J.K.A.U.: Earth Sci., vol. 3, Special Issue: 1st Saudi Symp. on Earth Sci., Jeddah, 1989, pp. 95-108 (1410 A.H. / 1990 A.D.)

Depositional and Diagenetic Facies Relationships, Khuff-C Reservoir, Eastern Saudi Arabia

HASAN SELCUK TALU and FAKHRY A. ABU-GHABIN
Geological Department, Saudi Aramco, Dhahran, Saudi Arabia.

ABSTRACT. The Khuff Formation represents the earliest record of major carbonate sedimentation in the Arabian Gulf region which was initiated by a widespread Late Permian transgression of the Tethys Sea over the Arabian Foreland. The sediments comprise a carbonate-evaporite sequence which has been divided into four major depositional cycles correlatable with worldwide Upper Permian Cycles.

Porosity distribution is controlled by the degree of diagenesis. The diagenetic changes which affect porosity in the Khuff-C seem to have taken place in the early history of the sediments, including dolomitization, leaching and dissolution, and cementation. Penecontemporaneous dolomitization and early diagenetic replacement of the sediments by dolomite are probably the key processes that enhanced the Khuff-C porosity development, but porosities in the Khuff-C have most likely been enhanced by dissolution of calcite as well. On the contrary, porosities were destroyed by emplacement of equant calcite and anhydrite cements.

A conceptual model has been developed for explaining the diagenetic process in the study area. In this model, some very low relief "topographic highs" were formed and were occasionally subaerially exposed. The fresh water lenses developed on these highs controlled diagenesis of the sediments.

Stratigraphy

In the Late Permian, the study area was located on the western margin of a stable shelf which bordered the open marine basin of the Tethys Sea (Fig. 1). The Khuff Formation marks the earliest major carbonate sedimentation in the region which was initiated by a widespread Late Permian transgression of the Tethys Sea over the Arabian Foreland. The Khuff rocks overlie the Unayzah terrigenous clastics with transitional basal contact, and are conformably overlain by the Sudair shales (Fig. 2). The Khuff is a carbonate-evaporite sequence, which has been divided into four major depositional cycles referred to, from top to bottom, as the Khuff-A, B, C, and D. In Saudi Arabia, reservoirs within the Khuff Formation are confined to cycles A, B, C.

The deposition of the Khuff-D anhydrite approximately 750′ above the base of Khuff carbonate represents the regressive climax of the first major eustatic cycle of the Late Permian. The anhydrite may have been in a long-lasting sabkha environment of regional extent when sea level was lower than normal. The Khuff-C was the next major transgressive cycle. It finally culminated in another regional sabkha environment represented by the anhydrite rich, dolomitized supratidal-intertidal sediment in the uppermost part of the Khuff-C interval. The Khuff-B and Khuff-A sections from the overlying additional major Khuff depositional cycles. Each succeeding cycle is thinner than the underlying cycle.

Many small-scale cycles, *i.e.*, those less than a meter to a few meters in thickness, are common within these major cycles. This indicates that the rate of sedimentation and rate of subsidence were essentially in balance but subject to minor oscillations. It is often difficult to differentiate small-scale cycles because of the extensive diagenesis.

These major cycles (A-D) are correlatable with worldwide Upper Permian Cycles, which are eustatic origin, each having a duration of approximately 3 million years (Fig. 3).

The eustatic origin for these cycles has important implications on the deposition and diagenesis of the Khuff sediments (Fig. 4). In fact, minor changes in sea level over short periods of time, combined with evaporite-carbonate deposition, caused the complex diagenetic facies observed in the Khuff-C cores.

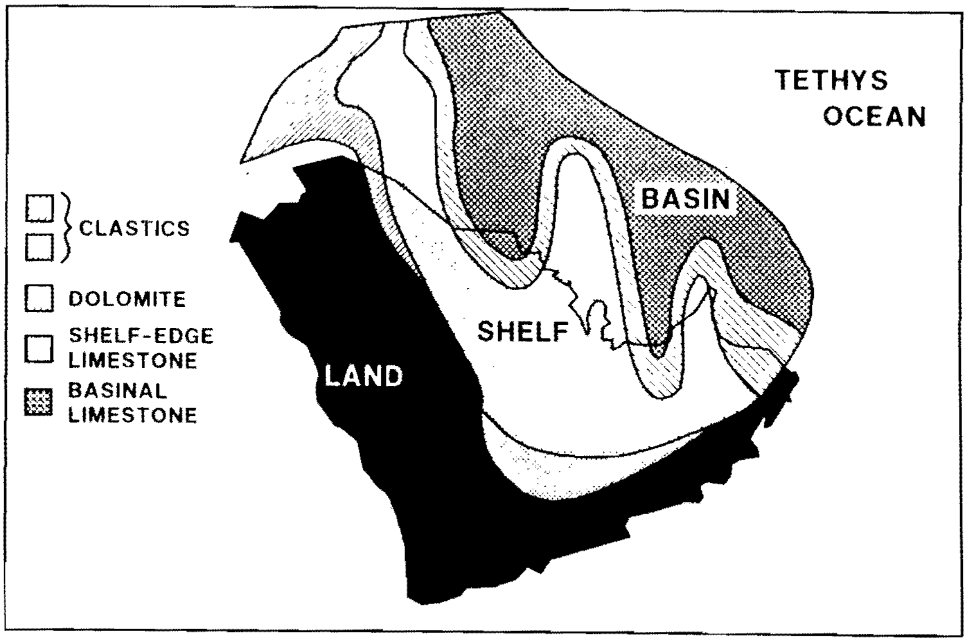

FIG. 1. Regional lithofacies map of Khuff Formation (after Devine 1969).

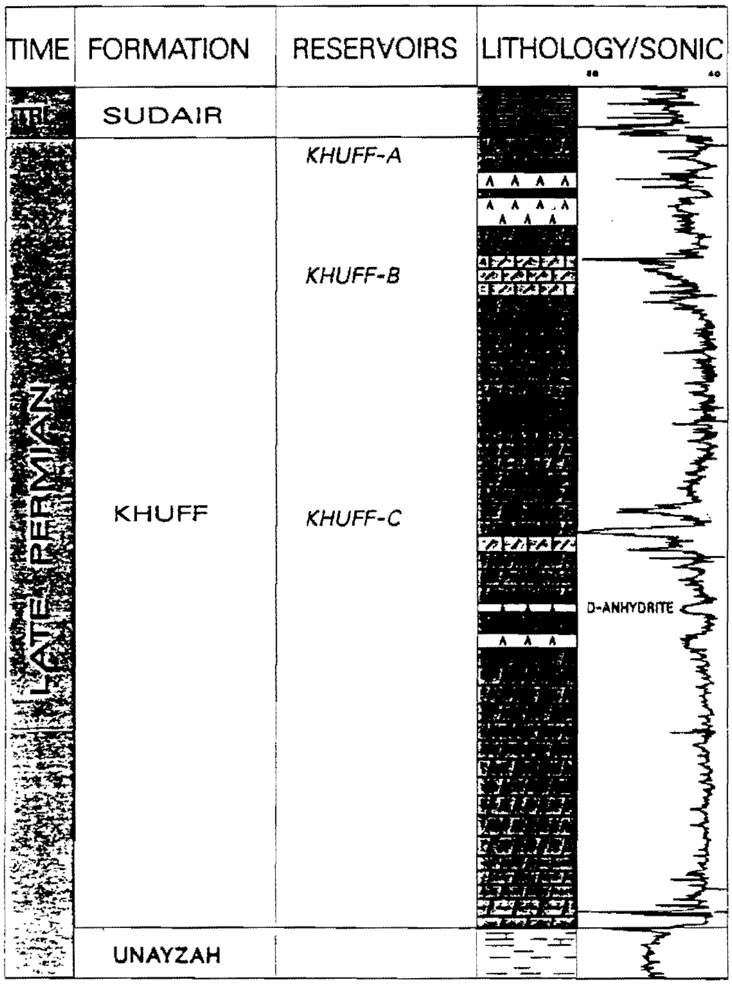

FIG. 2. Informal subsurface nomenclature and lithology.

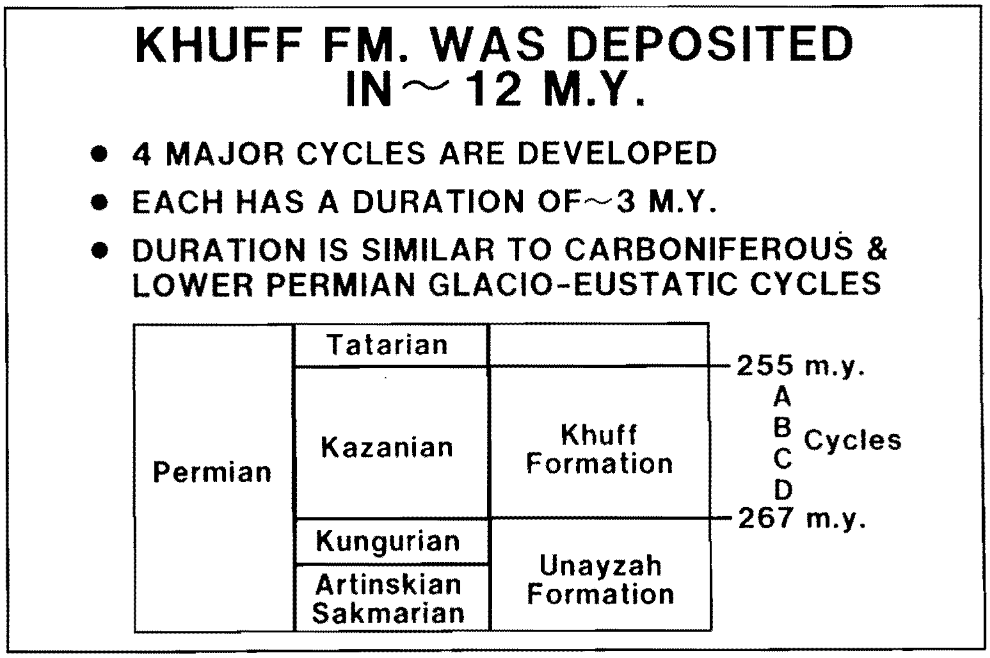

FIG. 3. History of Khuff Formation.

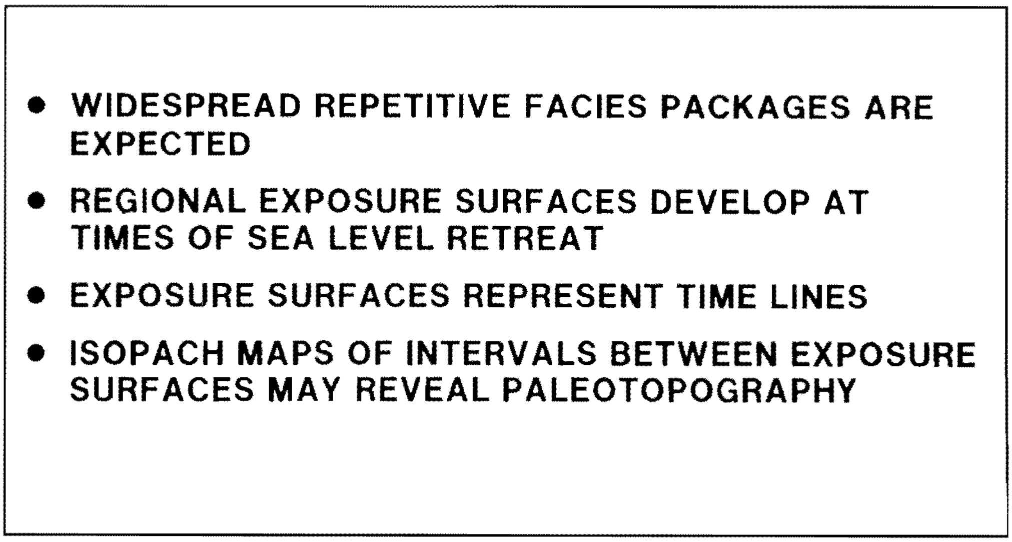

FIG. 4. Implications of Eustatic origin for Khuff cycles.

The Khuff-C Sediments

The Khuff-C sediments in the study area, eastern Saudi Arabia, consist of limestone, dolomite, and anhydrite. The bulk of the Khuff-C sediments consist of various types of carbonate rocks. The Khuff-C sediments have two grain types; skeletal and non-skeletal. Owing to hypersaline conditions, skeletal grains apparently are scarce and limited to a few species; primarily foraminifera, algae, bryozoa, and gastropods. Non-skeletal grains are mostly ooids, peloids, composite grains, and clasts. The identification of depositional facies has been obscured in much of the Khuff-C due to diagenesis. The anhydrite occurs uniformly throughout the section as nodules, mimetic replacement, cement, and/or thin stringers, and is indicative of the evaporitic conditions which existed during Khuff-C deposition. Sedimentary structures include lamination, cross-bedding, erosional contacts, mud cracks, and burrowing. The Khuff-C carbonate sediments were extensively dolomitized. Dunham's textural classification system for carbonate rocks has been used in this study (Plate I).

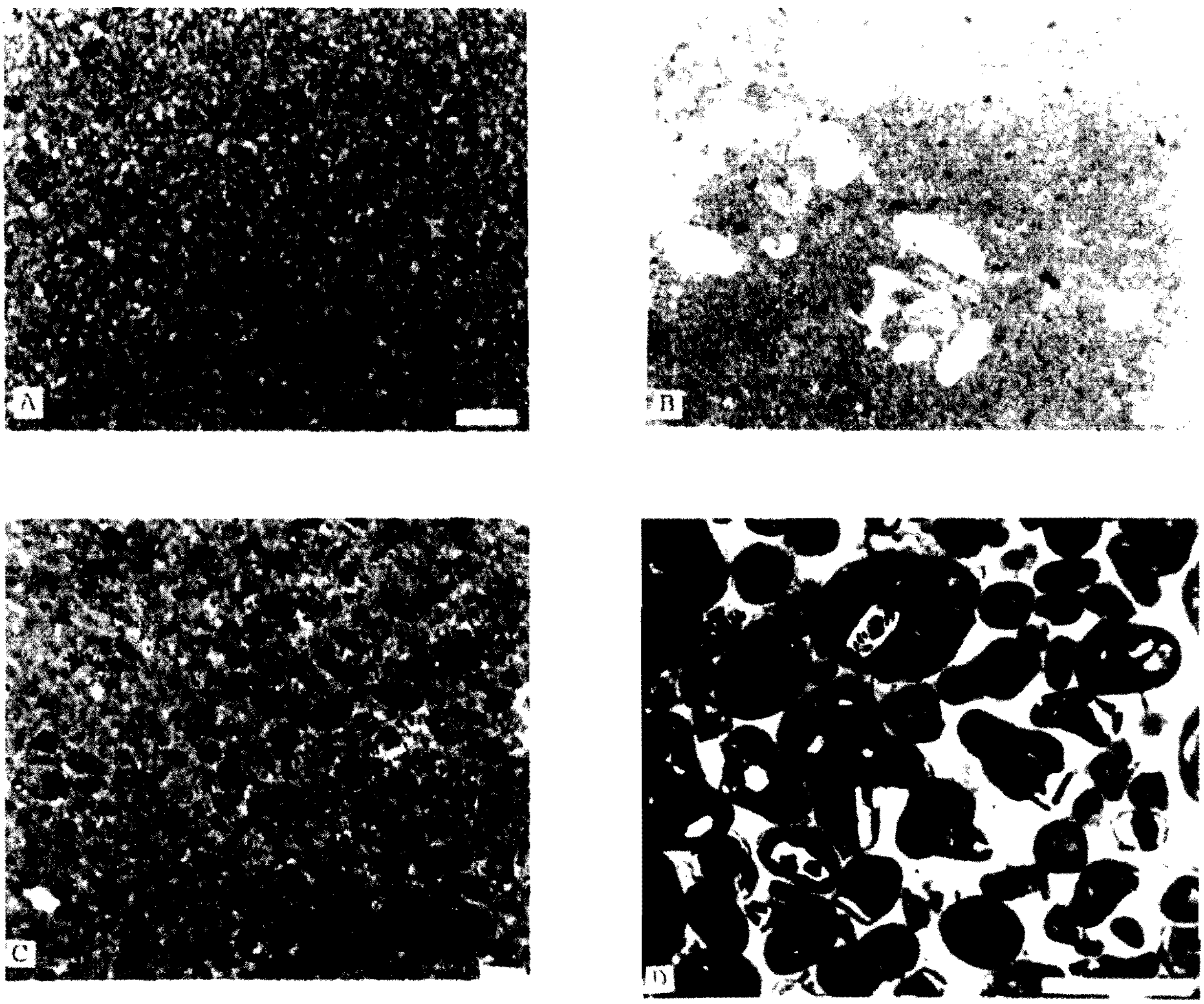

PLATE I. Rock Types.

(A) Completely dolomitized mudstone. Scale bar is 100 microns.
(B) Skeletal dolo wackestone. Skeletal fragments have been replaced by anhydrite. Scale bar is 200 microns.
(C) Pelletoidal dolo packstone. Scale bar is 200 microns.
(D) Coated grain-oolitic grainstone. Anhydrite cemented. Scale bar is 1 mm.

Depositional Model

Analysis of rock texture and composition of cores from the Khuff-C indicates a shallow marine epicontinental depositional environment with a large arid tidal flat and no significant terrigenous clastic input (Fig. 5). Shaw (1964) and Irwin (1965) have developed similar theoretical models for these environments. They emphasize that such seas would have depositional slopes of very low angle (on the order of less than one foot per mile) and a necessary consequence would have been sharp variations in water circulation and agitation across the epicontinental sea (Fig. 6). Depositional environments would be oriented approximately parallel to the shoreline.

Diagenesis

The reservoir interval within the overall Khuff-C section is comprised mostly of dolomites with only a minor amount of primary limestone remaining. As a result, diagenesis has played a more important role in defining the characteristics of the Khuff-C reservoir than the depositional environment. Depositional facies boundaries are approximately parallel to the D-anhydrite bed boundaries and can be correlated over 100 km without a significant facies change. The most important diagenetic processes observed within the Khuff-C Reservoir are dolomitization, leaching and dissolution, and cementation. Burrowing and deep burial diagenesis such as solution-compaction and formation of stylolites are other notable but less important diagenetic features.

Dolomitization

Most of the dolomites encountered during this study

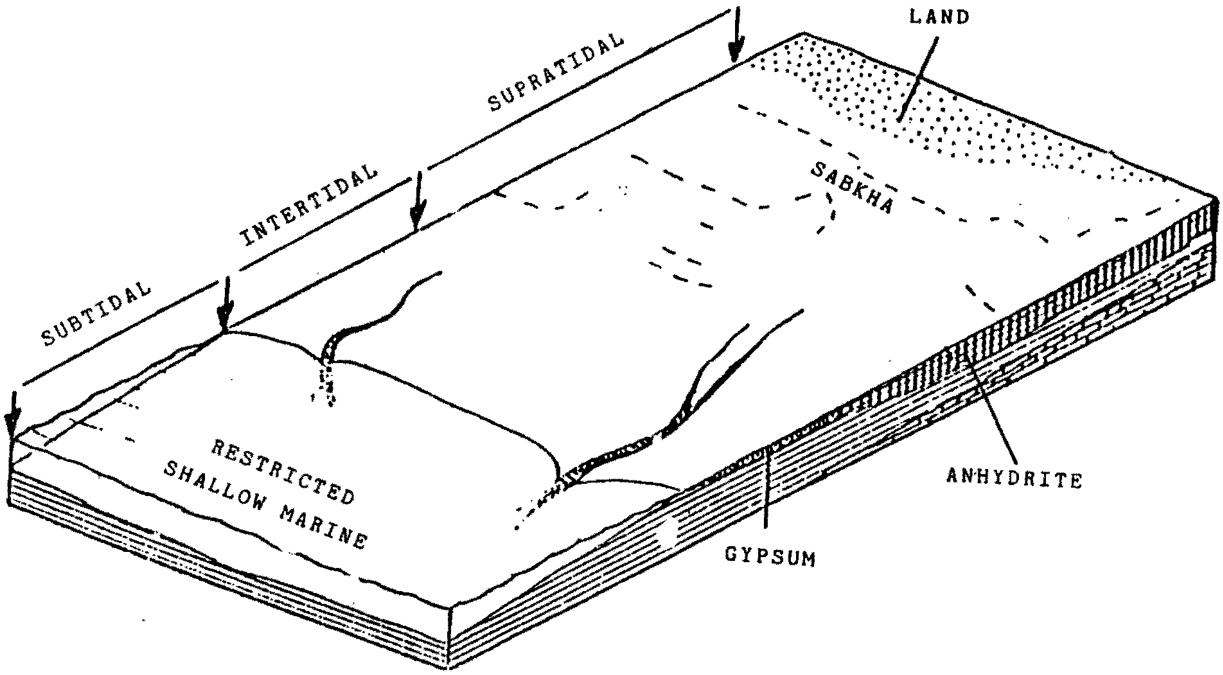

FIG. 5. Khuff-C depositional model.

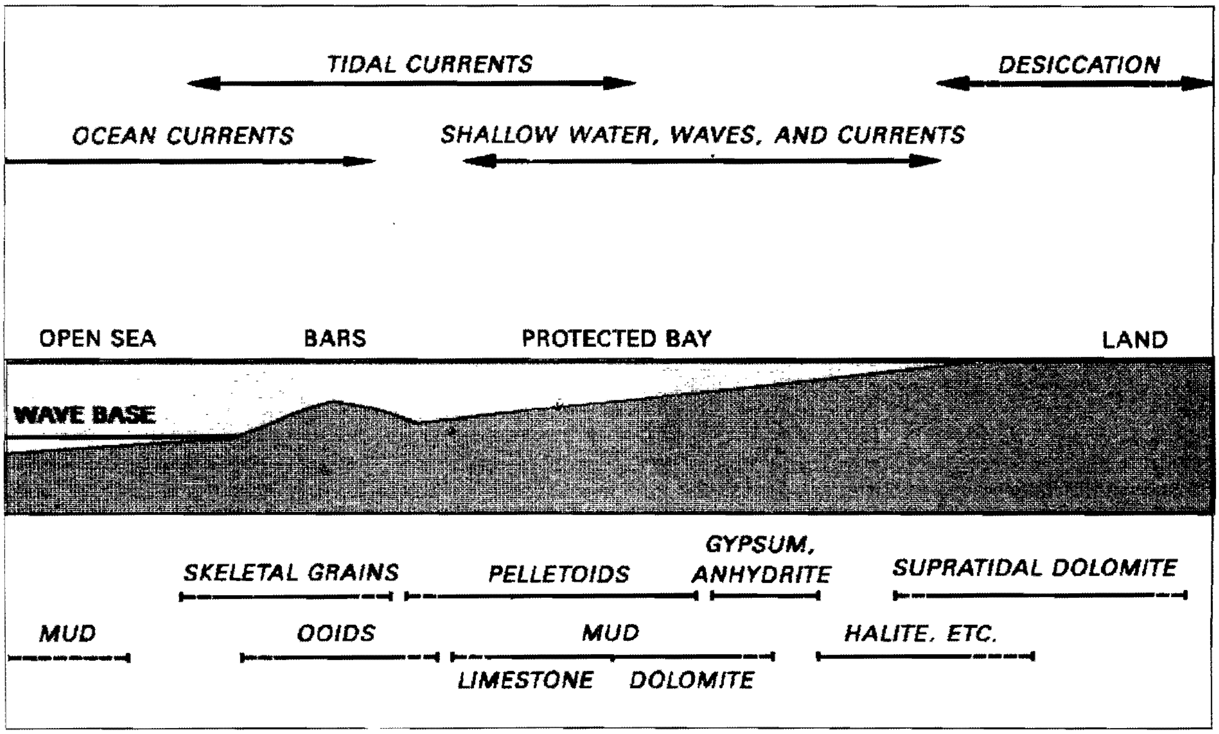

FIG. 6. Simplified presentation of the Irwin model for carbonate sedimentation in arid areas with no terrestrial influence.

were formed by either penecontemporaneous dolomitization (syndepositional replacement of the sediments) or early diagenetic replacement of the sediments (replacement after deposition, but prior to consolidation). (Plate II). Early dolomitization can preserve porosity, particularly in porous peloidal lime mudstones by creating a rigid framework that inhibits compaction of the soft pellets.

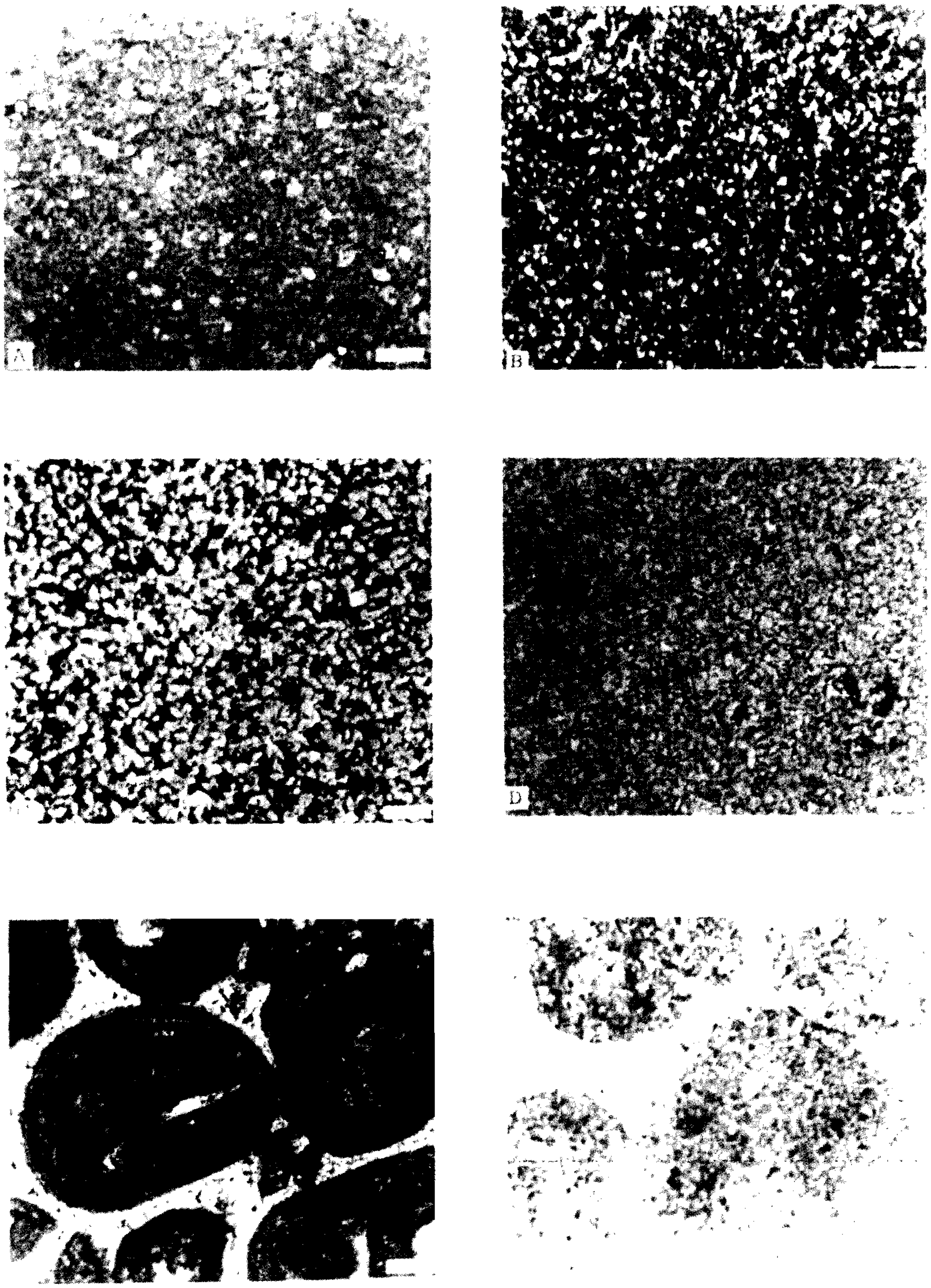

PLATE II. Dolomitization.

(A) Slightly dolomitized lime mudstone.

(B) Strongly dolomitized lime mudstone. Calcite matrix (red in photo) is still preserved.

(C) Strongly dolomitized lime mudstone. Calcite matrix has been removed by leaching, creating good intercrystalline porosity (blue in photo).

(D) Completely dolomitized mudstone. Continuing growth of dolomite crystals resulted in interlocking texture and loss of porosity.

(E) Completely dolomitized oolitic grainstone. Concentric structure of oolites are well preserved (mimetic replacement).

(F) Texture destroying dolomitization. Only the shape of the grains indicates their oolitic origin.

Note: Scale bar is 100 microns on all photomicrographs.

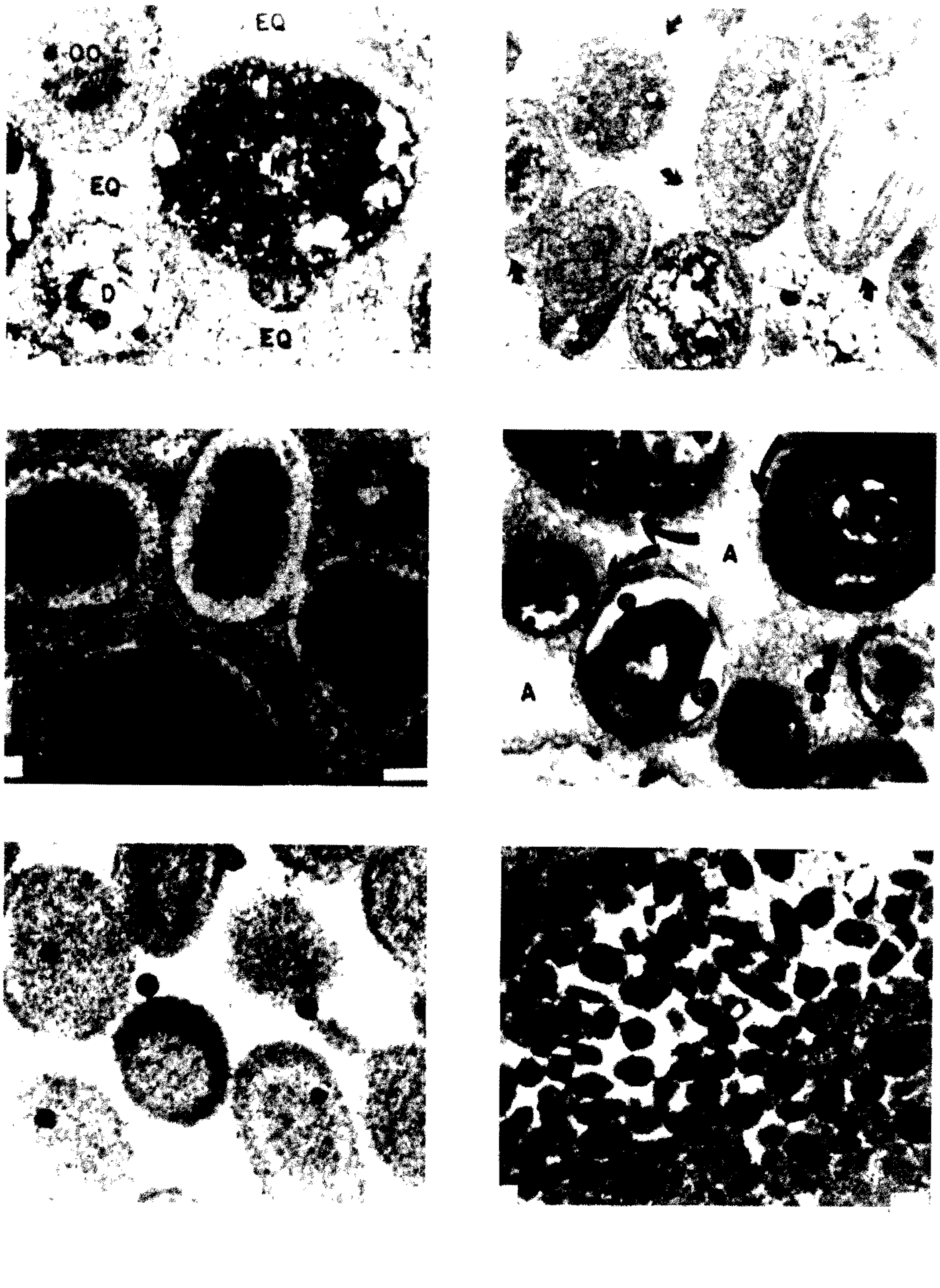

PLATE III. Cementation.

(A) Equant calcite cement (EQ) filling pore space between calcitic oolite (OO), dolomitized (D) and partially leached oolite (M). Scale bar is 100 microns.

(B) Dolomite rim cement (arrows) around calcitic oolites. Equant calcite cement fills the pore space between the grains. Scale bar is 100 microns.

(C) Dolomite cement filling pore space between partially leached calcitic oolites. Scale bar is 100 microns.

(D) Dolomite rim cement (arrows) and void filling anhydrite cement (A) in an oolitic grainstone. Scale bar is 100 microns.

(E) Anhydrite cemented oolitic dolo grainstone. Scale bar is 100 microns.

(F) Poikilotopic nature of anhydrite cement. X-nicols. Scale bar is 100 microns.

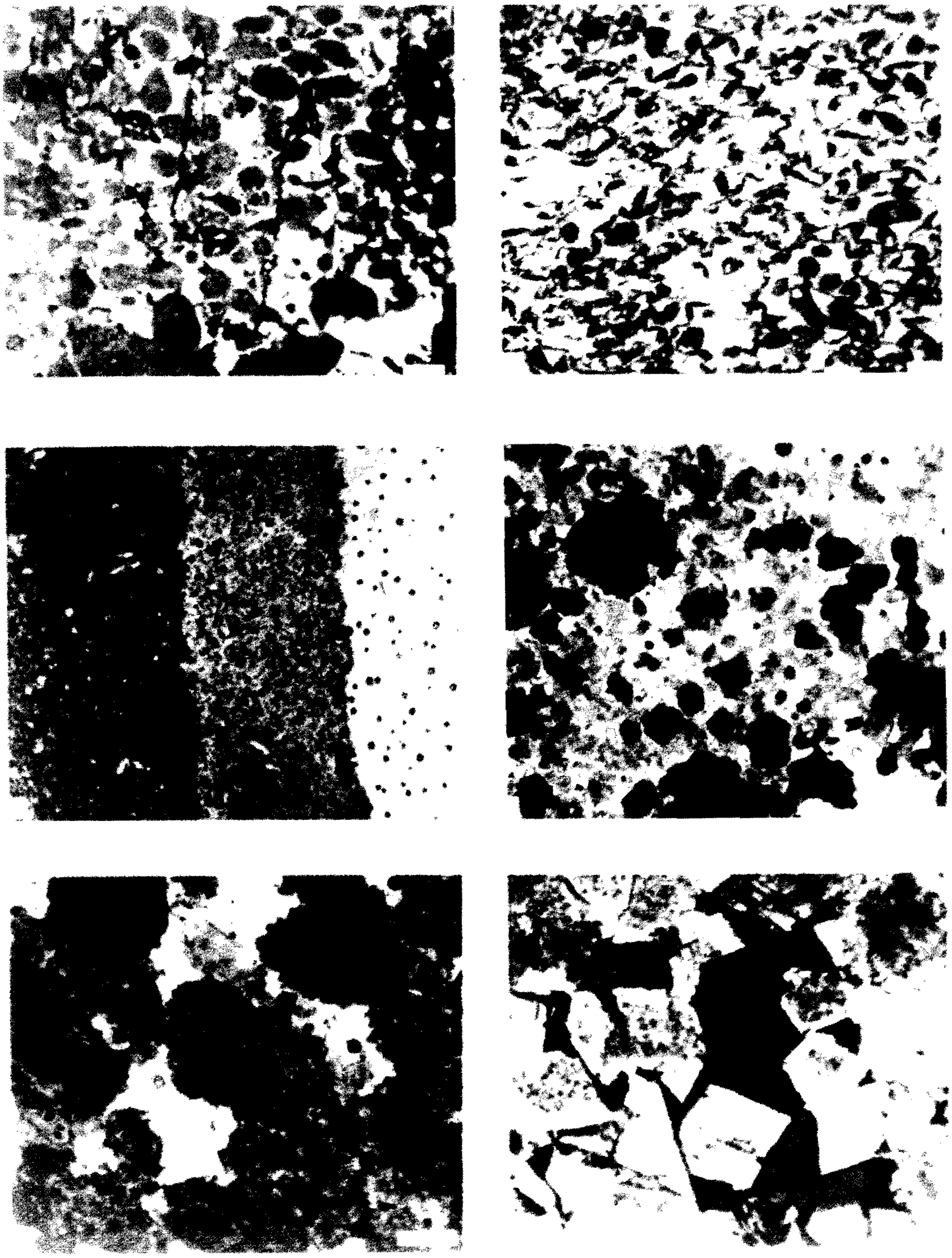

PLATE IV. Solution-Compaction and Burial Diagenesis.

(A) Microstylolite. Scale bar is 200 microns.
(B) Compaction of an oolitic grainstone. Scale bar is 200 microns.
(C) Silisified dolo mudstone. Scale bar is 200 microns.
(D) Pyrite concentration. Scale bar is 100 microns.
(E) Barite cement filling pore space between dolo grainstone. Scale bar is 100 microns.
(F) Coarse crystalline dolomite rhombs with clear rims (Hydrothermal origin). Scale bar is 100 microns.

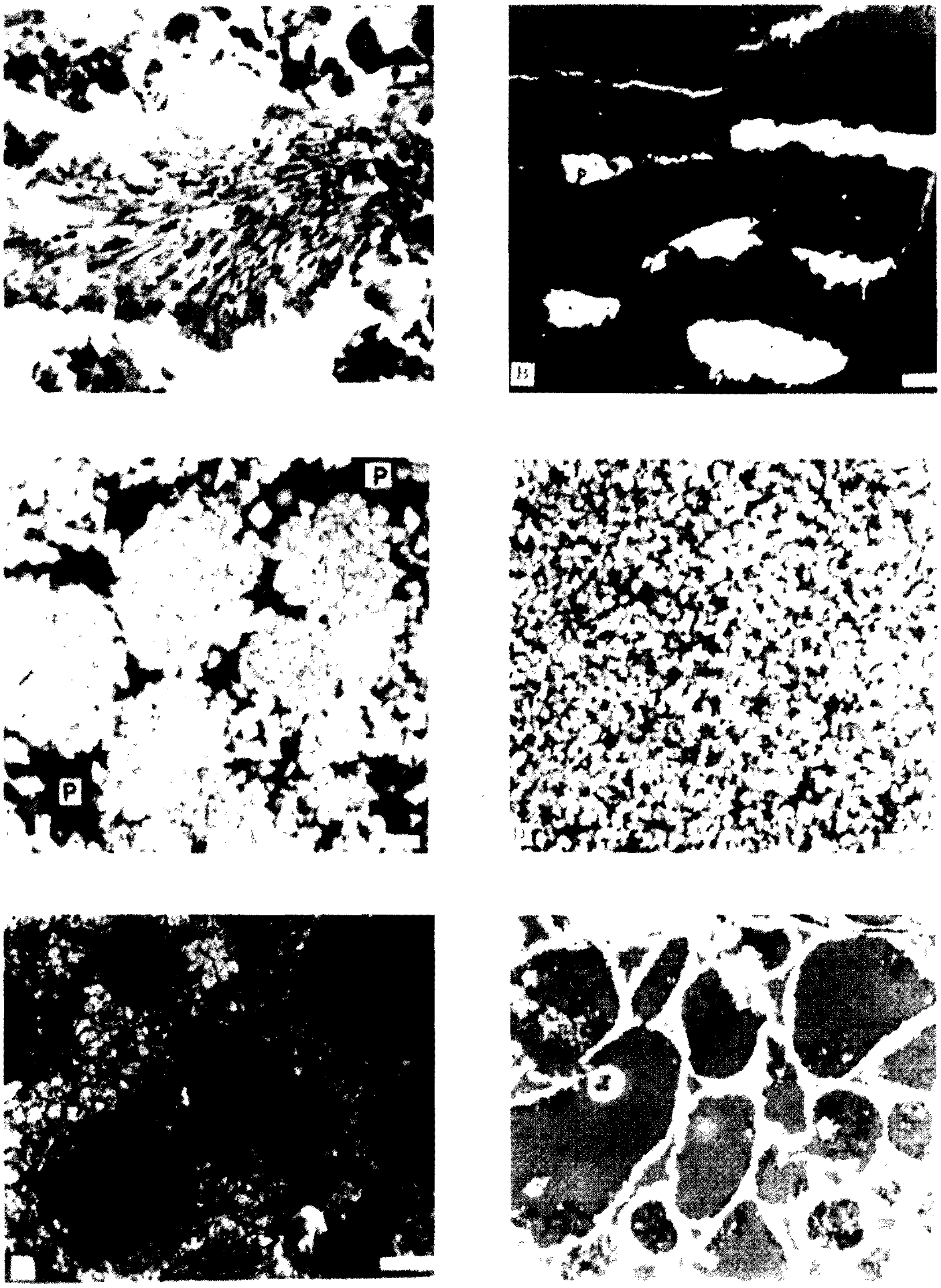

PLATE V. Pore Types

(A) Intraparticle porosity (blue) in a bryzoa. Scale bar is 1 mm.
(B) Fenestral porosity filled by anhydrite (white). Scale bar is 200 microns.
(C) Primary interparticle pore space (P) (blue) in a dolo grainstone. Scale bar is 200 microns.
(D) Intercrystalline porosity in a completely dolomitized mudstone (sucrosic dolomite). Blue color is the porosity. Scale bar is 100 microns.
(E) Moldic porosity in an oolitic grainstone. Primary pore space is filled by equant calcite cement (EQ). Scale bar is 100 microns.
(F) Moldic and interparticle porosity in a leached pelletoidal (?) grainstone. Scale bar is 100 microns.

Of all the theoretical models that have been proposed to explain dolomitization, three seem to be the most likely explanations of the extensive dolomitization of the Khuff-C sediments :

1. The Sabkha Model (Shearman 1966, and Kinsman 1969),
2. The Dense Brine Model (Barred-Basin Model, Schmalz 1969), and
3. The Mixing-Zone Model.

Leaching

One of the more important types of diagenesis in terms of porosity development is the formation of secondary porosity by leaching. Leaching of the Khuff-C sediments probably occurred during the low sea-level stands during which the sediments were subject to freshwater phreatic conditions. Meteoric water percolating down to the phreatic zone were under-saturated with respect to $CaCO_3$. As they moved downward, both aragonite and high-Mg calcite were dissolved making the waters more highly saturated with respect to $CaCO_3$ until finally they began to precipitate in the phreatic zone.

In the Khuff-C, the diagenetic end products of leaching depend on the rock type and composition of the material exposed to the fresh water. In lime grainstones or partially dolomitized grainstones, moldic porosity was created by the dissolution of oolitic and/or skeletal grains. In strongly dolomitized mudstones, intercrystalline porosity was enhanced by the removal of lime mud. Examples of these pore types are displayed in Plate V.

Cementation

Cementation is the most significant diagenetic process for porosity reduction in the Khuff-C sediments. Anhydrite and calcite are the dominant types of cement encountered in the Khuff-C grainstones and/or packstones. Dolomite has also been observed as cement but occurs only rarely in this mode (Plate III).

Anhydrite cement fills interparticle pore spaces, fractures, and fossil and oolite molds. The size of the individual crystals is variable and largely dependent on available void spaces. Pores may be filled with a single crystal, exhibiting rectangular cleavage or an aggregate of randomly arranged lath-like crystals, 25 to 500 microns in length, which extend in poikilotopic fashion.

Calcite cement is found in association with the leaching zones and represents the $CaCO_3$ saturated phase of percolating fresh water. It is represented by equant calcite mosaic where the individual crystals are approximately equal in dimension.

Solution-Compaction

Features in the Khuff-C which indicate post-depositional solution-compaction are embayed grain margins and stylolites (Plate IV).

Burial Diagenesis

The effects of deep burial diagenesis have only been observed in one well, the most northwesterly, and include very coarse dolomite crystals, pyrite concentrations and barite cement (Plate IV).

Reservoir Facies

Porosity Types

Four major types of porosity occur in the Khuff-C sediments :

1. Interparticle.
2. Intraparticle.
3. Intercrystalline, and
4. Moldic Porosity (Plate V).

Rock Types

The Khuff-C sediments have been divided into four groups based on the effects of diagenesis (Fig. 7, Plates VI & VII).

Group I

Lime mudstone/grainstones with minor or no dolomitization; some dissolution and calcite cementation; some moldic porosity in grainstones; low porosity and permeability; poor reservoir facies.

Group II

Dolomitized lime mudstones/grainstones; calcite matrix in mudstones and calcite cement in grainstones; low-very low intercrystalline and/or interparticle porosity; fair reservoir facies.

Group III

Sucrosic dolomites and dolomitized grainstones; intercrystalline and interparticle pore types most common; high porosity and moderate permeability; good reservoir facies.

Group IV

Tight crystalline dolomite and anhydrite cemented dolomitized grainstone; a non-reservoir facies; lowest porosity and permeability.

Diagenetic Model

It is believed that some very low relief "topographic highs" were present from time to time and early diagenesis was caused by periodic exposure of these

		MUDSTONES	GRAINSTONES	OTHER DIAGENETIC PROCESSES	RESERVOIR QUALITY
INCREASING DOLOMITIZATION	GROUP I	LIME MUD-STONES WITH MINOR OR NO DOLOMITIZATION	CALCITE CEMENTED LIME GRAINSTONE	SOME DIS-SOLUTION AND CALCITE CEMENTATON	POOR
	GROUP II	DOLOMITIZED MUDSTONES WITH CALCITE MATRIX	DOLOMITIZED GRAINSTONES WITH CALCITE CEMENT	CALCITE CEMENTATION	FAIR
	GROUP III	SUROSIC DOLOMITES WITH GOOD INTER-CRYSTALLINE POROSITY	DOLOMITIZED GRAINSTONES WITH PRIMARY INTERPARTICLE POROSITY	DISSOLUTION OF EXCESS CaCo3	GOOD
	GROUP IV	TIGHT DOLOMITE	ANHYDRITE CEMENTED DOLOMITIZED GRAINSTONES	ANHYDRITE CEMENTATION	NONE

FIG. 7. The end products of diagenesis

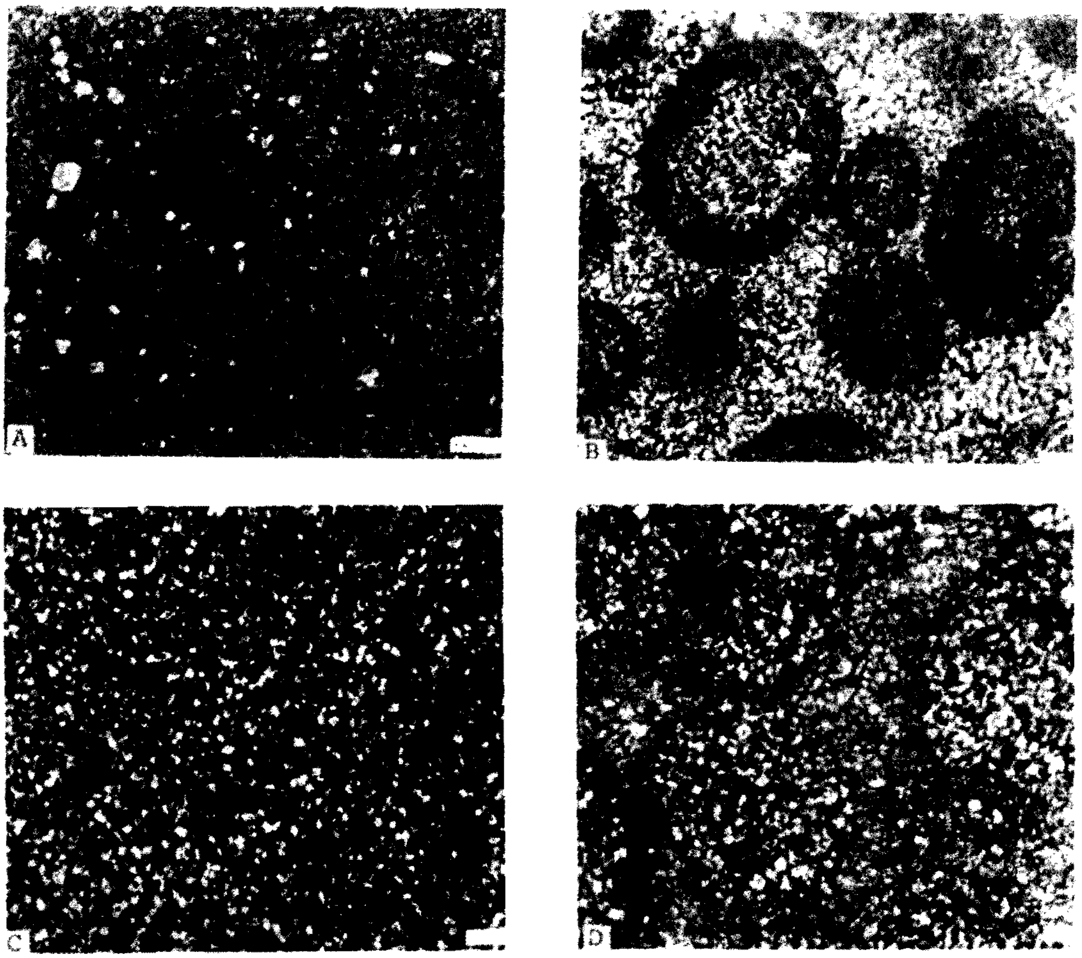

PLATE VI. Rock Groups (I).

(A) Rock Group IA: Slightly dolomitized lime mudstone.
(B) Rock Group IB: Lime grainstone. Oolitic grains and equant calcite cement.
(C) Rock Group IIA: Strongly dolomitized lime mudstone. Calcite matrix (red in photo) between crystals.
(D) Rock Group IIB: Dolomitized grainstone cemented by calcite cement.

Note: Scale bar is 100 microns on all photomicrographs.

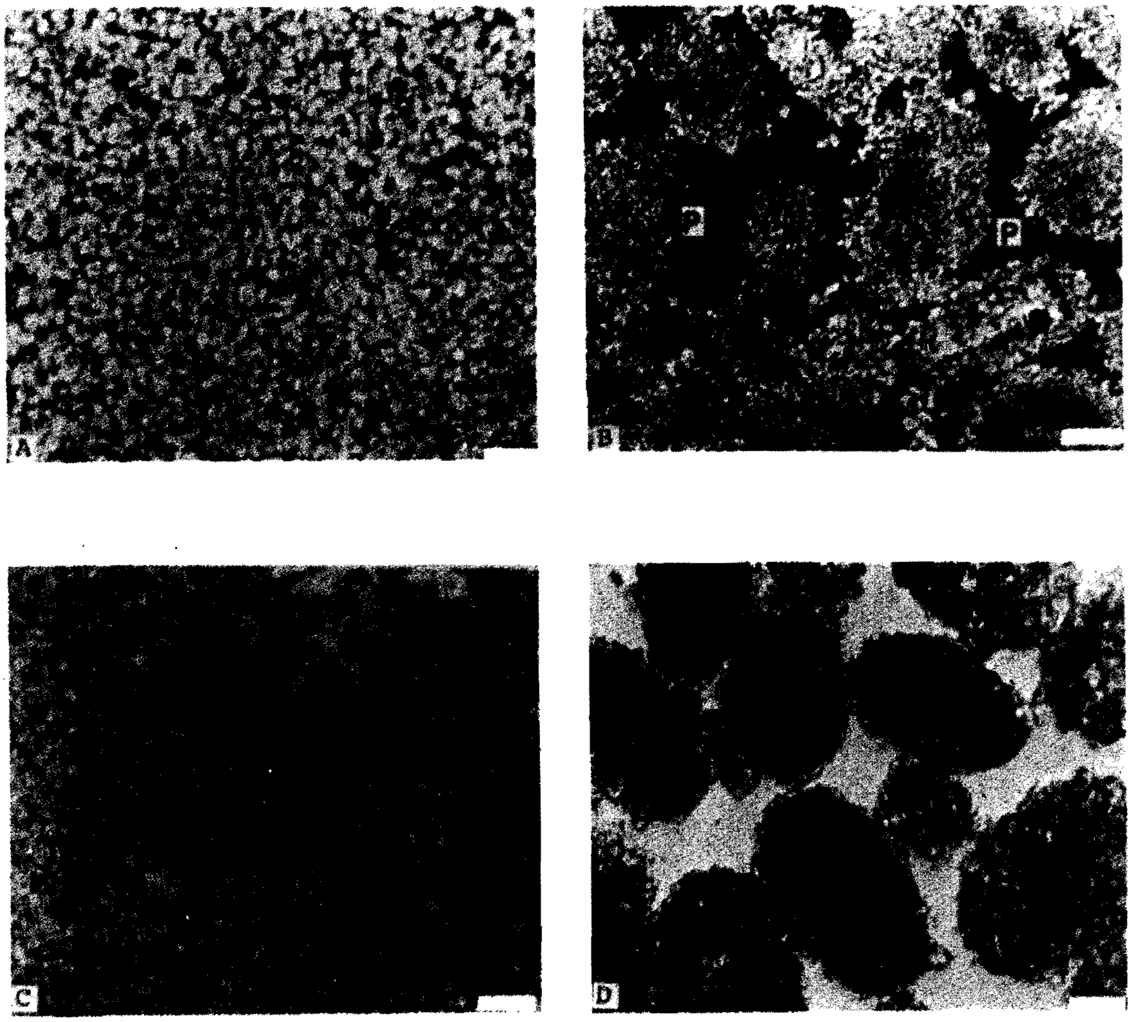

PLATE VII. Rock Groups (II).

(A) Rock Group IIIA: Sucrose dolomite. Removal of calcite matrix resulted in high intercrystalline porosity between dolomite rhombs.
(B) Rock Group IIIB: Dolo grainstone with primary interparticle porosity (P).
(C) Rock Group IVA: Tight crystalline dolo mudstone. Continuing dolomitization destroyed the porosity.
(D) Rock Group IVB: Anhydrite cemented dolo grainstone. Primary pore space between completely dolomitized grains filled by poikilotopic anhydrite cement. Note sharp-cornered blocky shapes of anhydrite cement.

Note: Scale bar is 100 microns on all photomicrographs.

highs. All the carbonate sediments in the Khuff-C were deposited in a very shallow environment. Thus, only small changes in the elevation of the sediment surface were probably required to expose these sediments subaerially. Sea-level fluctuations were probably the most important factor. The subaerial exposure must have taken place frequently since most of the Khuff-C sediments were affected by fresh water diagenesis.

A conceptual diagenesis model has been developed for the study area to account for the diagenetic processes on the basis of the observations of modern and ancient sediments (Fig. 8).

In this model, a freshwater lens forms on a low relief topographic high. Fresh water, in equilibrium with atmosphere CO_2, dissolves carbonates as it passes through the sediments in the vadose zone. As fresh water percolates further down to the fresh water phreatic zone, it reaches equilibrium with the aragonite of the oolites and/or lime mud. The $CaCO_3$ dissolved from the vadose zone is then precipitated as coarse equant calcite cement. Little or no dolomitization of

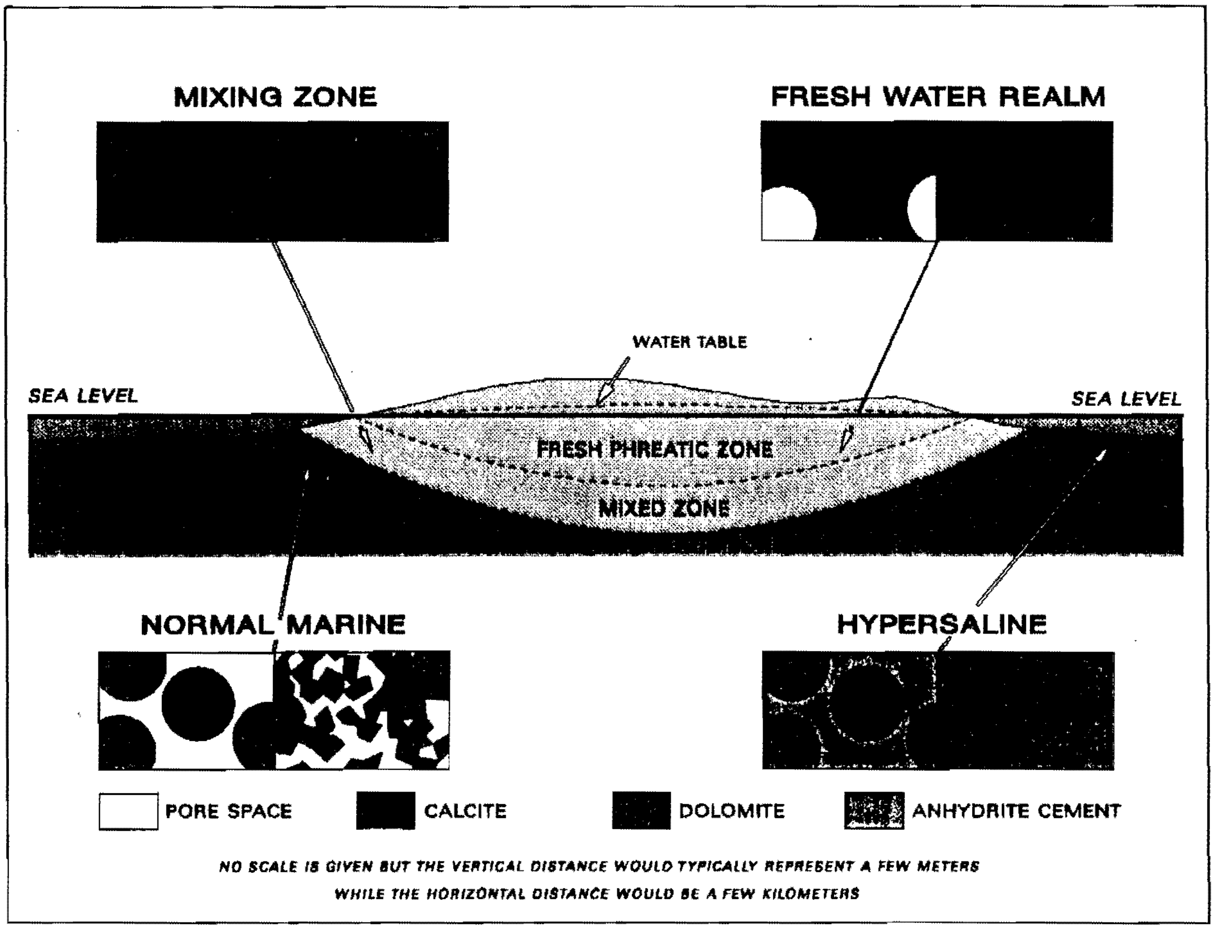

FIG. 8. Schematic cross section for proposed diagenetic model.

the sediments occurs in this zone due to lack of nucleation sites. Dolomite cement may precipitate at times, simultaneously with equant calcite cement where fresh and marine waters come into contact under favorable conditions. Dolomitization of the sediments is more widespread in the mixing zone because the circulation of marine waters is adequate to supply sufficient magnesium for the dolomitization. Some of the calcite is removed causing food intercrystalline porosity in the strongly dolomitized mudstones.

It should be noted that although mixing zone dolomitization is theoretically possible, no modern examples have been discovered in which the process is extensive. The influence of through-flowing sabkha-derived Mg/Ca ratios to cause dolomitization is possibly important as well.

In marine waters with normal salinities, cementation does not seem to be a major process. Primary interparticle and intercrystalline porosities are preserved. Outside the region of the fresh water influence, hypersaline conditions exist and anhydrite cementation occludes all the pore spaces. Mudstones are converted to tight interlocking crystals of dolomites, and all porosity can be completely destroyed, removing all reservoir potential.

Acknowledgement

Appreciation is given to the Saudi Arabian Ministry of Petroleum and Minerals Resources and to Saudi Aramco for permission to publish this paper.

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العلاقة بين السِّحنات الترسبية والتخلقية في الطبقة «ج» من مكمن خُفّ في المنطقة الشرقية من المملكة العربية السعودية

حسن تلو و فخري أبو غبن
إدارة الجيولوجيا ، أرامكو السعودية ، الظهران ، المملكة العربية السعودية

المستخلص . يمثل تكوين خُفّ أقدم سجلٍ رئيس لترسبات الكربونات الطبقية في المنطقة ، وقد بدأ يتكون في العصر البرمي المتأخر بفعل طغيان بحر التِّيثِس على مقدمة الأراضي العربية . والترسبات الطبقية المذكورة هي تبخرات كربونية متتالية جاءت في أربع دورات ترسبية رئيسة مرتبطة بالدورات البرمية العليا التي حصلت في العالم أجمع .

وتتحكم التغيرات الترسبية في توزيع المسامية . فالتغيرات التي أثرت على مسامية الطبقة «ج» من تكوين خُفّ حصلت في بداية العهد وشملت التحول الدولوميتي والغسل والذوبان والتّحجُّر . وكان التحول الدولوميتي وما تَأتّى عنه من حلول الصخور الدولوميتية محل الترسبات من العمليات الرئيسة التي ساهمت في تطور مسامية الطبقة «ج» من تكوين خُفّ . وقد ازدادت المسامية أيضًا بفعل ذوبان الكالسيت ، إلا أنها تأثرت بفعل الكالسيت البلوري والأنهيدريت المتحجرين .

وقد أعددنا نموذجًا حسب تصورنا للتغيرات الترسبية في المنطقة موضوع الدراسة . ويظهر من النموذج أنه تكونت مناطق منخفضة ثم انكشفت في بعض الأماكن فوق سطح الأرض مباشرة . وكان من فعل عدسات الماء العذب التي تكونت على هذه المعالم أنها تحكمت بالتغيرات الترسبية المذكورة .