Diagenesephase fiel makrokristalliner Calcit als intergranularer Zement aus, der die tonige Ausgangsmatrix substituierte und Klüfte sowie Hohlräume innerhalb der Kalksinterknoten ausfüllte. Beobachtungen und Interpretationen dieser Studie werden das Verständnis um den lithostratigraphischen Zusammenhang der klastischen Sequenz der Kuwait-Gruppe in der Region des nördlichen Arabischen Golfes erleichtern.

Abstract

An investigation of the upper Kuwait Group clastic sequence (Mio-Pleistocene) exposed along the Jal Az-Zor escarpment in north Kuwait revealed several horizons of fossil calcrete. Field occurrences and textural characteristics of the studied sequence indicated that the fossil calcrete was hosted in cyclic fluviatile muddy sandstones and developed through diagenesis during inter-fluvial periods. Depositional and diagenetic features of the calcretized fluviatile sandstone units suggested that each cycle started with the deposition of a fluviatile muddy host sandstone during a humid period. This was followed by a period of semi-aridity during which calcrete profiles developed. The upper part of the calcrete profiles was weathered and terra rosa type soil was formed during wet seasons. This was succeeded by a severe arid climate and the deposition of desert aeolian sand sheets. Fossil nodular calcrete was only developed within the fluviatile muddy sandstones. The calcretized sandstones were lithified in two stages of diagenesis-an early stage that was responsible for the authigenesis of microcrystalline calcite and the development of calcrete nodules, and a later stage during which macrocrystalline calcite cement was precipitated as an intergranular cement displacing and replacing the clay matrix of the host sediments and filling fractures and cavities in the calcrete nodules. The findings and conclusions of the present study will help in understanding the lithostratigraphic setting of the Kuwait Group clastic sequence in the northern Arabian Gulf region.

*) Authors' address: F. I. KHALAF and M. I. EL-SAYED, Environmental and Earth Sciences Division, Kuwait Institute for Scientific Research, P.O. Box 24885, 13109 Safat, Kuwait.

Résumé

La série clastique du groupe supérieur du Koweit (Mio-Pleistocène), exposée le long de l'escarpement de Jal Az-Zor (nord du Koweit) montre plusieurs horizons de calcrètes fossiles. Les relations de terrain et les caractères structuraux de cette série montrent que ces calcrètes se sont formées dans des sables argileux fluviatiles cycliques, par un processus de diagenèse intervenu au cours de périodes interfluviales. Les caractères sédimentologiques et diagénétiques de ces roches suggèrent que chaque cycle a débuté par le dépôt, en période humide, des sables argileux fluviatiles et s'est poursuivi en période de semi-aridité par le développement des calcrètes. La partie supérieure des calcrètes a subi une altération atmosphérique avec formation d'un sol de type »terra rossa« au cours des saisons humides. Le cycle se termine par l'installation d'un climat strictement aride, avec dépôt de sables éoliens désertiques. Les calcrètes, nodulaires, se sont formées uniquement dans les sables argileux fluviatiles. Leur lapidification s'est opérée en deux stades: un premier stade responsable de l'apparition de calcite authigène microcristalline et du développement de nodules carbonatés; un second stade marqué par la précipitation d'un ciment intergranulaire de calcite macrocristalline qui s'est substitué à la matrice argileuse du sédiment primaire et a rempli les fissures et cavités des nodules. Les résultats de cette étude permettent de mieux comprendre l'édification lithostratigraphique de la série clastique du Groupe du Koweit dans la région septentrionale du Golfe Arabique.

Краткое содержание

При исслеедовании кластических свит верхней группы Кувайт, обнажающейся вдоль зоны Jal Az-Zor в северной части Кувайта, в различных горизонтах установили фоссильные калькреты. Дальнейшие работы в поле и характеристаки текстуры свит дали указания на то, что калькерты, содержащие фоссилии захоронены в циклах отложения мелкозернистого флювиального песчаника и образовались диагенетически во время межфлювиальных периодов. Характеристики условий отложения и диагенеза обизвестленных флювиальных песчаников говорит о том, что каждый цикл отложения песчаника начинался при гумидных климатических условиях. Затем наступала фаза полуаридного климата, в течение которой появлялись калькреты. В их верхний части калькреты подвергались выветриванию в период дождей, образуя почвы «terra rosa». В течение последующего аридного периода откладывались эоловые пески, похожие на пески пустыни. Калькреты, содержащие фоссилии, находят только среди флювиальных песчаников. Литификация – сцементирование – песчаников имело место во время друх фаз диагенеза : на ранней стадии образовывался аутигенный микрокристаллиновый кальцит и желваки калькрета. При позднейшей фазе диагенеза выпадал макрокристаллиновый кальцит в виде межкристаллинового цемента, заместившего глинистую исходную матрицу и заполнивший трещины и полости внутри желваков калькрета. Наблюдения, проведенные во время данного исследования и интерпретация процессов облегчат понимание литографических зависимостей в кластических свитах группы Кувайт в регионе северной части аравийского залива.

Introduction

The term calcrete was coined by LAMPLUGH (1902) for carbonate-cemented gravel. In 1907, he used the term »valley calcrete« for carbonate-rich surface materials deposited as a result of the evaporation of lime-charged water in the valley of the Zambezi river in central Africa. Understanding the nature, mode of occurrence and genesis of calcrete has been of interest to many pedologists, civil engineers, geomorphologists and sedimentologists. In spite of the many publications on calcretes, several issues related to their occurrence and genesis are still controversial (GOUDIE, 1983; REEVES, 1976; NETTERBERG, 1978; MILNES & HUTTON, 1983). With regard to their origin, two main types of calcretes were recognized; groundwater calcrete and pedogenic calcrete. Both types of calcretes are usually developed in a profile that shows various degrees of calcretization of the host sediments. Calcrete development is mainly controlled by three factors: the nature of the host sediment, availability of carbonate-rich solution and climatic conditions. Previous studies indicated that the ideal environment for calcrete development is neither excessively arid nor excessively humid (REEVES, 1976). The suitable climate for calcrete formation is that with enough precipitation for translocation of carbonate and with temperatures that facilitate a high evaporation rate. Calcretes have been used as indicators of semi-arid to arid climatic conditions with precipitation less than 500 mm/yr (FLINT, 1959). A change in climatic conditions favorable for the precipitation of calcretes or deposition of more sediments on the calcretized profile fossilize the calcrete (NETTERBERG, 1978).

The use of calcrete as an indicator of climatic conditions and, therefore in reconstruction of paleoenvironmental settings stimulated the interest of several geologists in the study of fossil calcretes. Records of fossil calcretes in various geologic formations ranging in age from Proterozoic to Pliocene were reported by several authors (REEVES, 1976; GOUDIE, 1983). A progressive increase in the study of Quaternary calcretes facilitated the recognition of fossil calcretes. DUNHAM (1965) referred the absence of records on ancient calcrete to mistaking calcrete for algal stromatolites and oncolites. Fossil nodular calcrete hosted in the new red sandstones of western Scotland was described by STEEL (1974). BUCKLAND (1821) used the term cornstone for these calcretes and described them as concretionary carbonates of diagenetic origin. HUBERT (1977) described fossil pedogenic calcrete in the late Triassic Arkose in Connecticut, U.S.A.

MCPHERSON (1979) described in detail fossil calcrete horizons in the Upper Devonian fluvial sand beds in Antarctica. Most of the reported fossil calcretes were described as fossil soils or paleosols. REEVES (1976) indicated that ancient calcretes would not be recognized by geologists unfamiliar with calcrete origin and morphology. The recognition of calcretes within terrestrial sequences of clastic deposits is similar to the recognition of sabkha within a tidal flat sequence; however, the study of calcretes and their application in various geologic fields is still limited relative to the extensive studies and research conducted and supported by oil companies and research institutions on Recent and fossil sabkha deposits.

The present paper reports the occurrence of fossil calcrete profiles within the Neogene clastic sequence exposed along the Jal Az-Zor escarpment in Kuwait. It also describes the general petrography of this fossil calcrete and discusses its origin.

Geological Setting

Kuwait is part of the interior homocline of the Arabian Peninsula, where rocks of Eocene to Recent age are exposed. The Dammam Formation (Eocene) is unconformably overlain by a sequence of terrigeneous sediments locally called Kuwait Group (Owen & Nasr, 1958). In northern Kuwait, the Kuwait Group can be divided into three formations, from bottom to top: Ghar, Fars and Dibdibba. This stratigraphice subdivision is based on the occurrence of fossiliferous beds correlated with the Lower Fars Formation of Iran, which is lower to middle Miocene (Owen & Nasr, 1958). These beds separate the Dibdibba Formation, which is of Plio-Pleistocene age, from the Oligo-Miocene Ghar Formation. The stratigraphy and lithology of Kuwait Group deposits were studied by Cox & Rhodes (1935), Owen and Nasr (1958), Milton (1967), Fuchs et al. (1968), Salman (1979) and Al-Awadi (1980).

The upper part of the Kuwait Group, Dibdibba and Fars Formations, is best exposed along the Jal Az-Zor escarpment that extends parallel to the northern coast of Kuwait Bay.

In the present study, Kuwait Group rocks were investigated along the western part of the Jal Az-Zor escarpment and the northern cliff of the Umm Al-Rimam depression north of Jal Az-Zor. In addition, cores from two boreholes, one drilled on the top of the Jal Az-Zor cliff and the other at its foot, were studied. Locations of the studied sites are shown in Fig. 1. The lithological logs of the studied sequence are presented in Fig. 2.

The Jal Az-Zor escarpment is characterized by flat, almost horizontal, step-like terraces separated by vertical cliffs formed of relatively hard and bold sandstone layers about 4–6 m thick alternating with thinner layers of less consolidated sands and mudstones (Fig. 3). Two lithotypes were recognized

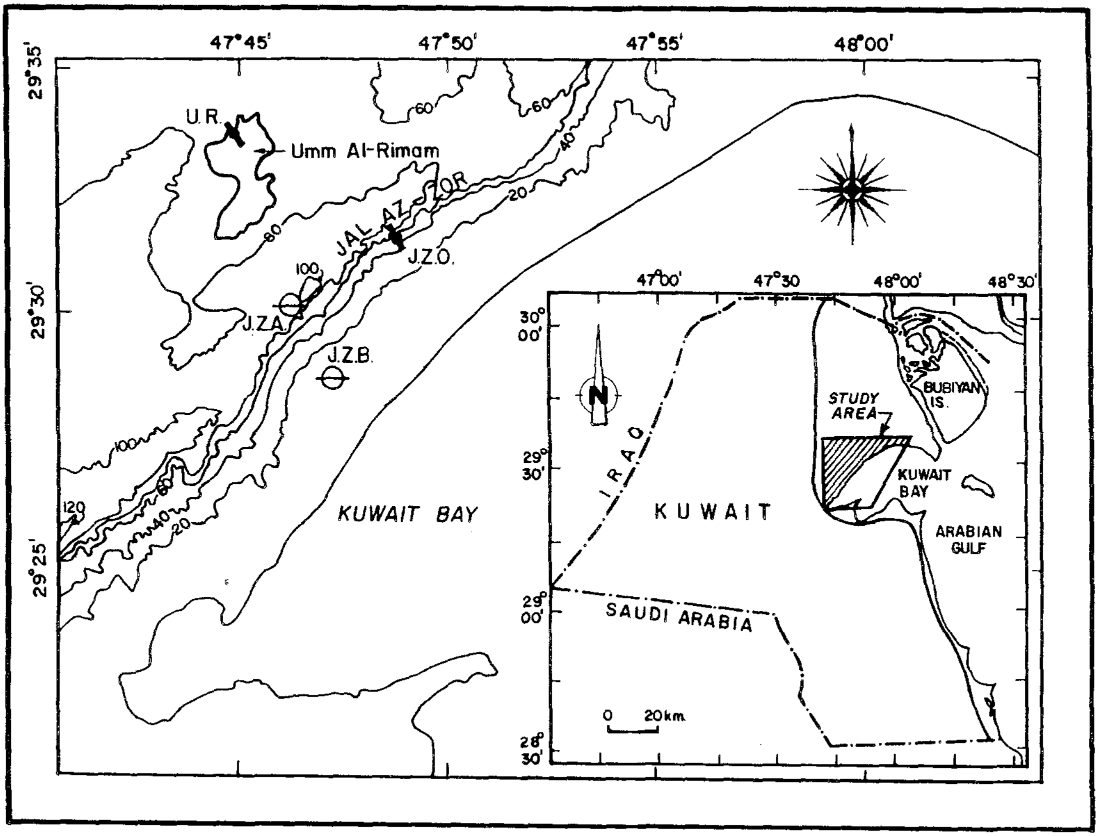

Fig. 1. Location map showing the investigated sites.

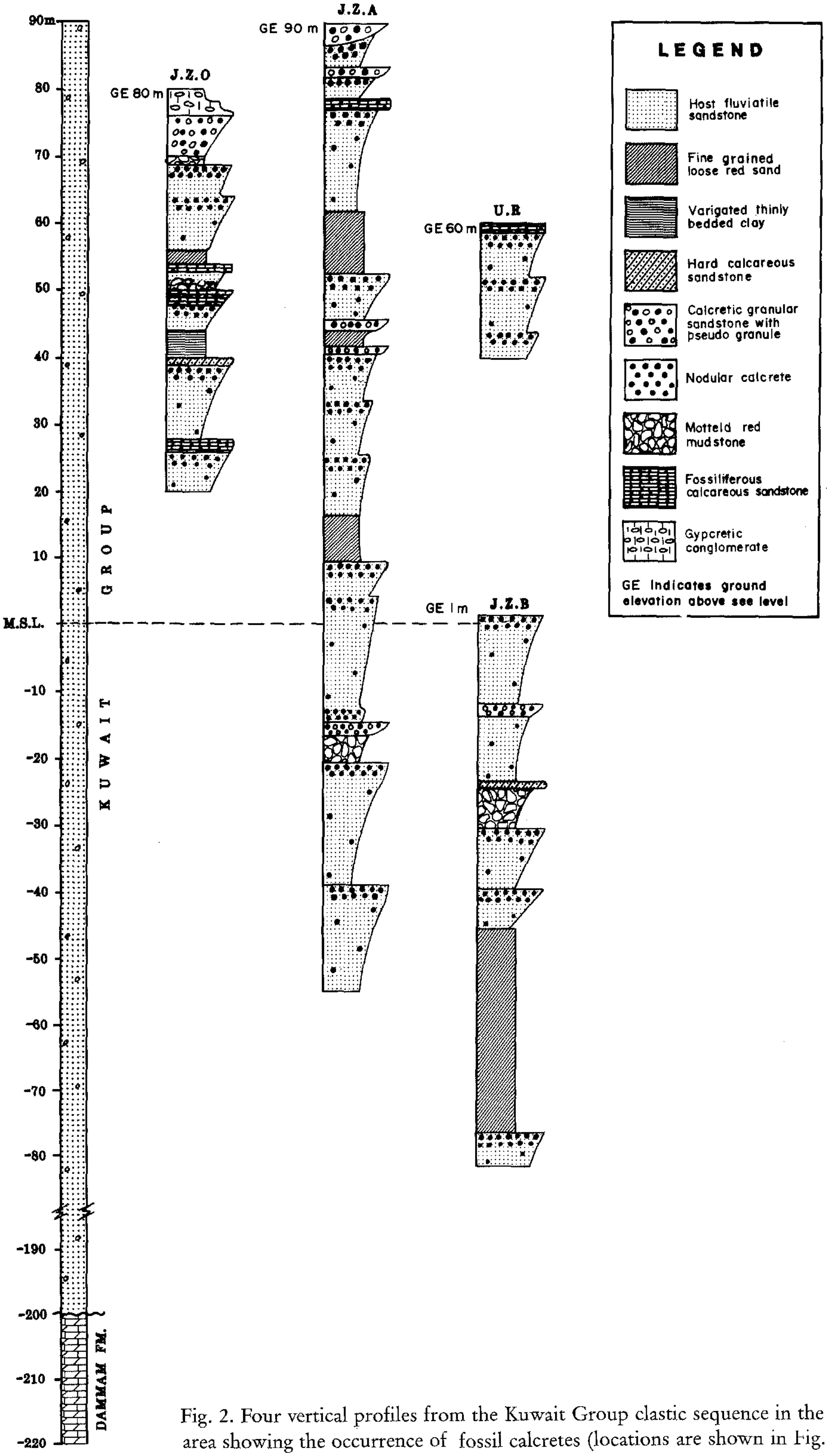

Fig. 2. Four vertical profiles from the Kuwait Group clastic sequence in the Jal Az-Zor area showing the occurrence of fossil calcretes (locations are shown in Fig. 1).

Fig. 3. Massive fluviatile calcretized sandstones exposed along the Jal Az-Zor escarpment. Note the overlying cross-bedded gravelly Dibdibba Formation (D) and the erosional surface (E) between two units of massive sandstone.

within the conglomeratic Dibdibba Formation that caps the Jal Az-Zor escarpment. The upper layer is formed of pebbly gravel cemented by fibrous gypsum and ranges in thickness from the less than a meter to about 4 m. This layer is underlain by a granular sandstone bed that is about 6 m thick. It is cross-bedded and composed of rounded and moderately sorted granules floating in sandstone. A thorough look at the weathered surface of this rock revealed the occurrence of two types of granules: quartzitic and feldspathic clastic granules and calcareous diagenetic granule-like nodules. Whenever the calcareous granule-like nodules are more dominant, the rock appears as a conglomerate and, therefore, the term pseudo-conglomerate may be used to indicate this type of nodular calcrete (Fig. 4).

The section below the Dibdibba Formation is generally formed of a monotonous sequence of sandstones in which two fossiliferous horizons were recognized. The upper one is formed of cross-bedded calcareous sandstone rich in pelecypods and was given a Pliocene age by AL-AWADI (1980). The upper surface of this layer forms a horizontal terrace extending to the north of the Jal Az-Zor escarpment and can be traced to the Umm Al-Rimam cliffs. The lower fossiliferous horizon is massive marly sandstone and is rich in *Ostrea latimarginata* and *Saccostrea cucullata* and is of Miocene age. The two fossiliferous horizons are separated by about a 24 m thick sandstone sequence.

The sandstone sequence is formed of successive hard beds about 6–8 m thick. They are jointed, exfoliated and interbedded with thin red clay bands that vary in thickness from 0.1 to 1.5 m. These bands usually occur on top of calcretic layers and are rich in rhizoconcretions that may indicate fossil plant roots. A thorough investigation of the weathered surfaces of the sandstone beds revealed the occurrence of hori-

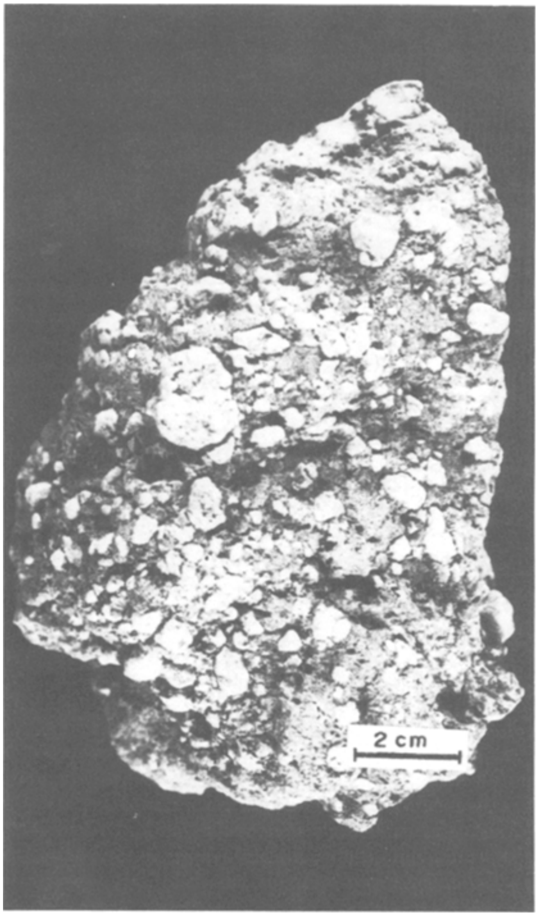

Fig. 4. Rock specimen from a weathered surface of calcretic sandstone from the lower Dibdibba Formation. Note the abundant calcretic nodules that give the rock a pseudo-conglomeratic appearance.

Fig. 5. Nodular calcrete in the massive fluviatile sandstones of the Kuwait Group sequence exposed along the Jal Az-Zor escarpment.

zontal bands of nodular calcrete (Fig. 5). Layers of fine-grained, loose red sands were recognized at the escarpment foot. About three layers of this sand were also recorded in two boreholes at various depths. Lenses of gravelly sandstone intercalating with the massive sandstone were also noticed at various depths.

Megascopic Description

Sandstones hosting the fossil calcretes are generally whitish to greyish, massive and vary from very consolidated to friable. They also vary in texture from very poorly sorted granular sandstone to sorted medium-grained sandstone. Fossil calcretes are represented by about a 30 cm thick band of dense calcareous nodules. Accumulations of calcrete nodules are also present as discontinuous lenses; however, the horizontal continuous bands of nodular calcretes are the most common mode of occurrence. Calcareous nodules are sparsely scattered in the massive sandstones below and above the nodular calcrete bands. The abundance, shape and mode of occurrence of nodular calcrete reflect, to a great extent, the degree of calcretization or the stage of calcrete development. Polished slabs of calcrete samples from both outcrops and borehole cores revealed the occurrence of different types of calcretes that represent different stages of calcretization.

Powdery calcrete. Powdery calcrete represents the very early stage of calcrete development or incipient calcrete. It is represented by a few small chalky calcretic lumps of irregular shape sporadically scattered in the host sediments. They range in size from 1 to 3 mm and constitute less than 10% of the calcretized rock.

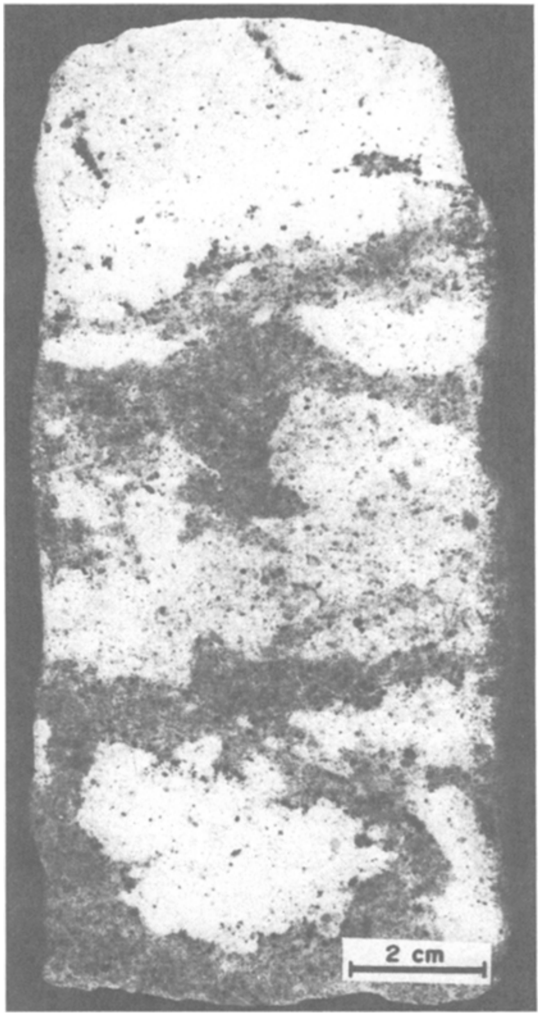

Fig. 6. Polished slab of nodular calcrete. Note abundant chalky calcrete nodules of varying sizes.

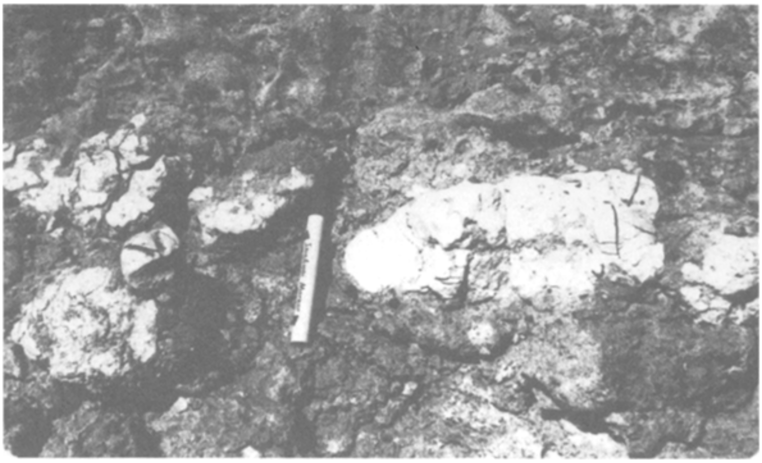

Fig. 7. Concretionary boulder-sized calcrete hosted in the granular sandstones of the lower Dibdibba Formation.

Nodular calcrete. Nodular calcrete is an immature stage of calcrete development. It is composed of moderately sorted granular chalky calcretic nodules scattered in the host sandstones. The nodules are of various shapes and range in size from 8 to 12 mm. They form about 50 % of the material of the calcretized bed. Calcrete nodules are usually fractured and are recognized from the host sandstone by their massive chalky texture. Clastic grains can be seen by the naked eye floating in the calcareous groundmass (Fig. 6).

Concretionary calcrete. Concretionary calcrete represents mature calcrete and usually occurs as large boulder-sized calcrete concretions (Fig. 7). The boulder-sized concretions are developed by coalescence of the individual calcrete nodules due to their progressive growth. These concretions can be easily separated from the host sediment and are characterized by a mammilary or brain-like surface. The slabbed concretions show remnants of the host sediments trapped between the coalesced calcretic nodules (Fig. 8). The calcretic material in this calcrete type is usually very dense, has a very smooth surface when slabbed and has abundant pinkish to reddish patches.

Textural Characteristics of Host Sediments

Two types of sandstones were recognized in the upper part of the Kuwait Group exposed along the Jal Az-Zor escarpment: greyish to pale greenish massive mostly consolidated sandstone and reddish bedded friable sandstone. Fossil calcretes are usually hosted in the greyish massive sandstones, whereas the red sandstones usually lack any sign of calcretization. Significant differences were recognized in the grain-size distribution of the two sandstone types. The calcrete host sandstone is generally muddy sandstone and its average textural composition is 2 % granules, 83 % sand and 15 % mud. The sand fraction of this sandstone is relatively rich in very coarse and

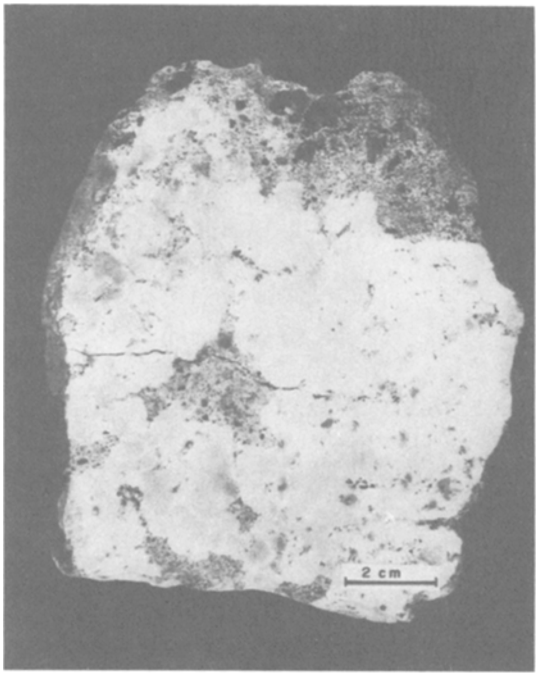

Fig. 8. Polished slab of a concretionary calcrete boulder. Note remnants of host sediments trapped between the coalesced calcretic nodules.

Table 1. Summary statistics of grain size parameters and weight percentages of the two types of sandstones within the studied Kuwait group sequence

Types of Sandstone	No. of Samples	Weight % of Size Fraction			Size Parameter (ϕ)			
		Granule	Sand	Mud	M_Z	σ_I	SK_I	K_G
Calcrete Host Sandstone	10	2.0	83.0	15.0	2.26	1.71	+0.30	1.47
Red Sandstone	8	0.0	93.5	6.5*	2.13	0.81	+0.20	1.59

* Present mostly as coarse silt (> 30 μm).

coarse sand sizes that constitute about 19 % on average. Medium and fine sand sizes form the bulk of the sand fraction; they constitute about 70 % on average. Red sandstone has an average textural composition of 93.5 % sand and 6.5 % silt. The sand fraction of the red sandstone is composed mainly of medium and fine sand sizes; they constitute about 87 % on average.

In spite of differences in their grain-size distributions as shown by their average histograms, the calcrete host sandstones and the red sandstones have similar average mean size values: 2.26 ϕ (0.44 mm) and 2.13 ϕ (0.47 mm), respectively; however, they significantly differ in sorting. The calcretic host sandstones are poorly to very poorly sorted, whereas the red sandstones are generally moderately sorted (Table 1). The grain-size distribution and average values of size parameters of the red sandstones are comparable with those of Recent desert mobile sand sheet deposits (FODA et al., 1984; MAXWELL, 1982; FOLK, 1971). Therefore, it is suggested that the red sandstones within the studied Kuwait Group sequence are most probably ancient desert sand sheet deposits, whereas the calcrete host sandstones are mostly fluviatile flood plain deposits.

Microscopic Investigations

The host sediments are mostly muddy sandstones composed of siliciclastic framework grains floating in a clay matrix. Framework grains are mainly composed of quartz; however, feldspar grains and volcanic rock fragments are present in subordinate amounts. The matrix is usually composed of micaceous clays. Based on their composition, the host sediments of the studied fossil calcretes can be described as immature feldspathic quartzarenites.

Calcite authigenesis is the main diagenetic process that affects the host sediments; however, due to different stages of authigenesis and the occurrence of different fabrics of calcite cement, several diagenetic features were recognized. Authigenic calcite is generally present in two forms: microcrystalline calcite and macrocrystalline sparry calcite. The first usually forms the bulk of the calcretic nodules, whereas the second exists as intergranular cement and cavity and fracture filling.

The fabric and composition of calcretic nodules depend on their degree of maturation. Mature calcretic nodules are usually composed of two zones: a rosey to brownish inner zone and a chalky outer zone. The outer zone is composed of a mosaic of equant microcrystalline calcite crystals with few scattered quartz grains that are finer in size than those of the framework grains of the host sediments. This may indicate diagenetic reduction in their size.

The inner zone is rich in remnants of siliciclastic grains that are usually fringed by a corona-like structure (Fig. 9). This structure is developed due to precipitation of drusy calcite crystals, coarser than those of the groundmass, as a rim around the siliciclastic grains. The morphology, thickness and fabric of the corona-like structure vary significantly. It may occur as an isopachous rim surrounding the clastic grains uniformly or as a rim surrounding certain sides of the grains. Two fabrics were recognized for the calcite forming the corona-like structure: bladed and equant crystals. The bladed drusy calcite rim is usually isopachous and continuous around the grains. It varies in thickness between 10 μm and 40 μm. Zonation within the bladed drusy calcite rim was noticed due to the occurrence of very thin sheaths of limonitic material; more than two zones were recognized. This fabric may indicate periods of stagnation in calcite precipitation.

The equant drusy calcite rim is usually present as patchy clear cement along certain sides of the clastic grains. In this fabric, calcite occurs as a mosaic of clear block crystals that vary in size between 20 μm and 50 μm. The reddish colour that characterizes the inner zone is generally due to the occurrence of limonitic material filling the intercrystalline pores in the microcrystalline calcitic groundmass. Siliciclastic grains in the inner zone are usually coated by micritic

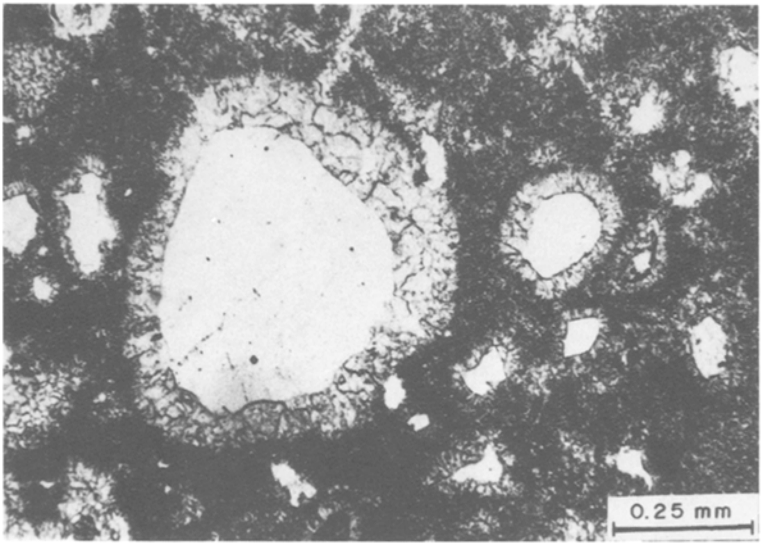

Fig. 9. Photograph showing corona-like structure around clastic grains in the inner zone of the calcretic nodule.

envelopes that, in most cases, were displaced away from the grains by the drusy calcite rim cement. These displaced micrite envelopes are responsible for the occurrence of a clotted texture within the calcretic nodules. Fractures and cavities filled with drusy mosaic block calcite are common in the calcretic nodules (Fig. 10).

The host sediments are characterized by the occurrence of macrocrystalline calcite crystals floating in the clayey matrix. These calcite crystals reach up to 0.5 mm in size. They generally displace the matrix material and framework grains of the host sediments. Scattered microcrystalline calcite crystals of about 10–30 μm in size were also noticed floating in the clay matrix. They could increase in number and agglomerate to form the nucleus of calcretic nodules.

The nature of the fabric of the calcite cement within the host sediments is responsible for the degree of induration of the rock. Calcite cement fills intergranular pores and, because it is developed within the matrix by displacive or replacive processes, cannot cohere the framework grains; it pushes them aside. In the case of hard lithified sandstones that usually occur as thin discontinuous bands within the soft friable host sediments, calcite cements are present either as poikilitic cement or drusy mosaic cement. In poikilitic cement, several framework grains are enclosed in one macrocrystal of calcite. Drusy mosaic cement is formed of calcite block crystals growing on the surfaces of framework grains and are interlocked. These two fabrics are mostly developed in clean and sorted sands that are usually of aeolian origin and are rarely host calcrete.

Discussion and Conclusions

The Mio-Pleistocene clastic sequence exposed along the Jal Az-Zor escarpment was stratigraphically investigated by several geologists. A sedimentological assessment of the sequence was not attempted and, therefore, the occurrence of fossil calcretes was not reported in previous literature.

Two types of sandstones were recognized within the studied sequence: greyish to pale greenish massive fluviatile muddy sandstones and aeolian red bedded sandstones. The fluviatile muddy sandstones are characterized by the abundant occurrence of nodular calcretes that are usually developed near the upper surface of the sandstone beds and at about 2–3 m below the surface. The calcrete host sandstones are usually topped by a thin layer of red mudstone resembling terra rosa soil that may have been developed by the accumulation of insoluable residues produced from the leaching of the top part of the fossil calcrete profile. Thin layers of loose coarse-grained sand rich in rhizoconcretions were also recognized on top of some calcretic sandstone units. These layers could indicate an ancient soil profile similar to that developed in desert areas covered with shrubs and vegetated sand sheets (Khalaf et al., 1984). Both red mudstone and rhizoconcretionary

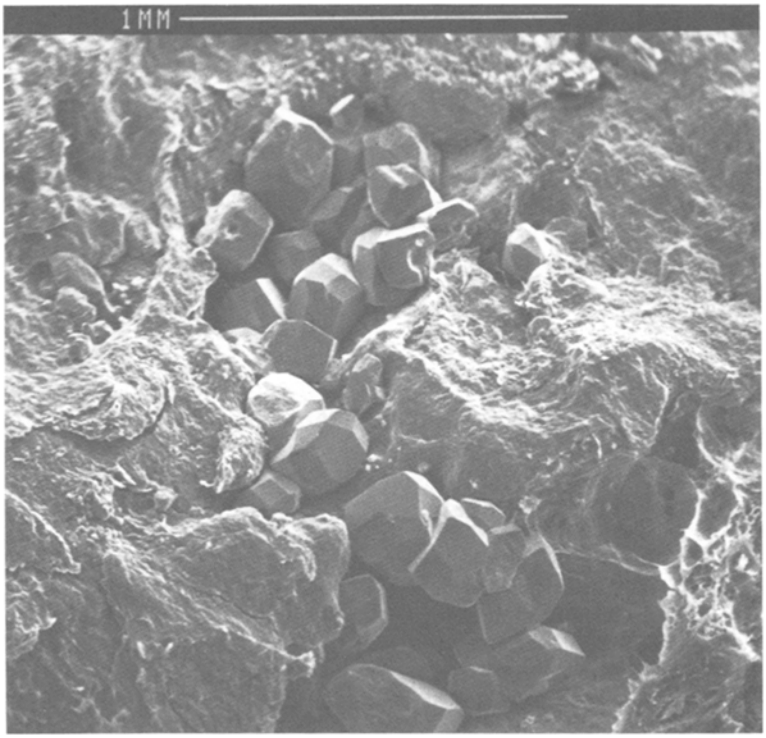

Fig. 10. SEM photomicrograph showing clusters of well euhedral equant calcite crystals filling cavity within the microcrystalline calcitic groundmass of a calcretic nodule.

sandstones are underlain by 3–6 m of aeolian red sandstone in some localities.

With the exception of the upper Dibdibba Formation, which is mostly an alluvial fan gravel sheet, the majority of the exposed rocks along the Jal Az-Zor escarpment are terrestrial sandstones. The occurrence of cross-bedded highly fossiliferous thin calcarenitic bands intercalated within massive terrestrial sandstones reflects short periods of sea transgression. The presence of two fossiliferous horizons intercalated within the massive terrestrial sandstones indicates the occurrence of two sea transgressions; the first took place during the Miocene, whereas the second occurred during the Pliocene.

Petrographic investigation and X-ray diffraction analysis revealed that the studied calcretic nodules are composed of remnants of siliciclastic grains scattered within a groundmass of microcrystalline calcite. These nodules float in the host sandstones that are partially cemented by macrocrystalline calcite. The diagenetic history of the calcretic nodules started with the precipitation of equant sparry microcrystalline calcite crystals of about 10–20 μm in size within the muddy matrix of the host sandstones. These minute individual calcite crystals increased in number and clustered at several spots within the host sandstone where micro-nodules of about 300 μm in size were developed. The growth of the micro-nodules continued by precipitation of micritic calcite. This process was accompanied by displacement, then replacement of the muddy matrix and entrapment of the framework grains by the growing micritic calcite cement of the calcretic nodules. At a later stage, the microcrystalline calcite of the calcretic nodules displaced, then partially replaced the enclosed framework grains.

The replacement of siliciclastic grains by calcite occurs in two steps. The first is the dissolution of silica leaving cavities between the dissolved grains and the microcrystalline calcitic groundmass of the nodule. This step is followed by precipitation of calcite in these cavities. This process is responsible for the development of a corona-like structure in the inner zone of the calcretic nodules. The occurrence of two different fabrics for the calcite forming the corona-like structure could be related to the availability of solution. The isopachous bladed calcite rim is developed in a cavity completely filled with calcium-rich water, whereas the non-uniform drusy calcite rim is developed in partially water-filled pores.

The macrocrystalline sparry calcite that partially cements the host sandstones and fills fractures in calcretic nodules is developed at a later stage of diagenesis when calcite precipitation is slow.

Therefore, it is suggested that the fluviatile sandstones that host the fossil calcretes were affected by two stages of calcite diagenesis. The first took place very early and was responsible for the development of the nodular calcrete. The second stage of calcite diagenesis was responsible for the partial lithogenesis of the host sandstones.

Comparison of the fossil calcretes in the studied sequences with the various types of Quarternary calcretes described by Goudie (1983), Netterberg (1978), Mann & Horwitz (1979) and Lattman (1977) indicates that the origin of the studied fossil calcrete is non-pedogenic and developed by accumulation of authigenic calcite cement within the zone of capillary rise. This type of calcrete usually developed in a profile that has dense laminar calcrete on the top and calcretic nodules scattered in the host sediments and decreases in frequency downward. The studied fossil calcretes usually lack the laminar calcrete that usually represents the upper horizon in the well-developed calcrete profile. It is believed that this horizon was weathered and terra rosa type soil was developed as a weathering product.

The Mio-Pleistocene clastic sequence of the Jal Az-Zor escarpment is characterized by cyclic sedimentation. Each cycle is represented by 4–6 m of massive muddy sands that were deposited in a fluviatile flood plain environment. Muddy sandstone units representing successive cycles are separated by an erosional surface. The fossil calcretes were developed by several diagenetic processes that took place between the two fluvial periods. The cycle starts with the deposition of the muddy sandstone host material during a humid period. Deposition ceased due to a change in climate from humid to semi-arid. During the semi-arid period, calcrete was developed within the fluviatile sandstone. The semi-arid period was followed by a slightly wet period during which the upper part of the calcrete weathered and terra rose type soil was developed. This was followed by a period of extreme aridity during which aeolian sand sheets were deposited. This friable aeolian sand sequence can be preserved and covered by the fluviatile sands or may be washed away by the floods of the next cycle and, in this case, no record of the arid period will be maintained. Fig. 11 is a

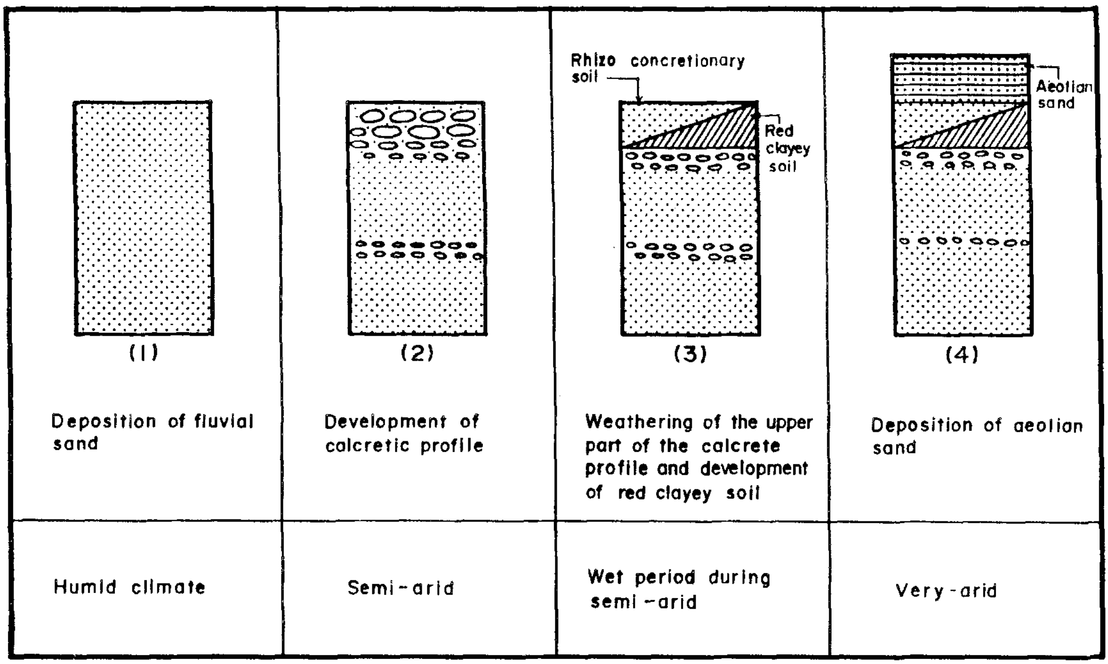

Fig. 11. Schematic diagram illustrating the development stages of the calcrete cycle.

schematic diagram that illustrates the suggested model for the development of fossil cyclic calcrete in the upper Kuwait Group sequence in Kuwait.

It is recommended that the stratigraphy of Kuwait Group clastic deposits in the northern Arabian Gulf region be revised on the basis of the findings and conclusions of the present study.

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