Lithofacies and Diagenetic Study of the Uthmaniyah Arab-D Limestone Member (Ghawar Oil Field)

by

Waleed M. R. AbdulGhani

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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King Fahd University of Petroleum and Minerals (Saudi Arabia), 1992

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This thesis, written by Mr. Waleed M. R. Abdulghani under the direction of his Thesis Committee, and approved by all its members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences.

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كلية الدراسات العليا
COLLEGE OF GRADUATE STUDIES

بسم الله الرحمن الرحيم

وَقُل رَّبِّ زِدْنِي عِلْماً

(طه - ١١٤)

In the name of Allah, the Beneficient, the Merciful

"And say: My Lord! Increase me in Knowledge!"

(Taha - 114)

This thesis is dedicated to

my beloved parents, brothers, sisters, wife and children

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All praise be to the Almighty, ALLAH, with whose gracious help it was possible to accomplish this work.

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موجز الرسالة

الاســـــــــم : وليد محمد رشاد عبدالغني

عنوان الدراســـــة : دراسات صخرية لتتابع الوحدة الصخرية المعروفة باسم "العرب – د" في منطقة العثمانية (حقل الغوار)

التـــــخـــــصص : جيولوجيا

تاريخ منح الدرجـــة : مايو ١٩٩٢م

تمت دراسة ١٩٣ عينة لبية مستخرجة من تتابع صخور العصر الجوري المتأخر المتمثل بالعضو "عرب – د" المكون اساساً من الصخور الكربوناتية وذلك في البئرين رقمي ٥٨٧ و ٦٢٨ في منطقة العثمانية الواقعة بمنتصف حقل الغوار تقريباً . هذا وقد تمت دراسة لكل من السحنات الصخرية وبقايا الحياة في تلك الصخور إضافة الى دراسة التتابع الطبقي في تلك الوحدة الصخرية .

من حيث السحنات الصخرية فإن تلك الوحدة الصخرية تنقسم الى ستة نطق رئيسية جرت دراستها في البئرين باستخدام كل من وصف العينات الصخرية وانقطاعات الرقيقة وسجلات الآبار . وقد ساعد تحليل هذه القطاعات الرقيقة في التعرف على وجود سحنتين صخريتين محددتين يمكن الاستفادة بهما في إستنتاج كل من العمر وظروف البيئة القديمة التي تم تحتها ترسيب كل من هاتين السحنتين ، وفي ذلك أمكن التعرف على تجمع غني من الأحافير التي تنسب الى قبائل الاوليات والحزازيات والجوفمعويات بالإضافة الى بقايا كثيرة للطحالب ، ومن أهم بقايا الاوليات بقايا كائنات دقيقة تنسب الى رتبة المنخريات ومن أهمها :-

Kurnubia spp., Nautiloculina spp, Pfnderina spp,
Psudocyclammina spp, Bramkampella spp, Clypiena Jurassica

وتدل هذه الاحافير على إنتماء فرد "العرب – د" الى العصر الجوري المتأخر (الكمريدجي – التيثوني) . ويمثل التعاقب الصخري دورة من الصخور الجيرية الضحلة التي تزداد ضحالتها من أسفل القطاع الصخري الى اعلا مما يدل على انتقال ظروف ترسيبه من بحيرات شاطئية مفتوحة الى بحيرات شاطئية ضحلة شبه مغلقة في الخلجان خلف الحافة الخارجية للرصيف القاري (أي خلف الحدود الطبيعية للشواطىء البحرية) .

ومن حيث التغيرات التي طرأت على هذه الوحدة الصخرية بعد ترسيبها فتشمل عملية التحام الحبيبات الصخرية مع بعضها البعض بواسطة ترسيب كربونات الكالسيوم في المسافات البينية لتلك الحبيبات مما يقلل من مسامية ونفاذية تلك الصخور ، كذلك هناك عملية معاكسة تماماً وهي عملية اذابة اجزاء من هذا المتكون الكلسي بواسطة تحرك المياه تحت السطحية مما يساعد على زيادة كل من المسامية والنفاذية ، ومن ثم زيادة قدرة هذه الوحدة الصخرية على تخزين النفط . كذلك حدث تعرض هذه الحبيبات الصخرية للتآكل بفعل بعض الكائنات الحية القديمة مما أدى الى طمس معالم تلك الحبيبات (سواء كانت من بقايا الكائنات الحية أو من أصل غير عضوي تماماً) كما يؤدي ذلك الفتات الناتج الى تقليل كل من المسامية والنفاذية في تلك الصخور .

واخيراً حدثت عملية الدلمته (أي إحلال كربونات الكالسيوم بكربونات المغنيسيوم وإنتاج المعدن المعروف باسم الدولومايت) ، وإذا حدث ذلك في الصخور الدقيقة الحبيبات المكونة للجزء السفلي من هذا التتابع الصخري فإنه يؤدي الى زيادة كل من المسامية والنفاذية بشكل ملحوظ ، بينما ترسب بللورات الدولومايت في المسافات البينية للأجزاء العليا من التتابع (المكونة اساساً من الصخور الحبيبية الخشنة) فإن ذلك يؤدي الى نقص كل من المسامية والنفاذية العامة لهذا الجزء من التتابع وبالتالي الى نقص قدرته على تخزين كلاً من الماء والنفط والغـــــاز .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران – المملكة العربية السعودية
مايو ١٩٩٢م

THESIS ABSTRACT

Name: Waleed M. R. Abdulghani

Thesis Title: Lithofacies and Diagenetic Study of the Uthmaniyah Arab-D Limestone Member (Ghawar Oil Field)

Major Field: Geology

Date: May 1992

The cored, late Jurassic, Arab-D Limestone Member in the two Uthmaniyah wells 587 and 628 has been studied. A total of 193 thin sections were prepared and examined for both its litho-and biofacies analysis as well as for the diagenetic study of the succession.

Lithologically, the succession is divisible into six units that are worthy of sub-member rank. These correlated in the two wells using core descriptions, and well logs thin section analysis. Such analysis has also led to the recognition of two distictive microfacies that are used to interpret both the age and the paleoenvironmental conditions of deposition of the succession. A rich assemplage of fossils has been recorded including: Textulariid, Miliolid, and Rotaliid (Foraminifrida), as well as abundant bryozoan, algal and coralline remains. Worthy of mention among these are *Kurnubia spp, Nautiloculina spp., Pfendrina spp., and Psudocyclammina spp., Bramkampella spp., and Clypeina jurassica..* These fossils suggest a Kimmeridgian-Tithonian age. The succession represents a shallowing upward carbonate cylce moving from open lagoons (at the base) to a shallow shelf lagoon, located in straits and bays behind the outer platform edge (at the top).

The main diagenetic changes observed in the succession are limited to cementation, micritization, dolomitization and dissolution. Diagenetically the cementation and micritization are pore reducing, whereas dissolution and dolomitization are pore enalrging.

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May, 1992

CHAPTER 1

INTRODUCTION

The importance of the Saudi Jurassic oil cannot be overstated, being the largest hydrocarbon reservoir in the history of the oil industry. The world's total proved oil reserve is around a trillion (a thousand billion) barrels. Saudi Arabia has 26% of that reserve, being mainly in Paleozoic-Mesozoic sequences, particularly in the Jurassic - Cretaceous succession.

Approximately two-thirds of the Saudi Arabia's oil reserve is in Middle-Late Jurassic carbonate reservoirs. This is, to mean that 17% of the world's proven oil reserve is in the Saudi Jurassic succession. Virtually, every single formation in this succession is oil producing, from the Marrat Formation at the base, to the Hith Formation at the top. At least 15 economic reservoirs have been so far dicovered in the Arabian Jurassic succession and are currently oil-producing. These are known from the base upwards as the Marrat, Faridah, Sharar, Lower Fadhili, Upper Fadhili, Hadriya, Manifa, Juabila, Arab-D, C, B, and A, Rimthan, Hith Stringers and Manifa Reservoirs (Fig. 1). These reservoirs are recognized in numerous fields discovered in Eastern Saudi Arabia, particularly in the supergiant Ghawar Field wihch is the largest onshore oil field in the world. It is basically a north-northeast trending, north-plunging compound anticline which has been proved productive over a distance in excess of 140 miles. The main hydrocarbon reservoirs in the

AGE	FORMATION	THICKNESS (FEET)	DEPTH SUBSEA (FEET)	LITHOLOGY	DESCRIPTION
	MIOCENE PLIOCENE (UNDIFFERENTIATED)	402			SANDY LIMESTONE AND SANDY MARL LOCALLY WITH SANDSTONE AND CLAY
	RUS	188			MARL, LIMESTONE AND CLAY, LOCALLY INCLUDING ANHYDRITE AND GYPSUM
	UMMER RADHUMA	820	SEA LEVEL		LIMESTONE AND DOLOMITE
	ARUMA	650	1000		LIMESTONE , DOLOMITE AND SUBORDINATE SHALE
	WASIA	1339	2000		SHALE , LIMESTONE AND SANDSTONE WITH SUBORDINATE DOLOMITE AND DOLOMITE-SIDERITE ROCK
	SHU'AIBA	235			DOLOMITE
	BIYADH	835	3000		SANDSTONE AND SHALE , WITH SUBORDINATE LIMESTONE , DOLOMITE AND DOLOMITE-SIDERITE ROCK
	BUWAIB	90			LIMESTONE
	YAMAMA	424	4000		CALCARENITE & FINE-GRAINED LIMESTONE
	SULAIY	557			FINE-GRAINED LIMESTONE , USUALLY WITH A BASAL CALCARENITE UNIT
	HITH	467	5000		ANHYDRITE WITH SUBORDINATE FINE-GRAINED LIMESTONE , DOLOMITE AND CALCARENITE
	ARAB	777			A B C CALCARENITE, CALCARENITIC LIMESTONE FINE-GRAINED LIMESTONE AND DOLOMITE WITH THREE ANHYDRITE BANDS
	JUBAILA	92			D FINE GRAINED LIMESTONE

Figure 1. Stratigraphic succession in the Uthmaniyah Field.

Ghawar Oil Field consist of four shallow marine carbonate units, (Arab - A to - D), separated by thin, laterally persistent, anhydrite bands, mainly in the Late Jurassic Arab Formation, added to two thin carbonate units in the overlying latest Jurassic (Tithonian) Hith Anhydrite (Fig. 1). The Arab-D Limestone Member in the Uthmaniyah area of the Ghawar Oil Field is the most important reservoir in the Kingdom and is the focus of this study. It contains productive oil reserves in nine widely separated smaller fields. The Arab-D unit comprises two shoaling upward cycles deposited during a relatively high sea level stand. These cycles are in their turn composed of smaller, upward shoaling cycles and are generally represented by a variety of skeletal grainstones and packstones with ooids and peloids. The grainstones are particularly common in the uppermost part of the Arab-D Carbonate Member.

This study was designed to investigate both the litho-and biofacies characteristics as well as the diagenetic history of the Arab-D Carbonate Member in order to understand, the nature of the Uthmaniyah Arab-D Reservoir, which is the main producing interval in the whole Ghawar Field. The Reservoir occupies the basal part of the Arab Formation (the Arab-D Carbonate Member) as well as the uppermost part of the underlying Jubaila Formation. Core samples and open hole geophysical logs from two wells in the Uthmaniyah area of the Ghawar Oil Field (U. 587 and 628) are the main sources of data for this study. From these cores, 193 thin sections were prepared and well logs were digitized and pertinent well data were entered into a computer for processing. In the first stage, lithologic variations, bed boundaries, and markers were defined. Rock properties obtained from the geological description of the cores were compared with the well logs, and lithological correlation between the two-wells was carried out.

I.1 OBJECTIVES

The objective of this study is to carry out a stratigraphical and microfacies as well as a diagenetic analysis for the Late Jurrassic Arab-D Limestone Member in the Uthmaniyah area of the Ghawar Oil Field. The study is aimed to use both the litho-and biofacies characteristics of the succession in an attempt to interpret both its paleo-environmental conditions of deposition and age. Diagenetic changes can also be used for interpreting both the enhancement and the degeneration of porosity in the Arab-D Limestone Member, and hence its capacity to act as a hydrocarbon reservoir.

I.2 GENERAL GEOLOGIC SETTING

The Arabian Peninsula is separated from Africa by the Red Sea and from Iran by both the Arabian Gulf and the Gulf of Oman. It is bounded on the south by the Arabian Sea and the Gulf of Aden (Fig. 2), and is divisible into three distinctive tectonosedimentary provinces as follows (cf. Henson, 1951 and Powers and others, 1966):

A) The Arabian Shield: Composed of at least seven geologically distinct microplates separated by six ophiolite-bearing suture zones (Stoeser, 1985). Five of these microplates are of island-arc type while the other two are of continental origin. The shield is mainly composed of metavolcanics and metasediments which are intensively intruded by gabbro, tonalite,

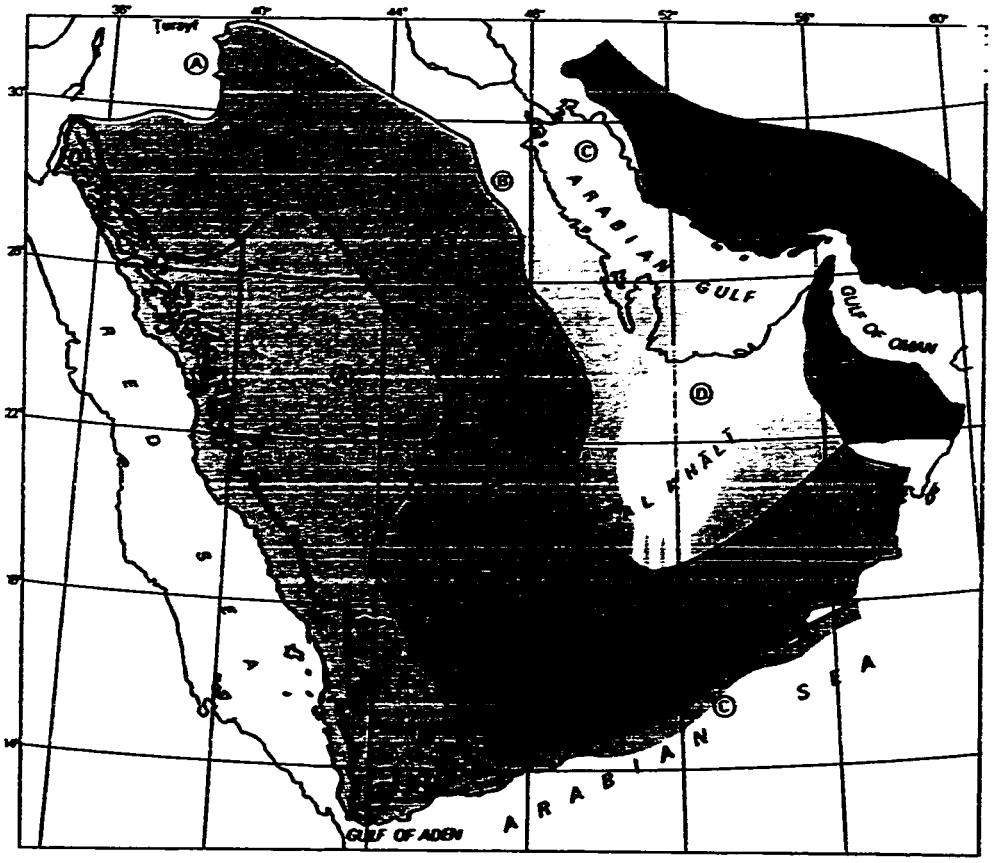


Figure 2. Map showing major tectono-sedimentational units in the Arabian Peninsula. After Schlumberger (1975).

STABLE REGION

ARABIAN SHIELD

A. Western Arabian Shield
B. Yemen-Aden Plateau
C. Southern Arabian Shield

ARABIAN SHELF

Interior Homocline

A. Tabuk Segment
B. Hail Arch
C. Northern Tuwayq Segment
D. Widyan Basin Margin
E. Central Arabian Arch
F. Southern Tuwayq Segment
G. Hadramawt Segment
H. Hadramawt Plateau

Interior Platform

Basins

A. Sirhan - Turayf basin
B. Dibdibba Basin
C. Northern Arabian Gulf Basin
D. Rub'al Khali Basin

MOBILE BELT

Mountains

A. Zagros Mountains
B. Oman Mountains

Foreheads

A. Zagros Mountains Forehead
B. Oman Mountains Forehead

Hajf-Haushi Swell

granodiorite and granite plutons. It is considered to be a vast complex area of mainly Pre-Cambrian rocks occupying about one-third of the total surface area of the Peninsula.

B) The Arabian Shelf: Located north, east and northeast of the shield, being mainly composed of sedimentary rocks deposited during the Cambrian to Holocene time, in epicontinental transgressions that moved back and forth across the lower part of the Arabian Shield. It gradually covers the shield by a thick, sequence of strata that are nearly horizontal to gently dipping. These were later on slightly deformed to produce an easterly to north easterly dipping sedimentary succession, with relatively undisturbed beds that represent the geologic Arabian shelf. The sediments are characteristically of both shallow-water marine and continental origin. This shelf is, in turn, divided into three distinctive sub-units: the interior homocline, the interior platform and several intrashelf basins. So far, most of the known hydrocarbon reservoirs of eastern Arabia are entraped in rocks of the Arabian Shelf.

However, it has to be understood that the limit between the Arabian Shield and the Arabian Shelf (the interior homocline) is in its entirety an erosional (post-Miocene) bounary, and is mostly related to the Red Sea movement. Again, the so-called intrashelf basins had a much varied history, and might have had much greater extensions than their present-day boundaries.

C) The Mobile Belt: Located to the north and east of the Arabian Shelf, being mainly composed of both the Zagros and the Oman Mountains, which can be considered as small links in the much greater Alpine-Himalayan orogenic system. It also includes narrow foreland areas that contain the major oil fields of southwestern Iran and of parts of Oman.

I.3 LOCATION AND GEOLOGY OF THE STUDIED SECTION

The Jurassic Tethyan transgression over Arabia began in the Late Liassic epoch (Toarcian), spread widely during the Middle Jurassic (Bajocian and Bathonian) time and continued without any (or only minor) apparent interruption into the Late Jurassic.

The outcropping Liassic Marrat Formation is mainly composed of a soft red shale unit, bracketed by resistant limestones. Such red-bed sedimentation is found only on the southwestern shore of the basin; it does not persist laterally as far as the Traissic red beds do. Contact with the underlying Minjur Sandstone is disconformable and with the overlying Middle Jurassic Dhruma beds is conformable. Here again the Dhruma Formation breaks naturally into three-distinctive lithologies, in this case a limestone bracketed by shales. The bulk of Early and Middle Jurassic rocks are shallow-water limestones, often pelletoid, with the percentage of carbonate increasing eastward. In Qatar, additional lithologic changes force recognition of three equivalent formations: Hamlah, Izhara and Araej, in ascending order.

The transition from Middle to Late Jurassic, long considered unconformable, is now known to take place without interruption or, at most, involves only slight disconformity. Middle Jurassic rocks pinch out to the south by progressive onlap with the loss of successively older beds at the base; however, latest Middle Jurassic rocks are laterally persistent and without evidence of truncation. The fact that Late Jurassic rocks do indeed rest with definite discordance on older units around the southern margin of the basin was initially misleading.

Late Jurassic rocks in eastern Arabia reflect a progressive change in sedimentation from nearly pure limestone (Tuwaiq Mountain Limestone, Hanifa, and Jubaila Formations) through limestone and anhydrite (Arab Formation) to predominantly evaporitic deposits (Hith Anhydrite). The evaporitic environment began in central Iraq during the late Jurassic (Callovian) time with a massive accumulation of both anhydrite and rock salt. These soon spread over much of the basin, and as progress continued southward, succeedingly younger rocks became involved. In the subsurface of Kuwait, the first traces of anhydrite appear in the latest Callovian time, although the bulk of evaporite (actually halite interbedded with subordinate amounts of anhydrite), does not appear until much later as the Gotnia Salt. In Saudi Arabia, evaporite deposition (mainly anhydrite) did not start until near the end of the early Kimmeridgian time.

The Ghawar Oil Field is located in the Eastern Province of the Kingdom of Saudi Arabia, as an elongate north-northeast to south-southwest trending, north plunging, complex anticline. The Uthmaniyah area is reflected at the surface of the central Ghawar structure by a dissected plateau capped as a resistant limestone layer. The plateau surface

extends for a considerable distance over the western flank of the Ghawar structure. The preservation of this plateau seems to be the result of a greater resistance of its outcropping rocks to erosion, despite its slow destruction by carbonate dissolution.

In southern Ghawar a generally high, shallowly dissected area covers the structure. Here the resistant capping layer is not developed to the extent of that farther north and only patches of it remain. The rest of the Ghawar structure differs somewhat in its northern and southern parts. In the Uthmaniyah area there is a crestal depression with closures along each rim. Uthmaniyah shows a low anticline having about 450 feet of relief along the eastern edge and a very low swell of less than 50 feet of relief along the western edge. Production comes mainly from the Arab Formation, which consists of four widespread carbonate/evaporite members (D, C, B, and A, from oldest to youngest). The Arab-D Limestone Member is the main reservoir and the focus of this study.

Deposition of the Arab Formation was initiated in the shallow Tethys Sea, on a broad, tectonically stable shelf or platform. The Ghawar structure rises in the Arabian Gulf coastal plain, being limited on the east by the Qatar-Surmeh High and on the west by the Central Arabian Arch which is concentric on the Arabian Shield (Wilson, 1975). The Basrah Basin lies to the north of Ghawar and the Rub' al-Khali Basin lies to the south of it (Fig. 3). Regional studies (Powers, 1962; Leeder and Zeidan, 1977; and Wilson, 1975) indicate that the Arab anhydrite intervals get thinner from west to east and from south to north. The paleoclimate was hot and arid, probably much like today's climate in the Arabian Gulf area.

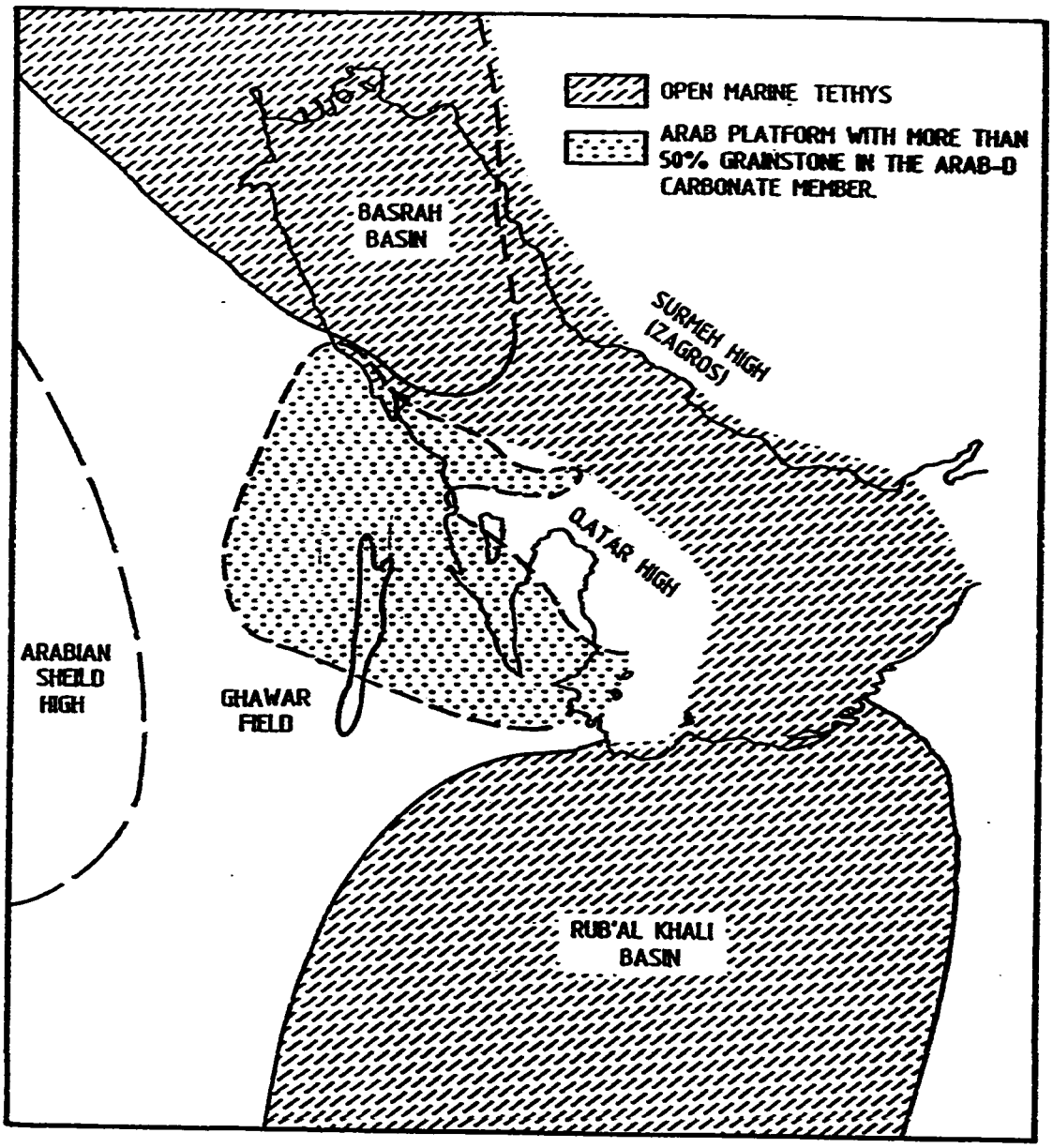


Figure 3. Location map, Ghawar Field and the Late Jurassic paleogeography, eastern Saudi Arabia. After Mitchell and others (1988).

Sediments comprising the Hanifa, Jubaila, and Arab Formations were deposited as an upward-shoaling package of sediments during the Oxfordian, Kimmeridgian and Tithonian times. This package is subdivided into six major upward shoaling cycles. The Hanifa cycle was initiated in the deepest waters and shoaled to near sea level. The cycle comprising the Jubaila Formation through the lower part of the Arab-D Limestone Member was initiated in deep subtidal water that also shoaled to sea level. The cycles constituting the upper part of the Arab-D Carbonate Member and the three overlying Arab Members were subsequently deposited as upward shoaling carbonates that dried up into evaporites.

In these cycles, carbonate deposition closed earlier in the west where precipitation of anhydrite first began. Saline conditions then moved progressively towards the east and eventually terminated the carbonate sedimentation over most of the Arabian Gulf area. These particular limestones (Fig. 4), especially the Arab-D Calcarenite, are of paramount importance for they contain the largest reserves of petroleum in the world. Further eastward in Qatar, the Tuwaiq Mountain Limestone changes into the Upper Araej Formation, the Hanifa-Jubaila, into the Diyab-Darb Formations, and the Arab D Limestone Member into the Fahahil Formation, with the remainder of the succession represented locally by the Qatar Formation, followed by the Hith Anhydrite. Elsewhere, formational nomenclature varies and, hence, only current usage is recorded on the accompanying cross sections. With the influx of normal marine condition and the end of the evaporite phase near the beginning of the Cretaceous time, shallow-water clastic-textured limestones were once again deposited. Excepting the basin margin, sedimentation was generally continuous across the Jurassic-Cretaceous boundary. Each of the successive sea level rises under which the

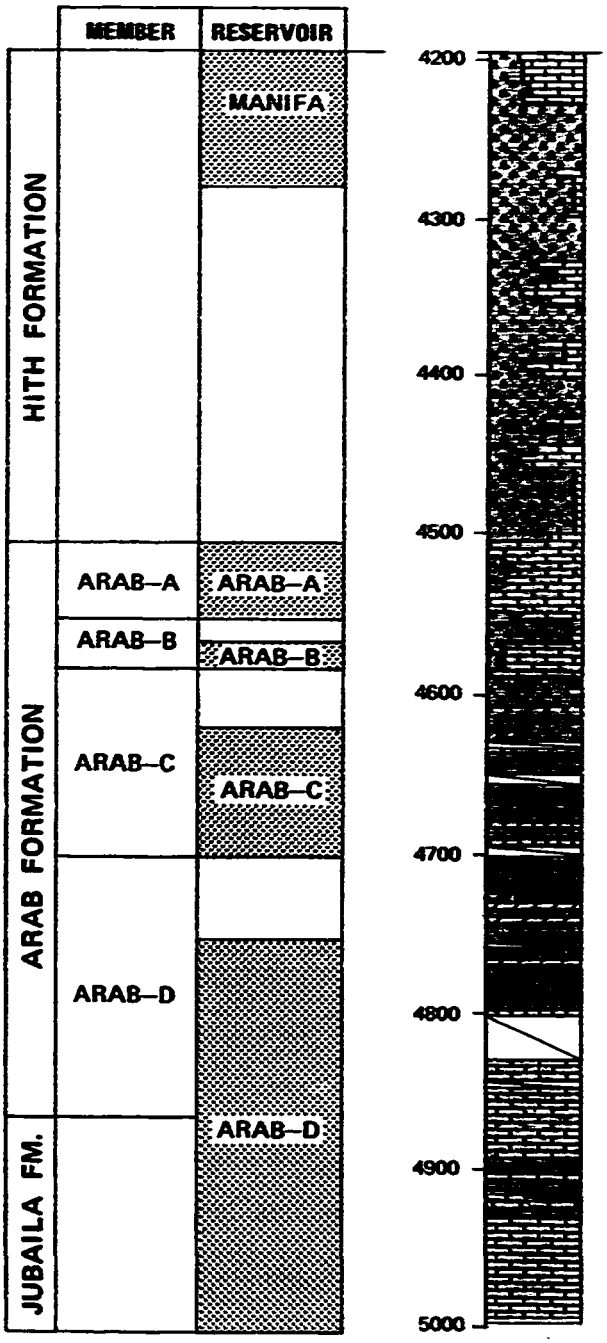
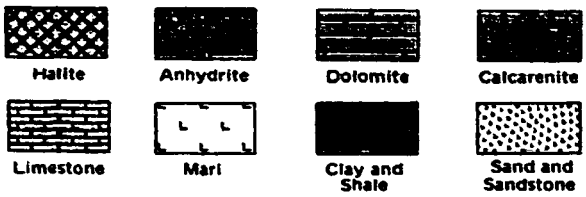


Figure 4. Arab-Hitb terminology. After Schlumberger (1975



various segments of the Jurassic succession were deposited, was of lesser magnitude than the preceding rise. Although small-scale lateral and vertical variations occur both from well to well and vertically within single wells, the overall patterns of sedimentation that resulted in areally extensive correlatable carbonate and evaporite units probably reflect eustatic sea level controls on this shelf carbonate complex.

The Arab-D Limestone Member comprises two major shoaling upward cycles that are composed of many smaller scale also upward shoaling cycles. These upward shoaling cycles are comprised of a variety of packstones and skeletal grainstones with ooid grainstones locally common in the uppermost part of the Arab-D Carbonate Member. In the Ghawar field, the Arab-D Member carbonates are further subdivided into reservoir zones and subzones that are based largely on porosity log pattern correlation and detailed lithofacies studies.

The top of the Arab-D Carbonate Member is characterized by this subtidal to intertidal/supratidal carbonates with sabkha evaporites. The upper part of the Arab-D Limestone Member comprises Sabkha evaporite with thin, carbonate interbeds that can be traced for hundreds of kilometers. Both palmate and bedded fabrics are preserved in these evaporite deposits. The top of the Arab-D Limestone Member is marked by a sharp flooding surface.

I.4 PREVIOUS WORK:

Although geologic investigations in Saudi Arabia started early in the 1930s by the geologists of SOCAL Company in their efforts to locate economic oil accumulations, publications about the geology of this country came out much later. In a meeting held at New York in 1955 Bramkamp and Sander read a paper entitled "Stratigraphic Relations of Arabian Jurrassic Oil" which included definitions of different sedimentary rock units in Saudi Arabia including the Arab Formation in the Eastern Province. The first formal definition of the main sedimentary rock units currently used in Saudi Arabia were published by Steineke, BramKamp and Sander (1958). In discussing the sedimentary geology of the Arab-D Limestone Member in the late Jurassic, Steineke and others (1952) described the Arab Formation of the Eastern Province of Saudi Arabia to represent four main cycles of deposition, each starting with more or less normal marine carbonate rocks, and closing with anhydrite. The Hith anhydrite over much of the drilled area is regarded as the closing evaporite unit of the fourth and last cycle, although possibly in areas to the east of the present drilling area other similar cycles may be present in beds equivalent to the Hith, in which the carbonate rock members were less extensive that they failed to reach the drilled area.

The four Arab cycles have been denominated informally as "A," "B," "C," and "D members," in order from top to bottom. Lateral changes in the various members are roughly the same in character, but the geographic locations at which such changes took

place differ from one member to another. Over fifty suites of diamond cores of the "Arab-D Carbonate Member" were studied by Steineke and others (1952, Fig. 5).

Lateral changes shown by the "Arab-D Limestone Member" are roughly as follows.

1. The anhydrite between both the "C" and the "D Members" progressively increases in thickness at the expense of the carbonate, from northeast to southwest through the Abqaiq-Ghawar area; nevertheless the overall thickness of the "D Member" includingits anhydrite cap (the anhydrite between "C" and "D Members") is nearly constant over the same area.

2. The "Arab-D Limestone Member" of the Abqaiq-Ghawar area is primarily calcarenite. Pellets (Illing, 1954) make up a high proportion of the sand-sized sedimentary particles. True oolites are nearly absent in central and southern Ghawar, but gradually increase to become well developed, although not to dominate, in northeastern Ghawar and Abqaiq. In obvious contrast to this, the "Arab-D Limestone Member" of the Dammam, Qatif, Bahrain, and Qatar structures shows extensive replacement of these calcarenites by fine-grained limestones, and hence cleanly washed calcarenites are not common in these fields. This trend is most apparent in the Qatif Field where the "Arab-D Limestone Member" contains much lithographic limestone originally deposited as lime mud including calcarenite particles, in places sufficient to make it muddy calcarenite. Much of these rocks have sufficient remaining original porosity to be moderately productive.

Figure 5. Lithologic sequence of the Arab-D Limestone Member, Uthmaniyah area, Ghawar field, Saudi Arabia. After Steineke and Others (1958).

3. Both Field and subsurface evidences suggest that the minimum thickness of the "Arab-D Limestone Member" and the maximum replacement of its upper part by anhydrite, are reached just west of the Ghawar field and that this situation persists from there westward to the outcrop section. This facies seems to have been lagoonal passing upwardly into evaporites (Fig. 6).

Both the lithology and distribution of the "Arab-D Limestone Member" suggest that the area of thick development of clean, current-washed calcarenite was a bar or the margin of a shelf. To the west these Calcarenites pass into rocks of lagoonal facies and to the east they pass into deeper water facies, composed mainly of lime-muds (calcilutites). It is tempting to assume that the change from the dominantly sand-sized particles of the calcarenite-rich area to the mainly mud sized particles of the dominantly calcilutite area toward the east represented the mud line of the shallow sea of that time.

Both cutting samples and diamond cores from the Arab-D Limestone Member were studied by Illing (1954) who described them as fine-grained limestone, partially dolomitized (dolomite rhombs in a fine-grained $CaCo_3$ matrix), with interbedded calcarenite (mainly fine grained) generally with an original fine-grained, matrix and, subordinate dolomite. The base is at the contact of the basal calcarenitic rocks of the Arab Formation with the underlying dense limestone of the upper Jubaila. Correlation by sequence matching, mainly from well to well, has been used to carry the correlation of the top of the Jubaila from its type area in the outcrop belt of Central Arabia eastward to the Dammam No. 7 well in the Eastern Region.

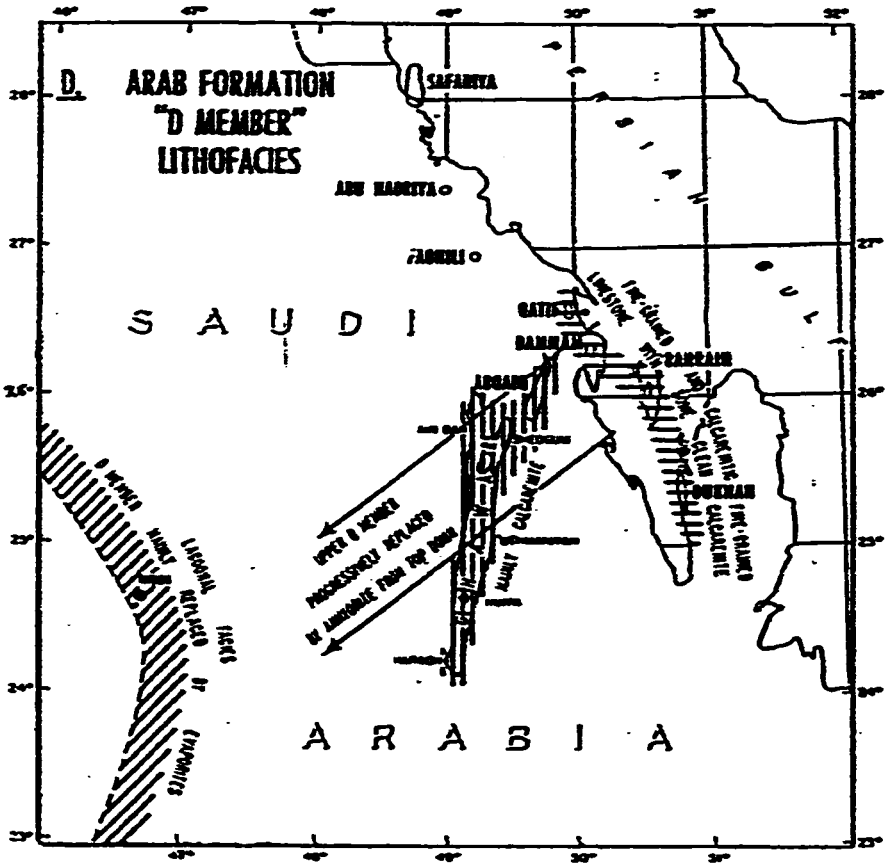


Figure 6. Distribution of the lithofacies of the Arab-D Limestone Member. Modified from Steineke and Others (1958).

The top is at the contact of essentially continuous anhydrite above with the underlying mainly limestone unit of the Arab-C Carbonate Member. The thin transitional zone from limestone to anhydrite has been included in the Arab-D Limestone Member. The fauna found so far in the Arab Formation has not proved to be diagnostic. Except for *Diceras*, identifiable forms range down into the Jubaila below. On continuity of sedimentation and fauna, the Arab Formation is safely placed in the late Jurassic (Kimmeridgian). The highest occurrence of *"Valvulina" jurassica* Henson so far detected in Saudi Arabia is in the "D Member" of the Arab Formation.

Kurnubia spp., Nautiloculina spp., Clypeina jurassica Farre, *C.* cf. *hanabatensis* Yabe and Toyama, *Cylindroporella arabica* Elliott, *Polygonella incrustata* Elliott and *Salpingoporella sp.* range throughout the Arab-D Limestone Member (Powers, 1962). Although some elements of this assemblage extend upward into the Arab-A Member, it is only the beds of the D Member that have been reliably dated.

Hudson and Chatton (1959) listed both *Calpionella alpina* Renz and *Pseudocyclammina sp.* in the Arab-D Limestone Member of the Musandam Peninsula. By comparison with the Alm Abyadh Limestones of southwestern Arabia, *Cidaris glandarius* beds of the Lebanon, the Kurnub Formation of Palestine, and with other formations, they concluded that the fauna is Sequanian (early Kimmeridgian) in age, a dating compatible with other lines of evidence.

In describing the Arab-D Limestone Member in the Ghawar Oil Field, Thralls (1955) mentioned that the "Arab zone itself is composed of rocks laid down between four

main cycles of desiccation, each of which starts at the base with apparently normal marine limestone deposition, and then changes, after a limited transition zone, to essentially pure anhydrite deposition. The productive "D" member is, for the most part, a detrital and oolitic limestone with some dolomite and, locally, a little coquina. In the southern part of the field, it is partly dolomitized limestone with some thin beds of oolite and detrital limestone. There is a reduction in amount of the clastic limestone textures and a change in thickness of the members of the Arab zone within the area iteself. Salt beds in the anhydrite immediately above the "D" member suggest slightly different environmental conditions from those found in the north. Effective thicknesses of the zone being produced at Ain Dar, Shedgum and Uthmaniyah are quite constant at about 142 ft. Weighted average porosity of this effective zone is something more than 22%. Both these figures are considerably greater than corresponding ones in Haradh's producible zone."

The late Jurassic Arab-D Limestone Member of the Ghawar oil field was also described in an unpublished report by the Arabian American Oil Company staff (ARAMCO, now Saudi ARAMCO) in 1959 as follows: "The productive beds lie in the first 220-240 feet of the upper Jubaila/Arab-D below the C-D anhydrite. This has been partly or completely diamond-cored in 60 wells. The Arab-D Member, decreases in thickness from northeast to southwest by gradual facies change from carbonate to anhydrite in its upper part (Fig.7). In the same general direction there is a gradual change from predominantly calcarenite in the northeast to mixed calcarenite and fine-grained limestone in the southwest. The interval from the base of the Arab-C Member to the top of the Jubaila Formation is surprisingly constant throughout the Ghawar field; the wedging-down of the Arab-D

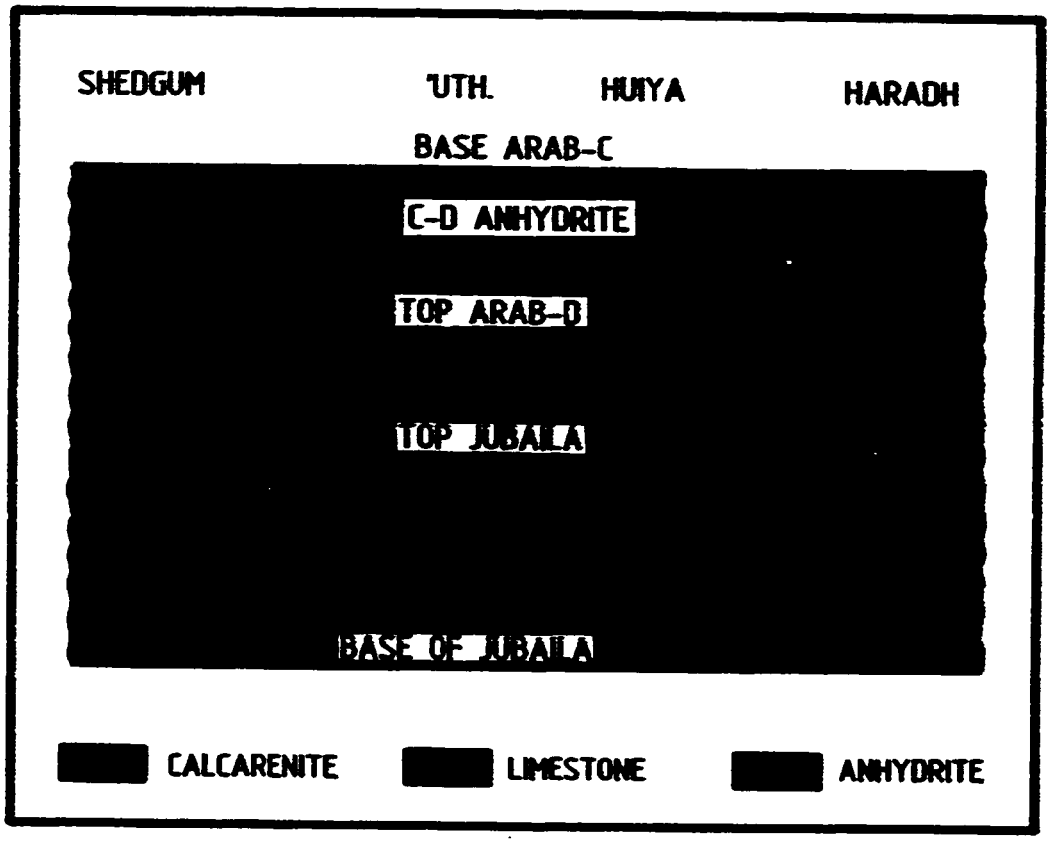


Figure 7. Diagrammatic section showing major variations in upper Jubaila and Arab-D producing zones of the Ghawar Field; from Shedgum (in the north) to Haradh (in the south). After ARAMCO staff (1959).

Member toward the southwest is compensated by increase in thickness of the C-D anhydrite."

The upper part of the Jubaila Formation is usually represented by interbedded permeable and impermeable rocks, and has much less vertical continuity of reservoir characteristics than the Arab-D Limestone Member. The permeable layers are calcarnite, calcarenitic limestone, and dolomite; the tighter rocks are fine-grained limestone and dense dolomite. The carbonate rocks which, make up both the Upper Jubaila and the Arab Formation are all of the shallow-water type, including sediments whose original grain size ranged from silt, and possibly even finer particles, through sand to conglomerates.

Figure 8 shows a typical, somewhat generalized sample of the carbonate sedimentary pattern of the Upper Jubaila/Arab-D Limestone Member of the Ghawar oil field. High oil productivity goes in general with the calcarenites. Dolomite locally shows high permeability, but much of it is tight. Calcarenitic limestone (the flow properties of which are determined by the matrix) and fine-grained limestone range from low to high porosities, but their average permeabilities are low. Fine grained sediments have been placed in the Arab Formation in two main categories: those with, and those without included sand-sized carbonate particles. These fine-grained limestones were deposited as calcium carbonate silts and muds in a relatively quite environment, either below wave base or where the bottom configuration afforded protection from currents and wave agitation. Part of the included sand-sized and coarser carbonate particles may have been washed in from nearby current-dominated areas, but a certain portion must have developed in place by organic and

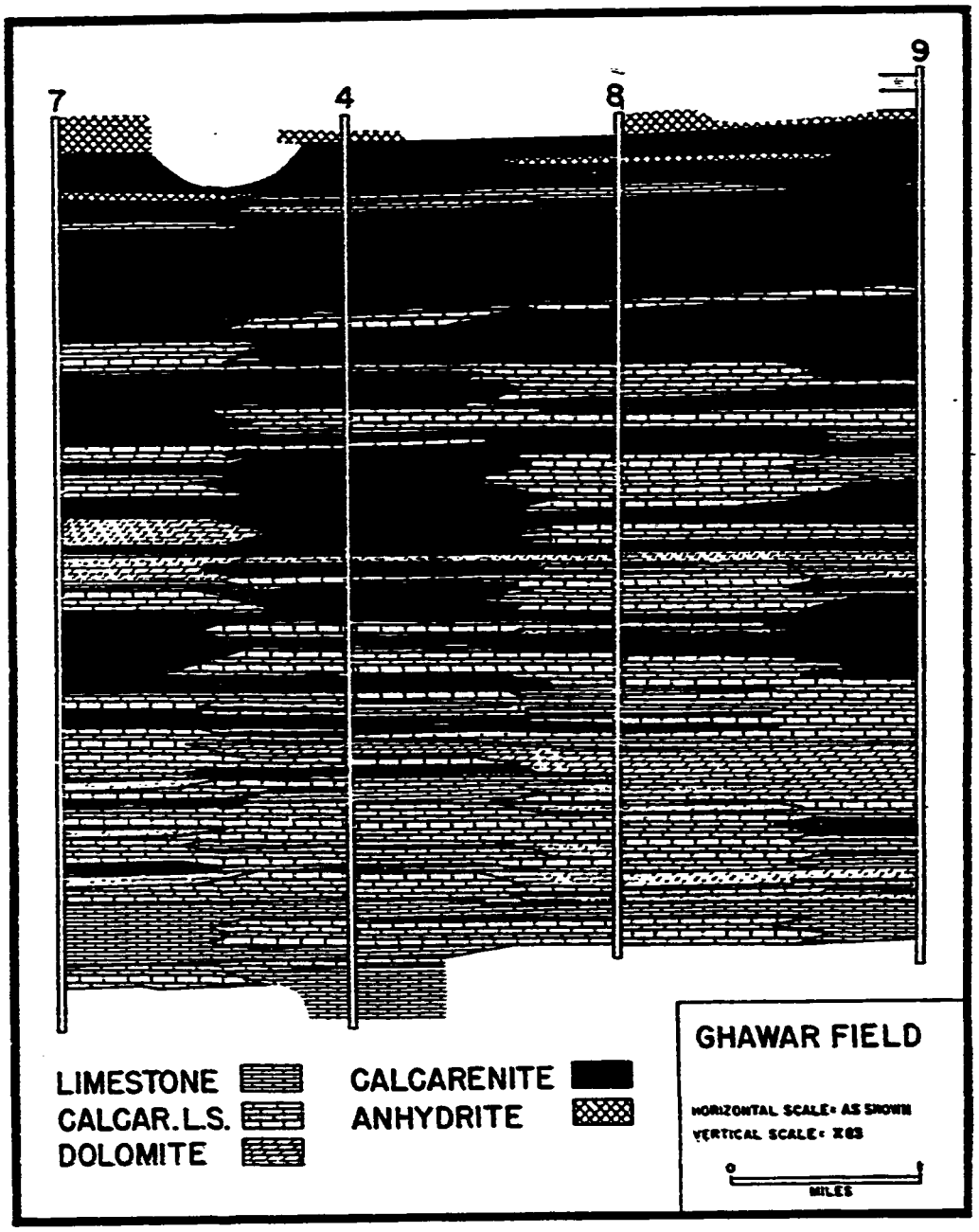


Figure 8. Schematic stratigraphic reconstruction of upper Jubaila and Arab-D producing zones in profile across northern part of Shedgum area. Upper heavy black line is top of Jubaila Formation. After ARAMCO staff (1958).

inorganic processes. Sand-sized carbonate sediments, the calcarenites, are important constituents of both the upper Jubaila Limestone and the Arab-D Limestone Member. These are commonly found to be made up of pellets.

Figure 9 (Bramkamp and Powers, 1958) shows the carbonate rock classification used for the study of the Arab-D Limestone Member. Its purpose is to bring out information needed for both gelogical and reservoir studies. Powers (1961) described the Arab-D Limestone Member in cores, the equivalent rocks in the outcrop section and the modern calcareous Arabian Gulf sediments. He (*op.cit*) showed that these carbonates can best be divided according to their particle size and texture into five groups - (1) aphanitic (micritic) or fine-grained limestone, (2) calcarenitic limestone, (3) calcarenite, (4) coarse carbonate clastic, and (5) dolomite. The classification of the Arab-D rocks according to this scheme has permitted (a) the recognition of distinctive stratigraphic units for correlation and reservoir zonation, (b) the delineation of original environment-sedimentation patterns, and (c) the relation of reservoir properties to original textures and secondary changes.

The Arab-D Limestone Member represents the transition from continuous carbonate deposition to the precipitation of nearly pure anhydrite through alternating carbonates and evaporites. The lower part of the Member consists of mixed lime-mud and nonskeletal sand. Near the middle, a thin persistent unit of micritic limestone records an episode of muddy deposiion over a wide area. Widespread shallow-water conditions during the time of deposition of the upper Arab-D Member are suggested by a pronounced increase in

ARABIAN CARBONATE RESERVOIR ROCK CLASSIFICATION

	ORIG. TEXTURE NOT VISIBLY ALTERED (except by cementation)	ORIGINAL TEXTURE ALTERED					ORIGINAL TEXTURE OBLITERATED
		MODERATELY		STRONGLY			
	LESS THAN 10% DOLOMITE	LESS THAN 10% DOLOMITE	MORE THAN 10% PORPHYROBLASTIC DOLOMITE	LESS THAN 10% DOLOMITE	**10-75% DOLOMITE	MORE THAN 75% DOLOMITE WITH RELIC TEXTURE	MORE THAN 75% DOLOMITE
GROUP 1 *FINE-GRAINED LIMESTONE* Fine-grained limestone with less than 10% sand size or coarser than sand size clastic carbonate fragments*	1A, 1B, 1C FINE-GRAINED LIMESTONE	11AR, 11BR, 11CR PARTIALLY RECRYSTALLIZED, FINE-GRAINED LIMESTONE	11AD, 11BD, 11CD PARTIALLY DOLOMITIZED, FINE-GRAINED LIMESTONE	12AR, 12BR, 12CR CRYSTALLINE LIMESTONE	12AD, 12BD, 12CD DOLOMITIC LIMESTONE	13A, 13B, 13C CALCITIC DOLOMITE	
GROUP 2 *CALCARENITIC LIMESTONE* More than 10% sand size or coarser than sand size clastic carbonate fragments* in more than 10% original fine-grained matrix	2A, 2B, 2C CALCARENITIC LIMESTONE	21AR, 21BR, 21CR PARTIALLY RECRYSTALLIZED, CALCARENITIC LIMESTONE	21AD, 21BD, 21CD PARTIALLY DOLOMITIZED, CALCARENITIC LIMESTONE	22AR, 22BR, 22CR CRYSTALLINE, CALCARENITIC LIMESTONE	22AD, 22BD, 22CD DOLOMITIC, CALCARENITIC LIMESTONE	23A, 23B, 23C CALCARENITIC DOLOMITE	GROUP 4 4A, 4B, 4C CRYSTALLINE DOLOMITE
GROUP 3 *CALCARENITE* Sand size clastic carbonate fragments* in less than 10% original fine-grained matrix	3A, 3B, 3C CALCARENITE	31AR, 31BR, 31CR PARTIALLY RECRYSTALLIZED CALCARENITE	31AD, 31BD, 31CD PARTIALLY DOLOMITIZED CALCARENITE	32AR, 32BR, 32CR STRONGLY RECRYSTALLIZED CALCARENITE	32AD, 32BD, 32CD DOLOMITIC CALCARENITE	33A, 33B, 33C CALCARENITE DOLOMITE	
GROUP 5 *COARSE CLASTIC CARBONATE* Coarser than sand size clastic carbonate fragments* in less than 10% original fine-grained matrix	5A, 5B, 5C COARSE CLASTIC CARBONATE	51AR, 51BR, 51CR PARTIALLY RECRYSTALLIZED, COARSE CLASTIC CARBONATE	51AD, 51BD, 51CD PARTIALLY DOLOMITIZED, COARSE CLASTIC CARBONATE	52AR, 52BR, 52CR STRONGLY RECRYSTALLIZED, COARSE CLASTIC CARBONATE	52AD, 52BD, 52CD DOLOMITIC, COARSE CLASTIC CARBONATE	53A, 53B, 53C COARSE CLASTIC CARBONATE DOLOMITE	

* Clastic carbonate fragments include sand size and coarser than sand size grains irrespective of origin, for example, particles of older carbonate rock, oolithe, pellets and biogenic trash.

** Dolomitic and calcitic portions of rock so intimately intergrown as to be generally visually indistinguishable.

KEY TO RESERVOIR ROCK CLASSIFICATION SYMBOLS

1st Numeral - Designates rock groups. Groups 1,2,3, & 5 distinguished on basis of original textural differences; Group 4 on complete alteration of any of these to crystalline dolomite.

2nd Numeral - Indicates degree of alteration in original texture, excluding compaction and cementation. 1 = Moderately altered original texture. 2 = Strongly altered original texture. 3 = Relic original texture.

1st Letter... Shows amount of visual porosity. A = Porous and/or poorly cemented. B = Compact and/or moderately cemented. C = Dense and/or strongly cemented.

2nd Letter... Type of alteration. R = Recrystallization involving rearrangement of materials already present. D = Recrystallization brought about by introduction of dolomite.

Figure 9. Carbonate rock classification used in geological studies. Key symbols facilitate machine data processing. Modified from Bramkamp and Powers (1958).

clean-washed calcarenite with abundant skeletal grains derived in large part from algal Foraminiferid, brozoan and stromatoporoidal remains. Many persistent features on outcrop have proved equally continuous in the subsurface, indicating that changes which affected sedimentation must have operated on a large scale.

Regionally, reservoir units show a gradual lateral change, suggesting a broad shelf with finer lagoonal sediments in the west, with dominantly calcareous sand in the form of offshore bars accumulating near the present coast, and presumably deeper water lime-mud with lime-sand further to the east. The sediment patterns cut across present-day structures, and hence are not related to them.

Lomando and Harris (1988) divided the Arab-D Reservoir in the Ghawar Field into five major zones based largely on porosity log pattern correlation (Fig 10). Major zone boundaries separated field-wide lithologic and porosity breaks and are time-stratigraphic except for the tops of zones 1 and 2A, which follow the lateral facies change from the non-porous Arab-D anhydrite to porous carbonates at the top of the Arab-D carbonate.

In the Ghawar Oil Field, the Arab-D Limestone Member is consisting mainly of grainstones and packstones, although wackestones and mudstones do occur in its lower part. Mud-rich sediments of Zone 3 grade upward into the high porosity, low mud packstones and grainstones of Zone 2. In general, interparticle porosity is abundant and moldic porosity is common in the reservoir, whereas intraparticle, fracture, burrow and shelter porosity are much less common or rare.

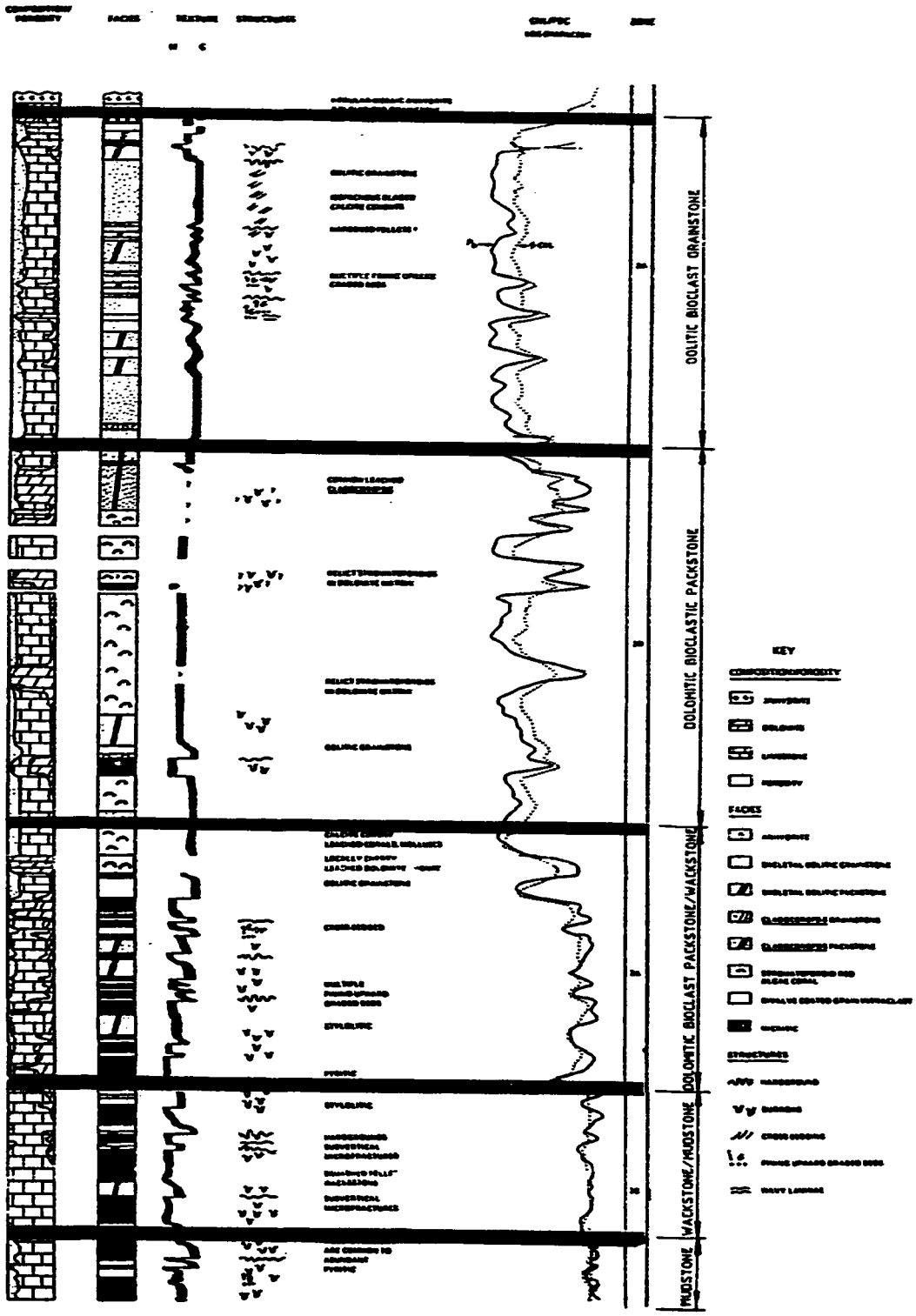


Figure 10. Typical Arab-D reservoir section, Uthmaniyah area. Ghawar field. After Mitchell and others (1988).

Intercrystal pores are common in the dolomites. Microporosity is present throughout the Arab-D limestones and dolomites. It occurs as microporous skeletal and non-skeletal grains, microporous matrix, and micropores between cement crystals.

Both skeletal and non-skeletal grains are common in the Arab-D Limestone Member, with the former (especially benthic Foraminiferids, and dasycladacean green algae) being dominant and the latter being locally common. Other common skeletal grains include remains of red calcareous algae, corals, stromatoporoids (including *Cladocoropsis*), brachiopods, bivalves, gastropods, echinoderms and ostracods. Non-skeletal grains include ooids, coated grains with irregular concentric cryptalgal laminations, composite grains, intraclasts, peloids, and pellets.

I.5 MATERIALS AND METHODS OF ANALYSIS.

Core samples and open hole geophysical logs from two wells in the Uthmaniyah area of the Ghawar Oil Field (U. 587 and 628) are the main sources of data for this study. From these cores, 193 thin sections were prepared and well logs were digitized and pertinent well data were entered into a computer for processing. In the first stage, lithologic variations, bed boundaries, and markers were defined. Rock properties obtained from the geological description of the cores were compared with the well logs, and lithological correlation between the two-wells was carried out.

The methods applied in the present study are:

1. Both light and fluorescence microscopy,
2. Scanning electron microscopy (SEM),
3. Pore casts.

I.5.1 Polarizing and Fluorescence Microscopy

A total of 94 thin sections were prepared from both the core and the rock chips of well 587 (from the depth interal of 6499.0 to 6743.5 feet, with a total thickness of 244.5 feet, the samples were taken at intervals of 2-4 feet). Another 99 thin sections were also prepared from the cored part of well 628 (from the depth interval of 6519.2 to 6746.8 with a total thickness of 227.6 feet) in the Uthmaniyah area of the Ghawar oil field.

The methods used in the study of the thin sections included examination and photographing by the use of a binocular, photographic, polarizing microscope.

Some samples were placed in a small cup, covered with epoxy, and vacuumed in a desiccator. The samples were then placed in a pressure chamber fixed in an oven and a pressure of 1000 psi and a temperature of 140 °F were applied. N-Butyl-glycidly-ether was added to the epoxy to prolong the curing time and reduce the viscosity required to obtain intrusion into micropore spaces. After the epoxy was cured, the sample was divided into two halves, one was used for thin sectioning and the other was used for preparing a pore cast of the sample.

The epoxy used was mixed with either a blue dye or a fluorescent dye (Rhodomine-B). Impregnating blue dye into the rock enhances pore visibility in thin sections and focuses attention on pore systems. Impregnating fluorescent dye into the rock is a method of viewing its micropores and microfractures. This method provides important insights into the nature and origin of the rock pore systems. Fluorescence micrscopy can reveal unexpected forms of microporosity and microfracture in thin sections.

The methods used in the study of the thin sections included examination under a polarizing binocular microscope. Photomicrographs were taken with the help of photographic attachments to the microscope.

1.5.2 Scanning Electron Microscopy

Because of its high resolution, large depth of field, and, in particular, the possibility of direct viewing of the sample, SEM is helpful in the characterization of rocks. Subject samples are cleaned and a freshly broken surface of the rock was coated with gold to make it conductive before it was investigated. Easy sample preparation, three dimensional observation, identification of the smallest minerals, greater depth of field and resolution, and higher magnification range are the advantages over polarizing microscopy.

1.5.3 Pore casts Analysis

Pore casts give a three-dimensional image of the pore geometry. A study of pore casts provides information on the distribution and shape of pores and their interconnections.

Pore casts were obtained from the same rock samples which were impregnated with epoxy to prepare the thin sections as explained above. One half of each epoxy-impregnated rock sample was used for pore cast preparation. The sample was etched with dilute hydrochloric acid for two to three days to dissolve the carbonate rock matrix. After removal of the carbonate matrix a cast of the pore system was obtained standing in relief for examination by binocular microscope and SEM.

CHAPTER 2

STRATIGRAPHY

II.1 GENERAL DISCUSSION:

The Jurassic period, (named for the Jura Mountains of Switzerland), began about 190 million years ago and ended about 136 million years ago. There were then only two major continents, Laurasia in the north and Gondwanaland in the south. During the early part of the period these were united at their western ends and separated by a major equatorial ocean called Tethys, which widened towards the east.

Sea-level was comparatively high in the Jurassic; large areas of the present continents were inundated by shallow seas, and the land appears in general to have been fairly low-lying. Early in the period, sea-level was at its lowest; subsequently the sea advanced more or less progressively to flood more and more of the low-lying continental areas, reaching a maximum toward the end of the period when something like 25% of the present continental area was covered by the sea waters. However, in the very final stages of the Jurassic, the sea withdrew markedly from the continents.

The climate during the Jurassic period was apparently more uniform than that of the present day. Temperate conditions extending as far as the present polar regions, and the climatic conditions which today characterize the tropics extended well north and south spreading as far as present-day Western Europe.

However, details of climatic zones, or of wind and ocean current distributions, have not yet been adequately worked out. Most of the Jurassic sedimentary rocks were laid down in the extensive shallow seas that flooded parts of the continents.

In the late Triassic time an extensive carbonate platform had developed, somewhat resembling the Great Bahama Bank of today. On this were laid down several thousand meters of extremely shallow-water deposits of limestone. These conditions persisted-everywhere from southern Spain and Morocco to the southern Alps, Austrian Calcareous Alps and Apennines to Greece-until late in the early Jurassic. A widespread collapse then took place and extensive sectors subsided considerably, resulting in the formation of deeper-water deposits. The thicker, more basinal deposits are marly limestones with trace-fossil mottling; the thinner deposits were laid down very slowly on structural highs (probably seamounts). These deposits were from deeper water than any known further north in Europe, and probably were laid down in depths of several hundred meters, They are overlain by even deeper-water deposits of middle to late Jurassic age, thought by many to have been laid down at depths of several thousand meters. The youngest Jurassic deposits are fine-grained pelagic limestones composed largely of coccolith debris. They have hardly any benthonic fossils but contain some ammonite remains. Trace of vulcanicity and sedimentary fissure fillings, together with dramatic lateral

changes in sedimentary thickness, provide additional support for a general, self-consistent interpretation of the Jurassic geological history.

The zone of the Jurassic limestone facies continues eastward into the Middle East as exemplified by the Zagros ranges of Iran and their continuation into Saudi Arabia. Here, however, the whole sequence is of shallow-water carbonate-platform type. Thick Late Jurassic limestones are also known in the southern part of European Russia and around the Gulf of Mexico. Elsewhere in the world, limestone facies are subordinate to sandstone and shales.

The Jurassic period was subdivided into several stages from older to younger as follows:

- The Hettangian stage: Proposed by Renevier (1864) after Hettange, Moselle, France. It started 195 Ma ago and ended 189 Ma ago (with a duration of 6 Ma).

- The Sinemurian Stage: Proposed by D'Orbigny (1850) after Semur, Cote d'Or, France. It started 189 Ma ago and ended 184 Ma ago (with a duration of 5 Ma).

- The Pliensbachian Stage: Proposed by Oppel (1858) after Pliensbach, near Boll, Wurttemburg, Germany. It started 184 Ma ago and ended 178 Ma ago (with a duration of 6 Ma).

- The Toarcian Stage: Proposed by D'Orbigny (1850) after Thouars, Deux-Sevres, France. It started 178 Ma ago and ended 177 Ma ago (with a duration of only 1 Ma).

- The Aalenian Stage: Used as an equivalent of the Lower Bajocian. It stared 177 Ma ago and ended 176 Ma ago (with a duration of only 1 Ma). However, in the recent years, there has been a more return to the use of the Bajocian *Senso lato* abondoning the Aalenian.

- The Bajocian Stage: Proposed by D'Orbigny (1850) after Bayeux, Normandy, France. It started 176 Ma ago and ended 167 Ma ago (with a duration of 9 Ma).

- The Bathonian Stage: Proposed by Omalius D'Halloy (1843) after Bath, Somerset, England. It started 167 Ma ago and ended 164 Ma ago (with a duration of 3 Ma).

- The Callovian Stage: Proposed by D'Orbigny (1850) after the Kellaways rock, Yorkshire, Great Britain. It started 164 Ma ago and ended 160 Ma ago (with a duration of 4 Ma).

- The Oxfordian Stage: Proposed by D'Orbigny (1850), after Oxford district, Oxfordshire, England. It started 160 Ma ago and ended 151 Ma ago (with a duration of 9 Ma).

- The Kimmeridgian Stage: Proposed by D'Orbigny (1850) after Kimmeridge, Isle of Purbeck, Dorset, England. It started 151 Ma ago and ended 146 Ma ago (with a duration of 5 Ma).

- The Portlandian Stage: Proposed by D'Orbigny (1850) after the Isle of Portland, Dorset, England. It started 146 Ma ago and ended 139 Ma ago (with a duration of about 7 Ma). The term Tithonian was used in the literature as a synonum to the Portlandian, and this will be followed also here.

II.2 THE JURASSIC SUCCESSION IN ARABIA:

The Jurassic succession of Arabia is a major sedimentary carbonate megacycle that ranges in facies from low energy deep-water mudstones, wackestones, and shales to high-energy shallow-water grainstones and packstones. The Early to Middle Jurassic Marrat and Dhruma Formations were deposited uniformly in an epeiric carbonate shelf, but their depositional facies were modified by minor relative sea level changes. A regional disconformity occurs between the Dhruma Formation and the overlying Tuwaiq Mountain Limestone (Figs. 11,12) and is developed allover most of the Arabian Peninsula (Steineke et al, 1958; Sugden and Standring, 1975). This was probably caused by a minor regression of the sea despite the fact that the late Jurassic in Arabia was generally a phase of transgression and overstepping. The successive epochs of the Jurassic period in Arabia can be briefly reviewed as follows:

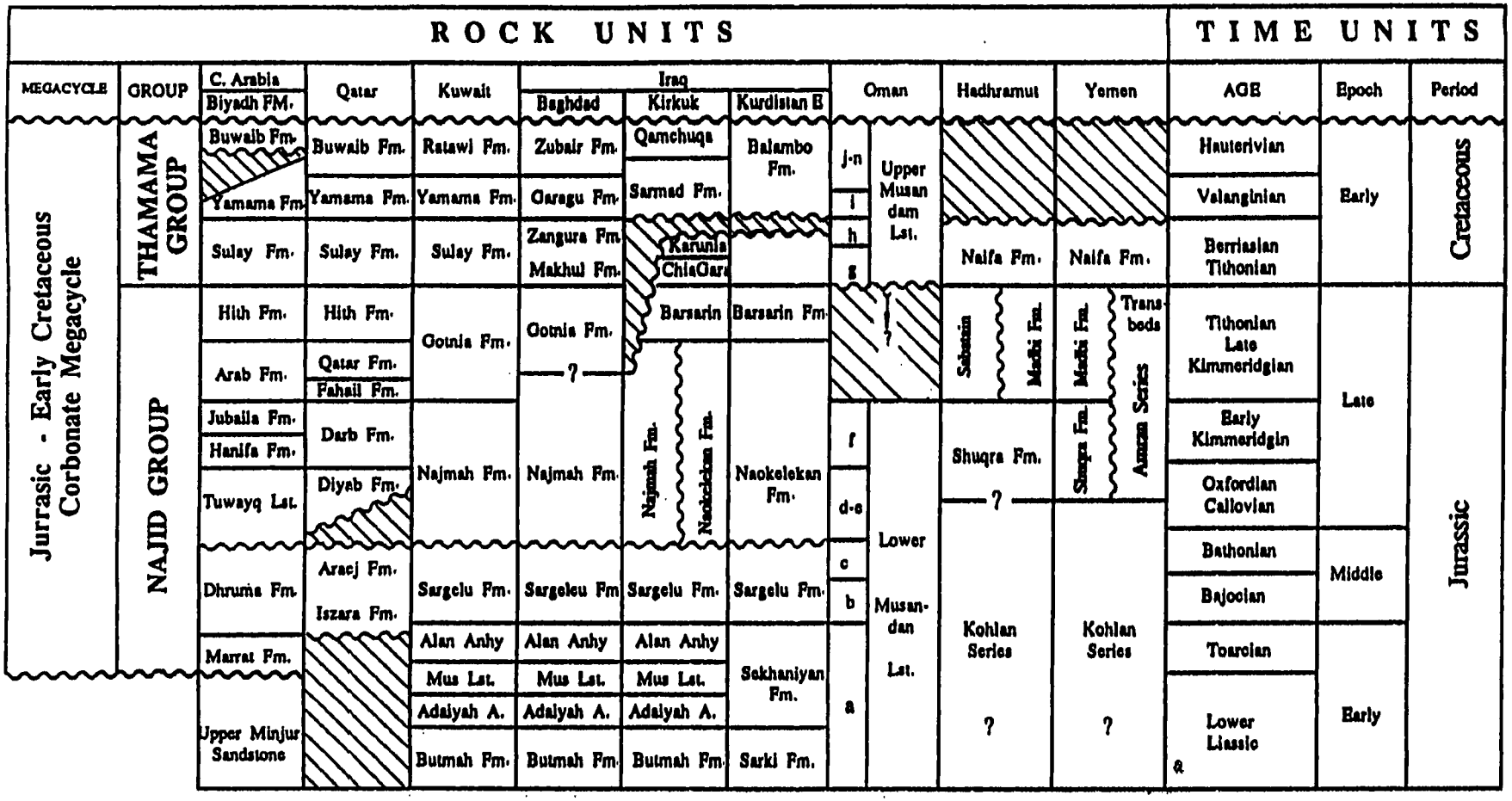


Figure 11. Correlation chart of the Jurassic and Early Cretaceous Rock Units in the Arabian Peninsula modified from Saint-Marc (1978).

AGE			FORMATION	GENERALIZED LITHOLOGIC DESCRIPTION	MAJOR STRATIGRAPHIC DIVISIONS
CENOZOIC	Quaternary & Tertiary		Surficial Deposits	Gravel, sand, and silt	
	MIOCENE AND PLIOCENE		Khurj	Limestone, lacustrine limestone, gypsum and gravel.	Miocene-Pliocene Clastics
			Hofuf	Sandy marl & sandy limestone; subordinate calcareous sandstone. Local gravel beds in lower part.	
			Dam	Marl and shale; subordinate sandstone, chalky limestone and coquina.	
			Hadrukh	Calcareous, silty sandstone, sandy limestone; local chert.	
	EOCENE	Lutetian	Dammam	Limestone, dolomite, marl, and shale.	Upper Cretaceous and Eocene Carbonates
		Ypresian	Rus	Marl, chalky limestone, and gypsum; common chert and geodal quartz in lower part. Dominantly anhydrite in subsurface.	
	PALEOCENE	Thanetian	Umm er Radhuma	Limestone, dolomitic limestone, and dolomite.	
		Montian ?			
			Possible Disconformity		
MESOZOIC	CRETACEOUS	Maestrichtian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in northwestern and southern areas of outcrop.	
		Campanian			
		Turonian ?	Wasia (Sakaka sandstone of northwest Arabia)	Sandstone; subordinate shale, rare dolomite lenses.	Middle Cretaceous Clastics
		Cenomanian			
		Aptian	Biyadh	Sandstone; subordinate shale	Late Lower Cretaceous Clastics
		Barremian			
		Hauterivian	Buwaib	Biogenic calcarenite and calcarenitic limestone interbedded with fine sandstone in upper part.	
		Valanginian	Yamama	Biogenic-pellet calcarenite; subordinate aphanitic limestone and biogenic calcarenitic limestone.	Upper Jurassic and Early Lower Cretaceous Carbonates
		Berriasian	Sulaiy	Chalky aphanitic limestone; rare biogenic calcarenite and calcarenitic limestone.	
	JURASSIC	Tithonian	Hith	Anhydrite	
			Arab	Calcarenite, calcarenitic and aphanitic limestone, dolomite and some anhydrite. Solution collapse carbonate breccia on outcrop due to loss of interbedded anhydrite.	
		Kimmeridgian	Jubaila	Aphanitic limestone and dolomite; subordinate calcarenite and calcarenitic limestone. Lower part sandstone between 20° N. and 22° N.	
			Hanifa	Aphanitic limestone, calcarenitic limestone and calcarenite.	
		Oxfordian	Tuwaiq Mountain	Aphanitic limestone; subordinate calcarenitic limestone and calcarenite. Abundant corals and stromatoporoids in upper part.	
		Callovian			
		Callovian ?	Dhruma	Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22° N. and north of 26° N.	Lower and Middle Jurassic Clastics and Carbonates
		Bathonian			
		Bajocian			
		Toarcian	Marrat	Shale and aphanitic limestone; subordinate sandstone	
	TRIASSIC	Upper	Minjur	Sandstone; some shale.	Permo-Triassic Clastics
		Middle	Jilh	Sandstone, aphanitic limestone and shale; subordinate gypsum.	
		Lower	Sudair	Red and green shale.	
	PERMIAN	Upper	Khuff	Limestone and shale; dominantly sandstone south of 21° N.	
					Early Paleozoic Clastics

Figure 12. The Stratigraphic Column of Saudi Arabia (After Powers, 1968).

II.2.1 The Early Jurassic (Liassic) Time:

II.2.1.1 The Early Jurassic Liassic Time:

The Early Liassic time was a period of marked changes. The climate became less arid, and there was apparently a relative drop in sea level, caused either by an eustatic lowering of the sea or a rise of the shield (Murris, 1980). Hence, non fossiliferous, fluvial sandstones and some shales were the prevailing sediments during that time. These sediments are informally known in Saudi Arabia as the Upper Minjur Sandstone. Here, it forms together with the underlying Lower Minjur Sandstone, a wedge-shaped slab of littoral to continental rock sandwiched between two marine units; the Jilh Formation below and the Marrat Formation above. The Upper Minjur Sandstone is delimited from above by the extensive pre-Marrat unconformity and from below by a minor break, separating it from the underlying Lower Minjur Sandstone: It represents a period of emergence involving much of the Arabian foreland. The Minjur Sandstone in Saudi Arabia is a monotonous Sandstone succession without any recognizable formal subdivisions (Powers, 1968). The Formation is absent in both Qatar and offshore Abu Dhabi but is found in onshore Abu Dhabi where it is still represented by sandstones and siltstones (Fig. 13). In Oman, the Early Liassic sequence is undifferentiated from the monotonous Permian-Triassic carbonate succession. In Dhufar, the Triassic sequence is eroded by the pre-Marrat unconformity while in the Musandam Peninsula, the Middle to Late Triassic/Liassic sequence is included in a separate group known as the Elphistone Group which consists of two formations: the Milaha and the Ghalilah. The Middle-Late Triassic Milaha Formation is composed of

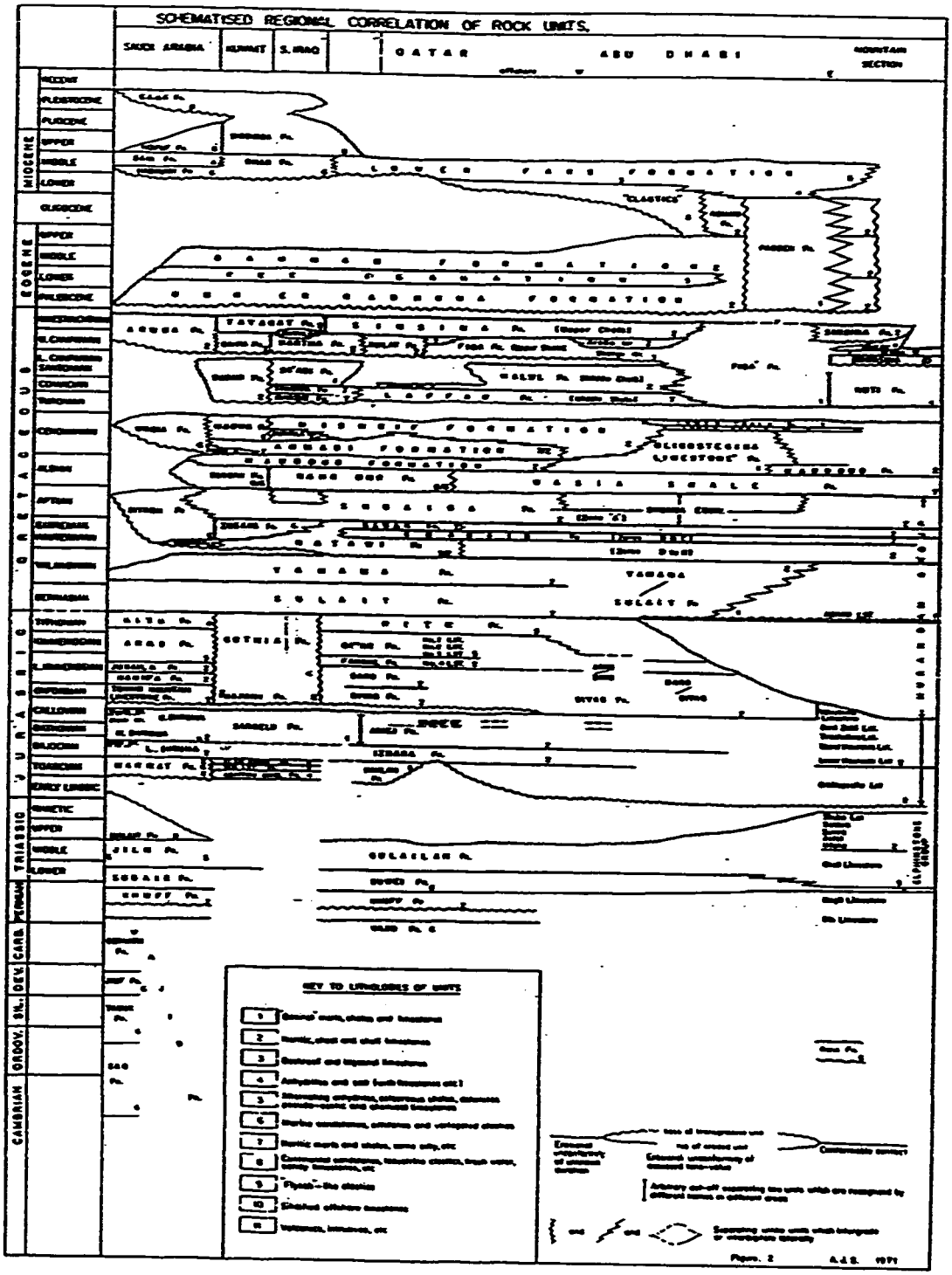


Figure 13. Correlation chart for the Phanerozoic rock units in Arabia showing the limits of the Minjur Sandstone modified from Sudgen (1975).

alternating shale and dolomitic limestone, while the overlying Early Liassic Ghalilah Formation is composed of interbedded sandstones and limestones (Glennie and others, 1974). The Late Triassic is represented by the Kurra Chine Formations in northern Iraq and by the Mulussa Formation and the lower Zor Hauran Formation in both southern and western Iraq respectively, while the Early Liassic is missing in Iraq (Al-Sharhan and Kendall, 1986).

II.2.2.2 The Late Liassic (Toarcian) Time:

During Late Liassic, tidal-flat and logoonal deposits covered the eastern and northern Arabia. Sea was deepening towards northeast (Fig. 14). In central Arabia, Toarcian rocks are represented by the Marrat Formation which is divided into four members from the base upwards as follows: The Shagra Shale Member, the Jabal Kumayt Limestone Member, the Qarain Red Beds Member and the Hadabah Limestone Member. The Shaqrah Shale Member is composed of complexly interbedded red and green shales, sandstones, and siltstones with thin beds of micritic, calcarenitic limestone at the middle and near the base of the section. This member is of shallow, tidal environment, and is overlain by the Jabal Kumayt Limestone Member which is composed, at its lower part, of dolomite with some interbeds of dolomitized micritic limestone, while the upper part is composed of porous chalky interbedded micritic limestone, with some lime-mud pellets. The Jabal Kumayt Member is overlain by the Qarain Red Beds Member which is composed of red, sometimes green or yellow, shale and siltstone with some reddish brown crossbedded sandstone interbeds with some thin micritic and calcarenetic limestone interbeds near the top.

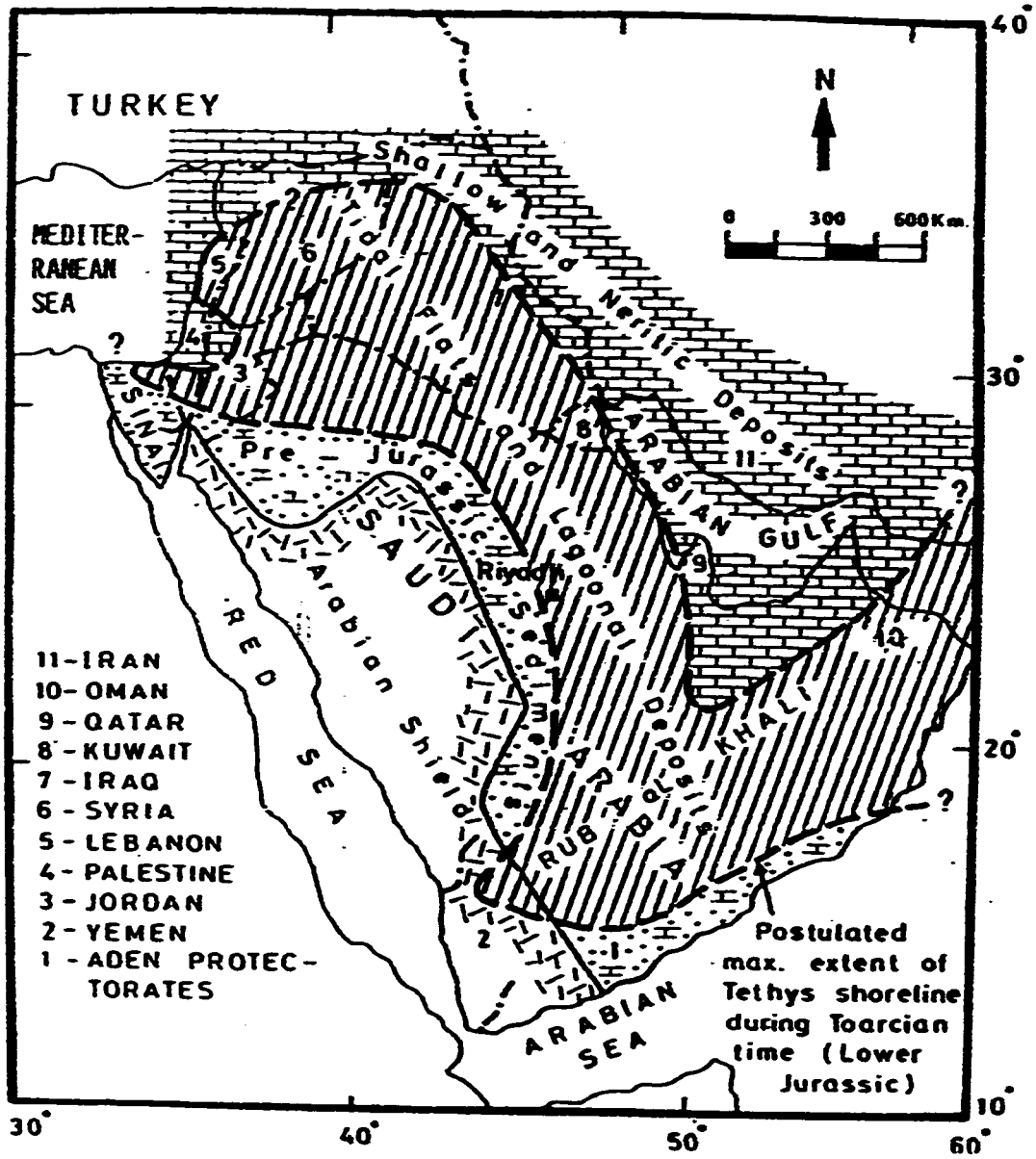


Figure 14. Postulated paleogeographic map of Early Jurassic deposits in Saudi Arabia and adjacent Middle East provinces during the Toarcian time (After Mosherif, 1987).

The upper Member is the Hadabah Limestone Member which is composed of chalky calcarenitic limestone with thin shale beds dominating its basal part (cf. Powers, 1966).

Towards the Arabian Gulf a lateral passage to shallow water platform carbonates with a remarkable decrease in shales is dominantly seen in all the drilled Jurassic sections. The Dhruma/Tuwaiq break is more evident in the subsurface Jurassic succession drilled in the Qatar Peninsula. The succession here is slightly more different and hence new rock names have been applied for parts of it such as the Izhara and Araej Formations for the Dhruma, The Diyab Formation for the Tuwaiq Mountain Limestone, the Darb Formation for both the Hanifa and the Jubaila Formations and both the Fahahill and Qatar Formations for the Arab Limestone.

In Yemen, Hadhermut and Dhufar, continental sedimentation occurred in such emergent regions and the Toarcian is represented by conglomerates, sandstones, current bedded shales and marls.

In the region of the Huqf-Haushi, the Middle Jurassic rocks rest unconformably over the truncated Early Permian succession, while in the Oman Mountains the succession forms part of a thick sequence of shallow water, platform carbonates that increase in thickness from S-W to N-E.

In northern Iraq, the Liassic succession is composed of dolomite with intercalating limestone horizons, while in southwestern Iraq, (the Gaar'a region) Toarcian rocks are absent due to an erosional or a non-depositional gap (Saint-Marc, 1978).

The Toarcian time was characterized in Arabia by a new regional depositional pattern, a more humid climate and a marked transgression of the Tethyan Sea. The greater part of the Arabian Peninsula was covered by a very shallow marine water as indicated by the presence of tidal-flat and lagoonal deposits in northern Oman, Rub' al-Khali, parts of Yemen, central, and southwestern Iraq.

The Early Jurassic succession in central Arabia shows lateral as well as vertical variations in both lithology and thickness, these variations are the result of both the tectonic movements and the changes in the eustatic Tethyan sea level. Moshrif (1987), related the variation in thickness to the effect of the central Arabian embayment, while the lateral variations of sediments was referred to an eustatic control factor, as suggested by the diversified types of lithofacies. Moshrif (*op.cit*), suggested various marine environments, for the Early Jurassic facies of Central Arabia. The gypsum and dolomites were deposited under open marine conditions i.e. supratidal, intertidal and lagoonal environments; the calcarenitic limestones were deposited under high current-energy marine conditions i.e. a relatively shallow marine environment. El-Naggar (personal communication), explained the calcarenitic limestone as the product of current washing in relatively closed basins, where the rate of subsidance had been much slower than the rate of infilling, so that the precipetated non-lithified limestones were current-washed before solidification.

Moshrif (1987), mentioned that the Marrat Formation had been deposited during the Late Liassic Toarcian transgression which maintained the greater part of the Arabian Peninsula under very shallow marine conditions. The maximum extent of the Tethyan Sea shoreline during the Toarcian time passed through the central area of Aden (Greenwood and

Bleackley, 1967) and turned towards the northwest, through northern Yemen, then northwards surrounding the pre-Jurassic sediments through central Arabia and continued north-northwestwards of Arabia. [Powers and others, 1966, Powers, 1968]

The Toarcian facies allover Arabia generally suggest tidal, lagoonal and neritic conditions of deposition from west and southwest to east and northeast, (Powers and others, 1966, Powers, 1968 and Murris, 1980).

II.2.3 The Middle Jurassic (Bajocian-Bathonian-Callovian) time:

In central Arabia, the Bajocian-Bathonian-Early Callovian Dhruma Formation crops out with an average thickness of 375 m at Khashm ad Dhibi , to west of Riyadh (Fig. 15). This can be separated into an upper, middle, and lower units (Steineke, Bramkamp & Sander 1958). Lithologically, the lower unit is mainly composed of shales and marls, with some limestone and gypsum interbeds at the base, while the middle unit is composed of limestone with intercalating calcarenite beds at various levels and oolitic beds in the upper part. The upper unit consists of two members; the Lower Atash Calcarenite and Calcarenitic Limestone Member and the Upper Hisyan Shale Member (of yellow-gray shale with limestone interbeds in the lower part, that change into limestone with shale interbeds in the

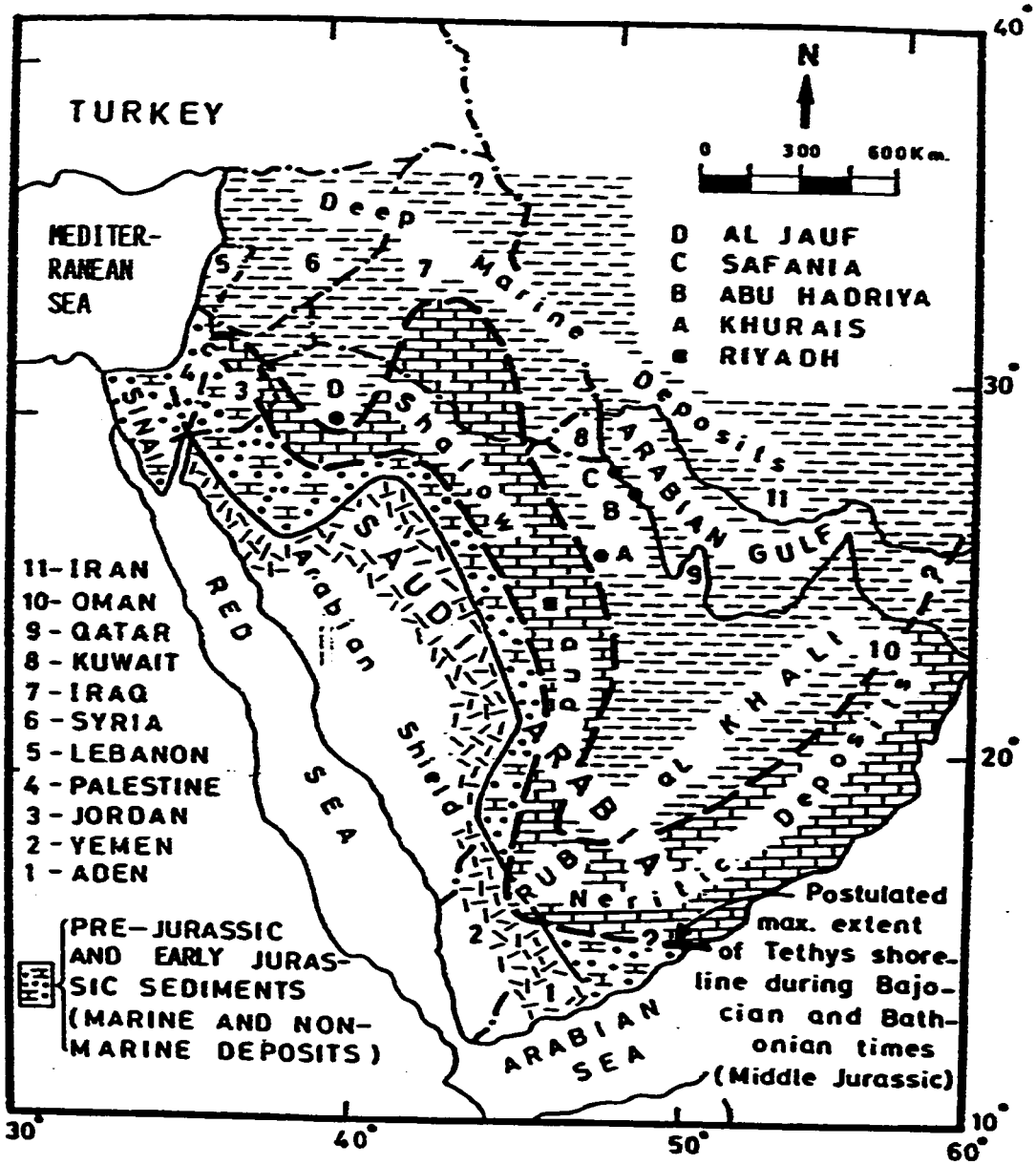


Figure 15. Postulated paleogeographic map for Arabia and the Arabian Gulf Region during the Middle Jurassic (Bajocian - Bathonian Early Callovian) time (After Mosherif, 1987).

upper part). Towards eastern Arabia (at Al Ubaylah) the Bajocian-Bathonian changes from the near-shore littoral conditions at the west to clean shelf limestone.

In Qatar, the limestone and dolomite of the Bajocian Izhara Formation rests unconformably over the Middle Triassic.

In Yemen, Hadhramout, and Dhofar, the Middle Jurassic succession is marked by a change of facies from near shore to typical marine conditions, while in the region of the Huqf-Haushi the Bajocian-Bathonian succession rests unconformably over the Early Permian and is made up of clean shelf carbonates.

In the Oman Mountains, the Middle Jurassic succession forms a part of a thick sequence of carbonates that was deposited in a shallow water shelf environment from the Liassic up to the Late Jurassic.

In Iraq, the Bajocian-Bathonian-Callovian rocks are composed mainly of deep water marine shales and radiolarian limestones which were apparently deposited in a subsiding trough whose longitudinal axis extended from Mousel in the northwest to Kuwait in the southeast.

During the Middle Jurassic (Bajocian-Bathonian-Callovian) time the Tethys Sea extended further to the west much more than during the Toarcian time. Consequently, most of the Arabian Peninsula was submerged below shallow-neritic to deep marine conditions from west to east. Moshrif (1987), reported that during that time, shallow neritic Tethys conditions extended to include the Oman Mountains, the western part of the Rub' al-Khali,

central Saudi Arabia and southwestern Iraq. At the same time, northern Oman, central Rub' al-Khali, eastern Saudi Arabia and central & eastern Iraq were covered by deep-waters.

As in the Toarcian time, the Bajocian-Bathonian-Callovian succession is represented by different lithofacies suggesting various marine environments during that period. The calcarenite lithofacies developed under high energy marine conditions, i.e under a relatively shallow water environment with bars and reef build-ups which assisted in the development of sheltered, lagoonal and tidal-flat environments. These assumed environments are confirmed by the predominance of oolites, the absence of micritic matrix, the presence of cross-bedded sandy beds, and also by the presence of algal beds throughout the Dhruma succesion. The predominance of calcarenitic limestones and calcarenites in the Toarcian-Callovian succession in central Arabia is explained on the basis of a rapidly infilling, slowly subsiding basin resulting in periodic current washing. Other lithofacies found in the Middle Jurassic succession of central and eastern Arabia is the dark shales and the argillaceous limestones which were deposited in the deeper part of the open sea shelf environment where the lowest level of energy was achieved. Moshrif (1987), mentioned that the Early and Middle Jurassic rocks were mainly deposited as carbonate and clastic facies under progressive marine conditions. This started westward with tidal-flats and lagoonal deposits, followed eastwardly by shallow to moderately deep (neritic) marine environments generally known as the Tethyan rifting lithofacies. Moreover, the intercalations of very shallow to shallow facies with deep marine facies are good indications of the Tethyan transgressive-regressive phases which dominated during the development of the Marrat-Dhruma lithofacies (Moshrif, 1987). The shoreline of the

Bajocian-Bathonian-Callovian Tethyan Sea extended further towards the west resulting in a shallow to neritic marine conditions in central Arabia. This shallow sea extended north and northwest to include northern Africa, Palestine, northwestern Jordan and central Iraq. The deep-marine argillaceous limestones and black shales dominate the eastern Rub' al-Khali, northwards to include the Safaniya, then extend across the north northwestern parts of Saudi Arabia, swinging over eastern Jordan and northwestern Iraq and across the Arabian Gulf and southwestern Iran (Powers and others, 1966; Powers, 1968; Al-Naqib, 1967; Saint-Marc, 1976; Murris, 1980; and Moshrif, 1987).

As mentioned above, the Middle Jurassic sediments are typically represented by shallow-water shales and carbonates of the Dhruma Formation which conformably overlie the Toarcian Marrat Limestones (Fig. 16).

In Kuwait, no Early Jurassic rocks have yet been described; while, the Middle Jurassic Sargelu Formation is composed mainly of shallow marine, low-energy limestones (Alrefai, 1967). At the type locality, the Sargelu Formation is composed of bituminous phosphatic marl with thin argillaceous limestone beds.

In Qatar, the Middle Jurassic sequence (composed of both the Izhara and the Araej Formations) consists at its base of thin marl that grades upward into alternating lime mudstones and wackestones followed by widespread sheets of clean peloidal bioclastic packstones and oolitic grainstones. These grainstones are thought to have accumulated in shallow, partly protected, to high-energy depositional settings and to possess good reservoir characteristics.

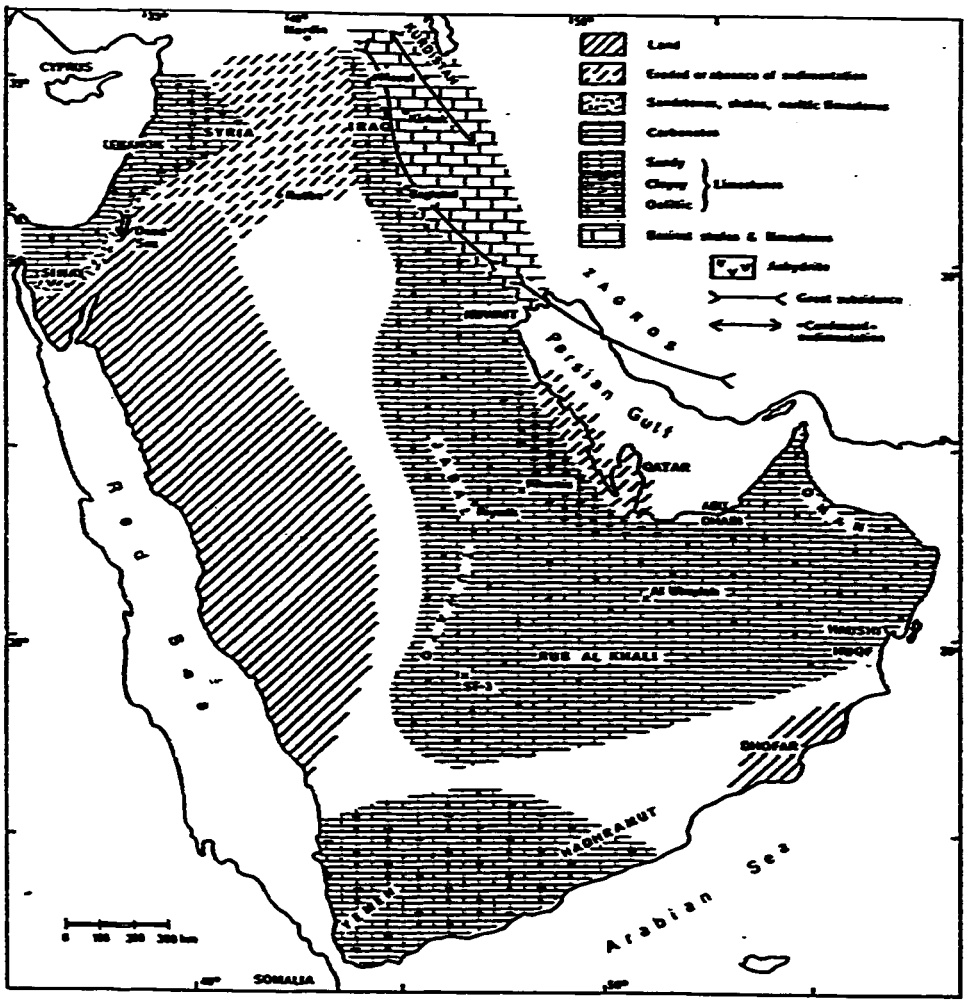


Figure 16. Paleogeographic Map for Arabia during the Callovian time (After Saint-Marc, 1978).

In Abu Dhabi, the Middle Jurassic Izhara Formation, consists of argillaceous limestone with subordinate shale and a thin interval of lime mudstone and wackestone, while the upper part of the Middle Jurassic is formed by the Araej Formation, which consists of thick carbonates that accumulated on a shelf in shallow to very shallow waters and contains good reservoir facies (Schlumberger, 1981).

In Saudi Arabia, the Bajocian-Bathonian-Early Callovian Dhruma Formation is dominantly composed of shallow-water limestones that are commonly peloidal and associated with subordinate shales and calcarenites (Steineke *et al.*, 1958, Powers *et al.*, 1966 and Powers *et al.*, 1968). In the subsurface, the Dhruma Formation is composed of a basal shale unit (which is a prominent and extensive marker) with subordinate limestone and gypsum. This shale is overlain by clean calcarenitic limestone with beds of oolite, which are topped by shales with subordinate limestones (Powers, 1968). The Araej Formation of both Qatar and Abu Dhabi is equivalent to both the upper and middle parts of the Dhruma Formation and takes its name from Jebel Araej in southern Qatar. Here, the Kharaib-1 well was chosen as the type section by Sugden and Standring (1975), and the formation is split into three members from base to top as follows: the lower Araej, the Uwainat and the Upper Araej Limestone Members. These are correlated with the middle Dhruma, and with the Atash and the Hisyan Members of the upper Dhrum, respectively. The Lower Araej Limestone Member is composed of shallow water shelf limestone, while the Uwainat Member consists of predominantly lime mudstone, wackestone, and packstone, and contains subordinate grainstone with well-developed porosity. The Upper Araej Limestone Member consists of argillaceous limestones overlain by a clean grainstone to packstone unit. These Middle Jurassic sediments of the Dhruma or Araej Formation accumulated on a

carbonate ramp (as defined by Read, 1985), and they contain widespread sheets of peloidal-ooidal packstones or grainstones, which cyclically alternate with argillaceous peloidal bioclastic mudstones or wackestones (Murris, 1980).

In the Dhufar region of south Oman, the only outcrops of Jurassic rocks are the Middle Jurassic Kohlan Formation, which is only about 81 m (266 ft) thick (Beydoun, 1964; Beydoun and Greenwood, 1968). It is composed of arkosic, coarse to medium-grained, friable, partly dolomitized and indurated sandstones, with intervals of marls, siltstones, shales, and conglomerates, and a cap of sandy marl and calcareous sandstone. It was deposited in a shallow marine to lagoonal setting.

Near the oil fields of western Oman, the Middle Jurassic Dhruma Formation grades upwardly from calcareous shales with thin interbedded argillaceous wackestones or packstones into the Musandam Limestone of the northern Oman Mountains. Here, the upper Liassic to Malm lower Musandam Group is divided into six members (A to F, from the base upward). Members A and B are composed of alternating lime mudstones and wackestones, and end with massive dolomites. Member C is composed of argillaceous, nodular, lime mudstones. Members D and E are thick bands of bio-turbated lime mudstones, and member F is a fossiliferous lime mudstone at the base, which grades upward to coral packstones.

In Iraq, the Middle Jurassic Sargelu Formation consists of basinal black, bituminous, phosphatic marls and argillaceous limestones, dolomites, and shales.

In southwestern Iran, the Middle Jurassic Sargelu Formation is composed of shales and argillaceous limestones, which terminate in a regional unconformity.

II.2.4 The Late Callovian-Oxfordian-Tithonian time:

In Saudi Arabia, the Late Middle Jurassic-Late Jurassic succession consists of shallow-water limestones, and anhydrites. These are subdivided into the Tuwaiq Mountain Limestone, the Hanifa, Jubailah, Arab and Hith Formations, (Figs. 17,18). These formations are also generally recognized in all the drilled oil wells in Eastern Arabia. Most of the type sections for these formations are described from outcrops in the Riyadh area, except for the Arab Formation, which in response to the dissolution of preexisting anhydrite, shows evidence of collapse along the entire outcrop belt. Therefore, the type section for the Arab Formation was chosen from the Dammam oil field in the Dammam 7 ARAMCO well (Steineke and others, 1958; Powers and others, 1966). Stratigraphy of the Arab Formation is presented in the Appendix.

A description of the type Tuwaiq Mountain Limestone was first published by Arkell (1952), and was later detailed by Powers *et al.* (1966). It is generally composed of dense micritic limestone (with stringers of calcarenitic limestone) that becomes marly downward.

The late Oxfordian to early Kimmeridgian Hanifa Formation is characterized by shallow-water limestone, which is composed of alternating micritic and oolitic calcarenitic limestone. At the time of Hanifa deposition, large intrashelf euxinic basins existed along the

Figure 17. Late Oxfordian to early Kimmeridgian environments of deposition. (After Murris, 1980).

Figure 18. Tithonian environments of deposition (After Murris, 1980).

western side of the Arabian Gulf in which laminated kerogenous micrites accumulated (Murris, 1980; Ayres *et al*, 1982). The Jubailah Formation is composed of interbedded peloidal, calcarenitic, limestones and calcarenites which grade upward into partly dolomitized micritic limestone that in the western Arabian Gulf, was deposited in an intrashelf basin (Powers, 1968, Wilson, 1985).

The Arab Formation is dominated by oolitic limestone that was locally recrystallized and dolomitized (Steineke and Bramkamp, 1952). It includes four main depositional cycles, each starting with shallow-water, normal marine carbonates and closed with the accumulation of nearly pure anhydrite (Steineke *et al.*, 1958; Powers, 1962, 1968; Powers *et al*, 1966). All of the Arab Members are oil producers (Powers, 1968; Ayres *et al*, 1982; Wilson, 1985), but the most important of these is the Arab D Member, which represents a transition from continuous carbonate deposition to the accumulation of nearly pure anhydrite. The lower part of the Member consists of mixed calcareous muds and non-skeletal sand grains, and produces oil in widely scattered fields (Powers, 1968).

In offshore Abu Dhabi, the Arab Formation (known locally as the Arab/Darb Formation) of the Umm Shaif oil field consists of a series of cycles of dolomite (61%) interbedded with anhydrite (8%) and algal limestones (25%) that accumulated in lagoonal to supratidal settings (Wood and Wolfe, 1969). The formation was deposited as a major regressive sequence that accumulated on a shelf, which filled to the supratidal area. It is dominated by both porous and dolomitic limestones with several thin, well-defined anhydrite layers (Hood and Downie, 1975). In Abu Dhabi, as in Saudi Arabia, the Arab Formation was deposited as cycles of carbonate and anhydrite.

In Qatar, the stratigraphic terminology is slightly different from that of Saudi Arabia. The Arab A to C is known as the Qatar Formation, and the Arab D is known as the Fahahil Formation (Sugden and Standring, 1975). The Qatar Formation consists of peloidal limestone, dolomitic packstone or grainstone, and tight sucrosic dolomite, separated by repeated anhydrite intercalations (Schlumberger, 1981). The Fahahil Formation consists predominantly of porous and permeable bioclastic to peloidal packstone or grainstone with intercalations of lime mudstone, which locally change into a chalky sucrosic dolomite (Sugden and Standring, 1975).

The Arab Formation consists of a series of depositional cycles each consisting of a lower unit of bioclastic lime mudstone or wackestone (with normal marine fossils), a middle grainstone unit (of clean washed calcarenite composed of rounded skeletal particles), and an upper, thin, tidal-flat, dolomitic mudstone unit that grades within a few feet to thick supratidal anhydrite (Wilson, 1975). The Arab C and D reservoir rocks of the Saudi Arabian Qatif oil field, for example, are composed of cycles of carbonate rock (Wilson, 1985) that occur in most of the fields drilled in both Qatar and offshore Abu Dhabi. The exception is in southeastern Abu Dhabi, where limestone, anhydrite, and dolomite were deposited in the same shallow marine setting as in Qatar, but with no Hith anhydrite.

Throughout the Gulf region, the Arab Formation is overlain by the Hith Anhydrite (Powers, 1968; Murris, 1980; Ayres *et al*, 1982). This represents the final regressive supratidal phase of the Late Jurassic sea and contains minor dolomite intercalations. The Hith anhydrite of each of Abu Dhabi, Qatar, and Saudi Arabia has been correlated with the Gotnia anhydrite of Iraq. The ages of the Gotnia and the Hith had been extensively

discussed by Dunnington (1967), who concluded that the top of the Gotnia anhydrite is correlative with the top of the Hith anhydrite and that both are older than the Makhul Formation of Iraq (Dunnington, 1967).

In Oman, the Late Jurassic sequence is locally missing in western and northwestern areas, but it is present in the deepest wells of the Fahud oil field. The Tuwaiq Mountain Formation is composed of dolomitized argillaceous mudstones to chalky wackestones, and in the Lekhwair oil field, is water bearing. The Hanifa and Jubailah Formations are relatively thin sheet-like, shelf carbonates of wackestones to packstone. At the top of the Hanifa, a porous section of peloidal oolitic grainstones to packstones occurs. The latest Jurassic Arab and Hith Formations do not occur there, but their lateral equivalents could merge in the basal part of the relatively deep-water carbonates of the Rayda Formation.

In southern Iraq, the Late Jurassic section is represented by the Najmah Formation which is composed primarily of oolitic and pseudo-oolitic limestones that were deposited under supersaline lagoonal to shallow marine conditions. In the northeastern folded zone, the Callovian to early Kimmeridgian Naokelekan Formation is equivalent to the Najmah Formation and is mainly composed of shaly limestones, dolomitic limestones, and calcareous shales. In the south, the Gotnia Formation occurs above the Najmah Formation, and consists of anhydrites with subordinate shales and limestones. It is a time equivalent of the Barsarin Formation of the northeastern folded zone.

In the Lurestan province of southwestern Iran, the Late Jurassic rocks are represented by the Najmah Formation which is mainly composed of pelleted algal

limestone. As in Iraq, these limestones pass upward into thick anhydrites with subordinate shales of the Gotnia Formation.

In the Fars province, the section from the Late Lias to the Early part of the Late Jurassic is represented by the Surmeh Formation, which is composed of shallow-water carbonates in the form of dolomites and dolomitic limestones. There, the latest Jurassic sequence is formed by tidal-flat carbonates associated with a penecontemporaneous replacement anhydrite, which is locally called the "Hith anhydrite" (James and Wynd, 1965).

CHAPTER 3

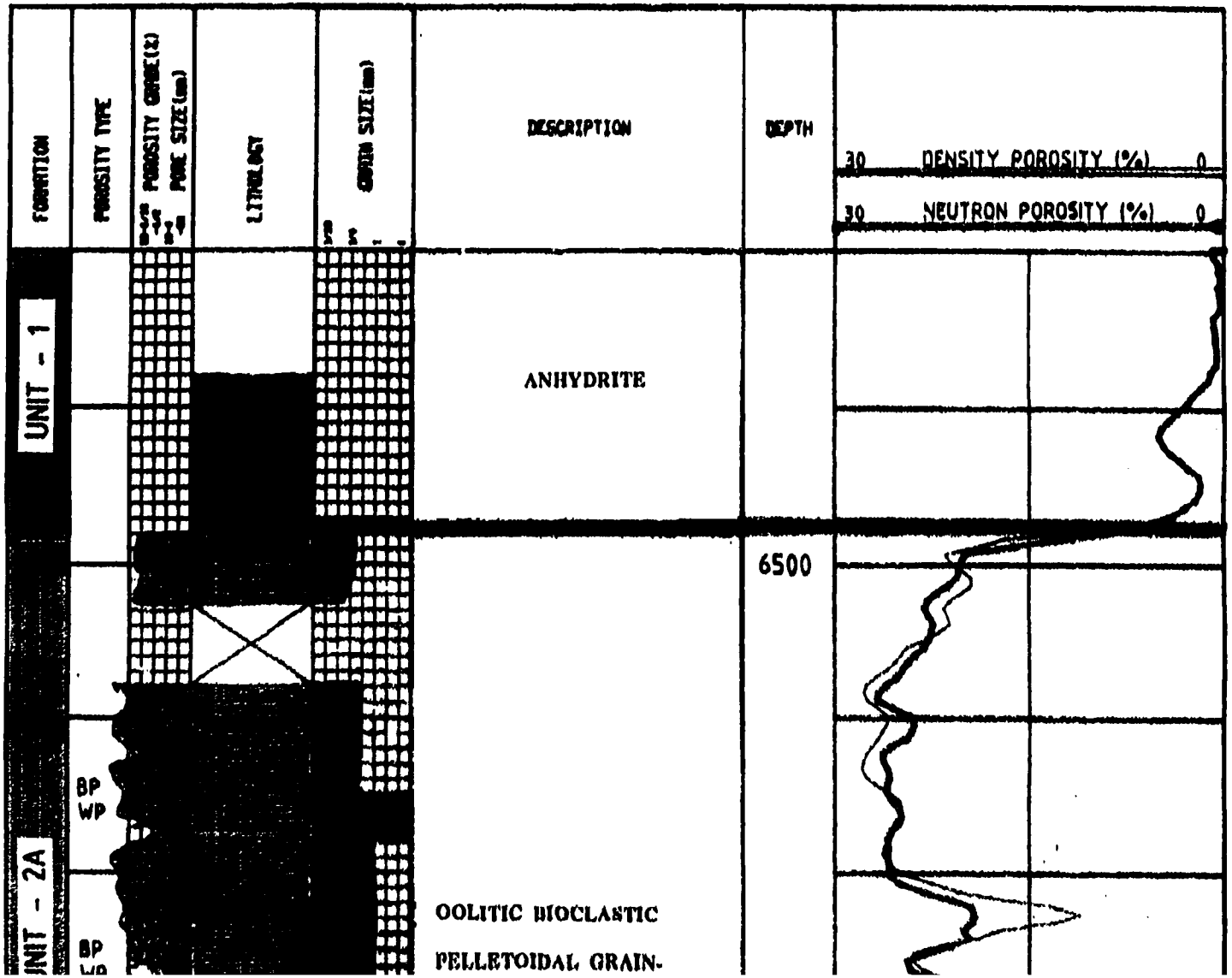
STRATIGRAPHY OF THE STUDIED WELLS

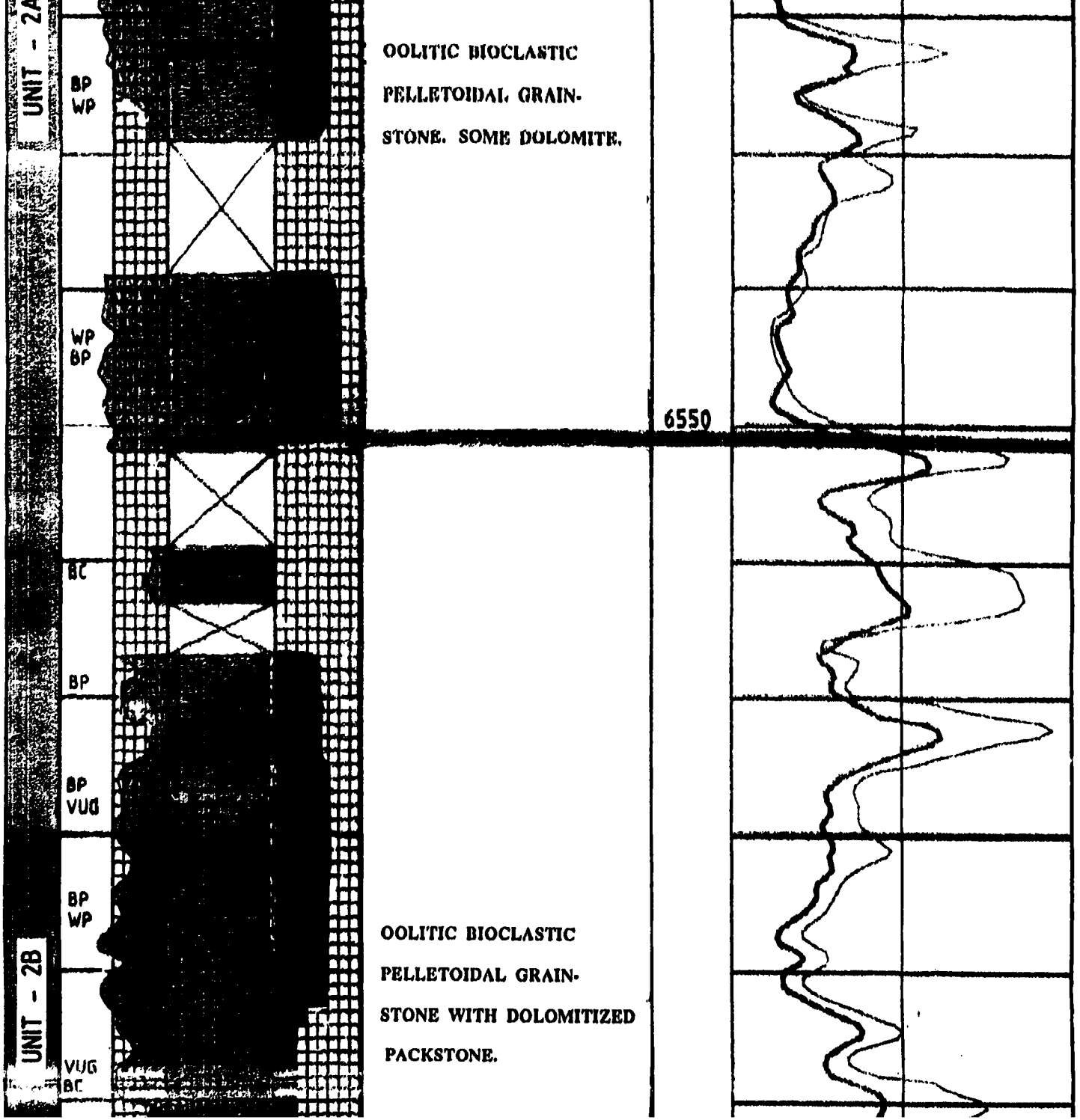
Columnar sections for the two Wells UTMN-587 and UTMN-628 (Fig. 1) show the Late Jurassic Arab-D Limestone Member to be composed of about 280 feet of carbonates and evaporites (between 5870 feet below the sea level) which follow conformably the Jubalia Formation, and is overlain by the Arab-C Limestone Member, from which it is separated by the Arab-D Anhydrite Bed. Detailed lithic logs for the two wells were prepared to help in selecting representative data for these studies and to highlight the lithological properties and their distribution in the Arab-D Limestone Member (Figs. 19, 20).

The lithic log for UTMN-587 well (Fig. 19) was prepared by visiting the Saudi ARAMCO's core storage facility and studying, from top to bottom, the available cores. Rock chips and plug ends were collected for lithofacies and diagenetic studies. A total of 94 thin sections were prepared from some plug ends in the core section and also from all samples of the rock chips.

The lithological observations were correlated with open hole well logs to adjust and locate the bedding boundaries and to define the lost core intervals. The Formation Density Compensated and Compensated Neutron Log (FDC-CNL) cross-plot technique was used

GHAWAR UTMN - 587
LITHIC LOG OF ARAB - D MEMBER

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PELLETOIDAL GRAIN-
STONE. SOME DOLOMITE.
WP
BP
6550
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BP
BP
VUG
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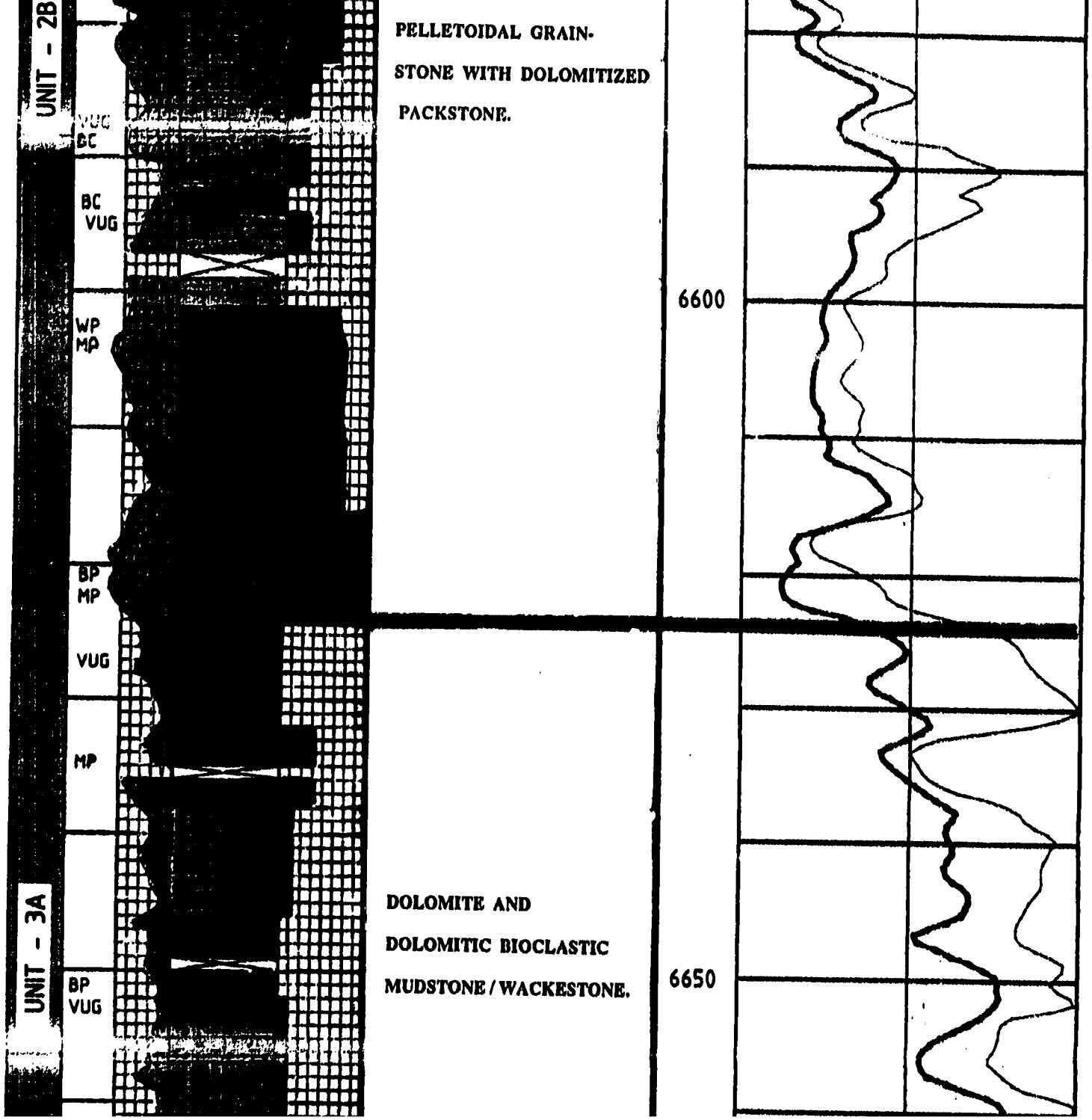
BC
OOLITIC BIOCLASTIC
PELLETOIDAL GRAIN-
STONE WITH DOLOMITIZED
PACKSTONE.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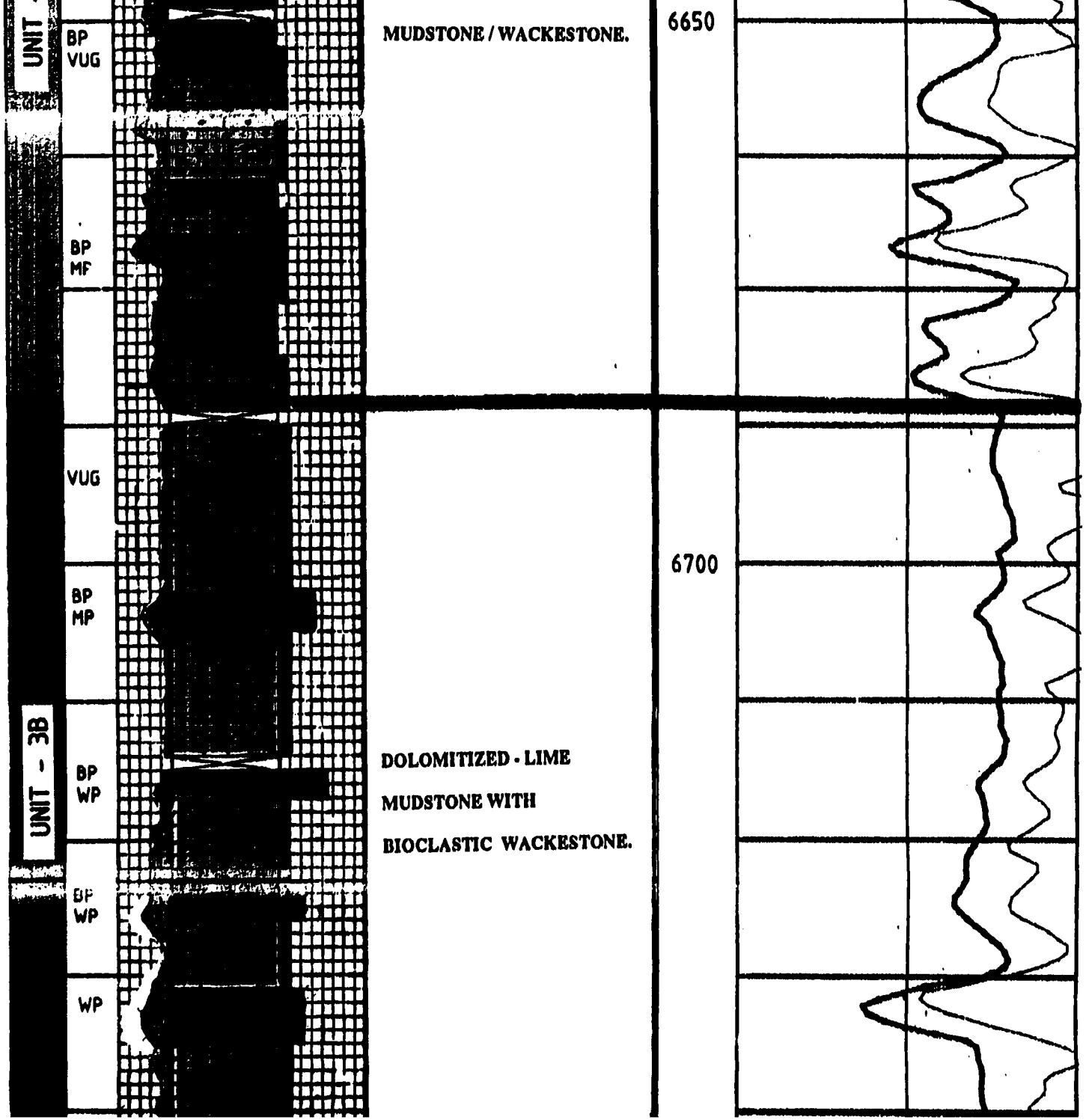
PELLETOIDAL GRAIN-
STONE WITH DOLOMITIZED
PACKSTONE.
6600
DOLOMITE AND
DOLOMITIC BIOCLASTIC
MUDSTONE / WACKESTONE.
6650


UNIT
BP
VUG
BP
MF
MUDSTONE / WACKESTONE.
6650
VUG
BP
MP
6700
UNIT - 3B
BP
WP
DOLOMITIZED - LIME
MUDSTONE WITH
BIOCLASTIC WACKESTONE.
BP
WP
WP

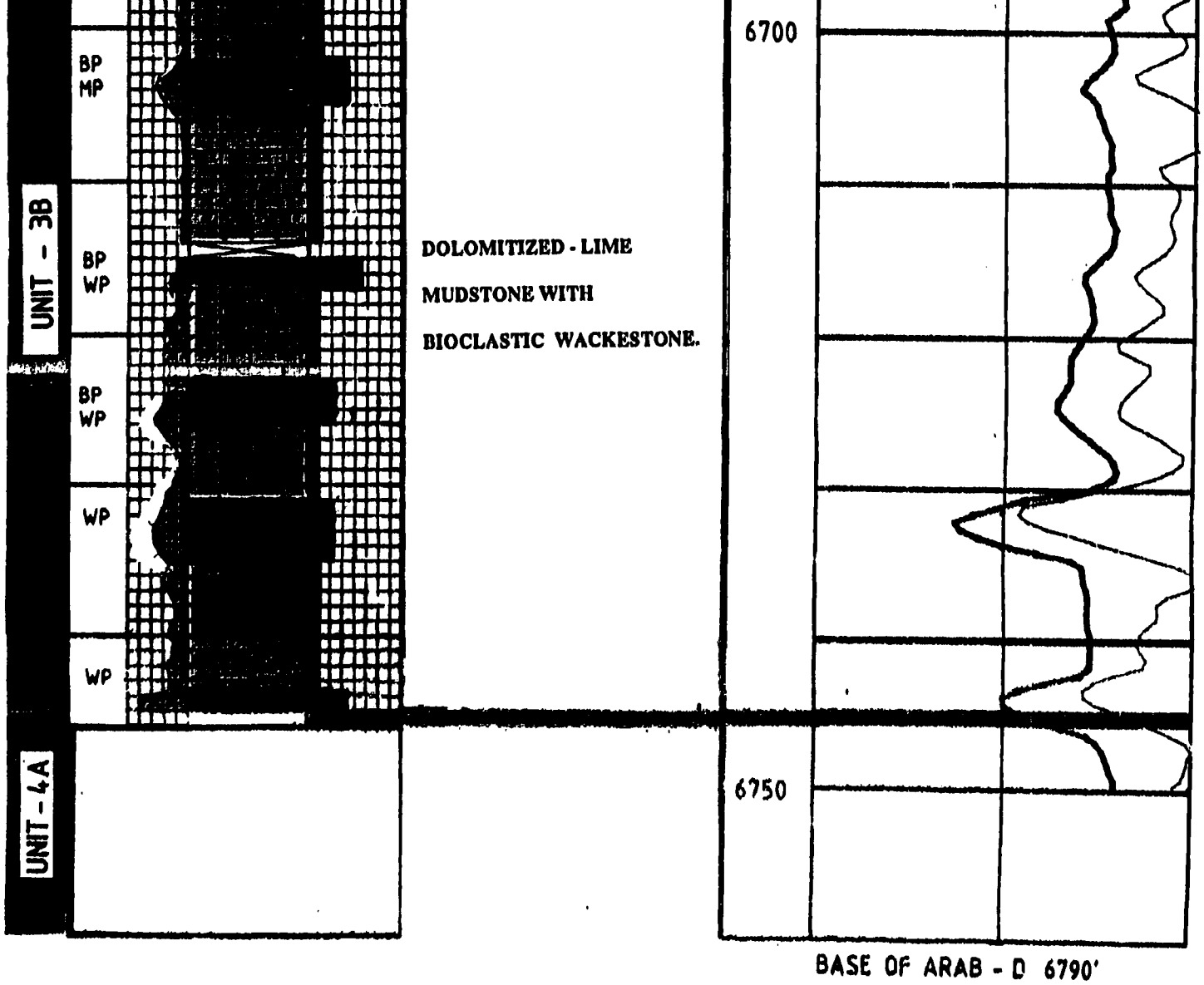


Figure 19. Lithic log of the UTMN-587 ARAB-D Limestone Member.

for lithology determination after the necessary corrections had been made on the logs. Both lithology, and porosity characteristics are plotted on the lithic log. Similarly, a total of 99 thin sections were prepared from the available core samples of the Arab-D Limestone Member in the UTMN-628 well. Since exposure of these preserved cores to air had to be kept to the minimum, a quick macrodescription during plug drilling and petrographic analysis of the plug ends were carried out. The lithological properties and the extrapolated zone boundaries are shown on the lithic log (Fig. 20).

III.1 LITHOFACIES ANALYSIS

Lithological analysis of the Arab-D Limestone Member has led to the recognition of units and sub-units from top to bottom as follows:

Unit 1: This unit is only 8 feet thick in the well UTMN-587, and is represented by a thin dolomite bed followed downward by a thin anhydrite layer of equal thickness which rests on Unit 2A with a very sharp contact. The dolomite layer is recognized by a FDC-CNL peak between the underlying anhydrite layer and the overlying Arab-D Anhydrite Bed. Porosity of the dolomite layer is estimated to be less than 5%.

Unit 1 in the well UTMN-628 is represented by only a 4 feet-thick dolomitic limestone bed, with an average porosity of 7%. Its contacts with both the underlying Unit 2 and the overlying Arab-D Anhydrite bed is very sharp due to an abrupt porosity change.

Unit 2A: This unit is mainly composed of grainstones (43-53 feet thick) with a very sharp upper and a rather sharp lower contacts in both wells.

Considering the allochem domination, three sub-units of almost equal thickness have been differentiated in the Unit 2A from top to bottom as follows:

1. Bioclast grainstone: The dominant allochems here are bioclasts and this sub-unit is highlighted by the existence of oolites and pellets (probably micritized oolites). Such oolitic and pelletoidal grainstones are not common in other sub-units or units of the Arab-D Limestone Member.

2. Alternating Bioclast grainstone and dolomitic limestones: This sub-unit forms the heterogeneous central part of Unit 2A. Dolomitic interbeds can easily be recognized from both the well logs, and core analysis.

3. Bioclast/Intraclast grainstone: Consisting dominantly of both intraclasts and bioclasts with an apparant prevalance of the former (over 30%).

Although dolomite interbeds are dominant in the middle sub-unit, some thin dolomitic streaks also exist in the other two sub-units. These are seen more in the UTMN-628 well than in the UTMN-587 well, where the thickness of sub-unit 2A is 53 feet in the latter, but decreases to 43 feet in the former well. The most common bioclasts here are mainly composed of *Miliolid*, Textulariid, *echinodermal*, and algal remains. Grains are generally subrounded with an average radii of 500 microns and a maximum of 1 cm.

Sub-unit 2A is the best reservoir interval of the Arab-D Limestone Member, having an average porosity of over 25%. Pore structures of the relevant rock types are discussed later (Chapter 3).

Unit 2B: This unit is about 80 feet-thick and 82 feet in the UTMN-587 and 79 feet in UTMN-628 well consists of rather heterogeneous lithologies with a very distinct, upper contact and a less apparent lower one. It is mainly composed of Bioclastic/intraclastic/grainstone with some dolomite in well 587. Dolomite (in the upper 30 feet) and dolomitic carbonate mudstone intercalations is the dominant lithology of this unit in the UTMN-628 well. Consequently, two subunits are distinguished:

1. A dolomitic upper interval (about 30 feet thick), and
2. A heterogeneous carbonat mudstone interval (about 50 feet thick).

Unit 2B is a transitional in composition between the more muddy Unit 3 below and the mud-free Unit 2A above. Therefore, mud-bearing rock types such as packstone, wackestone, and mudstone are encountered in the lower part of this unit in Well-628. Moderately and poorly sorted, subrounded to subangular grains are common and range from 150 to 1000 microns in diameter. Stromatoporoidal fragments of 1 to 7 cm in diameter were observed in the lower part of the UTMN-587 well, where the most common bioclasts are miliolid, *Clypeina jurassica*, and echinoidermal remains.

A thin horizon of siliceous dolomite appeared between the depths of 6630 and 6632 feet in the UTMN-628 well. This horizon was reported by Powers [1952] as a marker which can be traced over most of the Ghawar field.

Unit 2B is a good reservoir interval with an average porosity of 20%, but lesser porosity is developed downword with the increase of the lithologic heterogeneity.

Unit 3A: This unit ranges in thickness between 55 and 60 feet and (55 feet in the UTMN-587 well and 60 feet in UTMN-628) is composed largely of dolomite and dolomitic mudstone. A grainstone streak (about 6 feet thick) distinctly marks the bottom contact of this unit in both wells, while its upper contact is gradual with abundant grainstone streaks. The grains in the streaks are mainly pelletoids, intraclasts, and bioclasts. The fossil grains are brachiopod, echinodermal, benthonic Foraminferidal, stromatoporoidal, and poriferal remains. Dolomitization is effective in aphanitic rocks as replacement of mudstone (cf. Powers, 1962).

Unit 3A has an average porosity of 7%, which increases slightly in the dolomitic intervals and decreases slightly in the limestone streaks. Due to poorly sorted grains and the existence of carbonate mud in the samples, the limestone streaks generally have a poor porosity.

Unit 3B: This unit is composed of tight limestones (58 feet thick in both wells), with a sharp and distinct upper contact and a rather vague lower one. The bottom boudary is taken at the base of a limestone streak which is prominent in the well logs of UTMN-587 and recognizable (through less prominent) in UTMN-628.

Dolomitic mudstone/wackestone is the dominant lithology, but dolomitization is less effective here than in the Unit 3A. Some packstone/wackestone interbeds exist, but both their thicknesses and porosities fall short of forming a reservoir except for a single, 5-feet thick streak which is laterally continuous in both wells, and shows a porosity of 14%. The remaining intervals are rather uniform with an average porosity of 5%.

This Unit is generally differentiated from the overlying one by an abrupt reduction in average porosity, and a rather homogeneous stratification without frequent peaks on the porosity logs.

Unit 4A: This unit is about 25 feet thick (UTHN-628 well) and is dominantly composed of tight limestone with a sharp upper contact. The top 5 feet of the zone are composed of poorly porous wackestone/mudstone followed downward by a 20 feet of pure dolomite.

The recognized bioclasts in the two wells are mainly miliolid, Textulariid, bryozoan, poriferal, coralline echinodermal and algal remains. Of these *Rotalina sp. Nautiloculina spp., Quinqueloculina spp., Pyrgo spp., Triloculina spp., Trochammina sp.,*

Psudocyclammina spp., Pfenderina spp, Ammodiscus sp., Bramkampella spp., Kurnubia sp., Clypyeina jurassica, and Valvulinella spp. are worthy of mention.

III.2 MICROFACIES AND DIAGENETIC ANALYSIS

III.2.1 General Discussion:

Analysing all of the paleontological and the lithological characteristics of sedimentary rocks in thin sections, peels and/or polished slabs are included under the term microfacies analysis (Brown, 1943, Flugel, 1982). This analysis is the most important of the various levels of observation possible in the broad field of carbonate petrology (Wilson, 1975). Such importance is derived from the fact that microfacies analysis can lead to the interpretation of both the age and the paleoenvironmental conditions of deposition by using both the fossil content and the lithological characteristics with equal weight.

The importance of microfacies analysis can be further enhanced by the fact that it can be used for correlating the local microfacies with the standard microfacies of

Wilson (1975). This can provide a sort of standardization that enhances the construction of regional facies models, and can contribute to better understanding of the related sedimentary basins.

The correlation of the local microfacies with the standard ones is usually difficult because of the susceptibility of the limestones and dolomites to diagenetic alteration such as neomorphism, cementation and mineralogical replacement. However, the standard microfacies are broad frameworks that can accommodate local environmental variations but keep its applicability.

III.2.2 Microfacies and Diagenetic Analysis of the Studied Section:

The studied section was found to be dominated by two main microfacies as follows:

III.2.2.1. The Nautiloculina/Kurnubia Grainstone Microfacies

This microfacies represents the uppermost part of the Arab-D Limestone Member, and occupies an interval of 40-130 feet in thickness (between the drilled depths 6501 ft and

6634 ft in well # 587 and an interval between the drilled depths 6519 ft and 6559 ft in well # 628). It consists of bioclastic packstone/grainstone in which the over-packed skeletal grains are represented mainly by both superficial and well developed ooids, peloids, intraclasts and different skeletal fragments. The matrix is almost absent except for some patches. The grains are evenly lined with a fine drusy cement suggesting a shallow marine environment. This is supported by the occurrence of rhomboid dolomite crystals which are probably of a supratidal origin.

This microfacies mainly consists of grainstone where the diameter of the grains ranges between 500-1000 μ. The grains are clean, washed and moderately sorted and are represented by bioclasts, intraclasts, oolites and pellets. The term bioclast is used here in reference to skeletal fragments (such as Foraminiferid, algal, and echinodermal remains), while the term intraclast is used for any subrounded to subangular grains of lithological rather than biological origin and is different from the surrounding matrix. The grain size varies from 150 μ to 1 cm, and is commonly in the range of 600 μ. Such variation in the grain size, shape and sorting plays the major role in controlling the pore geometry. A photomicrograph in Figure 21 taken by Scanning Electron Microscope (SEM) shows a bioclastic intraclastic grainstone (sample 62/587). Here sorting causes smaller grains to fill the inergranular porosity and reduces the voids between the grains. Figure 22 shows a thin

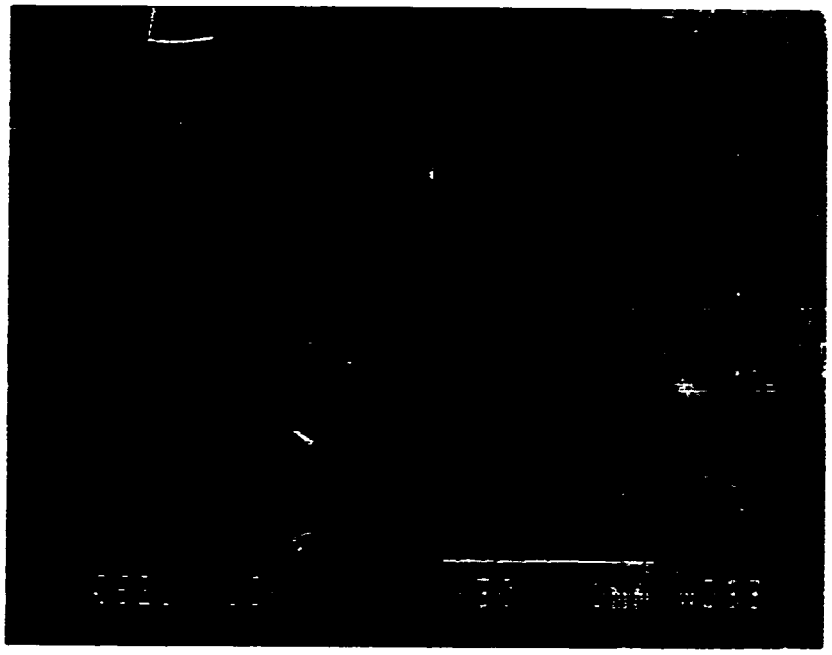


Figure 21. SEM photomicrograph of a bioclastic intraclast grainstone (Sample 62/587). Poorly sorting causes smaller grains to fill and reduce the voids between coarser grains.

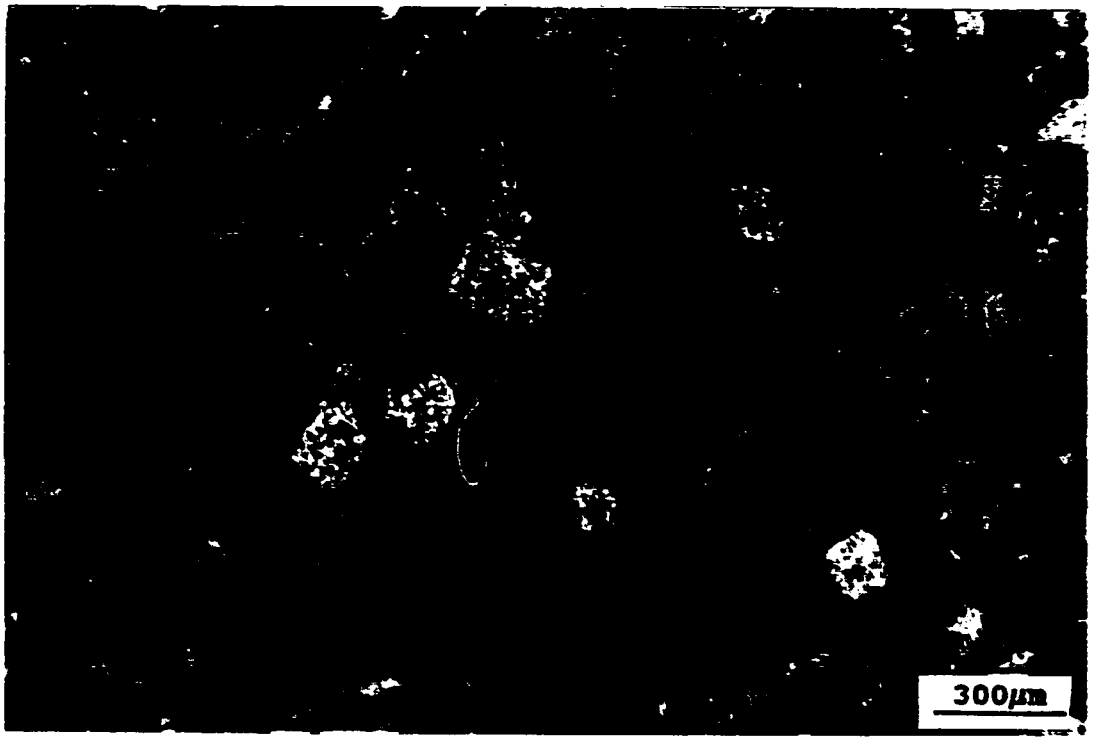


Figure 22. Thin section photograph of the same sample shown in Figure 21. Smaller grains (<200 microns) are mainly forminifera and coarser grains (.500 microns) are intraclasts. Pink areas represent pore spaces between the grains. Transmitted, plain polarized light.

section photomicrograph of the same samplewhich is shown in Figure 21 where bioclasts, and smaller grains (<500 microns) or intraclasts (including dolomite rhombs) are separated by pink areas representing the pore spaces between the grains.

The term oolite is applied for any spherical to ellipsoidal grain with a nucleus of any origin surrounded by concentric layers, and a diameter up to 700 μ, while the term pellet is used to include subangular to subrounded grains without any internal structure and with a diameter of about 130 μ. Most of these well sorted oolites are coated by isopach drusy crystalline cement. Figure 23 shows a photomicrograph of a moderately to well sorted, bioclastic oolite grainstone (sample 2/628) and Figure 24 shows an SEM photomicrograph, of the same sample where the isopach drusy crystalline cement is clear. In general the grainstone lithofacies has a total porosity of 20 to 30%, but this is reduced by the lime mud filling, drusy, isopachous calcite cementation and dolimitization (Fig. 25). This last-mentioned figure is an SEM photomicrograph showing drusy isopachious calcite cement coating the grains, and a plugged dolomite crystal which is reducing the porosity. Several types of porosity are developed in this microfacies including: (1) interparticle porosity: (i. e. Porosity between the grains), which is volumetrically the most important type of porosity for the storage of oil in the Arab-D reservoir. Figure 26 is a thin section

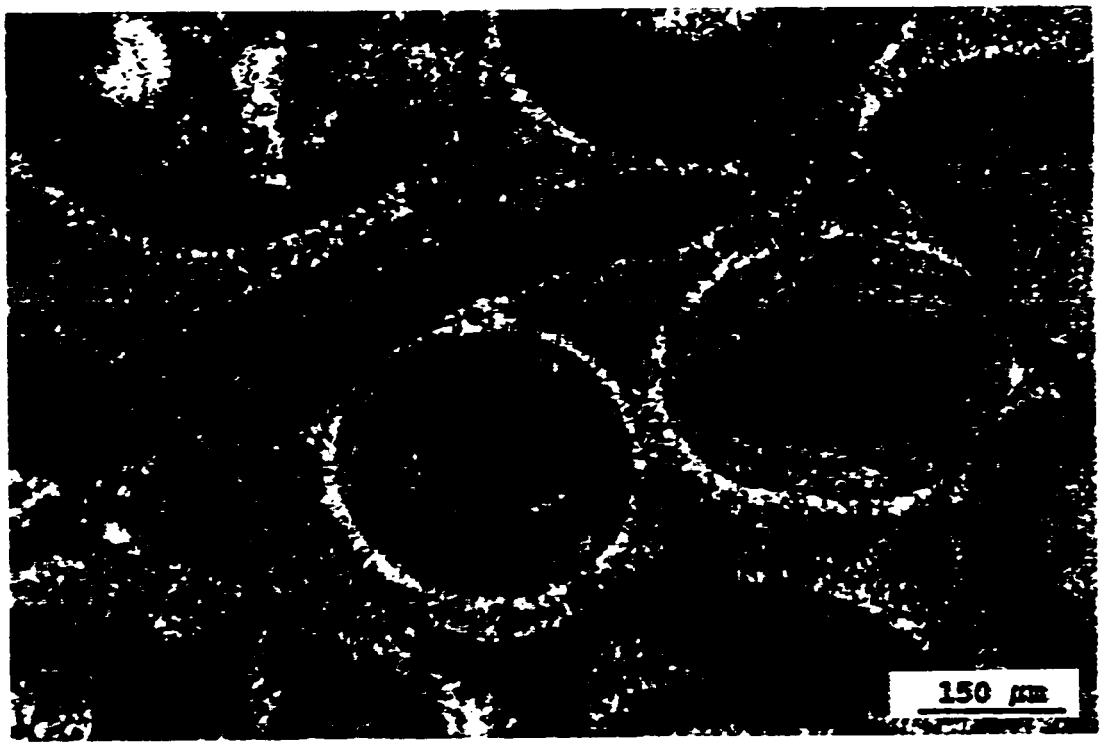


Figure 23. Moderately to well sorted, bioclastic oolite grainstone (Sample 2/628). Transmittted, plain polarized light.

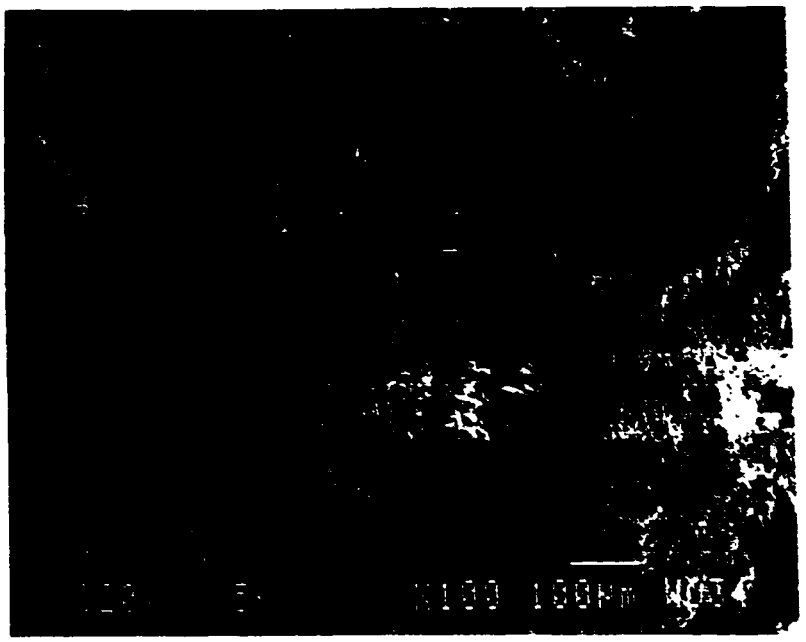


Figure 24. SEM photomicrograph, of the same sample shown in Figure 23. Isopachous drusy crystalline cement coast the grains.

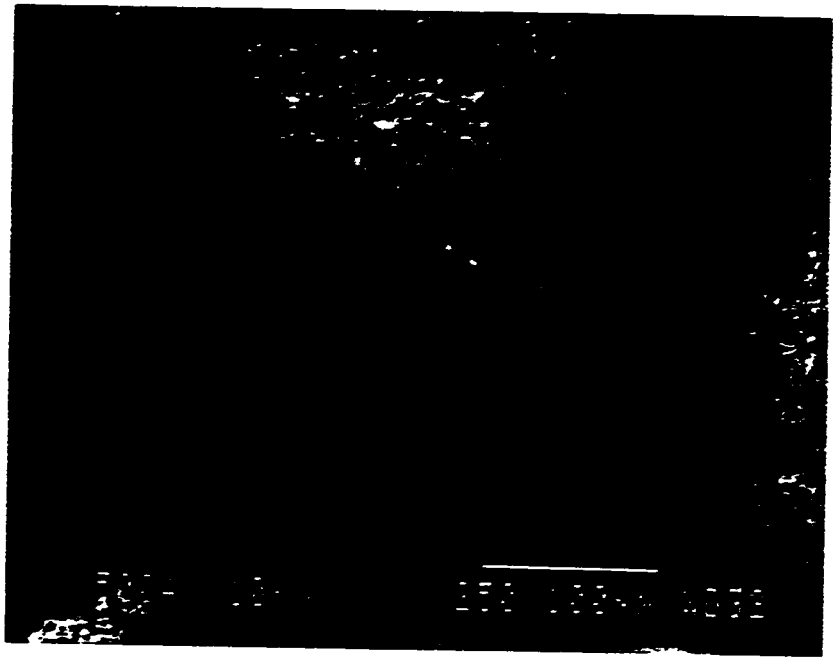


Figure 25. A well-developed dolomite crystal plugs the space between limestone grains in bioclastic intraclast grainstone (Sample 50/587).

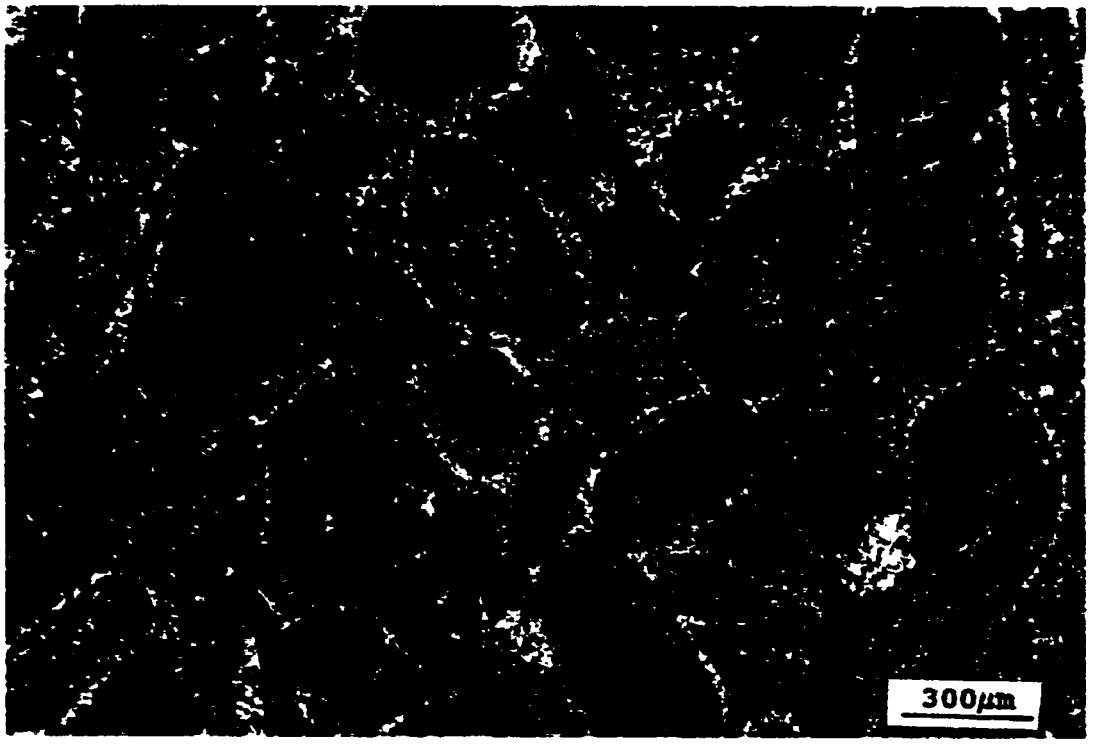


Figure 26. Thin section photomicrograph of superficial oolitic grainstone (Sample 10/587) showing interparticle and intraparticle porosities (blue color).

photomicrograph of an oolitic grainstone (Sample 10/587) from a depth of 6511.4 feet. Grains are subrounded to rounded and calcite-cemented. The blue colored areas show both the inter-and-intraparticle porositites in the rock. The pore sizes vary between 50 and 300 microns; (2) intraparticle porosity: (i. e. Porosity within the grains), where a skeletal network creates effective porosity; (3) vuggy or microvuggy porosity: (i.e. irregular voids due to solution activity). Sometimes their sizes reach upto 1-2 cm especially in muddy lithofacies (Fig. 27); (4) intercrystalline porosity, which develops between the crystals as a result of late diagenesis recrystallization. The porosity ranges between 5 and 10% and it may reach as high as 15% (Fig. 28) The three dimensional geometry of the intercrystal sheet-like pores can be seen clearly, with a visual porosity of 10 to 15% in this crystalline dolomite (sample 80/628) from the lowr part of Unit 2B at a depth of 6629.9 feet; and (5) fracture porosity, which is a very occasional porosity type in the Arab-D Limestone Member and appears only in the form of microfractures. Figures 29 and 30, show plane-polarized and fluorescent light images of a tight dolomite, respectively. The microfractures and the micropassageways between the dolomite crystals became only visible when fluorescence microscopy was used.

The Fossil content of this microfacies is represented by Textulariid, Miliolid, and Rotaliid (Foraminifrida), as well as by abundant bryozoan, algal and coralline remains. Worthy of mention among these are *kurnubia spp. Nutiloculina spp., Pfendrina spp., Psudocyclammina spp., Trocammina sp., Bramkampella spp., Clypeina jurassica.*. These fossils suggest a Kimmeridgian-Tithonian age. This microfacies is here correlated with the Standard Microfacies No. 18 of Wilson (1975) (Fig. 31), and hence its paleodepositional

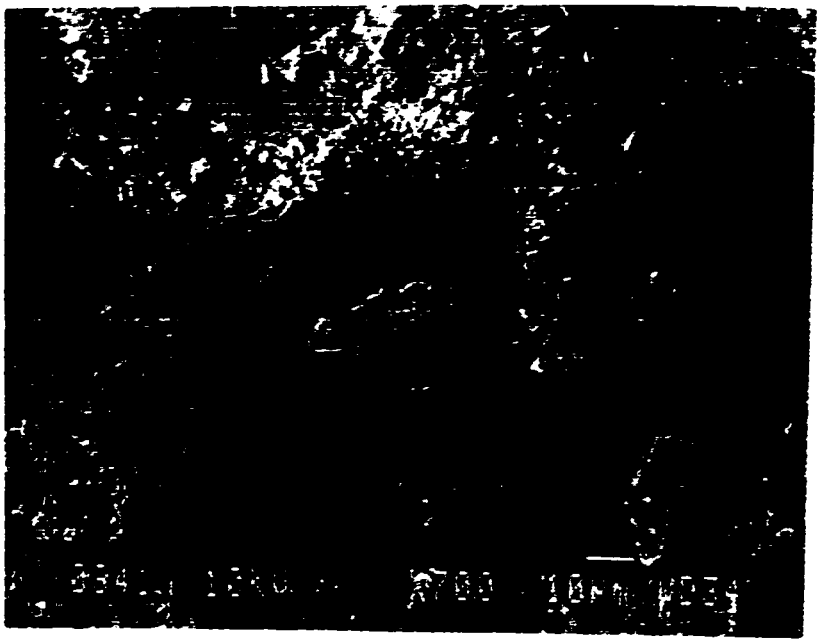


Figure 27. SEM photomicrograph shows the microvuggy porosity in calcite mitrix (Sample 84/587).

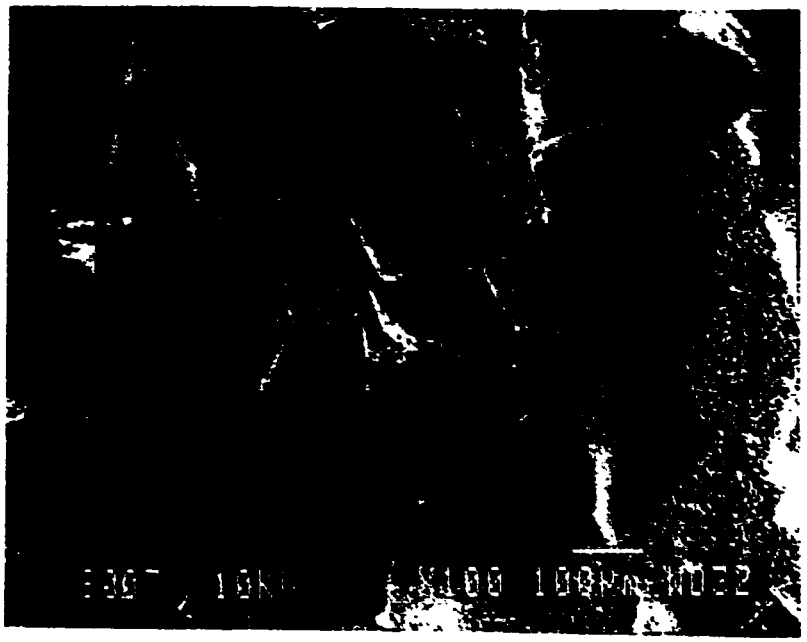


Figure 28. SEM photomicrograph of epoxy pore cast for Sample 80/628 shows sheet-like, uniform, intercrystal pores in crystalline dolomite.

Figure 29. Thin sectionphotomicrograph of a tight dolomite (plane polarized light).

Figure 30. Thin section of the sample presented in Figure 29 showing microfractures and micropassageways between dolomite crystals (fluorescent light).

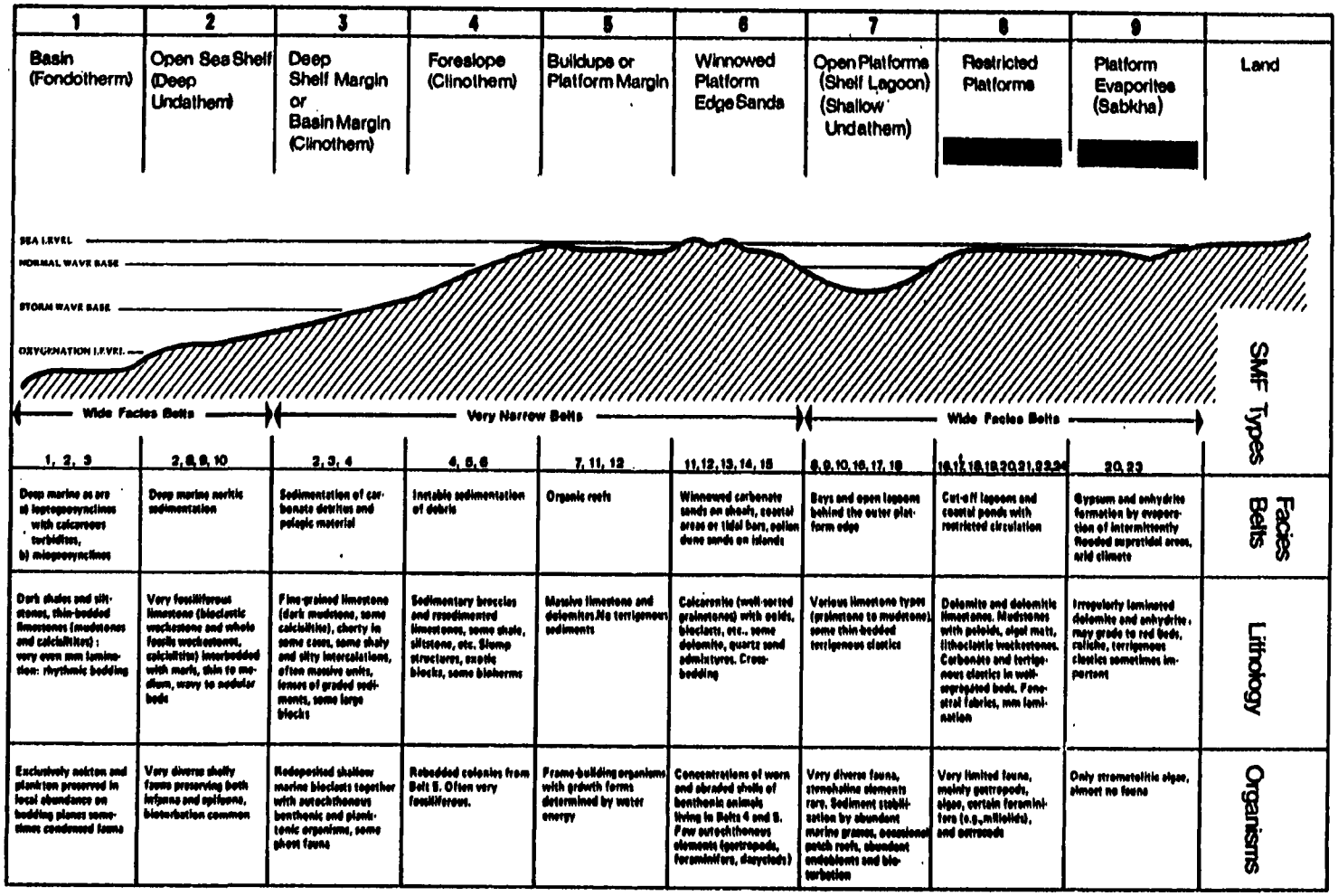


Figure 31. Facies scheme after Wilson (1975). Sequence of the Standard Microfacies Types.

environment is interpreted as to represent an open marine platform, usually found in open lagoons behind the outer platform edge. The variability and abundance of organic remains and the presence of solitary corals suggests a normal marine salinity.

III.2.2.2. The Pseudocyclammina/Kurnubia, Dolomitic Wackestone/Packstone Microfacies:

This microfacies underlies the first one and characterizes the lower part of the Arab-D Limestone Member. It is represented mainly by wackestone/packstone which is highly dolomitized (Fig. 32). The skeletal grains are mainly bioclasts and coquinas of essentially whole shells. Peloids and intraclasts are also present but in a lesser amount. The matrix is represented mainly by micrite (Fig. 33). The size of these micrite crystals ranges between 1 to 4 microns, usually anhedral to subhedral in shape with planar and curved grain contacts. The dominant porosity types in this microfacies are the intercrystalline, the fracture and the fenestral porosities, the first two types of which have already been expalined in the first microfacies. The fenestral porosity however results from openings within the mud supported or grain supported fabrics as a results of biological activity. The dolomitization is extensive, and both the matrix and the grains are partially replaced. The dolomite crystals are large and clear, suggesting a supratidal environment. Dolomite of the supratidal environment developed as a result of Mg-rich fluids attacking nearby limestonses (known as the evaporative reflux model). These Mg-rich fluids were drived from the loss of Ca though the evaporative precipitation of gypsum and anhydrite in tidal flats, and supratidal areas (Sabkhas).

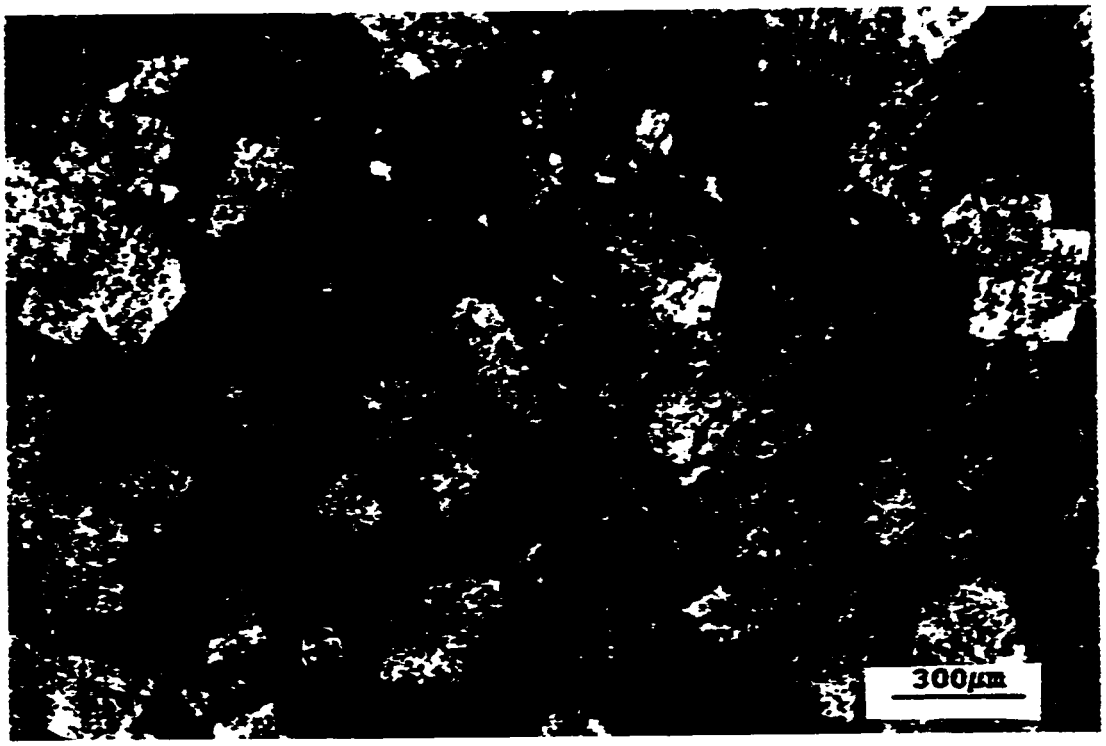


Figure 32. Thin section photomicrograph of sample 75/587 shows that dolomitization occurred in both aphanetic mud (dark brown) and in the grains, but it is more extensive in muddy parts. Transmitted plain polarized light.

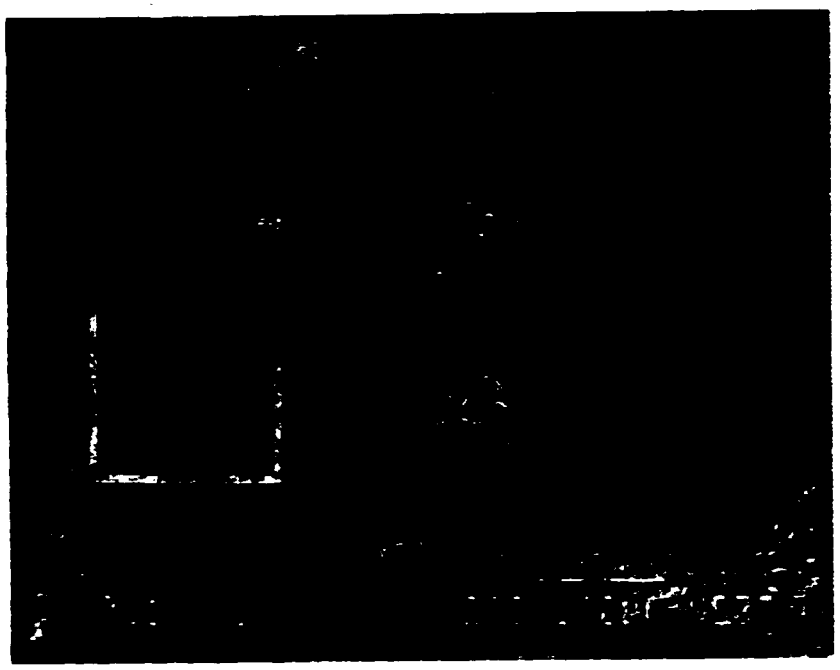


Figure 33. SEM photomicrograph shows the microcrystalline calcite (micrite) and microporosity within the dolomite crystals shown in the above figure.

This microfacies occupies an interval that ranges between 107-197 feet thick (between the drilled depths 6635 ft and 6742 ft in well # 587 and an interval between the drilled depths 6560 ft and 6757 ft in well # 628) and is dominated by the skeletal remains of *Kurnubia spp.*, *Clypeina jurassica*, *Nutiloculina spp.* and *Psudocyyclammina spp.* which suggest a Kimmeridgian-Tithonian age.

This microfacies is here correlated with the Standard Microfacies no. 9 of Wilson 1975 (Fig. 31), and hence is interpreted to have been deposited in a shallow shelf lagoon, located in straits and bays behind the outer platform edge.

CHAPTER 4

SUMMARY AND CONCLUSION

A total of 193 cored samples were collected from the Arab-D Limestone Member of both the 587 and the 628 Uthmaniyah wells. These were studied in hand specimen, thin-sectioned and examined under the binocular polarizing microscope for the lithological diagenetic and microfacies analysis of this very important rock unit. Lithologically, the succession is divided into six units from top to bottom as follows:-

1. Unit 1 is represented by 8 feet of thin anhydrite in well 587 and 4 feet of dolomitic Limestone in well 628 (with porosity ranging from 5-7% in the latter well).

2. Unit 2A is represented by 53 feet of Bioclast/Interclast grainstone in well 587 and 43 feet of alternating Bioclast grainstone and some dolomitic Limestone in well 628. This unit is the best reservoir interval of the Arab-D Limestone Member, having an average porosity of over 25%.

3. Unit 2B is represented by about 82 feet of Bioclastic/interclastic grainstone with some dolomitic Limestone in well 587 and 79 feet of dolomitic intraclaslic packstone/wackestone in well 628. (with an average porosity of about 20%).

4. Unit 3A is represented by 55 feet of bioclastic packstone in well 587 and 60 feet of dolomite and dolomitic Mudstone in well 628. (with an average porosity of about 10%).

5. Unit 3B is represented by 58 feet of dolomitic mudstone/wackestone as the dominant lithology (with an average porosity of 6%) in both wells.

6. Unit 4A is represented in well 628 by 25 feet of wackestone/mudstone and pure dolomite with an average porosity of about 6%. Data about this unit in well 587 was not available at th time of the study.

The main diagenetic changes observed in the succession are limited to cementation, micritization, dolomitization and dissolution. Such changes have affected the reservoir characteristics of the Arab-D Limestone Member as follows:

1 In grainstones cementation reduced the porosity.

2. In some intervals micritization masked the primary texture of the rock and caused more reduction in porosity.

3. Late dissolution in some intervals enlarged the pore spaces.

4. Dolomitization in mudstone/wackestone facies increased the porosity while it decreased it in grainstone facies.

Similarly, the Microfacies analysis of the succession has resulted in recognition of two distinctive microfacies (from top downwards) as follows:

1. The Nautiloculina/Kurnubia Grainstone Microfacies

This microfacies represents the uppermost part of the Arab-D Limestone Member. It occupies an interval between the drilled depths 6501 ft. and 6634 ft. in well # 587 and between the drilled depths 6519 ft. and 6559 ft. in well # 628. It consists of bioclastic packstone/grainstone in which the skeletal grains are represented mainly by both superficial and well developed ooids, peloids, intraclasts and different skeletal fragments. In general, this Microfacies has a total porosity of 20 - 30%, but this is reduced by either/or the lime mud filling, drusy, isopapchous calcite cementation and dolimitization. Several types of porosity are developed in this microfacies including both inter-and intraparticle porosity, both vuggy and microvuggy porosity and intercrystalline porosity.

The Fossil content is represented by textulariid, miliolid, and rotaliid (Foraminifrida) remains, as well as by abundant bryozoan, algal and coralline skeletal fragments. These fossils suggest a Kimmeridgian-Tithonian age. This microfacies is here correlated with the Standard Microfacies No. 18 of Wilson (1975) and hence its paleodepositional environment is interpreted as an open marine platform, usually found in open lagoons behind the outer platform edge.

2. The Pseudocyclammina/Kurnubia, Dolomitic Wackestone/Packstone Microfacies:

This follows the previous microfacies downwardly and is dominated by highly dolomitized wackestone/packstone in which the skeletal grains are mainly bioclasts, with

minor peloids and intraclasts. The dominant porosity here is the intercrystalline, the fracture and the fenestral types. This microfacies occupies an interval between the drilled depths 6635 ft. and 6742 ft. in well # 587 and between the drilled depths 6560 ft. and 6757 ft. in well # 628. The presence of *Kurnubia-spp., Nutiloculina spp. Psudocyyclammina spp. and Clypeina jurassica,* suggests a Kimmeridgian-Tithonian age.

This microfacies is here correlated with the Standard Microfacies no.9 of Wilson 1975, and hence is interpreted to have been deposited in a shallow shelf lagoon, located in straits and bays behind the outer platform edge.

CHAPTER 5

REFERENCES

Adams, A. E., W. S. Mackenzie, C. Guilford, 1984, Atlas of Sedimentary Rocks under the Microscope; ELBS (ed.), Longman, p. 104.

Al-Naqib, K. M., 1967, Geology of the Arabian Peninsula, South western Iraq, U.S.G.S. Prof. Paper 560-G, p. 54.

Al-Sharhan, A. S., and C. G. Kendall, 1986, Precambrian to Jurassic Rocks of Arabian Gulf and Adjacent Areas: Their Facies, Depositional Setting and Hydrocarbon Habitat: Am. Assoc. Petr. Geol. Bull., v. 70, no. 8, p. 977-1002.

Al-Sharhan, A. S., 1989, Petroleum Geology of the United Arab Emirates; Jour. Petro. Geol. v. 12(3), p. 253-288.

Alrefai, B. H., 1967, The stratigraphy and sedimentation of Jurassic and Lower Cretaceous of Kuwait: 6th Arab Petroleum Congress, Baghdad, Iraq, p. 10.

Antbony, E. L., Morris, 1978, Arabian Gulf, American Association of Petroleum Geologist, Tulsa, Oklahoma, U.S.A.

Arabian American Oil Company Staff, 1959, Ghawar oil field, Saudi Arabia, AAPG Bull., v. 43, p. 434-454.

Arabian American Oil Company (ARAMCO), 1975, Eastern Arabia and adjacent areas, in Schlumberger Well Evaluation Conference, arabia: Schlumberger, p. 9-25.

Argyriadis, I., P. de Graciansky, J. Marcoux, and L. Ricou, 1980, The opening of the Mesozoic Tethys between Eurasia and Arabia-Africa: 26th Int. Geol. Cong. (Paris), Colloque C5, p. 199-214.

Arkell, W. J., 1952, Jurassic ammonites from Jebel Tuwaiq, central Arabia, with stratigraphical introduction by R. A. Bramkamp and Max Steineke: Roy. Soc. London Philos. Trans, Ser. B, v. 236, p. 241-313.

Arkell, W. J., 1956, Jurassic Geology of the World: Oliver and Boyd Ltd. Edinburgh, p. 806.

Avedissian, Y., 1980, Plate tectonics and petroleum occurrences in the Persisan Gulf (abs.); 26th Int. Geol. Cong. (Paris), no. B, v. 111, p. 1044.

Ayres, M. G., M. Bilal, R W. Jones, L. W. Slentz, M. Tartir, and A. O. Wilson, 1982, Hydrocarbon habitat in main producing areas, Saudi Arabia: AAPG Bull., v. 66, p. 1-9.

Banner, F. T., and G. V. Wood, 1964, Lower Cretaceous-Upper Jurassic stratigraphy of Umm Shaif field, Abu Dhabi Marine Areas, Trucial Coast, Arabia: AAPG Bill., v. 48, p. 191-206.

Beydoun, Z. R., 1964, The strategraphy and Structure of the East Aden Protoctorate; Report XXIddst. Int. Geol. Cong. Copenhagen, part XXI, p. 131-149.

Beydoun, Z. R., 1966, Geology of the Arabian Peninsula, Eastern Aden Protoctorate and part of Dhufar; U.S.G.S Prof. Paper 560H; U.S. Governament printing Off., Washington, p. 49.

Beydoun, Z. R. and Greenwood J.E.G.W., 1968, Protectorat D'Aden et Dhufar; Lexique Stratigraphique International, v. III, fasc. 10, p. 2.

Bathurst, R.G.C., 1971, Carbonat sediments and their diagensis 2nd ed.: Developments in Sedimenatology, v. 12, Amsterdam, Elsevier, p. 658.

Beydoun, Z. R., 1973, The petroleum Geology of the Middle East: A synopsis, P. 1-99.

Beydoun, Z. R., and H. V. Dunnington, 1975, The petroleum geology and resources of the Middle East: London, Scientific Press, p. 101.

Beydoun, Z. R., 1988, The Middle East: Regional Geology and Petroleum Resources; Scientific Press, p 292.

Billo, S. M., 1983, Petroleum geology of the Arabian Peninsula: Oil and Gas Journal, P. 91-100.

Bozorgnia, F., and S. Banafti, 1964, Microfacies and microorganisms of Paleozoic through Tertiary sediments of some parts of Iran, National Iranian Oil Company, Tehran, Iran. plts 1-158, p. 1-22.

Bramkamp, R. A., and N. J. Sander, 1938, Stratigraphic relations of Arabian Jurassic Oil; in L. W. Week (ed.), Habitat of Oil, a Symposium: Am. Assoc. Petrol. Geol., p. 1294-1339.

Bramkamp, R. A., and Powers, R. W., 1955, Two Persian Gulf lagoons (abst.): Jour. Sed. Petrology, v. 25, no. 2, p. 139-140.

Bramkamp, R. A., and R. A. Powers, 1958, Classifications of Arabian carbonate rocks: Geol. Soc. America Bull., v. 69, p. 1305-1317.

Bricker, O.P. (ed), 1971, Carbonate Cement, Johns Hopkins University Studies in Geology, London, no. 19, p. 376.

Broote, D.R., D. Mow, and R. I. Waite, 1990, Structural evolution of the Suneineh Foreland, Central Oman Mountains; In Robertson, A.H.F.; Searle, M. P. and Ries, A. C.: Geology and Tectonics of the Oman Region; Geological Society, London, Special Publication, no. 49, p. 495-519.

Brown, J. S., 1943, Suggested use of the word microfacies. Econ. Geol. 38, 325, New Haven.

Brown, G. F., and R. G. Coleman, 1972, The tectonic framework of the Arabian Peninsula: 24th International Geological Conference, Montreal, v. 3, p. 300-305.

Choquette, P.W., and L.C. Pray, 1970, Geologic Nomenclature and Classification of porosity in sedimentary carbonates, Am. Assoc. Petroleum Geologists Bulletin, v. 54, p. 207-250.

Clarke, R. H., 1975, Petroleum formation and accumulation in Abu dhabi: 9th Arab Petrol, Cong. (Dubai), Paper no. 120 (B-3), p. 20.

Contrell, D. L., 1987, Detailed Geologic description, Abqaiq 262, Arab-D: Exxon Production Research Company, p. 1-10.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture. Am. Assoc. of Petroleum Geologist. Mem. 1, p. 108-120.

Dunnington, H. V., 1958, Generation, migration, accumulation, and dissipation of oil in norther Iraq; in L. G. Weeks (ed), Habitat of oil, a Symposium: Am. Assoc. Petrol. Geol., p. 1194-1251.

Dunnington, H. V., R. Wetzel, and D. M. Morton, 1959, Iraq, Mesozoic and Paleozoic, Lexique Stratigraphique Internationa, v. III, f. 10a.

Dunnington, H. V., 1967, Stratigraphical distribution of oil fields in the Iraq-Iran-Arabia basin: Inst. Petroleum Jour. v. 53, p. 129-161.

El-Naggar, Z. R., and I. A. Al-Rifaiy, 1972, Stratigraphy and microfacies of tyupe Magwa Formation of Kuwait, Arabia; pt. 1: Rumaila Limestone Member: AAPG Bull., v. 56, p. 1464-1493.

El-Naggar, Z. R., and I. A. Al-Rifaiy, 1972a, Microfacies analysis of the type Magwa Formation of Kuwait, Arabia: 8th Arab Petrol. Cong. (Algiers), Paper no. 95 (B-3), p. 1-101.

El-Naggar, Z. R., and I. A. Al-Rifaiy, 1973, Stratigraphy and microfacies of type Magwa Formation of Kuwait Arabia; pt. 2: Mishrif Limestone Member: Am. Assoc. Petrol. Geol. Bull., v. 57, no. 11, p. 2263-2279

El-Naggar, Z. R., and M. A. Akhdar, 1978, M.S., Stratigraphical and Microfacies Analysis of the Early Cretaceouls Succession in the Saudi Arabia/Kuwait Partitioned zone, Kuwait Univ., p. 190.

Elliott, G. F., 1955, Fossil calcareous algae from the Middle East: Micropaleontology, v. 1, no. 2, p. 125-131.

Ellis, B. F., and A. R. Messaina, 1966, Cataloque of Index Forminifera; special publication, v. 2, the Amer. Mus. Nat. Hist., N. Y.

Flugel, E., 1982, Microfacies Analysis of Limestone. Springer-Verlag, Berlin-Heidelberg, New York, p. 633.

Folk, R. L., 1959, Practical Petrographic Classification of Limestone; AAPG Bull. v. 43, p. 1-38.

Folk, R. L., 1962, Special subdivision of Limestone types, In: Classification of Carbonate Rocks: A Symposium, W. E. Ham (ed.), Am. Assoc. Petroleum Geologist, Mem. 1, p. 62-84.

Glennie, K. W., M.G.Beuf, M.W. Hughes Clark, M. Moody-Stuart, W.F. Pilaar and B. M. Reinhardt , 1974, The Geology of the Oman Mountains: Verhandelingen van het Koninklijk Nederlands geologish mijnbouwkundig Genootschap, 31, p. 423.

Halbouty, M. T., R. E. Meyerhoff, R. H. King, H. D., Dott, Klemme and T. Shabad, 1970, World's giant oil and gas filelds, geologic factors affecting their formation, and basin classification-Part I. Giant oil and gas fields in Halbouty, M. T. (ed.), Geology of Giant Petroleum Fields: Am. Assoc. Petroleum Geologists Mem 14, p. 502-528.

Hassan, A. A., 1963, The distribution of Triassic and Jurassic Formations in the Middle East: 4th Arab Petroleum Cong. Paper no. 25 (B-3), p. 359-368.

Haynes, J. R., 1981, Foraminifera; Macmillan Publishers LTD., p. 433.

Hood, B. F., and W. A. Downie, 1975, Development of the Umm Shaif field in Abu Dhabi: 9th Arab Petroleum Congress, Dubai, Paper 130, p. 7.

Horowitz, A. S., and P. E. Potter, 1971, Introductory Petrography of Fossils; Springer-Veralg, 100 pls, p. 302.

Hudson, R. G., and M. Chatton, 1959, The Musandam Limestone (Jurassic and lower Cretaceous) of Oman, Arabia. Notes Mem. Moyen-Orient, v. 7, p. 69-93.

Ilhan, E., 1967, Toros-Zagros folding and its relations to Middle East oil fields: Am. Assoc. Petrol. Geol. Bull., v. 51, no. 5, p. 651-667.

Illing, L. V., 1954, Bahaman calcareous sands: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 1-95.

Jaber, A. S., 1975, Stratigraphy of the Jurassic succession in the offshore Saudi Arbaia.

James, G. C., and J. G. Wynd, 1965, Stratigraphic Nomenclature of Iranian Oil Consortium Agreement Area: Am. Assoc. Petr. Geol., Bull, v. 49, no. 12, p. 2182-2245.

Johnson, J.A.D., and S. R. Budd, 1975, The geology of the zone B and zone C. Lower Cretaceous limestone reservoirs of Arab Field, Abu Dhabi: 9th Arab Petrol. Cong. (Dubai), Paper no. 109 (B-3), p. 24.

Kamen-Kaye, M., 1970, Geology and productivity of Persian Gulf synclinorium: AAPG Bull., v. 54, p. 2371-2394.

Kanaan, F. M., et al., (stratigraphic committee), 1978, Saudi Arabia code of lithostratigraphic classification and nomenclature: Dir. Gen. Mineral Rsources, Jeddah, Saudi Arabia, Technical Manual, TM-1979-1, p. 15.

Kassler, P., 1973, The structural and geomorphic evolution of the Persian Gulf, in B. H. Purser, (ed.), The Persian Gulf, springer-Verlag, Berlin, p. 11-32.

Kendall, C. G., and W. Schlager, 1981, Carbonates and Relative Changes in Sea Level; Marine Geology, no. 44, p. 181-212.

Kent, P. E., and H. R. Warman, 1972, an environmental review of the world's richest oil-bearing region-the Middle East: 24th Int. Geol. Cong. (Canada) Proc., sec. 5, p. 142-152.

Koop, W. J., and R. Stoneley, 1982, Subsidence history of the Middle East Zagros Basin, Permian to Recent: Phil. Trans. Roy. Sopc. London, A305, p. 149-168.

Krumbein, W. C., L. L. Sloss, 1951, Stratigraphy and Sedimentation, Freeman and Co. Publication, p. 660.

Law, J., 1957, Reason for Persian Gulf oil abundance: Am. Assoc. Petrol. Geol. Bull., v. 41, no. 1, p. 51-69.

Longman, M. W., 1980, Carbonate diagenetic textures from nearsurface diagenetic environments, Am. Assoc of Petroleum Geologists. v. 64, no. 4, p. 461-487.

Majewske, O. P., 1969, Recognition of invertebrate fossil fragments in rocks and thin sections: E. J. Brill, Leiden, pls. 1-106, P. 1-101.

Maync, W., 1965, Some Comments on C. D. Redmond's New Lituolid Foraminifera from Saudi Arabia: Rev. Micropaleontology, v. 8, no. 1, p. 37.

Milliman, J. D., 1974, Marine Carbonate, Berlin-Heidelerg, New York: Spronger-Verlag, p 375.

Milton, D. L, 1967, Geology of the Arabian Penninsula, Kuwait; U.S. Geol. Survey Prof. Paper 560-F, p. 7.

Ministry of Petroleum and Mineral Resources, 1977, Geology of sedimentary rocks east of Arabian Shield, Saudi Arabia: Technical Affairs, Dammam, Saudi Arabia, p. 14.

Mitchell J. C., P. J. Lehmann, D. L. Cantrell, I. A. Al-Jallal, M. A. R. Al-Thagafy, 1988, Giant Oil and Gas Fields, A Core Workshop, SEPM Core Workshop no. 12, Houston, March 19-20.

Morris, A. E. L., 1976, Geology and productivity: Arabian Gulf: Am. Assoc. Petrol. Geol. Foreign Repreint Series, no. 2, p. 266.

Moshrif, M. A., 1987, Sedimentary History and Paleography of Lower and Middle Jurassic Rocks, Central Saudi Arabia. Journ. Petrol. Geol., v. 10 (3), p. 335-350.

Munthe, J., 1991, Guide Book Jurassic field trip: Riyadh area, Saudi Arabia: Saudi ARAMCO - Exploration, p. 1-84.

Murray, R. C., 1960, Origin of porosity in Carbonate rocks: Journal of sedimentary Petrology, v. 30, no. 1, p. 59-84.

Murris, R. J.,1980, Middle East: Stratigraphic Evolution and Oil Habitat. Am. Assoc. Petr. Geol., Bull., v. 64, no. 5, p. 597-618.

Murris, R. J., 1981, Seals for major Middle East Fields (abs.): Am. Assoc. Petrol. Geol. Bull., v. 65, no. 5, p. 984.

Oppel, A., 1856-8. Die Juraformation Englands, Frankreichs und des sudwestlichen Deutschlands (Stuttgart).

Orbigny, Alcide, D'., 1842-51, Paleontologie Francaise; Terrains Jurassiques, v. 1, Cephalopods: Paris. p. 642, pls. 234.

Owen, R. M., and S. M. Nasr, 1958, Stratigraphy of Kuwait-Basra area, in L.G. Weeks (ed), habital of oil; AAPG Symposium, June 1958, p. 1252-1278.

Patton, and O'Connor, 1988, Cretaceous Flexural History of Northern Oman Mountain Foredeep, United Arab Emirates; AAPG Bull., v. 72, no. 7, p. 797-809.

Pennington, D. J., 1981, United Arab Emirates/Qatar; in Well Evaluation Conference, Schlumberger publications, p. 1-32.

Powers, R. W., 1962, Arabian Upper Jurassic Carbonate Reservoir Rocks: in Ham, W. E., (ed), Classification of Carbonate Rocks, Am. Assoc. Petroleum Geol., Memoir 1, p. 122-152.

Powers, R. W., et. al., 1966, Sedimentary geology of Saudi Arabia: U.S. Geol. Survey Prof. Paper 560-D, p. 177.

Powers, R. W., 1968, Saudi Arabia, in L. Dubertret, Lexique stratigraphique, international, Paris, Centre Natl. Recherche, Internat. Geol. Cong. Comm. Stratig., v. 3, Asie, f. 10, p. 177.

Read, J. F., 1985, Carbonate platform facies models, Am. Assoc. of Petroleum Geologists Bulletin, v. 69, no. 1, p. 1-21.

Redmond, C. D., 1964a, The forminiferal family Pfenderinidae in the Jurassic of Saudi Arabia: Micropaleontology, v. 10, no. 2, p. 251-263.

Redmond, C. D., 1964b, Lituolid foraminifera from the Jurassic and Cretaceous of Saudi Arabia: Micropaleontology, v. 10, no. 4, p. 405-414.

Redmond, C. D., 1965, Three New Genera of foraminifera from the Jurassic of Saudi Arabia: Micropaleontology, v. 10, no. 2, p. 133-140.

Saint-marc, P., 1978, Arabian Peninsula, in M. Moullade and A. E. M. Nairn, eds, The Phanerozoic geology of the word; part II, the Mesozoic: Amsterdam, Elsevier, p. 453-462.

Sampo, M.,1969, Microfacies and microfossils of the Zagros area, Southwestern Iran (from pre-Permian to Miocene): E. J. brill, Leiden, pls. 1-105, p. 102.

Sartorio, D., and J. Venturini, 1988, Southern Tethys Biofacies; Agip S.P.A. p. 230.

Sayyab, A., 1973, Stratigraphy of the Cretaceous-Jurassic contacts at Iraq and neighboring area, in Colloque du Jurassique a Luxembourg 1967: Stratigraphie general du Jurassique hors de l'Europe: France, Bur. Recherches Geol, Minieres Mem. 75 (1971), p. 695-700.

Schlumberger, 1976, Well Evaluation Conference, Iran.

Schlumberger Log Interpretation Charts, 1979, Schlumberger Well Surveying Corporation.

Schlumber, 1981, United Arab Emirates and Qatar: Schlumberger Well Evaluation Conference, p.271.

Scholle, P. A., 1978, A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements, and Porosities; AAPG Memoir 27, p. 241.

Scholle, P. A., D. G. Bebout, and C. H. Moore, (eds.), 1983, Carbonate Depositional Environments; AAPG Mem. 33, p. 708.

Scoffin, T. P., 1987, an Introduction to crbonate sediments and rocks, Chapman and hall, New York, p. 274.

Setudehnia, A., 1978, The Mesozoic Sequence in South-West Iran and Adjacent Areas: J. Petr. Geol., v. 1, no. 1, p. 3-42.

Seyed-Emami, K., 1975, Jurassic-Cretaceous boundary in Iran: Am. Assoc. Petrol. Geol. Bull., v. 59, no. 2, p. 231-239.

Sharief, F. A., 1982, Geological biblography of the Arabian Gulf: King Saud University: Riyadh, p. 127.

Shurrab, A. H., 1960, Geology of eastern Nejd: 2d Arab Petroleum Cong. (Beirut), v. II, Paper 26.

Steineke, M., and R. A. Bramkamp, 1952, Mesozoic rocks of eastern Saudi Arabia (abs): AAPG Bull., v. 36, p 909.

Steineke, M., R. A. Bramkamp, and N. J. Sander, 1958, Stratigraphic Relations of Arabian Jurassic Oil, Habital of Oil, Am. Assoc. Petrol. Geol., p. 1294-1329.

Stocklin, J., 1968, Structural History and Tectonics of Iran. the Am. Assoc. of Petr. Geol. Bull. v. 52, no. 7, p. 1229-1558.

Sugden, W., and A. J. Strandring, 1975, Qatar Peninsula, Lexique Stratigraphique International; Centre National de la Recherche Sci., Paris, v. III, Fascicule 10b3, p. 120.

Sujkowski, Z. L., 1958, diagenesis: Am. Assoc. Petroleum Geologists Bull., v. 42, no. 11, p. 2692-2717.

Thralls, W. H., 1955, Giant among giants of the Persian Gulf Basin: Arabian American Oil Company, p. 3.

Thralls, W. H., and R. C., Hasson, 1956, Geology and oil resources of eastern Saudi Arabia. Symposium Sobre yacimientos de Petroleo Y Gas. 20th Intern. Geol. Congr., Mexico, 1, p. 9-32.

Tucker, M. E., 1981, Sedimentary Petrolgy, an Introduction; Blackwell Scientific Publications, p.252.

Tucker, M. E., and V. P. Wright, 1990, Carbonate Sedimentology; Blackwell Scientific Publications, p. 482.

Willis, R. P., 1967, Geology of the Arabian Peninsula. Bahrain, U.S.G.S. Prof. Papter 560E, p. 4.

Wilson, A. O., 1981, Jurassic Arab-C and D Carbonate Petroleum reservoir, Qatif field, Saudi Arabia: Society of Petroleum Engineers, Manama, Bahrain, p. 171-177.

Wilson, A. O., 1984, Jurassic source rocks in the western Arabian Gulf area: Seminar on source and Habitat of Petroleum in Arab Countries, OAPEC, Kuwait, p. 9.

Wilson, A. O., 1985, Depositional and diagenetic facies in Jurassic Arab C & D reservoirs, Qatif field, Saudi Arabia, in P. O. Roehl and P. W. Choquette, eds., Carbonate petroleum reservors: New York, Springer-Verlag, p. 319-340.

Wilson, J. L., 1975, Carbonate facies in geologic history Springer-Verlag, New York, p 469.

Wood, G. V., and M. J. Wolfe, 1969, Sabkha cycles in the Arab-D, Arab Formation of the Trucial Coast of Arabia: Sedimentology, v. 12, no. 3-4, p. 165-191.

MICROFACIES

PLATES (1-20)

Plate 1

The Arab Formation (Arab-D Carbonate Member, Well No. 587)

The Nautiloculina/Kurnubia grainstone Microfacies; (Microfacies I)

Fig. 1-16 photomicrographs showing random sections in density packed skeletal grains cemented by isopachous calcitic crystals with some patches of micritic matrix. The skeletal grains include: Textularids (1-11, 13-16); *Quinquloculina spp.* (1,5,9,13), *Pyrgo sp.* (3,6,11), *Triloculina Sp.* (10,11,12), Rotalina sp. (9), Bryozoan remains (7), *Nutiliqulina sp.* (6,8, 11), ooids (7,9-15) and Peloids (3,6,7,9-16).

All C.N. except 16 p.p. light. All X. 55 except (12,14,15,16) X. 28 and (1,5,8) X. 137.

PLATE 1

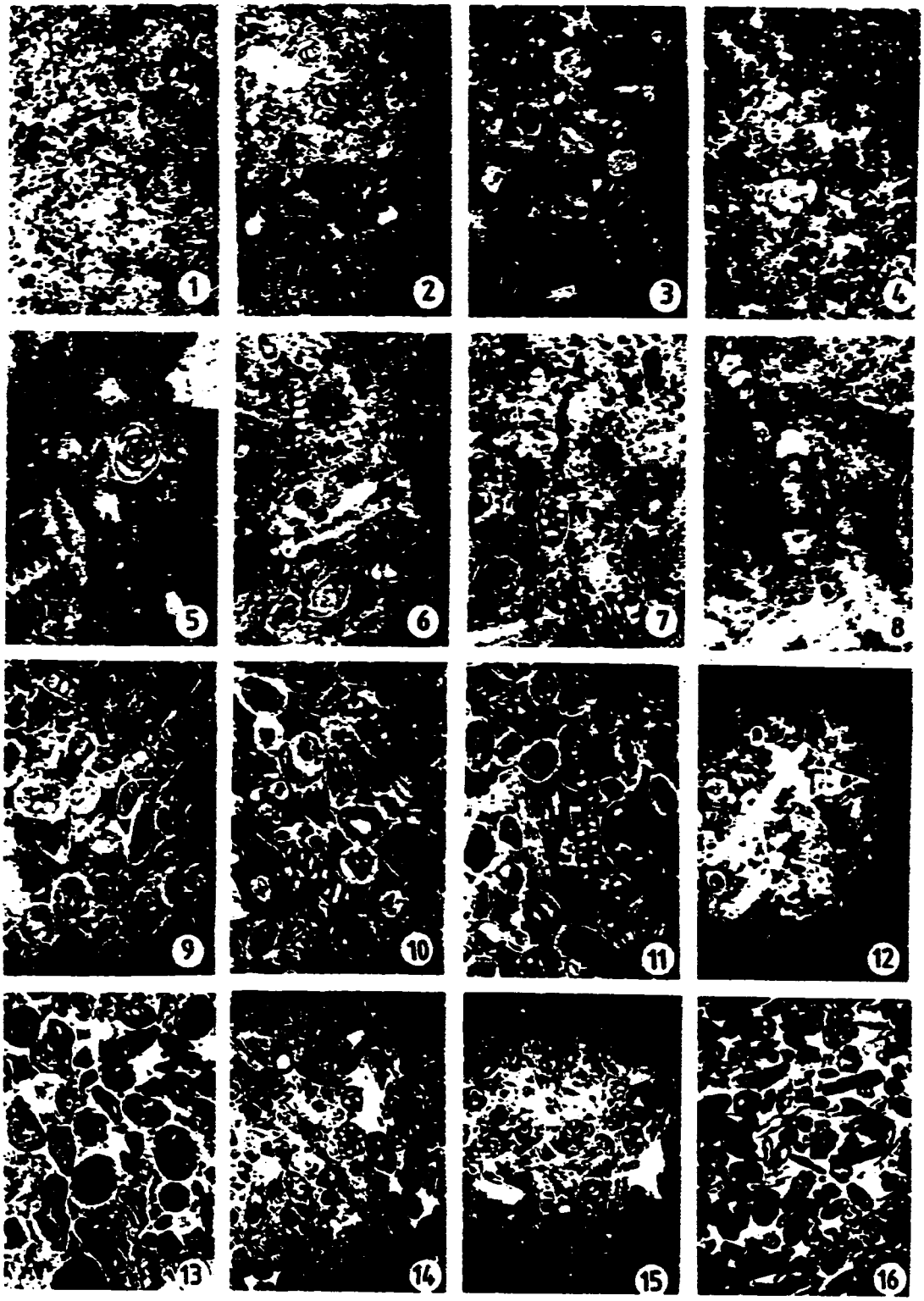


Plate 2

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections in Foraminiferid remains density packed within a disrupted matrix of gypsum and micrite. The Foraminiferid remains include: Textularids (1-7, 11-13, 15-16), *Trocammina sp.* (8,9), *Quinquloculina sp.* (3,6,11,12), *Psudocyclamina sp.* (2,15), Sponges (10), *Nutiliqulina sp.* (2,7), *Pfendrina sp.* (7,12) and peloids (1-7, 11-16).

All C.N. except 11-16 P. P. Light. All X. 55 except (3,4,6,9,14,15) X. 28 and (12) X. 137

PLATE 2

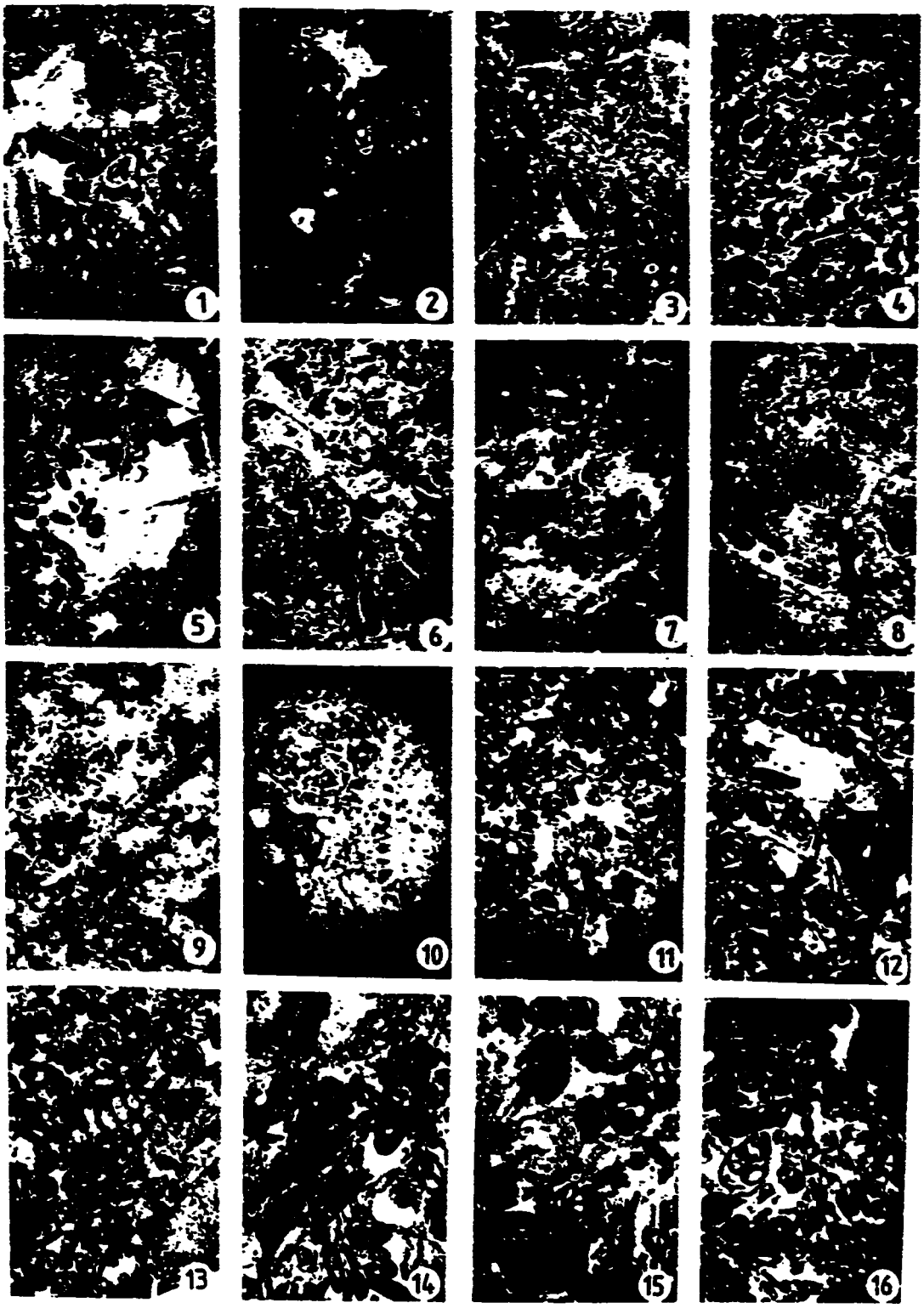


Plate 3

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections in various skeletal grains including *Quinquloculina sp* (1,2,6,7,12,16), *Triloculina sp.* (1,5,6), *Ammodiscus sp.* (3,15), Sponge (2,5,8,9), Textularids (4,7,10,13,14), *Bramkampella sp.* (11), Peloids (1-5, 10-16).

All C.N. except 1-8 P. P. light. All X. 55 except (7,8,11,12,13) X. 28.

PLATE 3

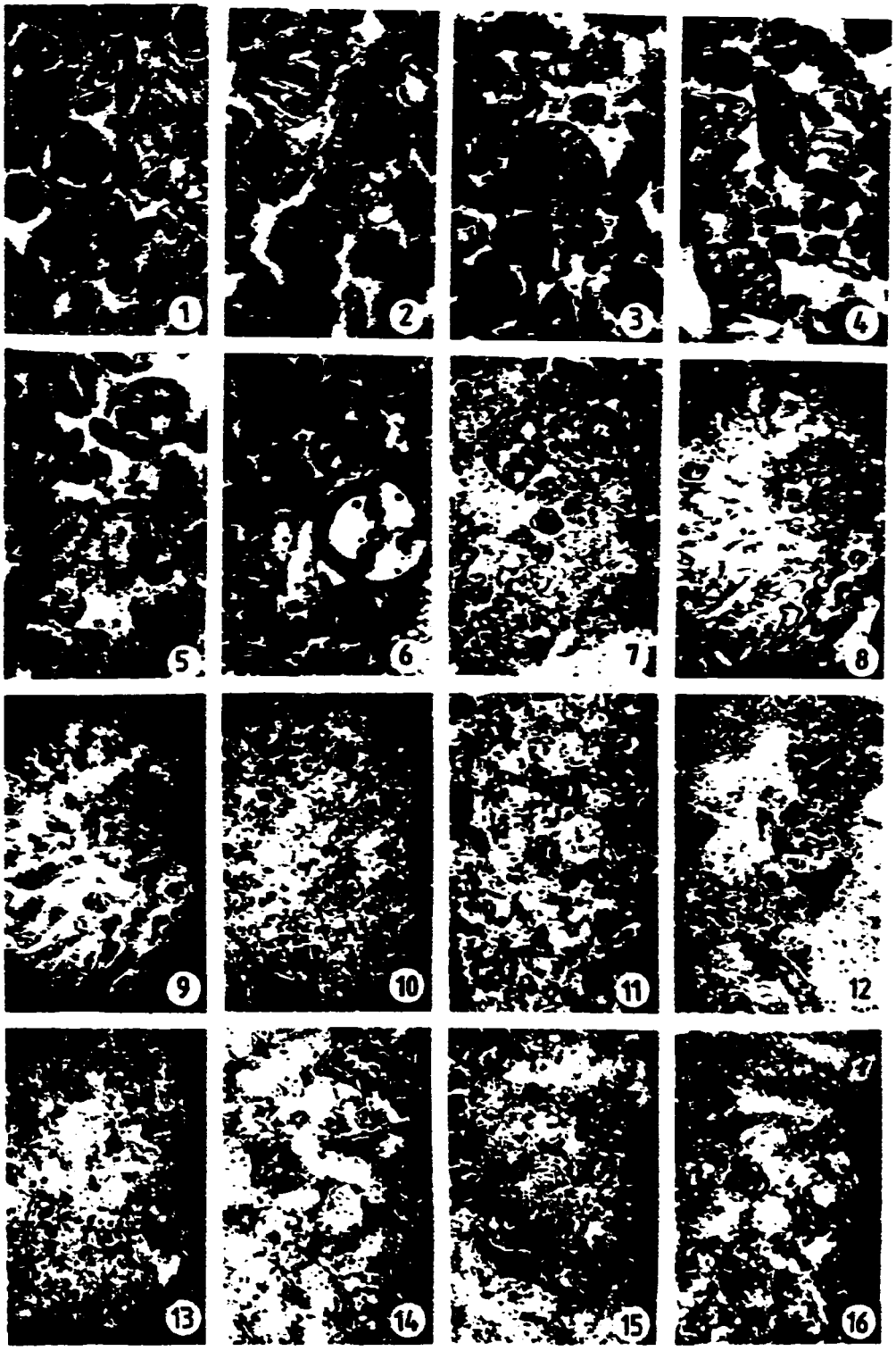


Plate 4

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections in highly packed skeletal grains cemented with isopachous calcite crystals with no micritic matrix. The skeletal grains include Miliolids (1,2,3,6,9,12,13,15), echinoid stem (2,7,12), *Nutiliqulina sp.* (3), *Kurnubia sp.* (7,12), Sponge (5,9), Peloids (1-16), and *Textularia sp.* (1,4,8,11,14,16).

All C.N. except 2,3,7,8 P. P. light. All X. 55 except (1,13,16) X. 28.

PLATE 4

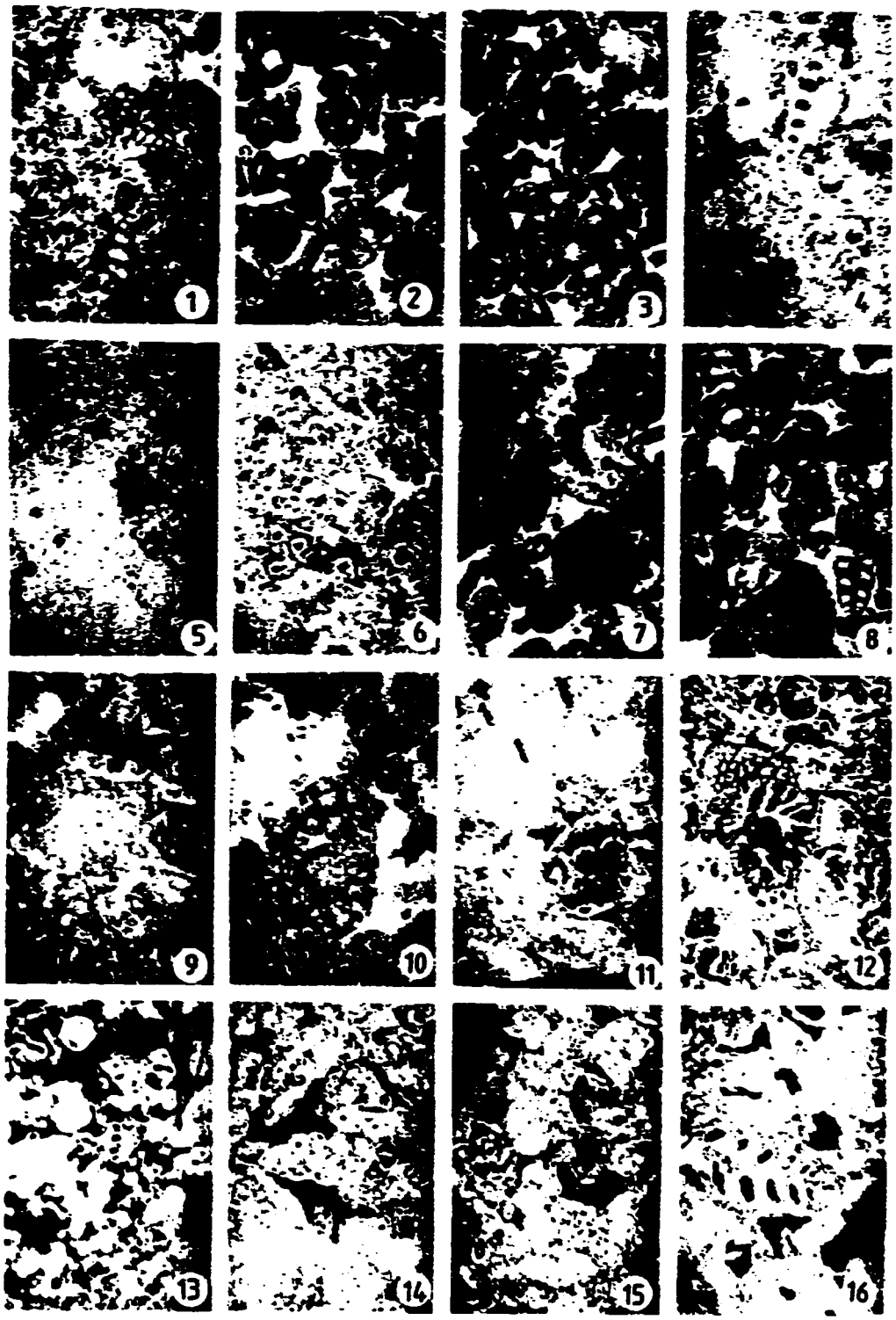


Plate 5

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections various skeletal grains, tightly packed and partially to completely replaced by sacarosic dolomite crystals (14-16). The skeletal grains are represented mainly by *pseudocyclamina sp.* (6), *Textularia sp.* (2,7,10,12,13), Miliolids (2,6,8,10), Sponges (3,5,7,8,9,11,13), *clypyna jurassica* (1,3,9) and recrystallized solitary corals (4).

All C.N. except 7,8 P. P. Light. All X. 28 except (1,3,6,12,13) X. 55.

PLATE 5

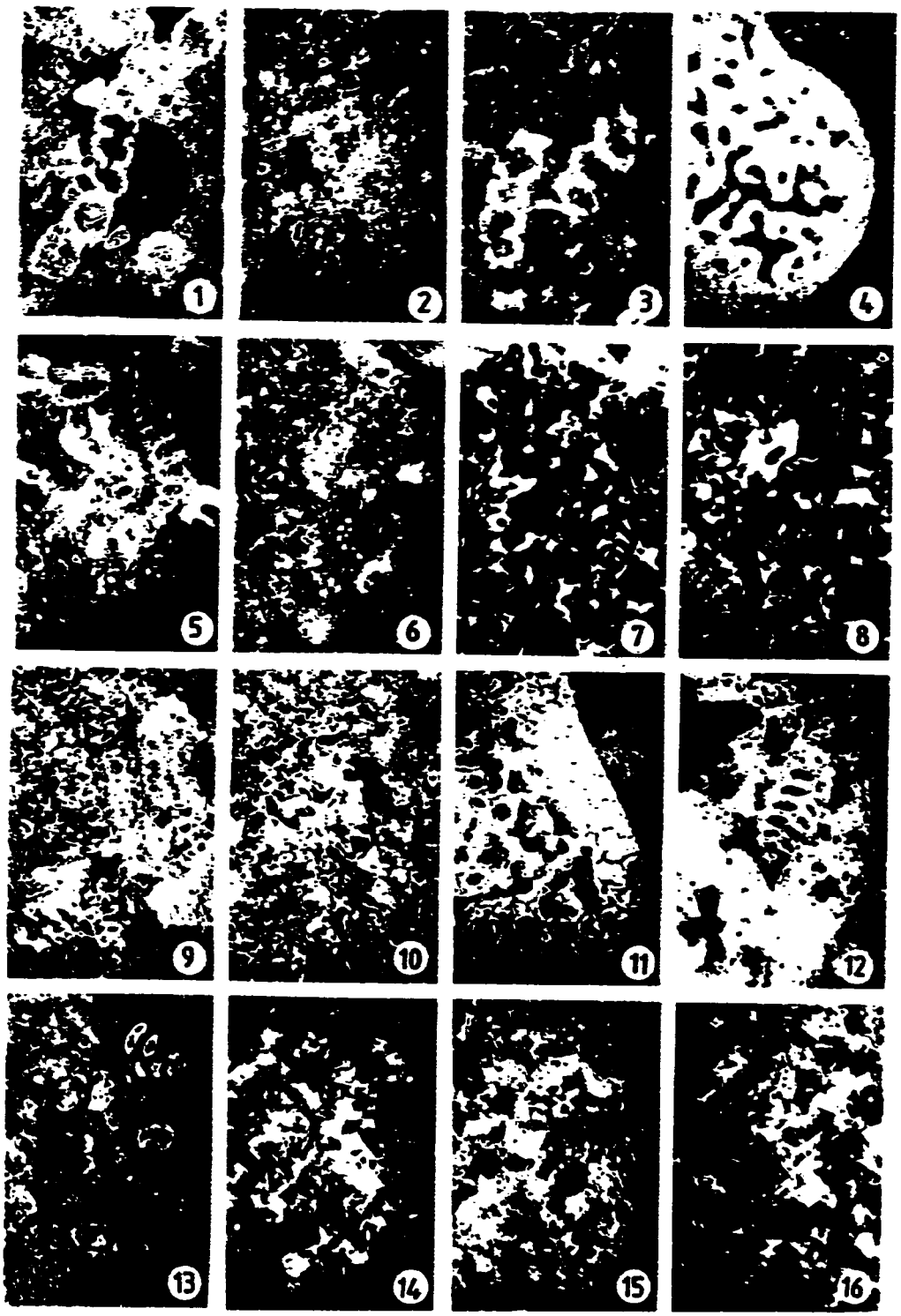


Plate 6

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections in Skeletal grains that is highly micritized (2,4,7,8,10) and partially dolomitized (3,15). The skeletal grains include sponge (1,2), *Kurnubia sp.* (4), Valvulina sp. (3), *Pfendrina sp.* (7,14), *Textularia sp.* (8,12), *Psudocyclamina sp.* (9,10), Solitary corals (5,6,11), *Quinquloculina sp.* (13), echinod stem (15), bryozoan remains (16), Peloids (7,15,16), and intraclasts (10,14).

All P. P. light except (3,6,11,12) C.N. All X. 55 except (2,5,6,9,10,11,13,16) X. 28.

PLATE 6

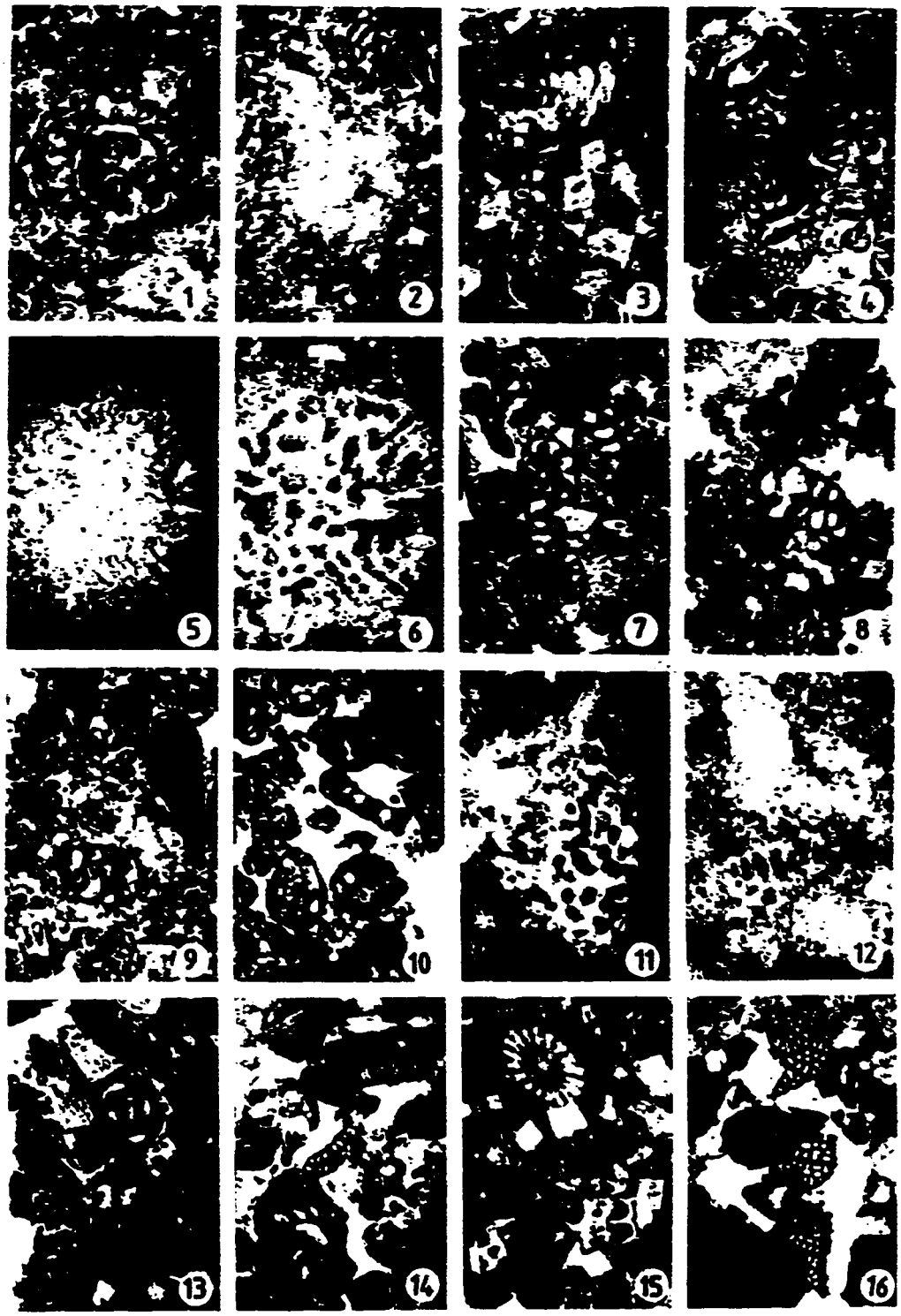


Plate 7

The Arab Formation (Arab-D Member)

Microfacies I;

Fig. 1-16 photomicrographs showing random sections in Skeletal grains cemented by isopachous cement with the original porosity still almost preserved, and some dolomite crystals (1,3,11). The skeletal grains are represented mainly by Textularids (1-4,9, 13, 15, 16), *Quinquloculina sp.* (6,8,11,12,13,15,16), *Nautiloculina sp.* (8), *clypina jaurassica* (9,16) and *Psaudocyclumina sp.* (15).

All C. N. All X. 55 except (3,4) X. 28.

PLATE 7

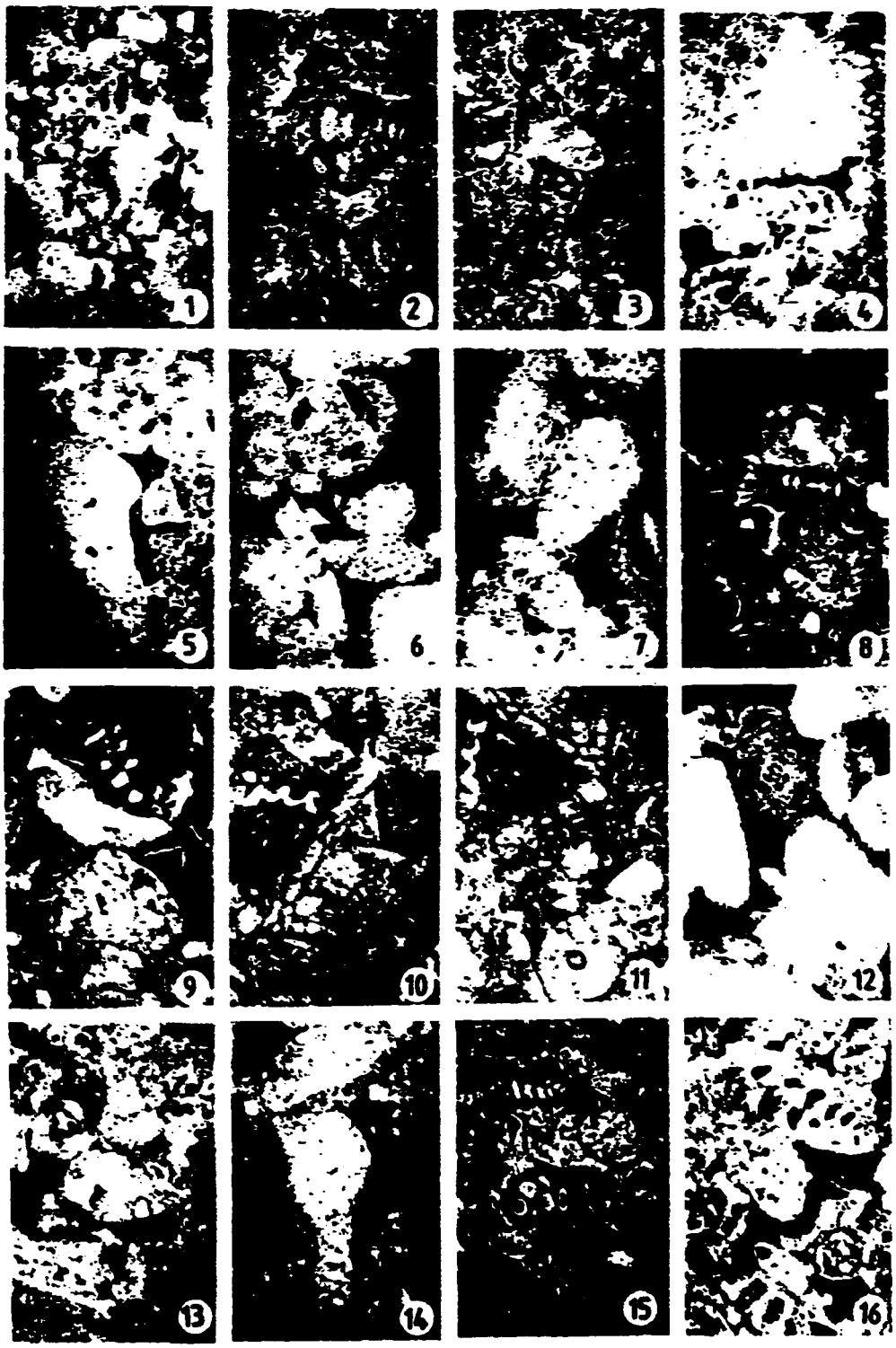


Plate 8

The Arab Formation (Arab-D Member, Well No. 587)

Microfacies II, The Peloidal, Skeletal, Dolomitic wackestone-packstone microfacies

Fig. 1-16 photomicrographs showing the dolomitized micritic matrix characterizing this microfacies. The skeletal grains are represented mainly by *Nautiloculina sp.* (2,7), *Psaudocyclamina sp.* (2,4), *Kurnobia sp.* (1), *Textularia sp.* (5,9,15) bryozoan remains (6), *Clypina Jaurassica* (7), Solilary corals (3,8), echinoid stem (12), Quinquloculina sp. (1,2,7,12,15,16), *Bramkambella sp.* (13).

All C.N. except 1-3, 15 P. P. Light. All X. 55 except (2,8,9) X.28 and (3,10) X. 137.

PLATE 8

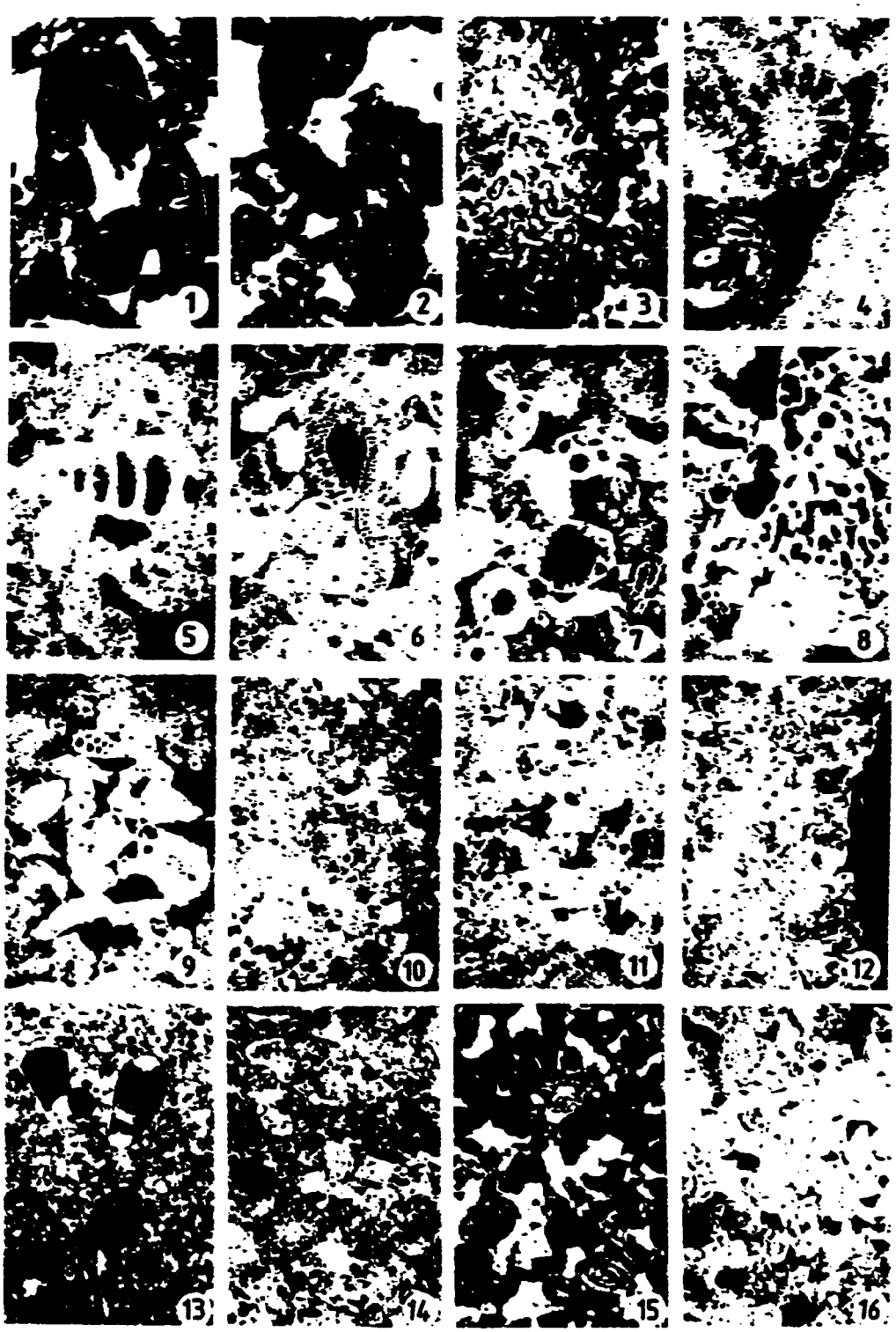


Plate 9

The Arab Formation (Arab-D Member, Well No. 587))

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing the random sections in various skeletal grains embedded in partially to completely dolomitized micrite matrix. The skeletal grains are represented by *Kurroba sp.* (2,9,13-15), *Psaudocyclamina sp.* (1,4), *Quinqulauculina sp.* (1,2,3,9), *Nautiloculina sp.* (4,15), *Ammodiscus sp.* (10), bryozoan remains (12), echinoid stem (1), *Rotalia sp.* (16), intraclasts (2,4,7,10), brachiobod shell (16).

All C.N. except 3,9,10,12,16. All X. 55.

PLATE 9

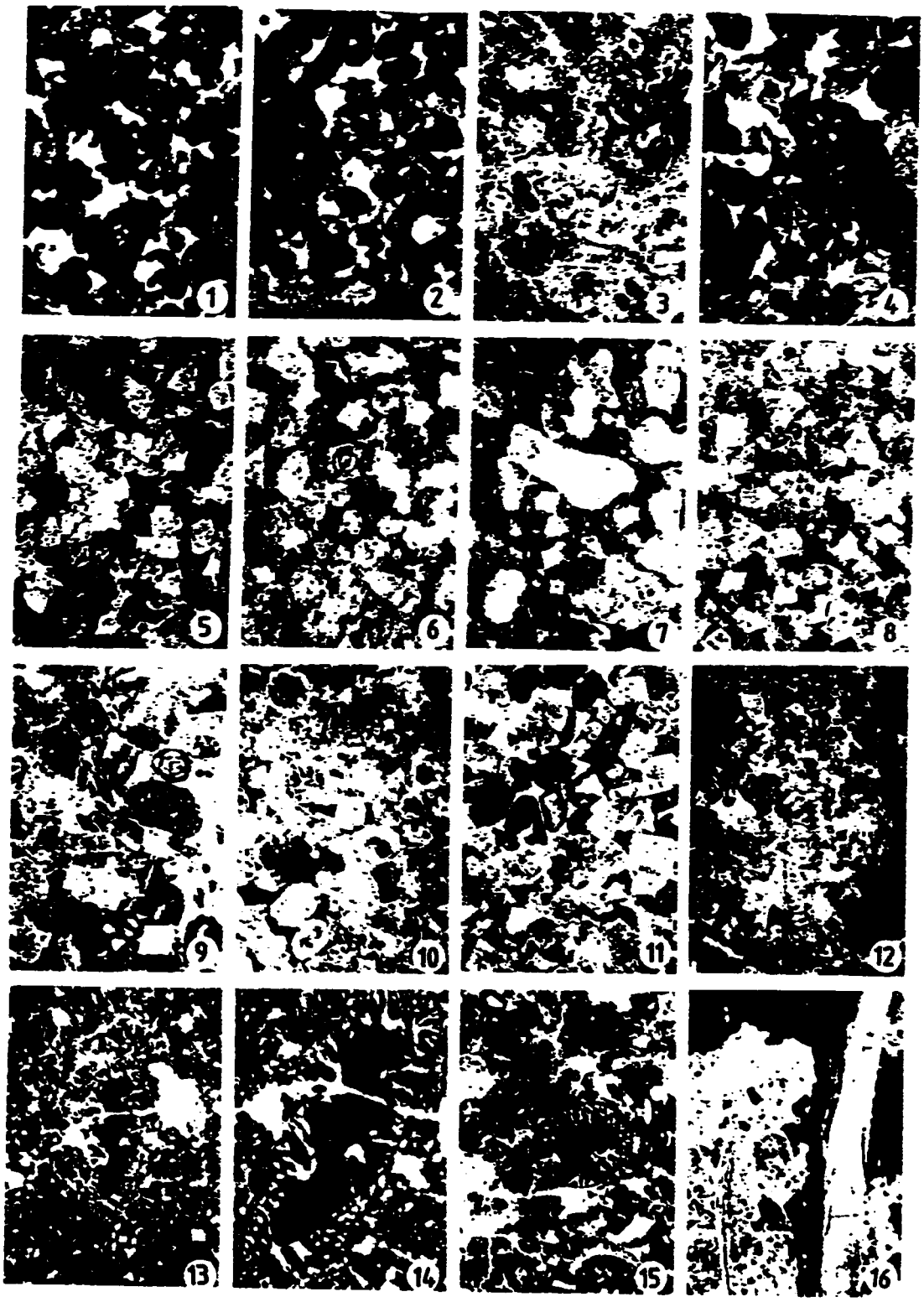


Plate 10

The Arab Formation (Arab-D Member, Well No. 587))

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing the random sections in Foraminifrid remains embedded within partially to completely dolomitized mudstone - wackestone. The Foraminifrid remains include Textularia sp. (1), *Salpngoporella sp.* (1), *Psandocyclamina sp.* (3), *Natiloculina sp.* (4,15), *Kurnubia sp.* (3,5), echinoid stem (6), Solitary corals (2), intraclasts (7) and Peloids (8,9).

All C. N. All X. 55 except (5) X.28.

PLATE 10

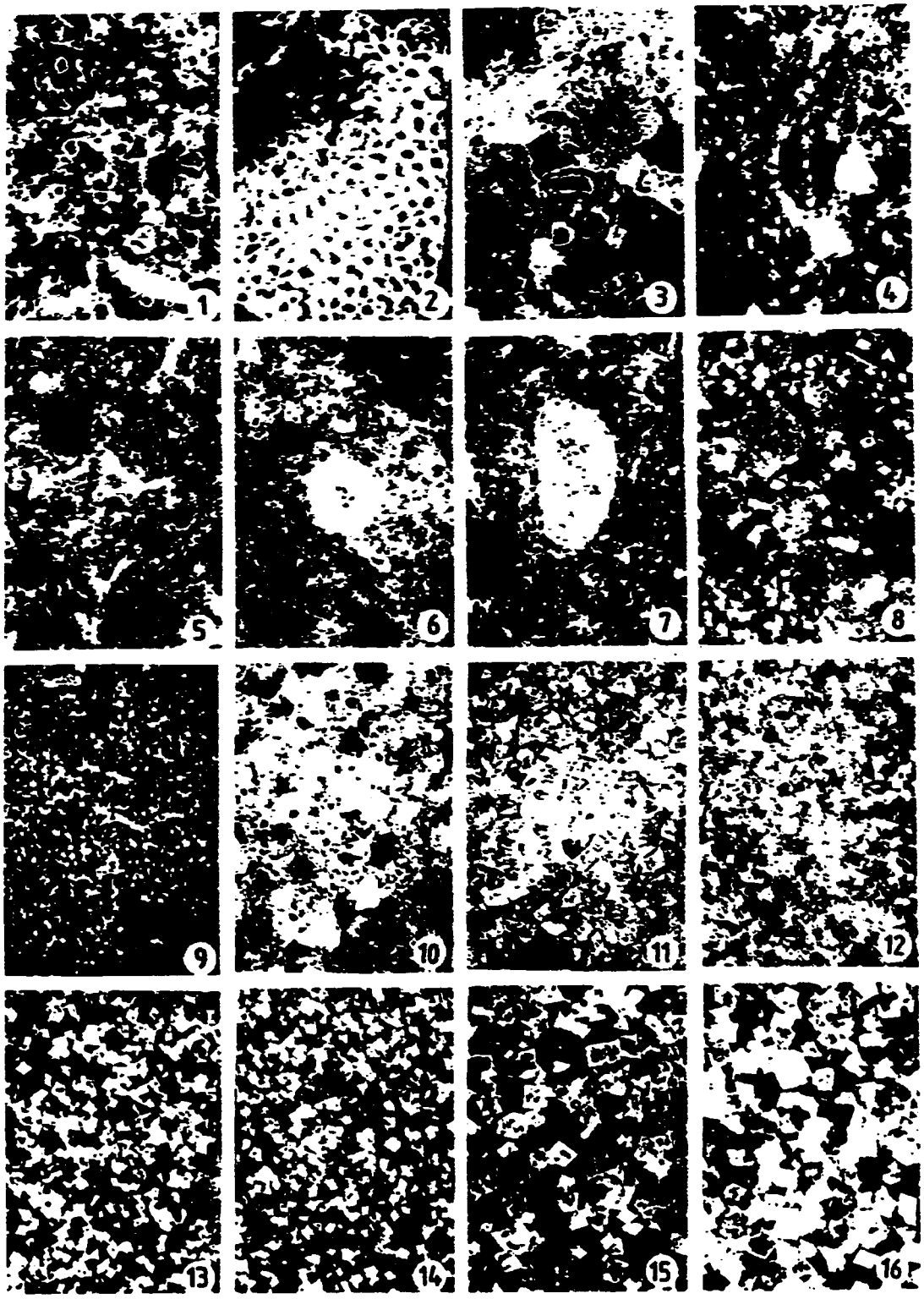


Plate 11

The Arab Formation (Arab-D Carbonate Member, Well No. 628)

The Nautilioculina/Kurnubia grainstone Microfacies; (Microfacies I)

Fig. 1-16 photomicrographs showing the grainstone nature of this microfacies with tightly packed skeletal grains cemented by isopachous calcite crystals with no enterparticles micritic matrix. The skeletal grains are represented mainly by Foraminifrid remains including:

Textularia sp. (1,2,5,7,11,12), *Quinquloculina sp.* (1-16), *Psaudocyclamina sp.* (8,13), *Natiloculina sp.* (13,15,16), *Kurnubia sp.* (12). Some of the Foraminifrid remains acted as a solid ?*nuclesus*? surrounded by concentric layers of organic/calcareous layers were developed (12-16). The skeletal grains are also represented by brachiopod remains (9), and a pair of molluscan shell (10).

All C.N. except 5,7,11 P.P. light. All X. 55 except (9,12) X. 28 and (1,7,8) X. 137.

PLATE 11

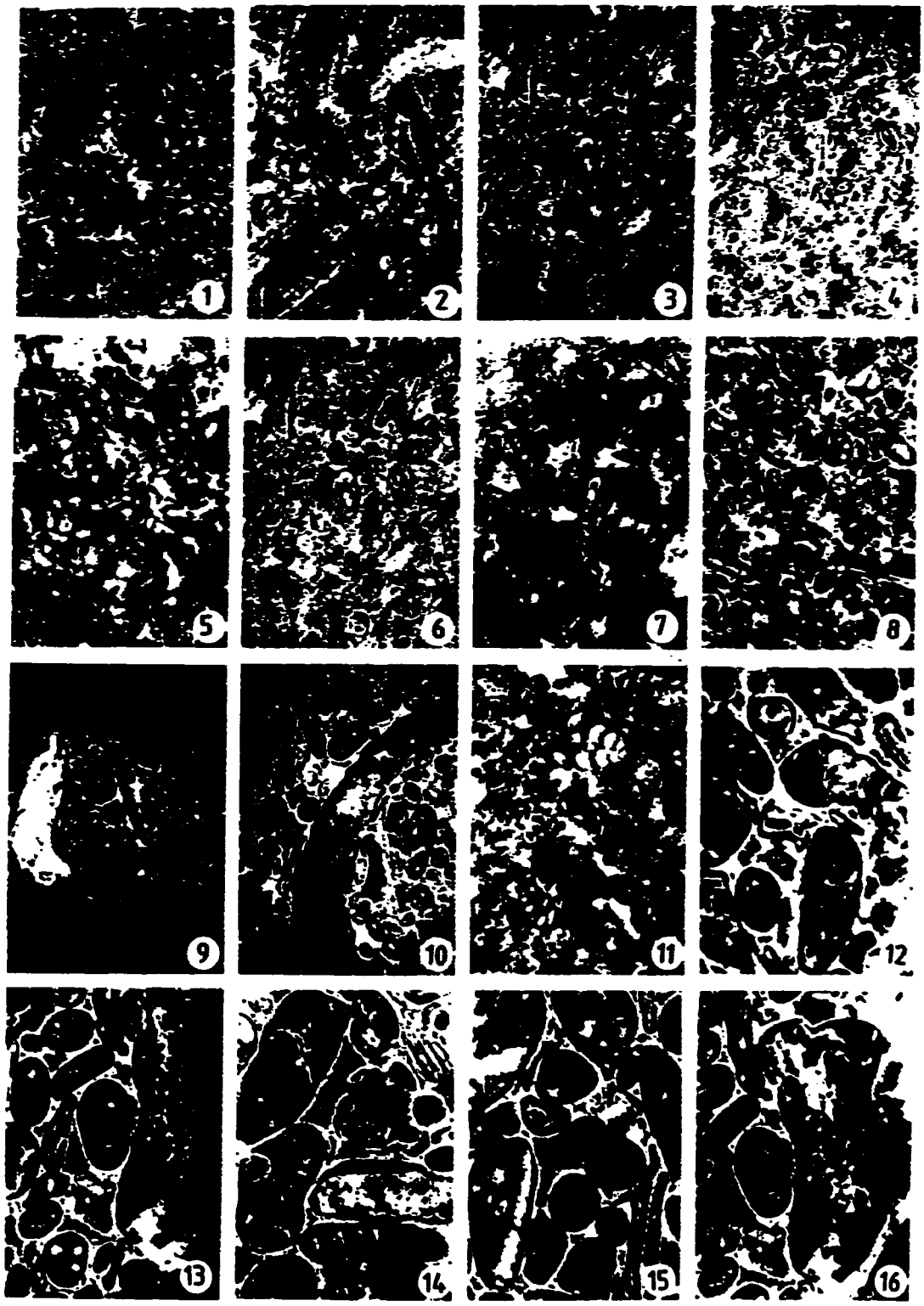


Plate 12

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies I :

Fig. 1-16 photomicrographs showing random sections in various skeletal grains tightly packed with occasional patches of partially dolomitized micritic matrix (4,8,9,11,13). The skeletal grains include *Textularid sp.* (1-3,5-7,10,14-16), Quinqulocalina spp. (1-6,11,14-16), *Pyrgo sp* (7), Nautiloculina sp. (2,10,16), *Kurnubia sp.* (1,3,14-16), *Rotalia sp.* (6), Echinoid stems (14), Shell fragments (14) and bryozoan remains (8,9,13).

All C.N. except 9, 14 P.P. light. All X. 55 except (7,13,14) X. 28 and (8,9) X. 137.

PLATE 12

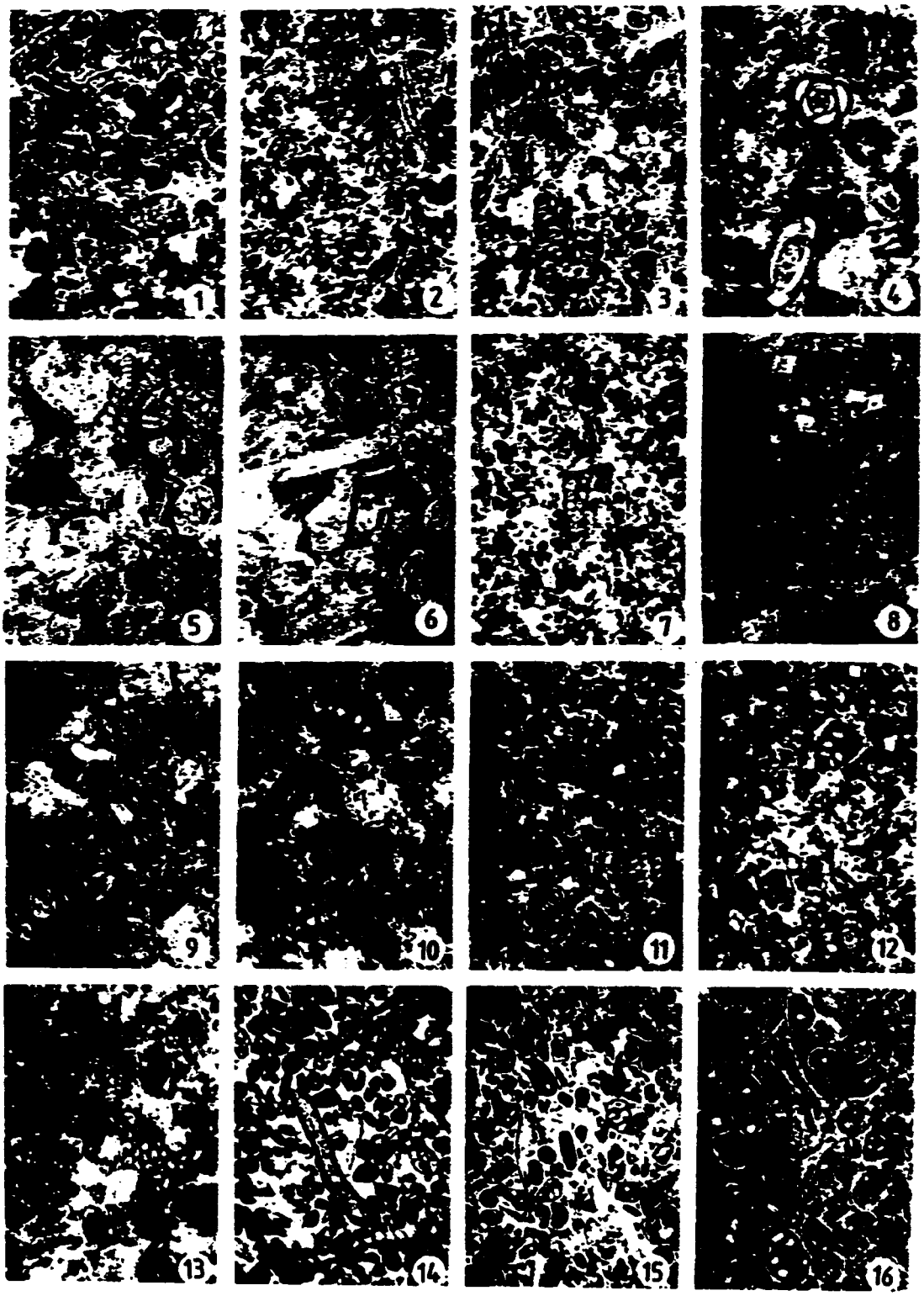


Plate 13

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies I (cont.)

Fig. 1-16 photomicrographs showing random sections in slightly cemented skeletal grain with some patches of partially dolomitized micritic matrix (14-16). The skeletal grains are represented mainly by peloids (1-3,6,8), Textularids (1,2,4,5,7,8,9,12), *Nautiloculina sp.* (7,8), *Quinquloculina sp.* (1,3,6,7), *Psaudocyclamina sp.* (1,6,7), Solitary corals (11), and *Kurnubia sp.* (16).

All C.N. except 2,4,14-16 P.P. light. All X. 55 except (2,3,4,6,7,8,9,10,11) X. 28.

PLATE 13

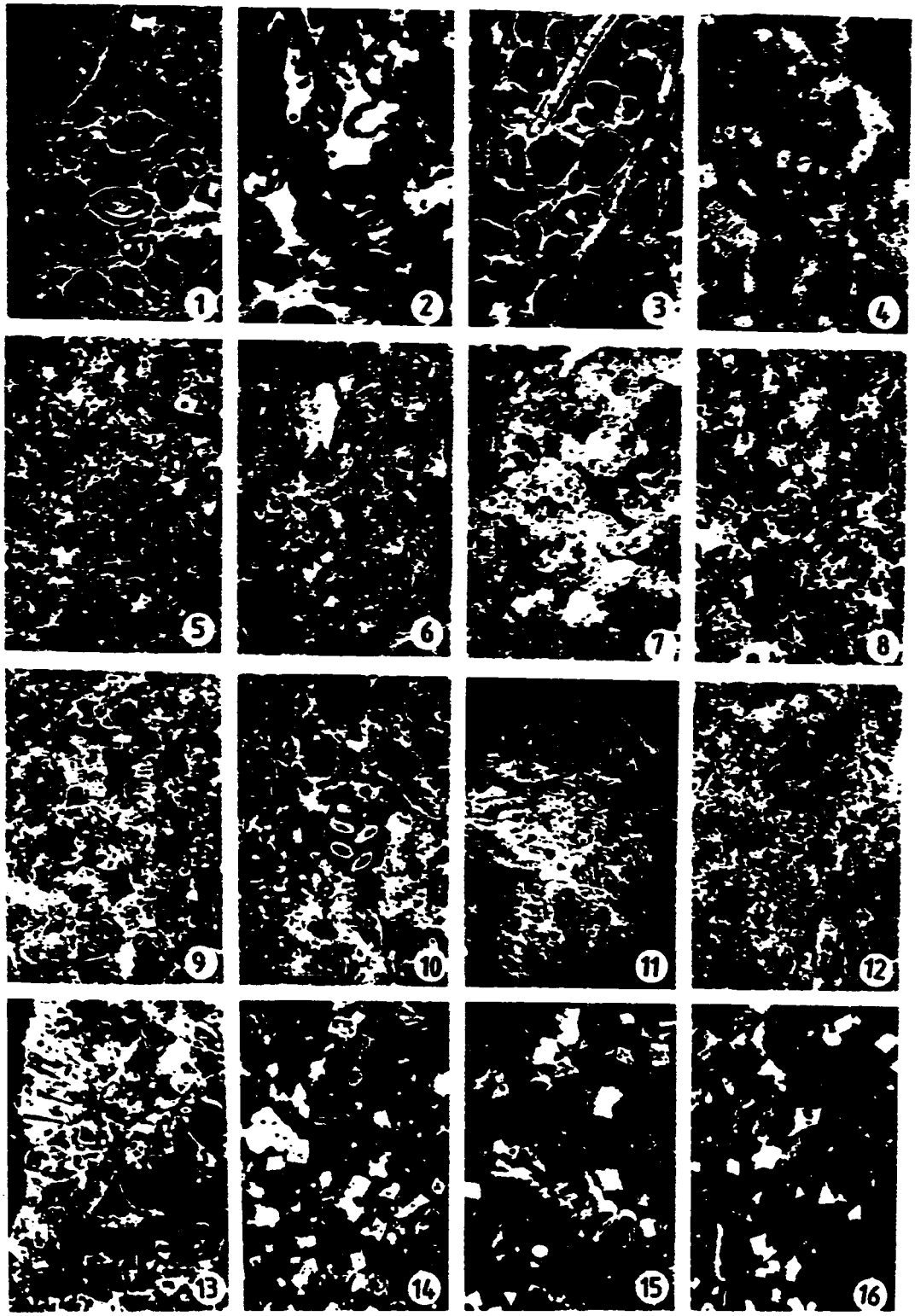


Plate 14

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies I (cont.)

Fig. 1-16 photomicrographs showing the dolomitized micritic matrix occasionally found in this microfucies. The skeletal grains are less common than elsewhere in the microfacies and represented mainly by *Textularia sp.* (6,13), *Kurnubia sp.* (7), *Clypina jurassica* (5), *Psaudocyclamina sp.* (14,15), echinoid spine (1), Sponges (2,9,11), bryozoan remains (14,15) with some intraclasts (16).

All C.N. except 1,15 P.P. light. All X. 55 except (8,9,10,11,12,13,16) X.28.

PLATE 14

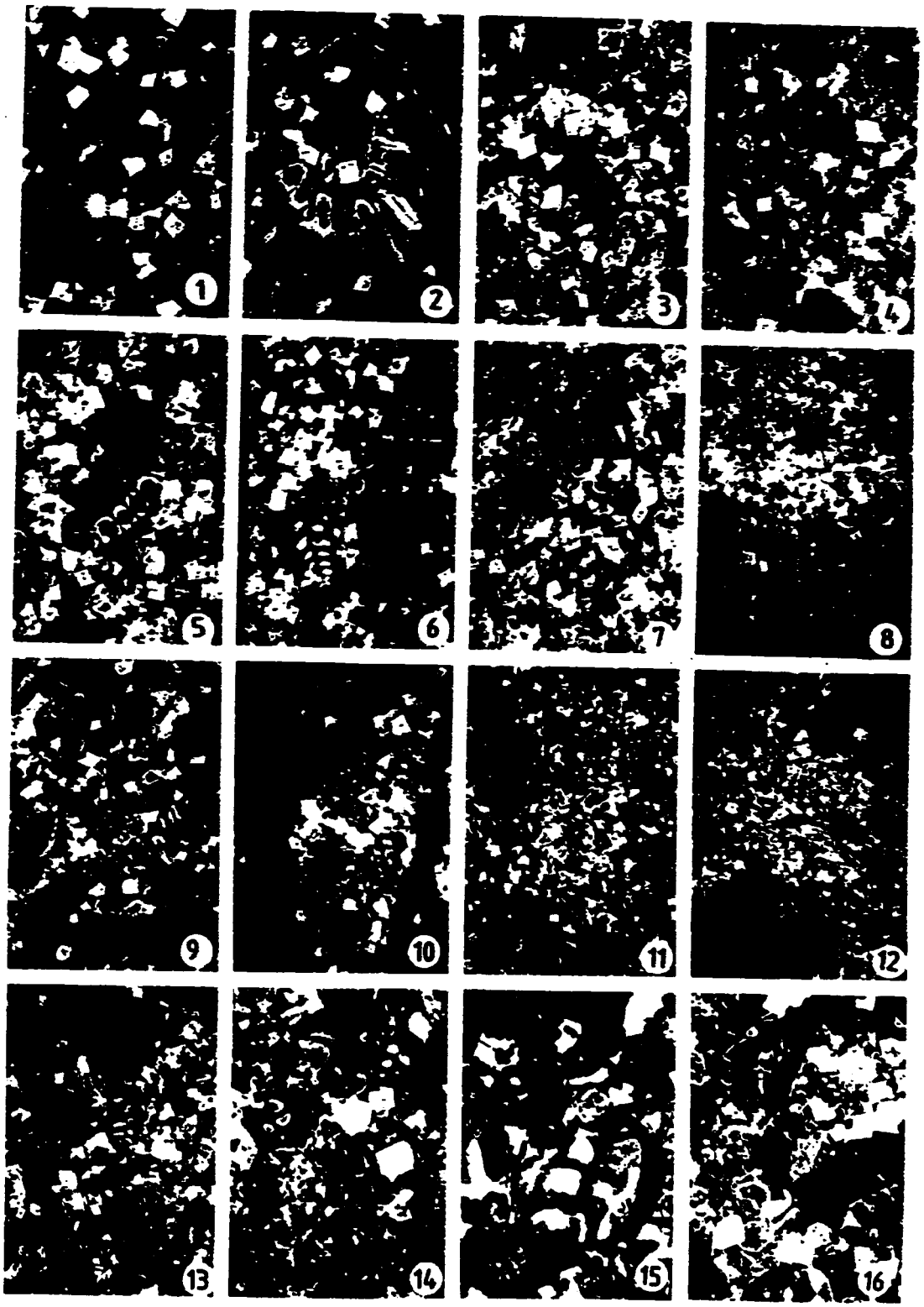


Plate 15

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies I (cont.)

Fig. 1-16 photomicrographs showing random sections in skeletal grains tightly packed and partially cemented. The skeletal grains include *Textularia sp.* (4,5,7,8,9,11,15,16), *Psaudocyclamina sp.* (4,7-10), Miliolida (4,5,7-12,15), *Nautiloculina sp.* (10), *Kurnubia sp.* (3,12), and peloids (1,6,13,16).

All C. N. All X. 55.

PLATE 15

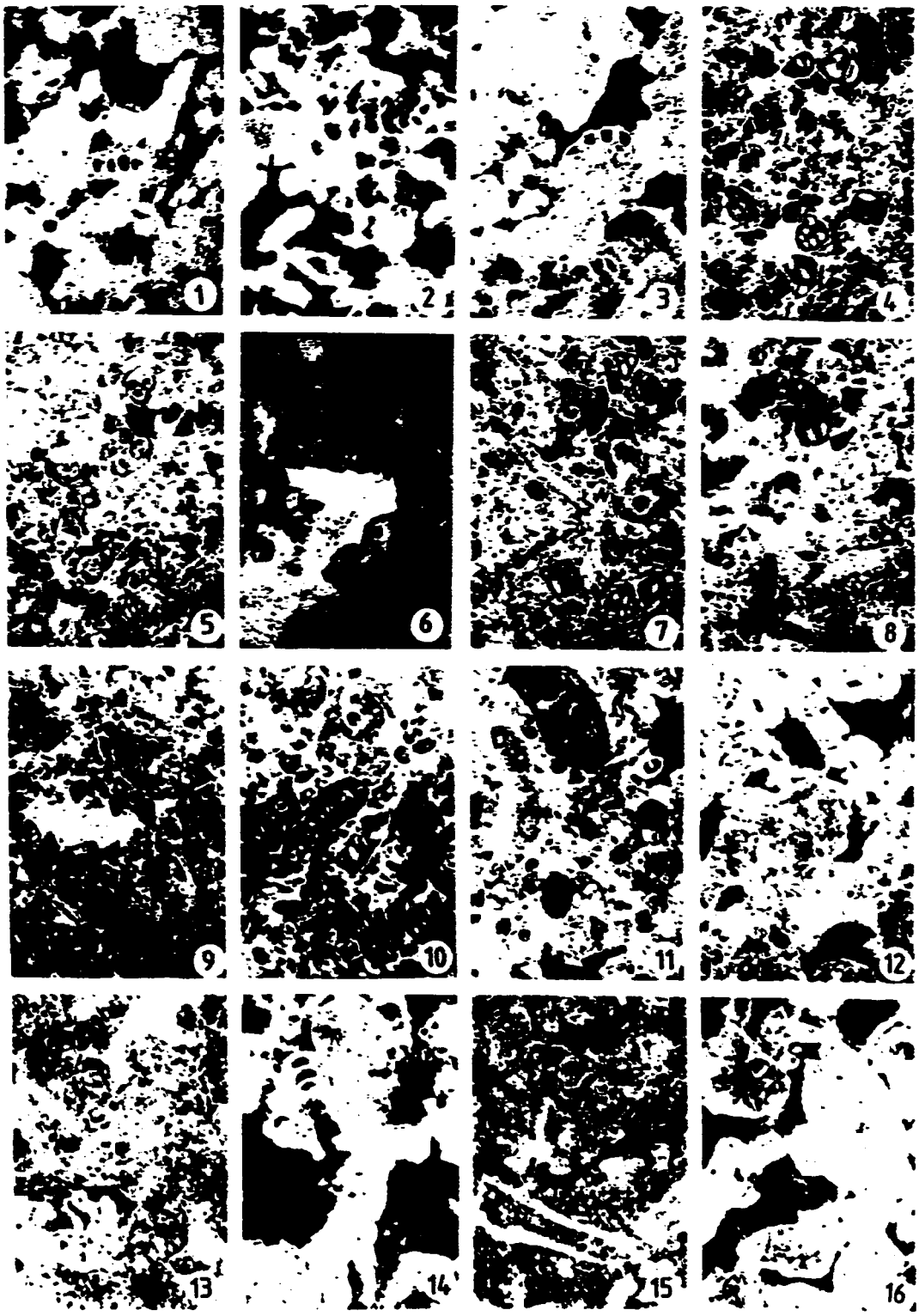


Plate 16

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies II , The Peloidal, skeletal, Dolomitic wackestone-packstone microfacies

Fig. 1-16 photomicrographs showing the dolomitized micritic matrix characterizing this microfacies. The skeletal grains are represented mainly by *Kurnubia sp.* (3-5,9) *Quinquloculina spp.* (1,2), *Psaudocyclamina sp.* (1), *Textularia sp.* (10,14), *Globigerina sp.* (13), Coastropod shell (10, and solitary corals (11,15)

All C.N. except 5,13 P.P. light. All X. 55 except (6,11,15,16) X.28.

PLATE 16

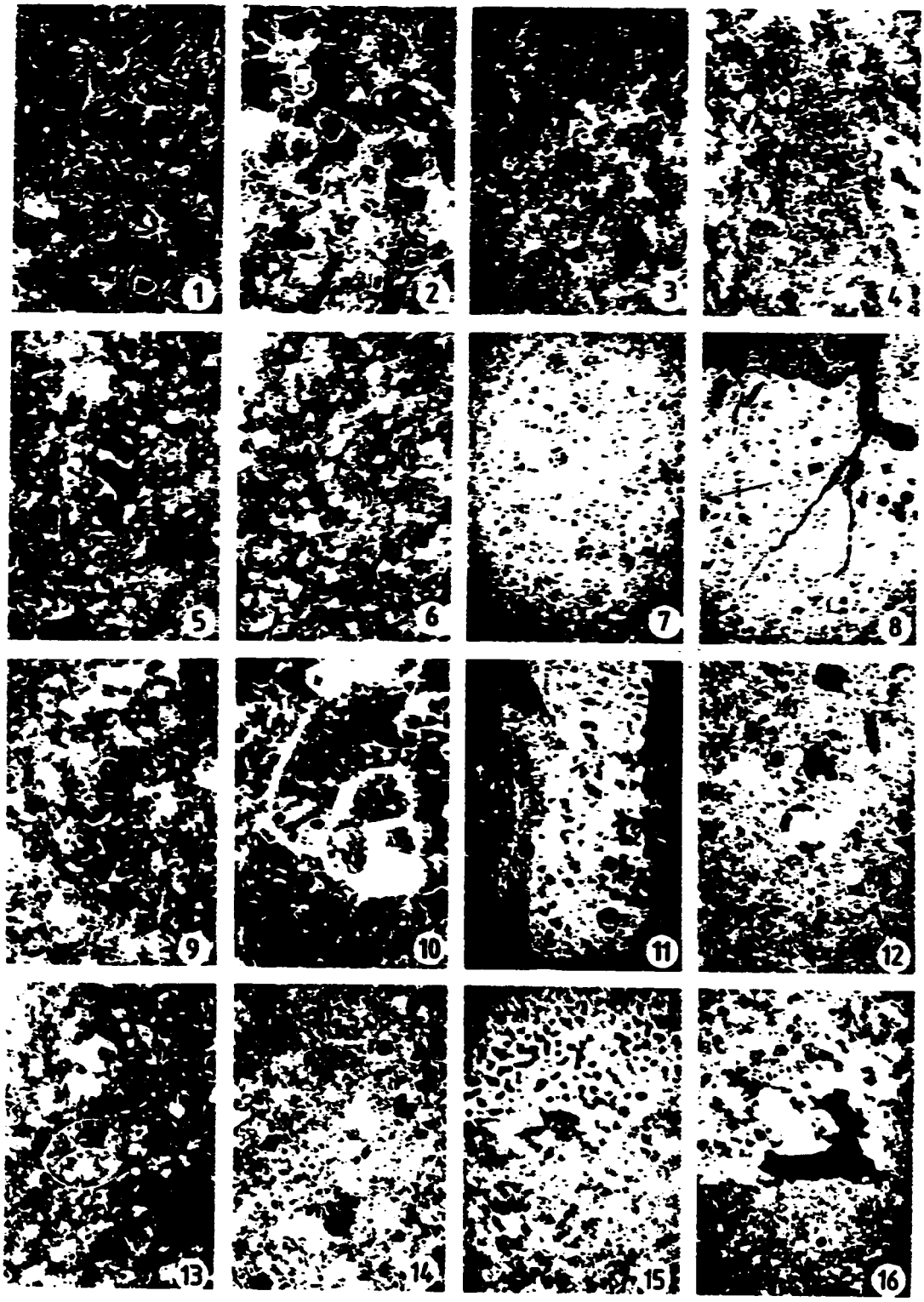


Plate 17

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing random sections in various skeletal grains embedded in a partially to completely dolomitized micritic matrix. The skeletal grains are represented mainly by *Kurnubia sp.* (11-13), *Textularia sp.* (14,15), and solitary corals (2,7). The photomicrographs also showing several types of porosity e.g. interparticle (3,5,6,8), intraparticle (4,8,13,16), intercrystal (II).

All C.N. except 12,14 P.P. light. All X. 55 except (1,6,9,10,11,14) X. 28.

PLATE 17

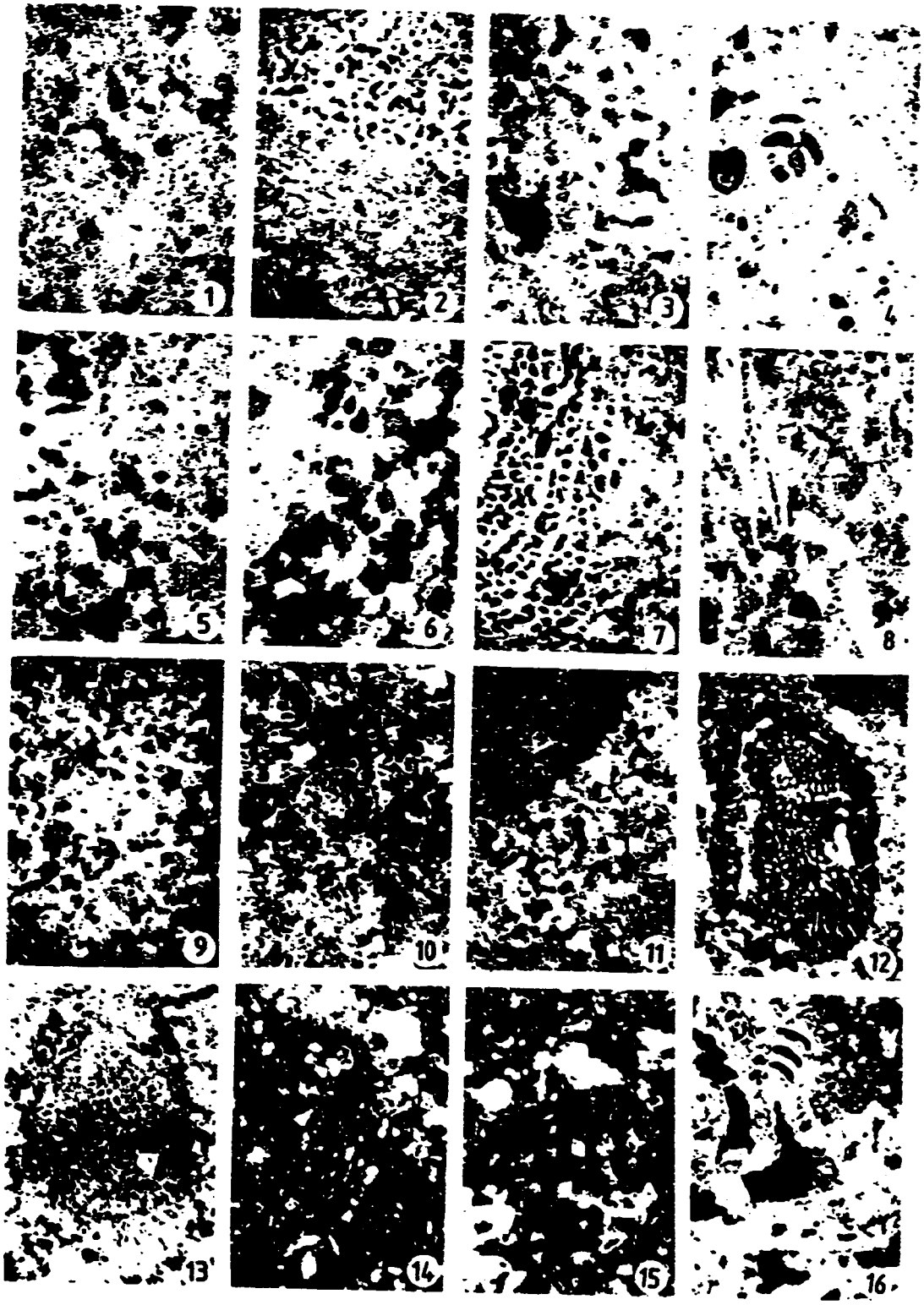


Plate 18

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing the micritic nature of this microfacies. The skeletal grains are mainly represented by *Kurnubia sp.* (1,2,3,8), *Textularia sp.* (11,13), *Nautiloculina sp.* (8), echinoid remains (1,6,7), sponges (7) and solitary corals (4,15). The photomicrographs shows also different types of porosity e.g. moldic porosity (12,13), interparticles porosity (16).

All C.N. except 1-3, 6,8,9,11 P.P. light . All X. 55 except (7,11,13) X. 28.

PLATE 18

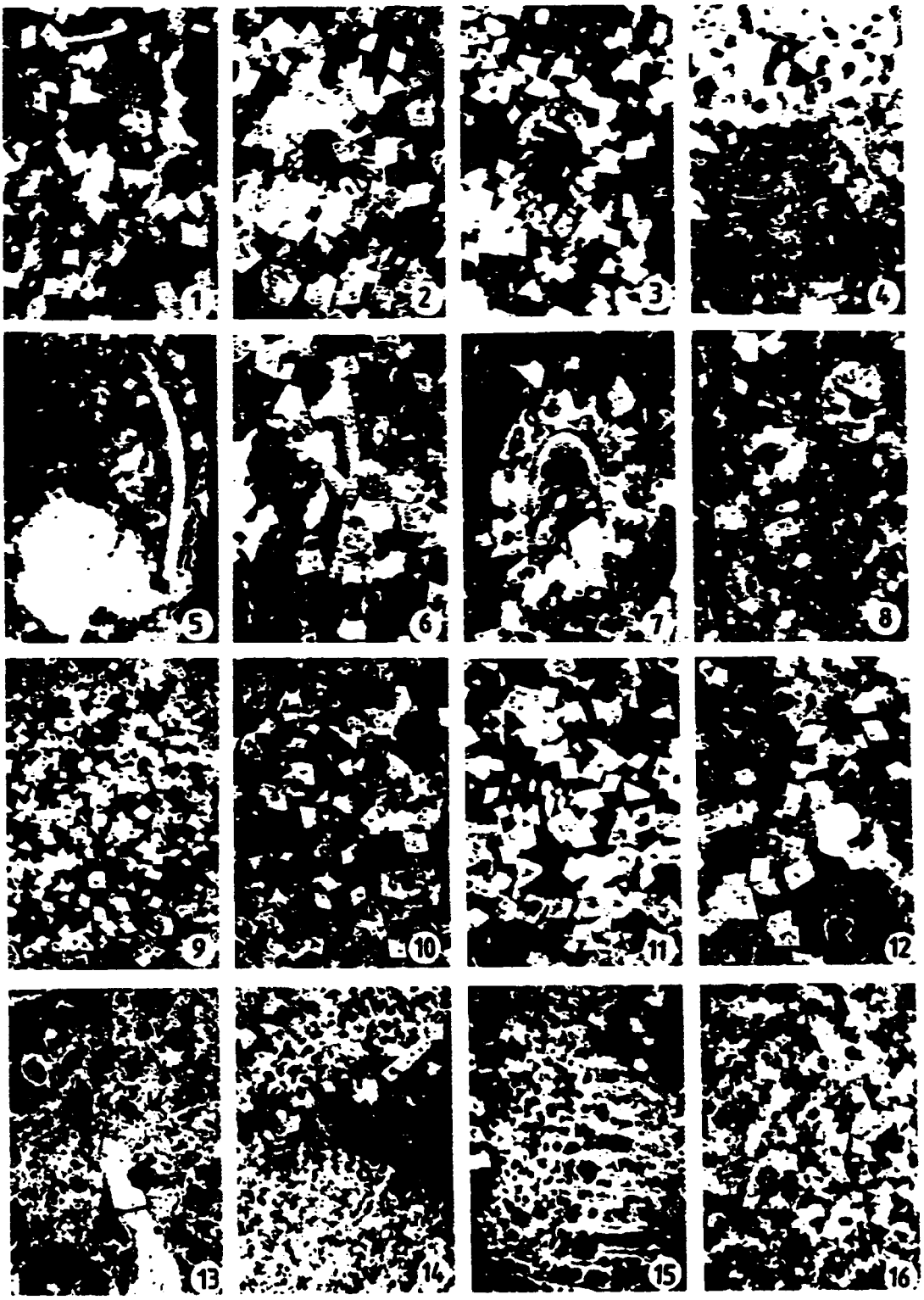


Plate 19

The Arab Formation (Arab-D Member, Well No. 628)

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing the same microfacies where the rhombic dolomite crystals medium to large in size, with sharp crystal edges and straight extinction. The skeletal grains include *Kurnubia sp.* (8,9,10,13), *Textularia sp.* (7,11), *Nautiloculina sp.* (16). and brachiopod remains (16).

All C.N. except 5,9,11,12,15 P.P. light. All X. 55 except (1,3,7,9,15) X. 28.

PLATE 19

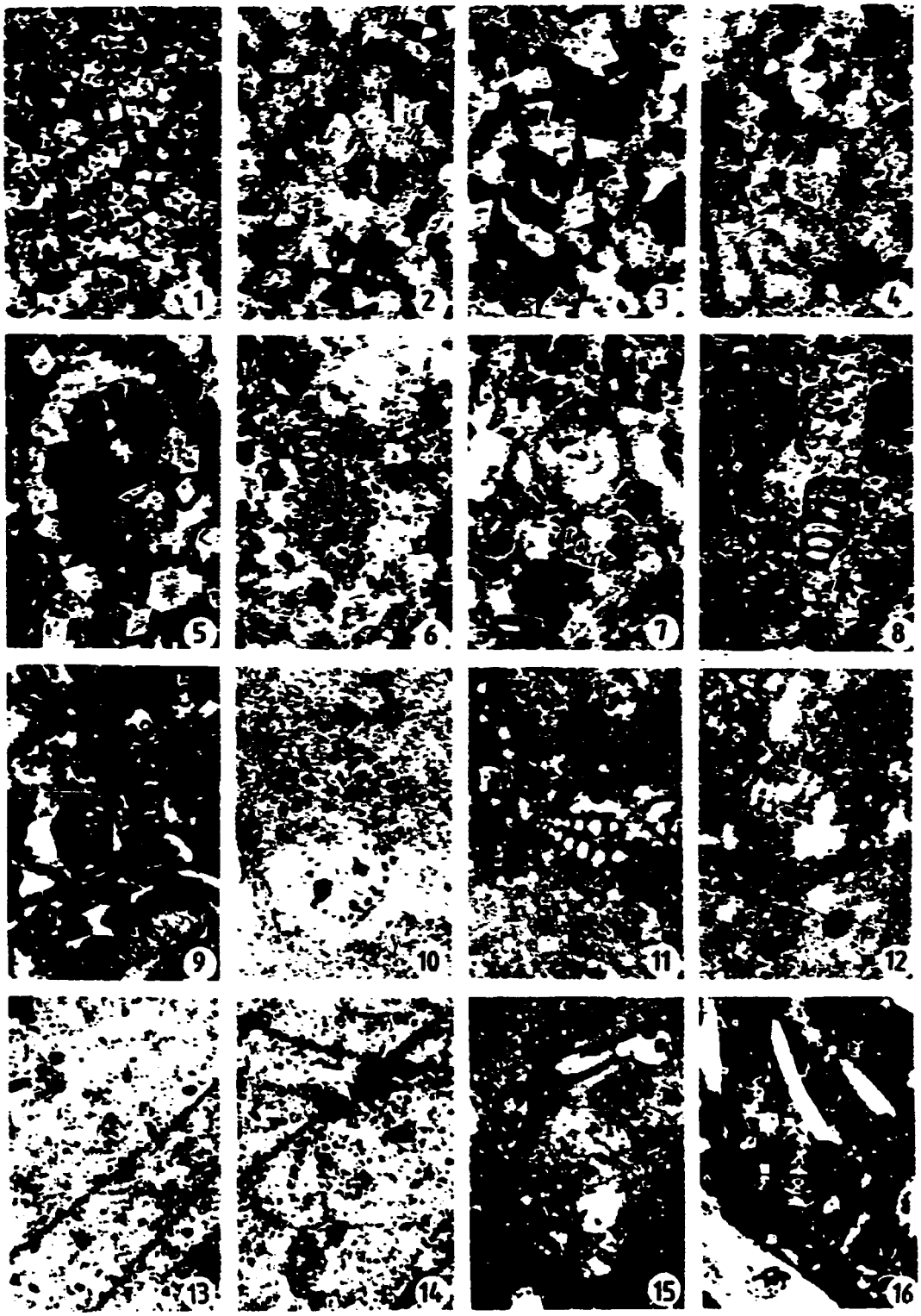


Plate 20

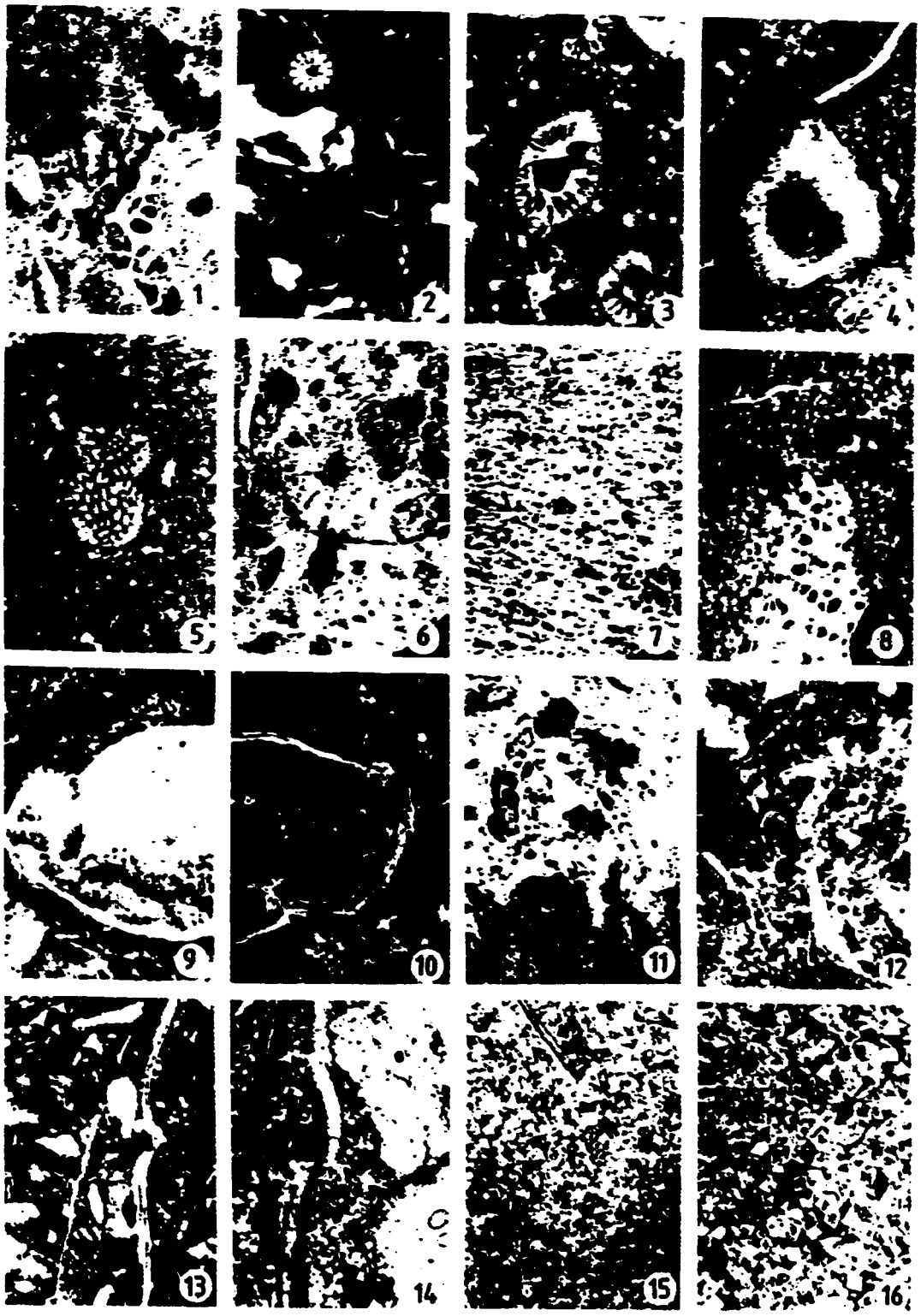
The Arab Formation (Arab-D Member, Well No. 628)

Microfacies II (cont.)

Fig. 1-16 photomicrographs showing the same microfacies. The skeletal grains are represented by interaclasts (1,4,6,9,10), *Kurnubia sp.* (3,5), echinoid stem (1), brachiopod remains (12,13,14), peloids (1,12), sponges (11), and solitary corals (7). The intraclasts are surrounded by concentric layers of organic materials (9,10).

All P.P. except 1,6,7,9-11 P.P. C. N. All X. 28 except (1,2,3,5,6,16) X. 55.

PLATE 20



APPENDIX

APPENDIX

THE STRATIGRAPHY OF THE LATE LATE JURASSIC ARAB FORMATION IN SAUDI ARABIA.

The Late Jurassic succession in Saudi Arabia is represented by the Late Kimmeridgian-Early Tithonian Arab Formation and the Late Tithonian Hith Anhydrite. The present study is concerned with the Arab Formation, consequently, the following discussion will be focussed mainly on this rock units.

Arab Formation:

Author. - Not established, first-known usage is that of R. A. Bramkamp, 1951; unpublished work.

Type section details:

Location: Dammam well 7 (lat. 26° 19'04" N, long. 50°07'38" E) between drilled depths 1,371.6 and 1,499.1 meters,

Thickness: 127.5 meters.

Lithology: Interbedded limestone and anhydrite. Calcareous intervals are comprised of micritic limestone, calcarenitic limestone, calcarenite, and dolomite in varying proportions; all with subdued tones of gray or brown.

Fossils: *Diceras sp., Nerinea sp., Clypeina jurassica* Favre, C. cf. *hanabatensis* Yabe and Toyama, *Cylindroporella arabica* Elliott, *Polygonella incrustata* Elliott, *Kurnubia spp.* and *Nautiloculina spp.*

Age: Late Late Jurassic (Late Kimmeridgian-EarlyTithonian) on stratigraphic position and correlation with other subsurface sections.

Underlying Formation: Jubaila Formation; contact conformable, taken at downward change from clean-washed calcarenite to tight micritic limestone.

Overlying Formation: Hith Anhydrite; contact gradational, taken at change from micritic limestone below to massive anhydrite above.

Other localities: Rocks of the Arab Formation form a thin, essentially unbroken belt from Al Hasi (lat. 20° 08' N) to Juwayy (lat. 25° 49' N), a distance of nearly 700 kilometers, width of the outcrop over this distance is relatively uniform averaging about 10 kilometers. The formation is widespread in the subsurface and has been penetrated in all oil fields. In the north, it is found in bore holes as far west as Al Batin; in the south, it occurs in all wells but those along the southern and easternmost fringes of the Rub' al-Khali.

The area of Arab Formation exposure is mainly a broad, gently undulating plain. A few low, isolated hills "haystack jibal" stand above the general ground level. Effects of slumping are everywhere evident, a phenomenon that can be readily attributed to the removal of anhydrite beds and the subsequent collapse of the carbonate units left behind. The little that is known of the basic rock types on outcrop indicates that they are similar to the calcarenite-calcarenitic limestone-micritic limestone-dolomite rocks found in wells to the east.

No satisfactory estimate of the total thickness of the Arab Formation at the surface has been made because of the complex slumping. Only the basal 15 to 25 meters have been measured with any assurance, and even this interval contains a persistent brecciated zone that suggests some loss of section due to anhydrite solution. There is every reason to believe that this basal Arab carbonate unit is equivalent to the lower part of the type Arab-D Limestone Member at Dammam, it may well represent the total D Member not replaced by anhydrite in well sections at Khurais and Ma'aqala.

Only at the southern end of the solution-collapse zone have beds been found in place above the basal unit described above. Between Sha'ib al Haddar and Al Hasi, outcrops of anhydrite rest directly on the laterally persistent calcarenite that marks the top of the basal sequence. These overlying beds have an average thickness of about 14 meters and are mainly white anhydrite and gypsum with thin interbeds of brown dolomite.

At first the type locality of the Arab Formation was taken as a general area around Riyadh. Extensive loss of beds and subsequent slumping prevented accurate measurement of section, however, and forced selection of a subsurface sequence to best represent the unit.

In well sections, the Arab Formation is defined to include four main cycles of deposition each of which started with shallow-water, normal marine carbonate and closed with precipitation of nearly pure anhydrite, probably first deposited as gypsum. The carbonate portions of each cycle have been designated consistently but informally from top to bottom as the A, B, C, and D Members of the Arab Formation. The boundary between

the carbonate units and their capping anhydrites is known to be diachronous in at least two cases and perhaps it is in all. This, coupled with the fact that each carbonate-anhydrite cycle taken as a whole approximate a time-stratigraphic unit, prompted redefinition of the lower three members to include their anhydrite caps (Powers and other, 1966). The much thicker upper or closing anhydrite interval is still considered a separate formation - the Hith Anhydrite.

The Dammam well # 7 serves as the type section for the Arab Formation and its members: the A-Member, between 1,371.6 and 1,388.4 meters depth; the B Member between 1,388.4 and 1,399.1 meters depth; the C-Member between 1,399.1 and 1,440.6 meters depth and D-Member between 1440.6 and 1499.1 meters depth. In each instance, the contact between members is marked by change from carbonate to evaporite.

The episodic pattern of Arab deposition is clearly documented in most well sections where 5 to 50 meter-thick intervals of shallow-water, shelf limestone sharply alternate with layers of penesaline rocks of like thicknesses. The depositional regime was controlled by alternating periods of desiccation and influxes of freshening sea water.

Continuity of individual evaporite units makes regional correlation of the Arab members a relatively simple matter. There is some difficulty, however, in recognition of various members in the Al Batin-Jauf-Manifa area due to loss of anhydrite by facies change to carbonate.

From Haradh northward, limestone of the Arab Formation are characterized by a high percentage of lime sand, commonly skeletal and commonly in the form of massive clean-washed calcarenite beds. Calcarenitic limestone is the next most frequent rock type; pure aphanitic limestone and dolomite are quite rare except at Jauf where the entire unit is coarsely crystalline dolomite. Reef structures have not yet been found and the wide continuity, uniform thickness, and regularly bedded nature of the Arab suggest that large structures of this type are unlikely.

Specific particle types contributing to Arab Formation's calcarenites and calcarenitic limestone include calcareous algae, and aggregate pellets, "algal" nodules, and "fecal" pellets as the most important non-skeletal grains. Ooliths are rare although some concentrations occur in the C Member at Khursaniyah and in the C and D Members at Manifa.

South of Haradh, in the Rub' al-Khali area, carbonate intervals are thinner and consist almost entirely of micritic limestone and dolomite with occasional layers of mud-based calcarenitic limestone. A few true clean-washed calcarenite beds are present. The widespread accumulation of finer-grained sediments suggests that Arab rocks of this area were deposited mostly below the effective wave base.

Thickness of the Arab Formation usually ranges from 100 to 180 meters. However, thinner intervals occur around the edges of the Rub' al-Khali basin and at Ath Thumami where upper members are truncated by pre-Buwaib (pre-Hauterivian) erosion. Otherwise, except for Jauf where the whole of the late Jurassic is coarse dolomite, the Arab is

conformably overlain by massive, white anhydrite of the Hith Formation. The lower contact with the Jubaila Formation is also conformable, almost everywhere marked by change from quiet-water, muddy limestone to current-washed limestone characterized by lime sand, commonly skeletal, in the form of massive, clean, calcarenite beds.

Thicknesses of individual members change little from the coastal area towards the outcrop. Each anhydrite bed does, however, thicken considerably; a change compensated for by thinning of the underlying carbonate unit. There is little doubt that, to the west and south, carbonate beds are progressively replaced from the top down by facies change to anhydrite. In fact, regional considerations show maximum evaporite thickness occurs along a north-south line near the longitude of Riyadh. This is borne out by the fact that the amount of carbonate rocks remaining in the solution-collapse zone is small and the interval was apparently mostly soluble anhydrite. That hypersaline conditions obtained from time to time is attested to by the fact that at Khurais, Haradh and in the western Rub' al-Khali, salt occurs in the upper members of the Arab, normally in beds less than 10 meters thick.

The rather limited fauna so far recorded from surface exposures of the Arab Formation has not proved diagnostic. Except for *Diceras*, identifiable forms range down into the Jubaila below. Consequently, the subsurface sequence provides the only means of dating the Arab rocks.

Kurnubia spp. Nautiloculina spp., Clypeina jurassica, C. cf. hanabatensis, Cylindroporella arabia, Polygonella incrusta and *Salpingoporella sp.* range throughout the Arab-D Member (Powers, 1962). Although some elements of this assemblage extend on

into the A Member, it is only the D beds that have been reliably dated. These can be equated to at least part of Hudson and Chatton's (1959) group g beds through the No. 4 Limestone of Dukhan oil field in Qatar; the direct equivalent of the Arab D Member of Saudi Arabia.

Hudson and Chatton (1959) also list *Calpionella alpina* Renz, *Pseudocyclammina sp.*, and *Burgundia steinerae* Hudson from group g and equivalent beds. By comparison with the Alam Abyadh limestones of southwest Arabia, the *Cidaris glandarius* beds of the Lebanon and Kurnub, and with other formations, they conclude the faunas are Sequanian (early Kimmeridgian) in age, a data compatible with other lines of evidence.

The evaporites of both the post-D Member of the Arab and the Hith Formations have not yet been dated. But, as these beds occur between known Late Kimmeridgian and presumed Berriasian (Early Cretaceous), it seems safe to assume that they are, at least in part, Tithonian.

Although all members of the Arab Formation contain oil, accumulation in the thinner A, B, and C carbonates is much less extensive than in the D Member. Arab-A, and-B oil occurs in Abu Hadriya, Abu Sa'fah, Berri, Dammam, Khrusaniyah, Manifa, and Qatif. The C Member contains oil at the same fields plus minor accumulations in northern Ghawar and Abqaiq. Arab-D Member oil has been encountered at Abqaiq, Abu Sa'fah, Dammam, Fadhili, Ghawar, Khurais, Khursaniyah, and Qatif. In all these fields, the 25- to 40-meters-thick D Member, as well as the upper 45 or so meters of the underlying Jubaila Limestone are oil saturated.

The major oil deposits in the Arab Formation accompany maximum development of porous calcarenite. It is certain that intergranular pores associated with the rocks at the time of deposition almost exclusively controls present distribution of oil. To be sure, diagenetic changes including recrystallization, dolomitization, and cementation have all modified the original pore pattern to some extent but, in each case, the effect has not been drastic. The four members of the Arab Formation can be described from top to bottom as follows:

Arab-A Member:

Author: - Unknown. First used in 1939; unpublished letter.

Type section details:

Location: Dammam well 7 (lat. 26° 19'04" N, long. 50°07'38" E) between drilled depths 1,371.6 and 1,388.4 meters,

Thickness: 16.8 meters.

Lithology: Micritic limestone, tan to brown, compact, with thin layers of brown calcarenite; minor anhydrite near top.

Fossils: *Diceras sp.*

Age: Late Jurassic (Early Tithonian) on stratigraphic position.

Underlying Member: B Member of Arab Formation; contact conformable, placed at sharp change from limestone above to anhydrite below.

Overlying Formation: Hith Anhydrite; contact conformable, taken at break from micritic limestone with anhydrite above.

Other localities: The member has not been identified on outcrop because of extensive solution-collapse effects. It does occur, however, in numerous wells east of the collapse zone (both in the Rub' al-Khali and northern areas) and has been penetrated in all oil fields.

The Arab-A reservoir- synonymous with the A Member- contains significant amounts of oil in Abu Hadriya, Berri, Dammam, Khursaniyah, and Manifa; minor accumulations occur in north Qatif and Abu Sa'fah.

Arab-B Member:

Author: - Unknown. First used in 1939; unpublished letter. Redefined Powers and others, 1966.

Type section details:

Location: Dammam well 7 (lat. 26° 19'04" N, long. 50°07'38" E) between drilled depths 1,388.4 and 1,399.1 meters,

Thickness: 10.7 meters.

Lithology: Lower 6.1 meters micritic limestone, tan with thin interbeds of brown calcarenite; upper 4.6 meters anhydrite, white massive.

Fossils: None.

Age: Late Jurassic (Tithonian) on stratigraphic position.

Underlying Member: C Member of Arab Formation; contact conformable, taken at sharp break from carbonate rock above to massive anhydrite below.

Overlying Formation: A-Member of the Arab Formation; contact conformable, placed at change from massive anhydrite below to limestone above.

Other localities: The unit has not been recognized on the surface as the area in which it would be expected to crop out is a jumble of complexly settled rocks; presumably the collapsed carbonate residue left behind when evaporite layers were removed by solution. East of the outcrop, however, the member has been recognized in numerous well sections in the Rub' al-Khali and northern Arabia.

Arab-C Member:

Author: - Unknown. First used in 1939; unpublished letter. Redefined Powers and others, 1966.

Type section details:

Location: Dammam well 7 (lat. 26° 19'04" N, long. 50°07'38" E) between drilled depths 1,399.1 and 1,440.6 meters,

Thickness: 41.5 meters.

Lithology: Lower 28.7 meters calcarenite, tan to brown, generally fine-grained, moderately to strongly cemented with some thin beds of partially dolomitized micritic and calcarenitic limestone; upper 12.8 meters anhydrite, white to tan, massive with minor streaks of brown dolomite and limestone.

Fossils: None.

Age: Late Jurassic (Early Tithonian) on stratigraphic position.

Underlying Member: D-Member of Arab Formation; contact conformable, taken at change from calcarenite and dolomite above to white anhydrite below.

Overlying Formation: B Member of Arab Formation; contact conformable, placed at sharp break between anhydrite below and dolomite above.

Other localities: The unit has not been identified on outcrop owing to extensive collapse phenomena resulting from the loss of interbedded anhydrite. The member is present, however, in numerous wells to the east. Its distribution is essentially the same as that of the Arab-A Member.

Arab-D Member:

Author: - Unknown. First used in 1939; unpublished letter. Redefined Powers and others, 1966.

Type section details:

Location: Dammam well 7 (lat. 26° 19'04" N, long. 50°07'38" E) between drilled depths 1,440.6 and 1,499.1 meters,

Thickness: 58.5 meters.

Lithology: Lower 46.0 meters micritic limestone, tan to brown, partially dolomitized with common interbedded clean-washed, porous calcarenite and calcarenitic limestone and some dolomite; upper 12.5 meters anhydrite, white, massive with thin interbeds of dark-brown dolomite and strongly dolomitized calcarenite.

Fossils: *Clypeina jurassica* Favre, *C. cf. hanabatensis* Yabe and Toyama, *Cylindroporella arabica* Elliott, *Polygonella incrustata* Elliott, *Kurnubia spp.* and Nautiloculina spp.

Age: Late Jurassic (Late Kimmeridgian) on contained fossils and stratigraphic limestone below.

Underlying Formation: Jubaila Formation; contact conformable, taken at change from porous calcarenite above to tight micritic limestone below.

Overlying Formation: C Member of Arab Formation; contact conformable, placed at break from white anhydrite below to calcarenite and dolomite above.

Other localities: The Arab-D Limestone Member has not been recognized in its entirety on outcrop owing to extensive solution of anhydrite beds and subsequent slumping and brecciation of the carbonate units left behind. Most of the lower carbonate beds seem to be present in the vicinity of Sha'ib Nisah and again between Sha'ib Haddar and Wadi ad Dawasir but even within these sections a persistent brecciated zone suggests that at least one thin layer of evaporite was originally included. Anhydrite presumably equivalent to the upper part of the D-Member is known only from sporadic outcrops in the Sha'ib Haddar-Wadi ad Dawasir area. The member, widespread in the subsurface, has been encountered in all oil fields and numerous wells east of the outcorp belt. Its distribution is essentially the same as that of the Arab-A Member.