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PETROGRAPHY AND DIAGENESIS
OF LOWER PALEOCENE CARBONATE RESERVOIR ROCK,
DAHRA FIELD, LIBYA

by

Elhadi Razzagh Khoja

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PETROGRAPHY AND DIAGENESIS OF
LOWER PALEOCENE CARBONATE
RESERVOIR ROCK, DAHRA FIELD, LIBYA

Introduction

Libya is located on the northern coast of North Africa with approximately 1,700 kilometers of Mediterranean coastline. It is a large nation, 1,528 kilometers in an east-west direction and as much as 1,450 kilometers from north to south, with an area of 1,887,105 square kilometers (fig. 1). Except for the northern parts, the country is entirely in the Sahara. Difficulties of travel and survival have long caused the country to remain unmapped, and geological information has been acquired slowly.

Exploration, starting about 1800, gave the modern world a few glimpses of the country. Many Italian geologists, notably Desio and his co-workers, published reports on their studies in the country, chiefly from 1911 to 1943. The French geologists also published on their work in Fezzan, southwestern Libya, chiefly from 1943 to 1955. Geologists of the United States Geological Survey, under the auspices of the Agency of International Development and its predecessors, made country-wide hydrologic and geologic studies from 1952 to 1964. These led to the many short reports and publication of the 1:2,000,000 topographic and geologic maps of the country that were compiled in cooperation with the Exploration Society of Libya, and the several oil companies operating
in the country.

The Sirte basin is located in the north centry part of Libya (fig. 2). This basin accumulated sediments in Lower Cretaceous and Tertiary time. Terrigenous clastics filled the basin during initial transgression. As subsidence continued, shales and carbonates were deposited through the Cretaceous and Tertiary.

Pools studied in this investigation are from the Dahra (B) oil field, situated on the west margin of the Sirte basin. The field is 530 kilometers southwest of Tripoli and 120 kilometers inland. The Dahra (B) reservoir is in Lower Paleocene Carbonate rocks.

Objectives

The objective of this study is a detailed petrographic analysis of the Dahra (B) reservoir involving reconstruction of the original environment of deposition, facies pattern and diagenetic history. Thin section studies were used to: (1) classify the reservoir rocks according to texture, (2) understanding of the relation of rock fabric to porosity and permeability, (3) evaluate reservoir rocks in terms of reservoir quality and (4) reconstruct the physical and chemical conditions prevailed during the Dahra reservoir sedimentation.

The author fulfilled his objectives, that the reservoir contained much diagenetic chalk. The porosity was a consequence of this texture plus dolomite. Reservoir permeability and reservoir rocks quality was dependent solely on the dolomite content. These diagenetic features, not the original rock type, were most important.
Fig. 2.—Tectonic framework of Libya. Location of Sirte basin.
Petroleum Development

Libya became an independent nation on December 24, 1951. At that time, little was known about the surface geology and nothing was known about the subsurface geology of the country. Because of the tremendous oil deposits already discovered in neighboring Algeria, there was speculation about the possibility of similar deposits in Libya. In 1955, a petroleum law was passed which "invited" interested parties to apply for concessions, for exploration and exploitation of hydrocarbons. All governmental facilities were granted including the removal of taxes on all equipment and other materials needed for exploration.

The first granting of concessions occurred in November 1955, and continued through May 1956. Nine operators were successful recipients of a total of 49 concessions covering 488,323 square kilometers or 36 per cent of the entire country. Subsequent grants were made yearly, and by late 1962 about 60 per cent of the nation was under concession.

Concession grants were for a period of 50 years with the requirement that concessions in Petroleum Zones I and II (the northern part of the country) should be reduced to 75 per cent of their size at the end of the first five years, to 50 per cent of the original size at the end of eight years, and finally to 33 1/3 per cent of their original size, but not less than 3,000 square kilometers, after ten years. The requirements in zones III and IV were the same for the first two periods, but the final reduction was to 25 per cent of the original size, but not less than 5,000 square kilometers. In many instances the grants carried
some kind of work obligation to be performed.

Following the granting of concessions, Libya's rise in petroleum stature to that of a major producing country was exceedingly rapid. Just four and one-half months after granting of concessions, the first wildcat well was spudded in Cyrenaica by Libyan American Oil Company, and the first discovery was made by Esso Oil Company in their Atshan No. 1 within three years.

The first commercial discoveries were the Oasis Oil Company of Libya's Bahi and Dahra (B) oil fields. Following these successes, the oil industry intensified its efforts in central Libya which resulted in Esso's Zolten discovery. These commercial discoveries were made only four years after the granting of concessions.

The electrifying discoveries set off a chain reaction in the years that followed. Up to mid 1962 a total of 274 new-field wildcats resulted in 51 oil discoveries. From a total of 534 wells of all types drilled, 248 were successful. Some degree of success has touched all of the original nine concessionaires.

The Dahra (B) and Zolten fields were rapidly developed and pipeline projects were undertaken at an early date. The first shipment of Libyan crude to the world markets was made from Zolten field on October 1, 1961, or just less than six years after the original granting of concessions. The first shipment of Dahra (B) oil followed seven months later.

Other discoveries of significance are the Esso-Sirte Inc. Raguba field, Oasis Oil Co. of Libya Inc. Samah, Waha, and Jalo fields,
and the British Petroleum and Nelson Banker Hunt Sarir field. The most recent major discovery was by Occidental of Libya Inc. in 1967 in its Intisar oil field. Over two billion barrels of oil are believed to be in place. Through May 1969 Intisar field has produced over 175 million barrels of oil. Most of these discoveries are in the Sirte basin, which has proved to be the most prolific basin for oil accumulations in the world.

Libya today produces 127 million tons of oil per year. Its annual income from oil revenues only, is more than two billion dollars, with a population of only 1.8 million people. The author hopes that these revenues will be spent intelligently on domestic projects such as health and education to encourage the country's long range progress.

Geologic Setting of Libya

Successful exploration for petroleum in Libya has involved the work of a great many geologists, and a wealth of information has been amassed, most of which lies in the files of . . companies active in Libya and not available to the public.

Libya is situated on the northern part of the Mediterranean foreland of the African Shield. It contains a small but representative portion of the 1000 km wide belt of sedimentary rocks which fringe the various exposed basement massifs of Central Africa and extends from the Atlantic to the Red Sea and eastward into Arabia. The southern limits of the Palaeomediterranean, or Tethys Sea as it is known in most of textbooks, extended over various portions of this
foreland during Cretaceous and Tertiary time. In comparison with the
area to the west (the uplifted, folded and, in places, thrusted,
Saharan Atlas Mountains of Morroco and Algeria) the tectonic pattern in
Libya is relatively "simple" and the term "stable foreland" is appro-
priate to this area. In view of the various oscillations and differ-
ential movements which occurred on the different blocks of which it is
composed, the term "Saharan Platform" was suggested by Sander for the
tectonic unit of Libya and the Sahara. Epeirogenic downwarping, tilting
and block faulting differentially depressed the Libyan part of this
foreland allowing repeated transgressions of the Tethyan Sea upon its
borders.

In northern Libya, three major structural entities may be dis-
cerned (figs. 3 and 4): (1) The first is the Ghadames basin, filled
predominantly with Paleozoic clastics. This basin, one of the largest
in North Africa, widens and deepens to the west of Algeria. On the west,
Ghadames basin is bound by the Hasaoud High and on the north and south
by the Jefren and Gargaf basement arches, respectively. (2) The second
is the central Sirte basin, or "trough", extending roughly NW – SE,
formed in Cenomanian time. It is characterized by step-like fault
blocks, downthrown most strongly toward the east. Initial transgression
upon its exposed basement filled the basin with terrigenous sediments.
As subsidence continued, shales and carbonates were deposited throughout
the remainder of the Cretaceous and Tertiary. The maximum subsidence
of this basin may have occurred during the lower and middle Eocene.
(3) The last is the Cyrenaican platform, which is structurally higher
Fig. 3  Map showing major structural elements in Libya and adjacent areas.
Fig. 4. Major structural elements of Libya and northern Chad.
than the Sirte basin. A WNW - ESE hinge-line cuts across the northern portion of this area, exposing the thick and more complete Mesozoic section north of it on the gently folded Jabel Akhdar uplift.

These are the three fundamental structural subdivisions of Libya. Additional structural features exist, such as the Murzuk and Kufra basins and the Tebesti Harouj uplift, but because of their irrelevance to this research, they are not discussed in this context.

General Comparative Stratigraphy of Northern Libya

Historic Review

Various explorations which were more geographic than geologic in nature, undertaken by travelers usually lacking a specific competence in geological field (Desio, 1968, p. 81). The first geological information was reported by Hornemann (1802) on Cyrenaica. Della Cella (1819), Spratt (1865), Stracey (1867), Rohlfs (1881), Haiman (1882) and Schweinfurth (1884) contributed reports on the surface geology of Cyrenaica.

Gregory was the first geologist to publish geological investigations combined with a map on Cyrenaica in 1911. Further geological studies, especially on Cyrenaica, were carried out by Migliorini (1914) and Ricci (1915). From 1920 to 1950 is a period characterized by productive geological research; among the investigators of this period who published especially on the stratigraphy and paleontology of Cyrenaica are Stefanini (1921), Crema (1922), Raineri (1923), Zuffardi-Comerci
(1924, 1925), Cipolla (1933), Rispolli (1925, 1929), Crema (1925, 1930, 1933), Desio (1927a), Zanon (1927), Silvestri (1928a), Parona (1928), Floridia (1933), Marchetti (1934), Tavani (1946) and Naldini (1948).

The intensive search for oil in Libya which began in 1953 led to numerous stratigraphic publications. Among the most significant are Colley (1963), Contant and Gondarzi (1967) and Klitzsch (1968).

Colley (1963, p.7) illustrated diagramatically the subsurface stratigraphy of the three northern provinces (fig. 5). Very little of this section is exposed at the surface, and his interpretations were based on subsurface data gathered from oil explorations.

It is interesting to note the broad divisions in lithofacies that are apparent. Whereas an alternation of sands and shales characterize the Paleozoic, carbonates and shales predominate through the Late Cretaceous and Tertiary.

The time interval from the Permian to the Lower Cretaceous, inclusive, was a period of erosion or subaerial and evaporitic marine conditions over most of the Libyan foreland (Colley, 1963, p.42). Generally, the strata representing that span of time are of widely varying thickness of continental red beds separating marine phases of Paleozoic and Mesozoic. In the Sirte basin, however, these strata along with the greater part of the Paleozoic column are absent entirely (fig. 5).
GENERAL GEOLOGIC COLUMNS
NORTHERN LIBYA

Figure 5
Generalized stratigraphy of the northern basins
Tectonic Elements of Libya

The nucleation of the tectonic elements of Libya began by intensive folding which consolidated most parts of North Africa during the Precambrian orogenies. Since the Cambrian, the structural development was controlled by block faulting which resulted from epeirogenic movement. Differential subsidence in early Paleozoic time formed systems of troughs and uplifts. The geologic map of Libya (fig. 6) shows two sets of faults cutting through the mid-section of the country. The northern set probably influences the shape of the Gulf of Sirte. Near the intersection of the two trends is the largest outpouring of lava in Libya.

These two fault trends are approximately parallel with the well known great rift system in the Gulf of Suez and East African areas, and hence, might have originated as a result of drifting of the African continent.

Volcanic outpourings, chiefly of basalt, probably started in Oligocene time, and some flows are of recent age. The activity was probably concurrent with movements along deep-seated fractures perhaps related to the Alpine orogeny (Contant and Gondarzi, 1967).

Sirte Basin—Structure and Stratigraphy

The Upper Cretaceous – Tertiary Sirte Basin contains all the major oilfields of Libya, and is the most prolific oil producing basin on the African continent.

Following the Hercynian deformation which ended Paleozoic
EXPLANATION

Q Quaternary
Tpi Pliocene
Tm Miocene
Tae Oligocene and Eocene
Tc Continental beds of uncertain age
Tv Volcanic rocks, some of Quaternary age
Tae Paleozoic
Ku Upper Cretaceous
Kpm Nubian Sandstone including Continental Post Tassilian
(Permian to Lower Cretaceous)
J Jurassic
T Triassic
C Carboniferous
DS Devonian and Silurian
OC Ordovician and Cambrian
pC Precambrian
Gr Granite

\[\text{Oil field}\]

\[\text{Pipe line}\]

\[\text{Fault}\]
Dashed where uncertain; text and bell on downthrown side
Fig. 6 — Geologic map of Libya and area on south. Simplified from Conant and Goudarzi (1964).
deposition, the Sirte basin region underwent prolonged erosion before the beginning of sedimentation in the Mesozoic. The floor of the basin is formed mainly of Pre-Cambrian rocks (fig. 7) and the basin thus developed on the site of a deeply eroded high.

The general epeirogenic subsidence of the basin began late in the Mesozoic and continued well into the Miocene. The subsidence was spasmodic and differential and was locally fault controlled, with the result that considerable variation in thickness and facies exists in the contained sediments. The sediments are predominantly marine, mainly limestones and shales, but with local thick developments of evaporites. Sandstones also occur, notably at the bottom and the top of succession (fig. 5). Stratigraphic variation within the individual units is largely regional in character and is controlled by position within the basin (Berggren, 1968, p.106). Sharp local variations also occur and these are most directly related to contemporaneous faulting (Gillespie and Sanford, 1967, p.182). A similar case exists in the Tertiary sediments of the Gulf of Mexico (J. L. Wilson, 1970, personal communication).

Most of the faults are small and were active only early in the development of the basin. A smaller number are large and these had an important influence on the development of the basin (fig. 7). The latter were generally active intermittently throughout the history of the basin and control the present structure. The oil producing structures of the basin are due to these faults and to the sedimentary drape over them, rather than to any compressional folding.

Hydrocarbons occur in commercial quantities at several
MURZUK BASIN

Erg of Murzuk

Continental Mesozoics

Carboniferous

MURZUK-DJALO TROUGH

TRIPOLI-TIBESTI UPLIFT

DOR EL GUSSA

SECTION THROUGH TECTONIC ELEMENTS
Fig. 7. Structural cross-section from northern Niger to northern Cyrenaica.
stratigraphic levels within the basin: (1) in sandstones at the base of the Upper Cretaceous, (2) in sandstones and detrital limestones at the top of Upper Cretaceous, (3) in limestones, chalk and dolomites at various levels in the Paleocene and Eocene, and (4) in sandstones of the Upper Eocene - Oligocene. The overall distribution of oil in these reservoirs seems to be controlled by the regional facies variations within the major stratigraphic interval concerned. In general, the favorable facies belt lies in the southwestern half of the basin (Gillespie et al, 1967, p.182). Locally, oil occurrence is largely by structure which mainly resulted from depositional build up, aided by differential compaction, a case evidenced in our study of the Dahra (B) field reservoir. To a lesser extent, however, occurrence of hydrocarbons may be due to facies variations resulting from faulting of the basin's basement.

Techniques of Study

The first stage of this research was started in late May 1969 at the Geological Laboratories of Oasis Oil Co. of Libya in Tripoli, Libya. The company was most helpful in providing the author with cores and ditch samples from the Dahra (B) carbonate reservoir (PL-7B). The cores were already cut vertically. The total footage of cores is 863', taken from 23 wells (fig.12).

Detailed petrographic study was made foot by foot. Since some of the cores were saturated with crude oil, partial cleaning was carried out by the use of ethanol. The cut surface along the length of each
core was etched with 2% HCl for 15 seconds. Detailed petrographic
description for each foot-core was accomplished with a Leitz - binocular
petrographic microscope. Emphasis of the study was mainly on sedimentary
structure, visual porosity, and fossil content. Each core foot then was
covered with mineral oil and photographed at close range with a Nikon -
F - Camera. The objective of the photography is a documentation of
sedimentary structure and the reservoir rock types. After photography
a representative sample was taken vertically at approximately one foot
(0.33m.) intervals throughout the cores for detailed thin-section petro-
graphic studies. Ten-foot interval ditch samples were also collected
from the uncored zones of the seventy-one wells drilled in the Dahra
Field. The collected samples were placed in labelled paper envelopes
marked with exact depths. In August 1969 all the samples were shipped
from Tripoli to the Geology Department at Rice University in Houston,
Texas where petrography of the samples was accomplished.

High Power Optical Microscopy

Traditionally, petrology has approached microscopy with the
"standard" 30 microns thin-section and the petrographic microscope.
These served well in the study of comparatively coarse structure of
grains and identification of larger and distinct pore spaces. They
also provide good optical images at low magnification. However, when
the magnification is greater than 200X, the image becomes progressively
worse.

The main limitation of resolution lies in the thickness of the
"standard" section. The image is disturbed by the overlap of grains, and is blurred because the focal depth of the optical system is much less than the thickness of the section.

To avoid defects caused by excess thickness, very thin petrographic thin sections were prepared and observed for high magnification study. A piece of the chalky Dahra (B) carbonate reservoir was cut, ground and polished before being mounted on a petrographic slide glass with epoxy risin. It is then ground carefully with a fine abrasive to as thin as a few microns. The high power optical microscopy for 850 thin-sections was accomplished by means of a Zeiss Photomicroscope II (fig. 8), which is equipped with a 35 mm. camera and an automatic photomultiplier-controlled exposure up to 1/100 second. This microscope permitted photographing the diagnostic sedimentary structures, particle types and reservoir facies, and also allowed resolution of silt and clay particles up to 400 magnifications. This permitted better knowledge of detailed crystalline fabric and the mode of diagenesis of the "chalky" reservoir. Before a thin section was examined, it was etched in 2% acetic acid for 5 seconds, then stained with an acid solution of Alizarin Red "S" for 15 seconds to help the distinction between the calcisilt and calcilutite particles and dolomite crystals. With this stain, calcite becomes pink and dolomite remains unstained (Friedman, 1959).
**Electron Scanning Microscopy**

The scanning electron microscope is designed to produce an excellent image of a surface at very high magnification (up to 30,000X). Some of the main advantages of this instrument are: the large depth of focus at high magnifications, which gives considerable perspective to the image; the possibility of examining relatively large samples (1 cm. diameter) at low power and then at high magnification when objects of interest have been located; and the relative simplicity of sample preparation. It has been used to study the growth of crystals by Thornton, James, Lewis and Bradford (1966), and Minkoff and Nixon (1966); crystal decomposition reactions by Bowden and McAuslan (1956); oxidation and corrosion reactions by Pease and Ploc (1965) and Castle and Masterson (1966); in electronics by Mackintosh (1965) and Thornton (1965); and in investigating failure mechanisms by MacGrath, Buchanan and Thurston (1962) and Tipper and Dagg and Wells (1959).

**Description of the Instrument:**

The electron scanning microscope has been described by Pease and Nixon (1965), Smith (1961) and Oatley, Nixon and Pease (1965). The electron beam is focused to a point about 100 A° in diameter by electro-magnetic or electrostatic lenses. To scan the surface of the sample, the focused spot is moved by deflecting coils. The beam stimulates the emission of electrons, and high energy electrons are also "reflected" from the surface. A collector instrument which is usually a scintillation counter intercepts a portion of the electron currents. The output
is amplified and used to modulate the signal of a cathode ray tube, the spot of which is deflected in synchronism with movement of the focused electron beam over the sample surface. An image of the surface is built up on the screen of the cathode ray tube. In practice two cathode ray tubes are employed: one for direct viewing and one for photographing the image. The visual display tube has a long persistence screen, whereas the cathode ray tube used for photographic recording has a high resolution screen with short afterglow.

The magnification depends upon the ratio of the lengths of final and initial scanning movements. The length of the initial movement is readily changed, and the sample may be examined over a wide range of magnifications. The maximum useful magnification is limited by the instrument's resolving power or ability to separate fine detail in the image of the object. The theoretical limit at the present time is approximately 100 A°, though for many specimens it is probably closer to 200 A°.

In scanning electron microscope the sample is inclined to an angle of 20° to 45° to the electron beam, as this increases the fraction of the secondary electrons which escape from the sample and reach the collector. As the electron beam strikes the surface obliquely, the image is foreshortened and magnification varies from maximum to a minimum in orthogonal directions. As a result, the sample appears as if it were viewed at an angle. However, interpretation is not adversely affected by this because the maximum magnification is only two or three times the minimum.
Specimen Preparation for Scanning Electron Microscopy:

The design, construction and operating principles of the Stereoscan scanning electron microscope place certain requirements and limitations on any specimen to be examined.

The specimen stage in the stereoscan accommodates an aluminum mushroom type specimen stub with a 12 mm. diameter surface, on which the specimen is mounted. The construction of the standard specimen stage in the stereoscan is such that it allows a wide range of movement of the specimen while under examination. This feature, however, limits the maximum size of the specimen to 12 mm. diameter X 3 mm. depth. Larger specimens can be mounted on the specimen stubs but the range of movement is necessarily restricted. Additional specimen requirements for scanning electron microscopy are that the specimens be electrically grounded to their respective stubs, and that the specimen surface be electrically conductive.

Twenty specimens of the Dahra (B) reservoir were carefully selected. They included undolomitized lime mudstones, lime wackestones, lime grainstones and reservoir rocks which were variously dolomitized.

The following procedure briefly describes the stages followed in preparing the selected specimens for the stereoscan examinations:

1. The samples were cut to an appropriate size using a diamond saw.

2. The samples then were glued to the aluminum specimen stubs with a suitable adhesive (Dupont's Duco Cement), leaving the surface to be examined uppermost.
3. The mounted samples were submerged briefly in an ultrasonic designed water bath in order to remove any impurities or unwanted matrix fine (those created by prior sample preparation) from the sample surface, then allowed to dry.

4. Small amounts of silver paint (GC electronic's conductive silver paint, GC No. 21-1 / Walsco No. 36) were placed (or painted) on the sample-aluminum junction area to insure a good electrical ground connection from the sample to the stub. (Note: Care was taken to insure that no silver paint contacted the top surface of the sample).

5. The samples were then coated with a metallic thin film, by being placed upright on a rotating table within a vacuum (1 x 10^{-4} mm. Hg.). Small amounts of gold (8 millimeters gold wire, crimped/compressed to small masses) were previously placed in 3 tungsten helica baskets. The gold masses were then heated to their evaporation temperature of 2670°F, while the rotating table was turning at approximately 30 revolutions per minute. The three tungsten baskets, mounted on electrodes, were located 4 - 6 inches from the sample. They were at angles of 30°, 40° and 60° respectively, to the plane of the rotating table. Each of these sources was heated successively rather than simultaneously in order to prevent excessive heat within the vacuum chamber. Note: The evaporation of the gold in conjunction with the sample rotation, results in a uniform thin film that covers the entire sample surface area. (The resulting film, 200 - 400 Å thickness, provides the necessary surface conductivity, yet is so thin that it neither changes nor conceals any surface details).
6. Upon completion of the gold thin film deposition, the vacuum was released and the samples removed, ready for subsequent examination and photography using the electron scanning microscope.

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porosity and permeability data.

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This acknowledgment would not be complete without thanking my professors for being helpful and friendly, the staff of the geology department for being so nice, and my colleagues for their friendship.
DAHRA (B) OIL FIELD

History

The Dahra (B) oil field is situated in the Sirte Basin on concession 32 at a latitude of N29° 33' and longitude of E17° 47' (fig. 9). The first well was drilled on the structure in B1 in August 1958, and gave in (P1-7B) (top of calcilutite and calcisiltite and dolomite zone of Danian age, Lower Paleocene), 500 BOPD of an undersaturated oil. The development of the field began immediately and the first commercial production took place in May 1962; 38 wells were drilled by this date. In April 1968, 69 wells had been drilled on Dahra (B) and well No. 70 was being drilled in August 1968 while the author collected the samples for this research. At this time 41 wells flowed at an average rate per well of 1030 BOPD.

Field extension

The surface structure of the field is a large anticline of about 85 km² (fig. 10). It is actually an expression of the subsurface structure of the reservoir (fig. 11). A detailed explanation of the structural evolution will be discussed below.

Stratigraphy

The typical stratigraphy of the Dahra (B) field is the following, illustrated in well G1-32:
<table>
<thead>
<tr>
<th>Depth (ft.)</th>
<th>Thickness (ft.)</th>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 330</td>
<td>330</td>
<td>Upper Eocene</td>
<td>Lower Gatter</td>
<td>Marl-Anhydrite</td>
</tr>
<tr>
<td>330 - 720</td>
<td>390</td>
<td>Middle Eocene</td>
<td>Bir Ziden, Ben Isa</td>
<td>Ls., Marly Ls.</td>
</tr>
<tr>
<td>720 - 2370</td>
<td>1660</td>
<td>Lower Eocene</td>
<td>Gir</td>
<td>Anhydrite &amp; Dolomite</td>
</tr>
<tr>
<td>2370 - 3130</td>
<td>760</td>
<td>Upper Paleocene</td>
<td>Kheir - Dahra A</td>
<td>Limestones, Marls</td>
</tr>
<tr>
<td>3130 - 3450</td>
<td>320</td>
<td>Middle Paleocene</td>
<td>Dahra B (Pl-5)</td>
<td>Oolitic Ls., Marly Ls., Dolomite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dahra-Hofra Res.</td>
<td></td>
</tr>
<tr>
<td>3450 - 3790</td>
<td>340</td>
<td>Middle Paleocene</td>
<td>Rabia - Talith</td>
<td>Marls</td>
</tr>
<tr>
<td>3790 - 4180</td>
<td>380</td>
<td>Lower Paleocene</td>
<td>&quot;Chalk&quot; (Pl-7)</td>
<td>Calciultite, Calcisiltite, Ls., Dolomite, and Anhydrite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dahra B Res.</td>
<td></td>
</tr>
<tr>
<td>4180 - 4940</td>
<td>760</td>
<td>Upper Cretaceous</td>
<td></td>
<td>Quartzite</td>
</tr>
<tr>
<td>4940 - 5250</td>
<td>310</td>
<td>Cambro-Ordovician</td>
<td></td>
<td>Metamorphics</td>
</tr>
</tbody>
</table>
Oil Characteristics

Laboratory P.V.T. Analysis made on well B8 gave an oil saturation pressure of 398 psig at 148°F (reservoir temperature). This value was compared with the reservoir pressure of 1160 psig, indicating that oil exists in the reservoir in an undersaturated condition (Vanel, 1968).

The associated formation volume factor is \( \text{Bo} = 1.132 \) at 1160 psig. As there is a good pressure maintenance due to the excellent water drive, the formation volume factor remained equal to its initial value of 1.132 (Vanel, 1968).

During the differential pressure depletion in the laboratory, the viscosity of the crude oil varies from 1.25 centipoise at reservoir conditions to 1.18 at saturation pressure and 148°F; and then from 1.18 to 1.92 at atmospheric pressure and 148°F (Vanel, 1968). The gravity of the residual oil has been found to be 38.6° API at 60°F which corresponds to a density of 0.823. The crude oil contains an amount of hydrogen sulfide of 2.1 per cent in mole, or 0.49 per cent in weight. Average oil thickness is about 60 feet.

Estimated Oil Reserve in Place

Reserve of oil in place is estimated to be 666 million barrels, and associated gas is \( 98 \times 10^9 \) cubic feet. Oil recovery is excellent with a water drive, and is expected to be 50 per cent of the oil and gas in place.
PALEOCENE PALEOGEOGRAPHY

Shallow epicontinental sea covered broad shallow shelves of the Sirte basin during Paleocene time. These shallow shelves may be similar to the present day Persian Gulf shallow shelf and the Great Bahama Bank.

The lithofacies during Paleocene time in the Sirte basin are believed to be controlled by transgressions and regressions of this epicontinental sea across a broad shelf region that dipped gently into a deep and persistent shale basin located to the north and northeast of the Dahra (B) field. There are two major marine transgressions across the Sirte basin during Paleocene time (Terry and Williams, 1970, p. 33); one occurred midway through the series, the second at or near the close. These transgressions are marked by the shale deposits in the low-energy basin center and adjacent re-entrants. Carbonates, however, were deposited on the shelves during periods of regressions. The exact type of carbonate deposits on the shelves was controlled by water bathymetry and turbulence. For example, while in the Dahra (B) field micrite and micrite-supported low-energy carbonate rocks were depositing in very shallow water, foraminifera, algae and coral-rich bioherms of high energy and deeper water were forming to the east of the Intisar field.

First Cycle of Paleocene

A major basinal re-entrant existed throughout the central part of Sirte basin during early Paleocene time and continuing into the
middle Paleocene. Heira shale was deposited mainly in the center of the basin (see fig. 11). Lateral facies change from shale to Heira carbonate away from the basin toward the surrounding shelves (east, west and south shelves), marks the margin of these shelves. The shelf to the east was delineated by down to west faulting (Terry and Williams, 1970, p. 33). Heira carbonate was blanketed by a thin veneer of shale deposited during the first transgression of early Upper Paleocene. This incursion of the sea marked the end of the first Paleocene cycle.

Second Cycle of Paleocene

The remainder of the Upper Paleocene is characterized by several principal events. These, according to Terry and Williams, have controlled deposition and lithologies in NE Sirte basin. They are:

1. A very gradual and oscillating retreat of the sea.
2. Accumulations of benthonic fauna in carbonates above Heira shale in selected areas.
3. Growth of corals on pre-existing banks developed on the shelf margin.
4. A final major transgression resulting in deposition of marl beds and closing the Paleocene epoch.

Marine Paleocene dominantly in carbonate facies is extensively exposed in the Hamada basin. It is also exposed to the east of Jabel Gargaf, on the west-facing scarp of Houn graben, in Cyrenaica and in the Kufra basin. Thus, during Paleocene time, sea covered all Libya except in areas which were structurally or topographically high such as
PALEOCENE STRATIGRAPHY, SIRTE BASIN

Fig. 11

CET-JJW-1969
ADAPTED FROM RRL-1968 (CO.FILES)
west of Jabel Gargaph, Nefusa uplift, Jabel Auenat and Jabel Tebesti. It is well documented that Paleocene sea extended southward to the foothills of Jabel Tebesti (Gohrbandt, 1966). A tongue of this sea extended far south of Libya and connected with the Paleocene sea covering sedimentary basins in West Africa. Barsotti (1963) reported a similarity of the ostracode species of the Sirte basin to those reported from Senegal, Ivory Coast and Sudan districts.
Petrographic Analysis of Dahra (B) Reservoir

Introduction

Sedimentary petrography, a study of detailed constituents and texture of rock (Gubler et al, 1967, p. 51), is of great value in the understanding of petroleum reservoirs. Petrographic analysis of the Dahra (B) reservoir was accomplished by thin-section examination with high power optical microscopy using Zeiss Photomicrograph II (fig. 8) and other aids. This study resulted in a grain-by-grain examination and recognition of sedimentary structure and diagenetic alterations.

Particle Identification

Using standard procedures particle type usually can be identified with certainty only where the grain was originally sand- or gravel-size. However, in these studies identifications of much smaller particles were made by the use of the high power microscope. The original particles of the reservoir rocks are of two types: (1) skeletal, and (2) non-skeletal.

Skeletal Particles

Foraminifera, Mollusca, Brachiopoda, Ostracoda, Echinodermata, algae and calcispheres are the main skeletal elements of the Dahra (B) reservoir.
Foraminifera

Because of the depositional environment of the Dahra (B) reservoir carbonate sediments, the abundance of foraminifera is localized. Foraminifera are encountered only in the upper depositional cycles of the reservoir. Foraminifera in the reservoir rocks are limited to several genera and its identification in thin section is difficult. The small size, fragmentation of the tests by scavengers, solution effects and recrystallization make difficulties. Yet recognition of the foraminifera types may lead to an accurate delineation of the environment of deposition of the reservoir sediments and much careful study of the microfossils was carried out. Using Nakkady (1950), Cushman (1959), Mattai (1959), Treatise on Invertebrate Paleontology (Protista) (1964), Bonnefons and Dufaure (1967), the following forms were identified – Rotatids, Nummulite, Discocyclinid (from well B57 (3718-3719). Miliolids, Textularia, Ammobaculites, Ammomarginulina, Linderina, Cibicides, Ammonia, Discorbis and Anomalia are recorded from the marginal-shallow-lagoonal facies (wells B9-B6-B7). Gumbelina and Globogerina are less than 2 per cent of the rock volume, and recorded from the deep shelf facies (wells B2,B4 and B57).

The relative abundance of the foraminifera in the depositional environment is proportional to the abundance of sand-size particles in the rocks. The southward increases of foraminifera as shown in fig. 17 is due to the increase of water depth and more open circulation.
Mollusca and Brachiopoda

Mollusk and brachiopod bioclasts commonly occur in rock types deposited in normal marine environments. The particles in these rocks show no evidence of mechanical abrasion, but are of various shapes. The size varies from a few microns up to 2.5 mm. Grain size variation is interpreted to be due to fragmentation by the abundant scavengers. Brachiopod fragments are scarce, less than 2 per cent of the rock volume whereas pelecypods are more abundant. They constitute up to 40 per cent of the dense micritic rock which caps the reservoir.

The two types of fragments can normally be separated on the basis of difference in preservation. Brachiopoda fragments usually retain the shell internal structure in considerable detail whereas in molluscan shells the original aragonitic mineralogy is dissolved and replaced by calcite crystals which range in size from 3 - 20 microns and mosaic calcite up to several mm. in diameter. Mosaics in the molluscan bioclasts exist in the form of regularly arranged calcite twins. Neither mollusk nor brachiopod bioclasts are recorded from the supratidal zone rock types.

Ostracodes

Ostracode bioclasts are the most common particle in the reservoir rocks, regardless of the type of the subenvironment. Under polarized light, the ostracod bioclasts are distinguished from similarly shaped small pelecypod fragments by the prismatic microstructure. They are common in both restricted and normal marine carbonate rocks, a range
to be expected since they are notably euryhaline (Wilson, 1959, p. 87). They are most abundant in normal marine packstones up to 8 per cent. Generally, tests are disarticulated but not broken, because of their rotund shape and small size (200 - 600 microns). In most instances, the ostracod fragments enclose porosity due to a solution of the infilling lime mud. Sparry calcite may have gradually filled the cavity. The author attempted but failed to separate ostracod tests from core chips. Through thin section study, no generic identification was attempted.

Ostracoda from the Paleocene of the Sirte basin were reported by Barsotti (1963, pp. 1524-28) from the El Fogha formation where he identified twenty-three ostracod species. These ostracode species were found to be similar to ostracode assemblages of sedimentary basins of West Africa: Senegal, Ivory Coast, Dahomey-Togo and Sudan district. Presumably the same forms should occur in the Dahra (B) reservoir.

**Echinodermata**

Echinoderm fragments occur associated with algae, foraminifera, and molluscan particles. They are represented by irregularly shaped plates and partly preserved spines (Pl.1,A-B) usually embedded in a micrite matrix at various orientations. Distinction from other particles is based on the preservation of the internal meshwork of the individual plates, which form simple calcite crystals with unit extinction in polarized light (Pl. 1,B). The corona which Powers (1962, p.131)
reported to surround the echinoderm grain is not observed in this study. Echinoderm plates do not exceed 4 per cent volume of the rock in which they are found. The particles have no trace of magnesium calcite and appear to be nonsusceptible to dolomitization. Evidently, early in their diagenetic history the magnesium was lost and the plate altered to a single crystal of dense low magnesium calcite more resistant to later diagenesis than the surrounding aragonite.

Calcarous Algae

Green calcarous algae, dasycladaceans are relatively abundant especially in the subtidal environment. Because of their aragonite composition they are more susceptible to diagenetic processes which result in more mineralogical alterations than other particle types. Although the original aragonitic composition was replaced by sparry calcite mosaics, the original shape of the algae is well-preserved for comparative identification (Pl. 2). Well known genera and species have been identified by Elliott (1968) from the Paleocene of the Middle-East, Bismuth et al. (1967) from the Mesozoic of Tunisia and by Pia (1936a) from the Cretaceous of Libya. Dasycladacean particles are found in the shelf sediment in association with miliolid, echinoid and pelecypod particles. Their particle size range from 400 – 600 microns depending on the direction along which the fragment was cut. Identifications are approximate since they are made mainly through thin section. The following genera and species are identified: Trinocladus radoiciae, Dissocladella deserta, Furcoporella, Criphoporella, Neomeria,
Terquemella and Trinocladi. They are well preserved and seem to have been buried where they grew. Clypeina sp. is distinguished by the branches around a central stem. The green algae occur mainly in micritic rock types, hence must have thrived in a muddy environment. Fragments of the calcareous red algae are recorded from well B7 (3693-3694) and B2 (3782-83), (see Pl. 3). These are minor constituents and contribute less than 1 per cent of the skeletal composition of the Dahra (B) reservoir.

Calcispheres

Calcispheres or microcalcispheres measuring 15 to 40 microns in diameter are observed in rocks of lagoonal facies. Under the polarizing microscope they appear to be composed of a single calcite crystal. However, the scanning electron microscope revealed that they are composed of several calcite cryptocrystals arranged in a circular pattern.

Non Skeletal Particles

1. Fecal Pellets

Non skeletal particles constitute the major composition of the Dahra (B) reservoir. "Fecal" pellets are the most important. These pellets, in spite of being commonly smeared into more or less continuous mud layers, are in certain instances very well preserved. This permits identification of three types of pellets based on size and probable genesis: round to elliptically shaped, structureless, silt to very fine sand-size pellets; fine to medium sand-size, elliptically shaped,
structureless pellets; and coarse to very coarse sand-size Favreina. In addition to pellets, angular sand and gravel size fragments from mud are frequently recorded (lithoclasts). Rounded aggregates of unknown origin are also noticed to be among the non skeletal constituents of the Dahra (B) carbonate reservoir. Angular and rounded aggregates constitute less than 2 per cent of the reservoir rocks.

a. Silt to very fine sand-sized "fecal" pellets

This type of pellet lacks systematic distribution but is recorded mainly from the intertidal and subtidal zone. They are almost perfectly rounded and range in size from 60 – 100 microns. Similar pellet types were reported from Florida Bay (Ginsburg, 1956).

b. Fine to coarse sand-sized "fecal" pellets

This type is found in three subenvironments but constitutes up to 40 per cent of the pelleted mud in the supratidal and intertidal zones. The pellets in most instances are found in contact with one another, hence they form a continuous dark gray sheet with the center of each pellet usually darker than its margin. In other instances the pellets are rigid enough to retain original ovoid shape. They are cemented by calcite spar or cryptocrystalline calcite cement (Pl. 4,A).

c. Coarse to very coarse sand-sized"fecal" pellets

This type of fecal pellet, Favreina, is recorded mainly from the subtidal zone. These pellets are distinguished from the other two types on the basis of larger size, and upon the presence of
internal small canals which are parallel to one another. They constitute up to 20 per cent of the pelleted mud in the subtidal zone. They are often smeared out and constitute an important part of the mud matrix.

Johkowsky and Faure (1913) were the first workers to describe and illustrate this type of fecal pellet under the name of "organism B" from the Upper Portlandian limestones (Purbeckian) of Mt. Saleve in France near Geneva. Later workers had encountered "organism B" or similar fossils in Portlandian limestones of the Jura (Tutein-Nolthenin, 1921; Faure and Richard, 1927), Provence (Pfender, 1927), Anatolia (Parejas, 1948) and Cuba (Bronniman, 1955) as well as from the "Infra-tias", Bathouian, Callouian, Upper Jurassic and Neocomian of Aquitaine and the Northern Pyrenees (Cuvillier and Sacal, 1951, 1956; DuFaure, 1958), the Dogger of the Andennes (Garrot et al, 1959), the Toarcian of Lorraine (Maubenge, 1952), the Upper Jurassic of Western France and the Lias of southern Appennine (Sartori and Crescenti, 1960), the Infra-tias, Lias and Dogger of Morroco and the Jurassic of Algeria (Cuvillier, 1954), the Upper Jurassic of Qatar, Persian Gulf (Elliot, 1956), the Middle East (Elliot, 1962), and the Turkish Oligocene Parejas (1948) and the Miocene of Libya (Bronnimann, 1960).

Parejas (1935, 1948) recognized these pellet-microfossils as representatives of fecal pellets of certain crustaceans, and were described by him as species of Coprolithus from the Jurassic and Oligocene. Bronnimann (1955), dealing with Cuban examples, proposed
the genus *Favreina* for them which was classified to species depending on the shape and size of pellets and the shape and number of canals present. In the subtidal facies of the Dahra (B) reservoir, though these pellets are abundant, they are not very well preserved and cannot be classified with any reasonable degree of accuracy to the species level.

2. **Angular Aggregates**

Intraclasts (Folk, 1962, p. 63) or Lithoclasts: Discrete angular fine sand to gravel size fragments of lime mud which differ from the matrix lime mud in which they occur. This particle type is not very common in the Dahra (B) reservoir rocks; it is observed mainly in rocks of the subtidal zone. It occurs in only a few cores by less than 2 per cent; in a very few instances it reached 10 per cent by volume of the rock. These fragments appear to originate in two ways: (1) From penecontemporaneous, weakly consolidated lime mud sediments that have been eroded from adjoining parts of the depositional basin during times of current activity. (2) As a result of burrowing by various bottom dwelling organisms which have homogenized the originally deposited sediments, leaving remnant clasts at various positions. These types of fragments attain various shapes from angular to rounded and are from sand size to several centimeters across (Pl. 5, A-B). In spite of their small size in many instances, the particles always bears the composition, fabric, and structure of the originally deposited sediments, and therefore were utilized in the reservoir interpretation.
3. **Dolomite**

Dolomite crystals are the most commonly occurring textural element of the Dahra (B) reservoir. The bulk of the dolomite rhombs are believed to be of secondary origin; a mechanism for dolomitization is discussed in another part of the thesis. Dolomite crystals range in size from 4 - 30 microns (crystal size was measured along the crystal long diagonal axis). In the shelf facies where the dolomite is 10 to 30 per cent of the rock volume, the dolomite rhombs preferably replaced the lime mud matrix and appear as scattered euhedral rhombs attaining an average size of 10 microns. Dolomite, however, is most common in the rocks of the supratidal and intertidal zones in association with replacement anhydrite. It constitutes about 85 per cent of the rocks of the intertidal zone. As in the shelf facies, the dolomite of the intertidal facies preferably replaced up to 90 per cent of the lime mud, and in a few instances 100 per cent. The average rhomb size of this facies is 15 microns. Statistical data accomplished by the author on the upper 60 feet of the reservoir showed that dolomite constituted from 5 per cent by volume (as in well B4), up to 70 per cent by volume (as in well B18). Regardless of its volume-per cent in the rock, the dolomite crystals preferably attain subhedral to euhedral crystal form. In dolostones in which the dolomite rhombs are 80 per cent, the arrangement of the euhedral microcrystals give the rock its characteristic sucrose fabric. This fabric is a characteristic feature of the reservoir dolostones (Pl. 6).
4. **Sparry Calcite**

Because the reservoir rocks are micrite supported, sparry calcite is a rather rare element. However, whenever it was encountered it was logged and its volumetric percentage carefully estimated.

Whenever the calcite spar is found in the rocks, a remarkable decrease in their measured permeability was recorded, such as the measurements of wells B10 (3774-76, 3816-18), B9 (3733-34), and B75 (3710-12), and at other various depths (see cross-sections A-A', B-B', Appendix). Calcite spar in the Dahra (B) reservoir exists as a:

1. cement between bioclasts (Pl. 7, A).
2. a cavity fill of chambered foraminifera (Pl. 7, B).
3. in abandoned burrows which were filled at a later stage with unconsolidated sediments deposited at the site. Since the inside of the burrow and the fill sediments are water saturated CaCO₃ calcite precipitated from solution (Pl. 8).

5. **Anhydrite**

Anhydrite is the most important noncarbonate mineral of the Dahra (B) reservoir. It is nodular in form and commonly associated with the dolomite facies. It also exists as an accessory mineral in the shallow shelf lime wackestone facies. Three types of anhydrite are recognized (Murray, 1964, p. 515) - (1) nodular, (2) replacement, and (3) void-filling.

Nodular anhydrite is probably of early diagenetic origin. Nodular anhydrite reflects the early depositional and diagenetic environment and is the most important type. It forms massive beds which range
in thickness from one foot as in B8, up to ten feet as in B10. The
nodules are white to light gray, and range widely in diameter from a
few millimeters up to tens of centimeters. They vary in shape from
spherical to elongate, and may form a complex mass of closely packed
nodules separated only by thin wisps of microcrystalline dolomite or
algal filaments. The resulting fabric is termed "chicken-wire"
structure by Forotson (1958). This term was used subsequently by
Kinsman (1966), Holliday (1965), Kent (1968) and Butler (1969). The
German term "flaser" is also used to describe this type (Pl. 9).
Thin-section studies showed crystals of a few micron-size and no
regular shape. However, most of the crystals displayed a well-formed
rectangular outline because the normal crystal habit is tabular to
(001). The close packing of these euhedral grains builds the "pile-
of-brick" texture, typical of "primary" anhydrite (Brown, 1931; Goidman,
1933, 1952). Actually, the single crystals appear to be composed of
numerous individuals in a strictly paralleled position, which are
responsible for the step-like edges frequently displayed (Schaller
and Henderson, 1932).

The platy crystals exhibit various orientations; however, a
few are observed to be oriented more or less parallel over a small
area, and in certain cases with their greatest axis parallel to the
bedding.
6. Replacement Anhydrite

It is considered an accessory mineral; since its abundance does not exceed 7 per cent of the rock volume. It is associated with the dolomite facies in the intertidal zone and occasionally recorded from the normal marine shelf facies. It grows within the rock, occupying spaces previously occupied by other carbonate minerals, replacing cryptocrystalline lime mud and pellets, as well as bioclasts which are totally or partially replaced (Pl. 10,A). In reflected light, the rectangular crystals are cloudy, apparently from included relicts of the carbonate matrix. It commonly exhibits the subrectangular outline of the replacement crystals.

The replacement process appears to start as a void fill between the interparticle spaces of pellets and microvoids of lime mud; as the process advances, the anhydrite gradually replaces the carbonate particles and forms a mosaic in which inclusion of the replaced sediments is observed (Pl. 10,B).

7. Void-fill Anhydrite

It fills the micro-pores between the micrite particles and the microcrystalline dolomite rhombs. It also partly or completely fills the solution-originated vugs and foraminifera cavities. The individual crystal-size is from one to three microns, subhedral or anhedral. The crystal aggregates are clear white in plain light and characterized by strong birefringence and sharp extinction. Pore-filling anhydrite is the least common of the anhydrite types in the Dahra (B) reservoir. The replacement and the pore-filling anhydrite are the most important
in the development of vuggy porosity which resulted from subsequent
dissolution of these two anhydrite types.

8. **Iron Bisulfide**

   Authigenetic pyrite crystals constitute 2 to 10 per cent of the rock volume of the pelecypod-wackestone facies at the top of the reservoir. No pyrite is recorded from other rock types of the reservoir.

   The iron bisulfide exhibits microcrystalline cubic crystals of as fine as one micron. These crystals are also observed as groups to form larger crystals of cubic or rhombic shape, and up to 2 mm. in size. The microcrystalline iron bisulfide tends to replace the micrite and avoids to a certain extent replacement of the bioclasts. A few pelecypod fragments, however, are partially replaced by the iron bisulfide mineral.
PLATE 1

A. Microphotograph shows partially preserved echinoid spine in lime wackestone. B9 (3730-31), shallow-marginal shelf facies. Cross nicols, 40X.

B. Microphotograph illustrates echinoid fragments, shows unit extinction in polarized light. Dolomitie lime wackestone, B6 (3799-800), shallow-marginal shelf facies. Cross nicols, 40X.
PLATE 2

A. Microphotograph shows a longitudinal section of green algae
   (*Neomeris cretacea*, Elliott) in lime mudstone. B1 (3756-57),
   shallow-marginal shelf facies. Cross nicols, 40X.

B. Microphotograph shows a transverse section of green algae
   (*Clypeina* sp., Elliott), in dolomitic lime wackestone. B11
   (3704-05), shallow-marginal shelf facies. Cross nicols, 40X.
PLATE 3

Microphotograph illustrates red algae fragment (Lithothamnium primitiva, Johnson) in Lime packstone of deep-neritic shelf facies, B2 (3782-83). Cross nicols, 40X.
PLATE 4

A. Microphotograph shows "fecal" pellets. Notice rounded pellets cemented by calcite spar in the center of the photograph. Smeared and recrystallized pellets cover the large portion of the photograph. Lime mudstone, B11 (3692-93). Cross nicols, 40X.

B. Microphotograph illustrates the shape and size of the *Favreina* fecal pellets. Notice the internal canals are filled by calcite spar. Notice also the sparry calcite cement between the pellets. Lime wackestone, B9 (3751-52). Cross nicols, 40X.
PLATE 5

A. Microphotograph illustrates an intraclast of several centimeters in size. It is a small patch of the originally deposited sediment not disturbed by the burrowers. Notice the difference in fabric between the intraclast and the bioturbated sediment around it. Lime mudstone, B11 (3732-33). Cross nicols, 40X.

B. Microphotograph shows smaller-size lithoclast than above.

It is assumed to be caused by the same processes as above.

Lime mudstone B11 (3734-35). Cross nicols, 40X.
PLATE 6

Microphotograph shows the subhedral and euhedral dolomite crystals in a sucrose fabric dolostone, B1 (3802-03). Notice the variations in size and orientation of the rhombohedrons and their relation to the intercrystalline porosity. Notice also the distribution, shapes and sizes of the pores. Cross nicols, 40X.
PLATE 7

A. Microphotograph illustrates pellets cement by sparry calcite mosaics. Lime mudstone (shallow-marginal shelf facies), B9 (3756-57). Cross nicols, 40X.

B. Microphotograph shows calcite spar filling the chambers of miliolids tests. Notice also the distribution of the calcite spar also between and in smeared and neomorphosed pellets, Lime wackestone (shallow-marginal shelf facies), B9 (3713-14). Cross nicols, 40X.
PLATE 8

Microphotograph shows pelleted mud which was burrowed. The burrow-fill is of fine textured sediments with higher permeability than the burrowed sediments. The area of higher permeability was saturated with interstitial water which apparently precipitated calcite cement from solution. Lime mudstone B8 (3668-69). Cross nicols, 40X.
PLATE 9

Photograph shows (chicken-wire) nodular anhydrite from the supratidal flat facies of B1 (3811-12). Notice the nodules which are separated by thin wisps of microcrystalline dolomite.
PLATE 10

A. Microphotographs show replacement anhydrite (white) replacing bioclasts of lime wackestone B8 (3711-12). Notice also the replacement of pellets and micrite particles by anhydrite. Cross nicols, 40X.

B. Microphotograph illustrates the existence of relicts of carbonate matrix (dark) in the replacing anhydrite (white). Notice the partial dissolution of the anhydrite and creation of microvugs. Cross nicols, 40X.
NAMING AND CLASSIFICATION OF THE
DAHRA (B) RESERVOIR ROCKS

Grabau (1904, 1913) introduced a genetic classification for carbonate rocks. Pettijohn (1948, pp. 289, 313) introduced a chemical classification for the carbonate rocks. Various other authors such as Guerrero and Kenner (1955, pp. 46-48) and Teodorovich (1958, p. 299), also attempted a chemical classification for the carbonate rocks. Many carbonate reservoirs owe their favorable porosity and permeability to the original properties of depositional texture and a classification based on these parameters is important in understanding carbonate rocks in relation to oil accumulations. Within the last fifteen years, a tendency has developed among various specialists in carbonate rocks to emphasize the petrographic study of the rocks to interpret them as original sediments. Among the important papers on this trend are those of Pettijohn (1949), Lowenstam (1950), Beals (1956, 1958), Brankamp and Powers (1958), Dunham (1962), Folk (1962), Illing (1959), Leighton and Pendexter (1962) and Plumley et al. (1962).

The writer, in his classification of the Dahra (B) carbonate reservoir found Dunham's classification of basic rock types, as used by J. L. Wilson in his study of the Deperow Formation (Wilson, 1959, p. 17), to be satisfactory. This classification emphasizes the depositional texture rather than diagenetic alterations. The basic criteria used by the writer in recognizing rock types whose original sedimentation
can be inferred sufficiently to acquire their distinctive depositional texture are: (1) identity of particle types making up the original reservoir sediments (with special attention to paleontology of fossil fragments); (2) relative abundance, packing and sorting of particles; (3) relative abundance of lime mud particles versus a mosaic of calcite crystals as a possible cement between particles; and (4) relative abundance of lime mud versus sand-size skeletal particles. Dolomite, the diagenetic rock type which is abundant among the reservoir rock types is defined, but not further classified on the basis of crystal size.

In terminology and concepts, the writer has found that the system proposed by Dunham (1962, p. 108) is most useful in describing the reservoir rock types. Folk's (1962) terminology is also utilized at various stages of the petrographic research:

Lime mudstone (pure calcilutite); or pure micrite of Folk (1962) meaning a rock type which is composed of 10 per cent or less of fossil debris or skeletal grains. Burrowed lime mudstone is disturbed micrite or dismicrite of Folk (1962).

Lime wackestone; bioclastic-pelletal-lithoclastic calcilutite (Wilson, 1957, p. 18), or biopelmicrite (Folk, 1962), a lime mud-supported rock type containing more than 10 per cent grains (10 per cent grain-bulk). The grains are usually unsorted and jumbled. The lime mud matrix is abundant enough to separate and support the floating grains.

Lime packstone; calcarinitic limestone (Powers, 1962), or packed biomicrite (Folk, 1962), a grain supported, muddy rock type.
The grains are either fossil fragments, non-skeletal particles, or both, and may not show size sorting.

Lime grainstone; clean calcarenite (Wilson, 1957), or a sparite of Folk (1962), a mud-free carbonate rock type in which grains form a self supporting framework. The absence of mud may result from a winnowing effect of currents or the grains having accumulated too rapidly to be contaminated with mud. The grains are size- and shape-sorted.
DIAGENESIS

Diagenesis has been restricted to those processes that cause lithification. Such a limited application, however, is arbitrary, artificial and impractical (Newell et al., 1953; Ginsburg, 1957). Not only are there several distinctly different lithification processes which are frequently difficult to recognize and separate, but they are so gradational as to defy precise definition and can occur at any stage during the early history of the sediments. It is virtually impossible, therefore, to exclude other early alterations. It is preferable to apply diagenesis in a wider sense to processes that effect a sediment after deposition, and up to but not beyond lithification and/or filling of voids. In this context, the concepts of Ginsburg (1957) and Krumbein (1942) have been adopted: diagenesis includes all physiochemical, biochemical, and physical processes modifying sediments between deposition and lithification at low temperatures and pressure characteristic of surface and near surface environments. Many of these modifications occur prior to lithification; others may accompany or follow it. During the detailed petrographic research of the Dahra (B) reservoir, the reservoir was subjected to two types of diagenetic stages; (1) early diagenetic processes. These are brief, intense processes which have caused partial or complete alteration of the original sediment properties at the surface-water interface, and possibly continued to a depth of several feet (Emery and Rittenberg, 1952, p. 737).
(2) later diagenetic processes and lithification of longer duration and lower intensity. These later processes include dolomitization which often is observed to obliterate the original sedimentary properties and early diagenetic features of the rock (Ginsburg, 1957, p. 80).

Early Diagenesis

Several intense physical, chemical, and biological processes which operate during deposition and within a few feet of burial comprise early diagenesis. Understanding of the early diagenetic events to which the Dahra (B) reservoir carbonate rocks were subjected, helped in the reconstruction of the paleoenvironment of deposition, recognition of the reservoir facies, and in understanding the subsequent diagenetic processes of longer duration and of less intensity such as dolomitization.

The processes considered are mutually interrelated, but can be divided into three classes: (1) Organic processes; whose textural and structural aspects include aggregation, particle size reduction, burrowing and mixing. (2) Physico-chemical processes; those that are concerned with the sequence of authogenesis to which the Dahra (B) reservoir rocks were subjected. (3) Physical processes; which include such features as compaction, dessication shrinkage and penecontemporaneous deformation.

The early diagenetic processes to which the Dahra (B) reservoir was subjected have modified the original sediment to an extent which subsequently influenced the reservoir rock quality.
1. **Organic Processes**

   a. **Aggregation**

   Bottom conditions and hydrologic factors permitted the existence of various types of bottom dwelling communities in the sea forming the Dahra (B) reservoir sediment. All marine animals take mineral matter in feeding (Ginsburg, 1957, p. 81). The expelled fecal pellets formed from discrete mineral particles are bound together by a mucoid organic substance. Micrite pellets, however, may also form by inorganic precipitation (Beals, 1965, p. 51), by clothing of the sediments following the appearance of local centers of crystallization associated with bacterial decomposition in lime mud (Hadding, 1958), or by precipitation of aragonite on and in grains and clusters (Illing, 1954). Such pellets are abundant in the Dahra (B) reservoir. The textural identity of these pellets, however, was obscured and appeared to be smeared, resulting in a "mud blanket." Approximately only 5 per cent of the "fecal" pellets were preserved as firm particles.

   b. **Particle size reduction**

   Detritus feeders such as worms, crustaceans and echinoids may have been the principal agents in the breakdown of the larger calcareous grains of the reservoir (Pl. 11,B). In addition to often-noticed foraminiferal hash, skeletal particles such as those of pelecypods are variously reduced in size due to the micritization effect, of blue-green algae (Pl. 11,A).
c. Bioturbation and bioerosion

Caused by burrowing and boring organisms, which indicates that bottom conditions of the Dahra (B) reservoir's depositional basin permitted the existence of an appropriate fauna. The internal structures of the reservoir rock show that the organisms burrowed, bored and reworked the depositing sediments until it was lithified. The originally soft sediment was thoroughly bioturbated (Pls. 12 and 13). The role of burrowing worms is important in mixing and in obliteration of the original laminae of coarse and fine sediment of the Dahra (B) reservoir. Davison (in Dapples, 1938, p. 58) estimated that a natural population of the lugworm Arenicola can eat as much as 3147 tons of sediment per acre per year. Worm tubes which are filled with sediments of various textural size are recorded. These worms might have contributed significantly in the textural change of the original sediments by the production of pellets, and through obliteration of the depositional structure of the reservoir rocks. Ginsburg (1957, p. 87) showed that only five intertidal moligochetes were responsible for the complete obliteration of the original laminae of coarse and fine calcareous sediments within a period of only one month after their introduction to these sediments in a plastic aquarium cell. Reworking continued in semi-solid sediments and finally the lithified sediments were bored. Skeletal remains of some of the burrowing and boring organisms such as echinoids, pelecypods and gastropods were found. Crustaceans also existed, as may be concluded from the irregular shape of certain
burrows, the cross section of which is similar to what Shinn (1968) termed "stromatolite."

2. Physico-Chemical Processes
   a. Neomorphism

   Neomorphism (Folk, 1965, p. 21) indicates merely a diagenetic change in form of the carbonate minerals with composition remaining constant. It substitutes for the terms "inversion" and "recrystallization" of carbonate particles in which the nature of the initial mineralogy is unknown. In the reservoir, the neomorphic process affected both (1) lime mud (micrite) particles and (2) mollusk fragments. Particles of a few microns (lime mud) were the chief original non-skeletal elements of the reservoir sediment before diagenesis. Lime mud accumulated in the Dahra (B) reservoir probably originated in several ways: (1) chemically precipitated, caused either inorganically by agitation, salinity changes, and heating, or organically by biochemical processes of bacteria. That these processes may produce aragonite needles has been confirmed in the laboratory by Gee (1932) and Cloud et al. (1962). Field evidence is equivocal. (2) From the disintegration of calcified or partly calcified green algae, principally species of Penicillus and Halimeda (Lowenstam, 1955; Lowenstam and Eqstein, 1957). Penicillus algae, though leaving no record in the Dahra (B) reservoir, may have flourished in the lagoons of shallow shelf seas. Penicillus is responsible for about one-third of the mud accumulated in Florida
Bay and all of the lime mud in the reef tract (Stockman et al., 1967). (3) Boring action of blue-green algae in non-algal skeletal particles. (4) Particle abrasion occurring in the open shelf by action of waves, currents, living burrowers and crunchers. The mud particles eventually were mechanically deposited in the marginal zone of the shelf, a process operating at the present time in the Florida Bay (Ginsburg, personal communication, 1970). Hoskin (1962, 1963) shows that abrasion (organic and inorganic combined) is the main mud-producing process on the Alacran Reef, Yucatan. Mathews (1967) demonstrates the abrasion produced most of the lime mud on the British Honduras shelf.

Pellets form much of the mud; virtually 95 per cent of the pellets lost their identity due to a squeezing effect and formed a "lime mud blanket." The exact contribution of the pellets to the abundance of lime mud in the Dahra (B) reservoir rock types cannot be fairly estimated; however, it is safe to say that it is about 50 per cent, especially for those which deposited on the tidal zone and the shallow shelf area.

Diagenesis of carbonate mud to micrite is discussed by various authors (Bathurst, 1958; Folk, 1962; and Schwarzacher, 1961, p. 1499). There are many ways of converting an original carbonate mud to micrite; however, because of the fine grain size, most of these have to remain in the realm of hypotheses. However, it is certain that all aragonite and high magnesium calcite in the mud disappears and alters to calcite with only a few mole per cent magnesium. The tiny
aragonite needles and 2 to 3 micron particles of blocky carbonate are eliminated. Bathurst (1956, pp. 366–367) feels that there has been little change in grain size from the original carbonate mud to micrite, partly because of the uniform grain size of micrite throughout the geologic column, partly because of the similarity in grain size to algal "dust" (Wood, 1941), and partly because "calcite mudstones are also very similar in grain size to the aragonite mud from which some of them may have evolved." He feels that there is some alteration in grain size, but that is mainly in the solution of the supersoluble thinnest grains, those smaller than 1/2 to 1 micron. His main evidence of this is that modern aragonite muds have needles averaging 2 to 3 microns long. This is not much smaller than the diameter of many blocky calcite crystals in the micrite mosaic. However, Folk (1962, p. 34) reports that 10 to 1000 aragonite needles have to be consumed to make one micrite crystal, with significant coarsening in grain size. Micrite in the Dahra (B) reservoir is abundant. In well B7 it constitutes 73 per cent by volume of the rock in the upper 60 feet of the reservoir.

Micrite particles of the reservoir rocks are of four types: (a) Platy, irregularly shaped particles which have preferred orientation parallel to the depositional plane. These particles range in size from 1/4 to 3.5 microns. Cryptocrystals grow to coarser size grains by coalescive neomorphism driven by the surface tension of grain boundaries, with a result of intraparticle
microspores having a diameter of 1/5 to 1/3 micron (Pl. 14,A).

(b) Anhedral, platy cryptograins which range in size from 1/2 to 3 microns. These attain a preferred orientation parallel to the bedding plane. Rim cementation of the cryptograins is the mechanism which may be responsible for the development of larger micrograins (15 microns long and 9 microns in diameter). The identity of a few of the original 1/2 to 3 microns cryptograins is preserved in the micrograins (Pl. 14,B). The coarse micrograins are not microspar crystals which were caused by recrystallization of the 2 to 3 microns micrite crystals as Folk reported (1962, p. 37), but are micrograins which were composed of several micrite crystals bound together by rim cementation. These grains are referred to in this thesis as micrite aggregates. This type of grain growth does not result in the intracrystal cryptoporosity observed in type (a).

(c) Anhedral crystals of various shapes and sizes, showing no preferred orientation. Crystal size range begins at 1/4 micron and grows by coalescive neomorphism to larger crystals of 10 microns in diameter and 20 microns long (Pl. 15,A-B).

(d) Anhydral grains of 1/4 to 2 1/2 microns which result from recrystallization of skeletal constituents such as that of ostracods and foraminifera (Pl. 16,A-B).

b. Cementation

Cementation, as understood here, is the process of open space filling by physiochemical and biochemical authigenetic precipitates.
In general, cementation of limestones is very often associated with solution, corrosion, leaching, and replacement phenomena and can form a number of generations until the available void space is completely eliminated. Precipitation of carbonate cement can take place in littoral environments and subaerially; within the sediments but above the water table (vadose zone); below the water table (phreatic zone); in zones where fresh water mixes with marine water, and normal marine with supersaturated waters; and under a thick overburden (Chillingar, 1967, p. 186).

It is most likely that cementation of skeletal and non-skeletal particles of the reservoir rock must have taken place during the early stages of diagenesis when the rock was subaerially exposed. The time of subaerial exposure was prior to the deposition of the shale caping the reservoir. This is evidenced by the presence of dense micrite rock which is believed to be a caliche crust. Precipitation of the calcite-spar between grains and in foraminifera, ostracode voids, and microfractures must have followed dissolution of aragonite by percolating meteoric H₂O. From skeletal particles such as pelecypods and dasycladacean algae and supersoluble particles of lime mud. Penecontemporaneous cementation might have taken place in the intertidal zone (Ginsburg, 1953b). Calcite cement does not constitute more than 5 per cent of the reservoir rock's composition. It is observed that micrite is the most common particle type found between grains. However, foraminifera and ostracode cavities are always filled by sparry calcite because of precipitation of calcite
from the water which originally filled them. Cementation reduces rock porosity (Friedman, 1964, p. 809).

3. **Physical Processes**

The sediment of the Dahra (B) reservoir was subjected to several physical processes at the time of deposition, or very soon thereafter. Shrinkage cracks are a result of such processes. These cracks are well preserved and point to a tensiional stress within the sediments caused by capillary evaporation of the interstitial water at the time when the sediments were subaerially exposed. Shrinkage cracks are restricted to the supratidal facies of the reservoir rocks (Pl. 17). Similar tension cracks are reported from the evaporite part of the Duperow's Cycle IIIa (Wilson, 1959).

Anhydrite filled the cracks; subsequent partial or complete dissolution of the anhydrite created a vuggy porosity which improved the reservoir permeability.

a. **Compaction**

Compaction is virtually absent in the Dahra (B) reservoir after the early cementation processes were completed. Evidence includes the walls of the burrows which show no irregularities as might have been caused by compaction. Perfectly circular burrows were preserved (Pl. 18). Thin section studies of sand-size particles in grain supported rock type showed no evidence of crushing, and no pressure-solution effect where some grains have been pressed into others. Tabular carbonate grains produced by fragmentation of thin
pelecypode shells and calcareous algae are well preserved and do not show a sign of breakage to adjust to irregularities in surrounding grains as the overburden increased. However, slight compaction prior to lithification is evidenced in lime mudstone and mud supported reservoir rock types. Pellets may virtually lose their identity within a few feet of burial, forming a "lime mud blanket." The few pellets which retained their identity showed a rather ellipsoidal cross section due to squeezing and bending from minor compaction, since they were presumably soft at the time of deposition.

The soupy, water saturated lim mud must undergo considerable compaction prior to lithification. Powers (1962, p. 140) reported that a preliminary study of relatively undisturbed lime mud from the Persian Gulf Lagoon showed a nearly 50 per cent decrease in the column of mud during the first few days of settling. Many other authors have interpreted the absence of crushing of delicate fossils as an indication of minor compaction of lime muds in the formation of calcilitutes (Weller, 1959). Supporting data are the scarcity of drag or penetration effects where rigid clasts or fossils occur in calcilitute matrix; and the general similarity of fabric of non-compacted sediment within the fabric of the shell cavities. Larger scale evidence is provided by observations of attitude, thickness, lithology and geopetal fabric of calcilitutes which are laterally adjacent to other rocks for which minor compaction can be demonstrated. Examples of these relationships occur in biothermal facies,
such as those of the Mississippian of Western United States (Pray, 1960, p. 1966). The absence of compaction in the Dahra (B) reservoir calcilutites is caused by the rigid fabric which the rocks acquired, presumably due to some settling of particles and cementation prior to accumulation of much overburden.

Intermediate Diagenesis

The term late diagenesis refers to diagenetic changes not influenced by the depositional environment or by the physiochemical conditions of the supernatant water. Processes of alteration directly following early diagenesis occur before complete lithification, when permeability differences still exist in the sediments. These are phases of intermediate diagenesis. Late diagenesis in buried sediments is often called subsurface diagenesis.

As in other carbonate rocks, the carbonate content of the Dahra (B) reservoir was subjected to intermediate diagenetic processes such as anhydrite replacement and dolomitization, and to very late diagenetic processes which caused the creation of stylolites.

Anhydrite Replacement

The physical and optical properties of this type of anhydrite is described with considerable detail under the petrographic description of the reservoir, as clearly illustrated in Pl. 10; replacement anhydrite is logged from the lagoonal facies as shown in wells B11; B8, and from the intertidal and supratidal facies B11; B1; B9; B18 and B8. The source of the anhydrite is high sulfate waters caused by excessive
evaporation of sea water. In addition to anhydrite replacement of the skeletal particles (Pl. 10,A) it also replaced "fecal" pellets and micrite particles (Pl. 10,B). The replacement resulting in the plugging of the reservoir pore spaces. The remarkably low permeability of the dolomite rocks (3682-83; 3686-87 and interval 3688-3692) is due to the plugging effect. However, subsequent dissolution of the anhydrite created a vuggy porosity. This caused improvement of the reservoir rock's properties by increasing the permeability.

**Mechanism of Dolomitization**

Because modern primary dolomite is not clearly recognized and because modern depositional environment is replete with non-dolomitic carbonate, there is no reason to expect that the original carbonate sediments of the reservoir were composed of anything but aragonite and calcite. Sucrose dolomite having a rhombohedron size of 10 to 20 microns (Pl. 19, A-B) is closely associated with replacement and void filling anhydrite (see cross-sections A-A', B-B', Appendix). Evidence is established that both anhydrite and dolomite replaced carbonate particles at the same time during the end of the early diagenetic stage.

Dolomite primarily replaced lime mud particles of the matrix. However, as the dolomitization intensity increased, euhedral rhombs progressively replaced "fecal" pellets. Skeletal particles are not dolomitized even when the rock has 80 per cent by volume dolomite. Electron scanning microscope observation clearly showed the replacement
process "caught in action" by the presence of micrite grains of calcite composition in the dolomite rhombs (Pl. 19,A).

A short distance downward flow of dense brines had a molar Mg/Ca ratio much higher than that of sea water is the proposed mechanism for dolomitization. These brines were developed as a result of intensive evaporation in the supratidal and intertidal subenvironments. Dolomite is very common in rocks showing evidence of formation in these environments (Illing et al., 1965).

The sediments of the shelf environment escaped intense dolomitization because they were deposited in deeper water, were laterally remote from any possible gravity head to cause downward refluxing of brines, and were too far beneath the periodic surface brines trapped in very small intergranular capillaries under the control of climate and tidal rhythm.

Subsurface Diagenesis

As unconsolidated marine carbonate sediments are progressively buried beneath an increasing sedimentary load, the increase in temperature with depth will decrease the solubility of calcium carbonate, while the increase in pressure along the geothermal gradient will tend to increase it (Purdy, 1968, p. 203). Arnston (1963), Sippel and Gloyer (1964) presented data based on experimental investigation indicating that the temperature effect predominates over that of pressure, and therefore precipitation of carbonate should accompany progressive burial, providing that the interstitial water of the sediments is
initially saturated or nearly saturated with calcium carbonate. This condition is demonstrated by Berner (1966a) who indicated that pore water of marine sediments is in equilibrium with low magnesium calcite, so, this condition is fulfilled. Hence cementation is induced by the increase of temperature. This type of cementation according to Purdy (1968, p. 203) result in a change in carbonate sediment porosity of about 2 per cent. These major subsurface diagenetic changes may be anticipated only where fluids undersaturated or supersaturated with respect to calcium carbonate are moving through a carbonate body.

Thin section petrography of the Dahra (B) reservoir was not able to distinguish calcite precipitated during early diagenesis from calcite precipitated during subsurface diagenesis. It seemed to the author that the bulk of the calcite solution-precipitation was an early diagenetic phenomena as previously explained.

Progressive subsurface burial of the Dahra (B) reservoir rocks resulted in pressure solution effects by the development of stylolites. Stylolitization involves solution at points of mineral grain contacts and precipitation on nearby free surfaces (Purdy, 1968, p. 203). Solution is effected through the increase in solubility attending the increase in elastic strain at grain contacts that result from the increasing overburden pressure; precipitation results from the diffusion transfer of the dissolved carbonate to free surfaces where the elastic strain is less and therefore where calcium carbonate solubility is relatively lowered (Bathurst, 1958, pp. 22–23). Stylolites in the Dahra (B) reservoir are of four types: (1) "sutured type" of Park and
Schot (1968) (Pl. 20,A), (2) "horse tail" of Wilson (1967) (Pl. 21,A), (3) simple "horizontal" type (Pl. 21,B), and (4) "crinkly" type (Pl. 20,B). All four occur in dense limestone rock types. However, stylolites are not observed in the reservoir dolostones, an observation in agreement with that of Dunnington (1967b) and Glover (1968). Stylolites were developed when the reservoir was fully permeated with oil and when the overburden thickness had attained over 2000 feet (Dunnington, 1964, p. 14). This observation is supported by the fact that stylolites in the reservoir were only formed in slightly dolomitized rock types which were saturated with water. Because of their high permeability, dolostones were filled with oil, thus avoided stylolitization. The reservoir's original volume was reduced by 30 per cent through stylolite development (Dunnington, 1967b).
PLATE 11

A. Microphotograph shows pelecypod fragment micritized by the action of the borers possibly blue-gree algae. Notice the indentations of the pelecypod bioclast which are micrite filled. They are caused by the boring blue-green algae. Lime wackestone in pelecypods - wackestone facies B2 (3780-81), Cross nicsls, 40X.

B. Microphotograph illustrates fragmented skeletal particles. Since the micrite matrix indicates deposition in quiet water mechanical fragmentation of the grains is highly improbable and the particle reduction presumably was caused by scavengers. Lime wackestone B2 (3780-81). Cross nicsls, 21X.
PLATE 12

A. Photograph of one foot of core shows a patch of burrowed sediments. The burrowed sediments (light colour) has a different fabric from that which was not burrowed. Dolomitic lime mudstone, B9 (3769–70).

B. Photograph of one foot of core shows almost complete homogenization of the originally deposited sediments. Original rock fabrics and structure are also obliterated. Lime wackestone, B11 (3676–77).
PLATE 13

A. Photograph of one-foot of core. The half-foot on the left is intensely burrowed; notice the different orientations and sizes of burrows. The half-foot core on the right, its sediments obviously were first bioturbated then were reburrowed. Lime wackestone B9 (3743-44).

B. Photograph of one-foot core. Notice the circular to elliptical cross-sections of the burrows and orientations of the burrows to the bedding plane. It is assumed that the sediments were bioturbated, then were reburrowed. Lime mudstone B4 (3701-702).
PLATE 14

A. Electron scanning microphotograph shows the platy, irregularly shaped micrograins of type (a) micrite. Notice the presence of the cryptopores (1/5 - 1/3 micron in diameter). Notice also the size, shape and distribution of pore system. Lime mudstone, B18 (3689-90), 1500X.

B. Electron scanning microphotograph shows type (b) micrite. The micrograins (1/2 - 3 micron) are preserved in the larger grains. Notice the subhedral dolomite crystal at upper-middle of the photograph. Notice also the distribution of micropores. Lime mudstone, B8 (3720-21), 2000X.
PLATE 15

A. Scanning electron microphotograph shows micrite micrograins of type (c). Notice the denser grains than type (a) or (b).
Lime mudstone, B18 (3629-30), 1500X.

B. Scanning electron microphotograph illustrates micrite micrograins of type (c). Notice rotalids foraminifera in the middle of the photograph. Lime wackestone B9 (3769-70), 500X.
PLATE 16

A. Scanning electron microphotograph illustrates ostracode embedded in a diagenetic chalk matrix. Lime mudstone (shallow-marginal shelf facies), B6 (3775-76), 1500X.

B. Scanning electron microphotograph shows micrite micrograins type (d) resulted from recrystallization of ostracoda bioclast. Lime mudstone B6 (3775-76), 4000X.
PLATE 17

Microphotograph, illustrates vertically oriented mud cracks almost perpendicular to the depositional surface, in a pelleted lime mudstone. Supratidal zone, B10 (3827-28).
Cross nicols, 40X.
PLATE 18

Photograph of one-foot core shows orientation of burrows. Notice circular cross-section of burrows which indicate the absence of compaction in the sediments. Lime wackestone, B9 (3753-54).
PLATE 19

A. Dolostone, sucrose fabric (B18, 3672-73). Notice the size, shape and distribution of intercrystalline pore-system. Notice also the distribution of micrite cryptocrystals. Porosity = 34.6 per cent; Permeability, V = 63md., H = 39 md. 1000X

B. Dolostone, sucrose fabric (B14, 3776-77). Intercrystalline pores have different shapes and sizes. The unusually large pore on the upper left of the photograph is caused by solution processes. 500X
PLATE 20

A. Microphotograph illustrates stylolite "sutured type" in lime wackestone, B8 (3651-52). Notice the abundance of pellets at the lower part of the photograph; bioclasts are at the upper part. The black seam is a mixture of clay minerals and organic matter including "dead oil". Cross nicols, 40X.

B. Microphotograph, illustrates stylolite "crinkly type" in lime mudstone, B11 (3679-80). Cross nicols, 40X.
PLATE 21

A. Microphotograph shows a stylolite "horse tail" type in lime mudstone, B11 (3679-80). Cross nicols, 40X.

B. Microphotograph shows a stylolite "simple horizontal" type in lime mudstone, B9 (3757-58). Cross nicols, 40X.
RESERVOIR STRUCTURE

The reservoir structure is an anticline of about 85 km². The structure (fig. 12), has an irregular shape. The main anticlinal crest is situated between wells B14, B40 and B11, this axis trends toward north-south. The southward extension is made of two digitations. One is at the southeast; its crest is situated between wells B23, B65 and B61, with a folk axis trend toward N-S to NW-SE. The other is in the southwest. It has a crescent shape, its crest being situated between wells B56 and B43, and having a fold axis toward NE-SW. In addition, a synclinal low exists between wells B9 and B20 with a north-south fold axis. The whole structure very gently plunges toward the south. It is concluded that all the structural elements were growing simultaneously while the reservoir sediments were being deposited.

The author believes that the reservoir structure was not modified by subsequent deformation, but is the structure as it was developed by the end of the reservoir sedimentation cycles. This observation is supported by two facts. (1) The thickness of the mechanically deposited shale interval (fig. 13) which immediately overlies the reservoir decreases on the reservoir structurally high elements of the reservoir and increases on those which are the structurally low. (2) The bathymetry of the reservoir depositional environment is obviously controlled by the growing structure. Supratidal–Intertidal facies are located on the structurally high positions. Lagoonal facies
occupy the site of the syncline and around the flanks of the major anticline. Wells B6, G1, C1, B2, B4 and B57 are on the periphery of the structure and are characterized by lagoonal facies (fig. 14).

Though the structure appears to be a gently folded anticline, it might have essentially been controlled by normal faults which were growing in the basement below. Thus, the folding may be due to the higher beds having bent rather than fractured. According to Gillespie and Sanford (1967, p. 191), there are no compressional folds in the Sirte basin.

ENVIRONMENT OF DEPOSITION AND FACIES DISTRIBUTION OF DAHRA (B) RESERVOIR

Three dimensional construction based on the petrographic research showed that the reservoir is composed of three distinctive rock units. The following are as they occur from base to top in the reservoir they are: (1) Massive, nodular anhydrite beds ranging in thickness from one to ten feet. (2) Dolostone beds which are associated with pore-fill and replacement anhydrite. Dolomite rhombs of the dolostones replaced intensely burrowed and churned pelleted lime mud. The thickness of the dolostone is variable; however, it is accurately delineated as illustrated in the A-A' and B-B' cross-sections (Appendix). (3) Mud supported limestones with an appreciable amount of bioclasts. The thickness and distribution of these rocks are also illustrated in the cross sections. These three rock types are representative of a depositional transgressive cycle which was brought about as a result
of the gradual increase in a tectonically influenced water depth. The
tectonic instability was caused by the gradual subsidence of the Sirte
basin. On the basis of sedimentary structure and fossil content, the
reservoir rocks are interpreted to have been deposited in a near-shore,
marginal marine environment. Within this environment, three subenvironment were recognized: (1) Supratidal zone to (2) Intertidal zone to
(3) Subtidal environment. The latter is subdivided on the basis of
faunal content into (a) shallow-marginal, restricted shelf, and (b) deep
neritics shelf with normal marine fauna.

Supratidal Zone

It was developed on very low lying carbonate islands which
existed in a protected, shallow lagoon. These islands were separated
by inter-island flats which were covered by very shallow water. The
site of these islands is demonstrated by three localities of structural
highs on the reservoir structure map (fig. 12), and further illustrated
by the facies map (fig. 14). The massive nodular anhydrite beds
characterize this environment and are logged from wells B11, B18 and B8
which were drilled on the island located on the major axis of the
anticline, and are also logged from wells B1 and B10 which were drilled
on the southwest digit of the structure. The anhydrite beds were the
result of hypersaline precipitation in a shallow saline playas across
the (Sabkha) plain during periods of widespread aridity; similar anhy-
drite beds were reported by Kinsman along the Trucial Coast (1966,
p. 310). However, the bulk of the rocks are dolostones. Euhedral and
subhedral dolomite rhombs (15 to 25 microns) give the dolostone a characteristic sucrose fabric.

The carbonate sediments deposited on the supratidal zone lacks fossils, but pellets are abundant. Birdseye and shrinkage cracks and intraformational conglomerates are a characteristic feature of the rocks of the supratidal zone and imply intermittent subaerial exposure. Birdseye and shrinkage cracks are filled either by anhydrite or sparry calcite mosaics. Petrographic observation showed that subsequent leaching of the anhydrite created a vuggy porosity which caused a remarkable improvement of the reservoir quality. In places, the supratidal sediments contain burrows which formed when the sediments were partially consolidated. No sediment mixing was observed. The burrows were usually horizontal or perpendicular to the bedding plane. In many instances the burrow starts perpendicular to the bedding, then becomes parallel to it. A reverse situation is also observed. Apparently the organism changed its burrowing trend either because of a change in sediment texture, lack of nutrients at the burrowing site, or it preferred to go deeper or shallower. The burrows are preserved in the partially dolomitized rock types.

In its sedimentary structure, the supratidal facies are identical to the carbonate sediments which are at the present time accumulating on Crane Key and Sugarloaf Key in the Florida Bay, and on Western Andros Island (Bahamas) and on the "Sabkha" environment in the Persian Gulf. A close similarity exists in the development of the intralagoon "fossil islands" of the Dahra (B) reservoir depositional environment
and the present day Crane Key and Sugarloaf Key in the Florida Bay.

Intertidal Facies

This facies overlies the supratidal beds into which it grades and also contains much dolomite. The original sediments of this facies were deposited in the area of diurnal tide fluctuations. They are distinguished from the underlying supratidal facies on the basis of a difference in sedimentary structure. The thickness and the distribution of rocks in this zone are controlled by the reservoir structure. The diagnostic feature of this facies is the succession of burrows. The original carbonate sediments were churned, bioturbated and otherwise reworked. These fabrics could not be recognized in the 80 per cent dolomitized rock types, but are preserved in rocks which are less than 60 per cent dolomitized.

There is a progressive increase in rock susceptibility to dolomitization with the increase of burrowing intensity. Because of this, rocks of this zone are the most intensely dolomitized. The dolomite matrix of the fine-burrowed fabric is composed of 10 to 20 microns euhedral crystals. The rocks of this zone constitute the major segment of the potential reservoir.

Shelf Facies

The rocks of this facies overlie the intertidal facies, into which it grades. It is separated from the supratidal and the intertidal facies mainly on the basis of fossil types. Shelf facies were deposited in the shallow water environment between scattered islands
and around the major anticlinal structures. Wells C1, Q1, C1, B6, B4, B2, B9 and B57 are located in the shelf. Shallow to deep shelf water later covered the occasionally subaerially exposed islands; hence shelf facies are encountered overlying the intertidal facies from all the wells drilled in the Dahra Field. The thickness of this varies from one well to the other; it is actually controlled by the structure. The shelf facies texturally consist of lime mudstones, wackestones, packstones and grainstones. Euhehdral dolomite rhombs, 5 to 15 microns, replace from 10 to 40 per cent of the lime and matrix. On the basis of fossil composition the lagoonal facies is separated into two types, (1) marginal-shallow lagoonal facies, and (2) deep lagoonal facies.

**Marginal-Shallow Shelf and Lagoon Facies**

The thickness and the textural parameters are accurately defined in the cross-sections A-A' and B-B' (Appendix). The distribution is illustrated by the facies map (fig. 14). In the rocks of this facies various foraminifera were identified. Among the most important are the miliolids, textularids, *Marginulina*, *Nodosaria* and *Cibicides*.

In addition, the dasycladacean algae are a common constituent of these rocks. The ecological significance of the dasycladacean algae has been briefly summarized by Pia (1920), Cloud (1962) and Johnson (1961). Elliot (1968, p. 92) reported that they occur in warm shallow seas in sheltered situations in tropical and subtropical seas, and in areas marginal to the latter, as the Mediterranean. Their maximum abundance is from low-tide level to 5 to 6 meters. These statements
are exactly applicable to the interpreted depositional environment assigned to this reservoir type facies.

*Favreina* pellets are logged among the original non-skeletal constituents of the reservoir rocks of this facies. They are most abundant in the rocks of wells B9, B6 and B7. *Favreina* is believed to have been produced by an organism similar to present day *Callianassa* shrimp. This shrimp today inhabits quiet subtidal water in Florida Bay, and also is found in the intertidal water (MacGinitie, 1934; Shinn, 1967). In the rocks of this facies, tubular and roughly horizontal burrows with circular to elliptical cross sections up to 1 1/2 mm. across are preserved. These burrows are similar to those which are believed to be caused by *Callianassa* in the chalk hardgrounds described by Bromley (1967), from the chalk of southern England described by Kennedy (1967), and from the Weald Clay of southeast England reported by Kennedy and Macdougall (1969). Those chalks are believed to have been deposited in quiet water of the subtidal zone.

Also assigned to this environment is a dense, micrite rich rock type. This rock caps the reservoir and has a low porosity and permeability. Texturally, it is a wackestone characterized by an abundance of pelecypod fragments which make up to 40 per cent of the rock volume. In addition, the rock contains echinoid and brachiopod fragments. It contains from 1 to 10 per cent iron sulfide. Murray (1967) reported similar recent lagoonal sediments from Kohr El Basam, Persian Gulf. The author believes that the sediments of this rock were deposited in deeper shelf water with more normal marine salinity than the other
lagoonal facies. All the original sediments of the shallow-marginal shelf facies were mechanically deposited. Because of the absence of intense dolomitization in this facies, it lacks the quality of a good reservoir.

**Deep-Neritic Shelf Facies**

Fig. 14, illustrates the location of this facies with respect to the depositional basin. Cross-sections A-A' and B-B' (Appendix) illustrate its thickness. The rocks of this facies are characterized by an abundance of bioclasts, but less micrite than the rocks of the shall-marginal shelf facies. Planktonic foraminifera are logged exclusively from this facies, but are not more than 2 per cent of the rock volume. The genera are the Globigerinids, Globorotalia, Globotruncanana and Gumbelina. Rotalid, nummlites, and discosyclindid foraminifera, as well as fragments of echinoids and Lithothamnium red algae also characterize this facies. Dasycladacean algae are absent, but miliolid foraminifera are abundant. The depth of the water in this part of the lagoon ranges from 20 to 40 feet. Lithothamnium algae are now growing in the sandy areas of the Mediterranean, along the coast of Ireland, and along the west coast of France (Johnson, 1966, p. 28). Rocks of this facies are characterized by high porosity and permeability, and could constitute a potential reservoir. However, because of its location away from the Dahra (B) structure this facies is considered relatively unimportant as a reservoir.
RESERVOIR TEXTURE

Original Texture

The original texture of the Dahra (B) reservoir is easily interpreted from the preserved particles in the rocks. These particles were described in considerable detail under the reservoir petrography discussion. On the basis of the abundance of these particles, the reservoir rocks are texturally classified as: lime mudstones, lime wackestones, lime packstones and grainstones. The textural significance of each of these rock types is defined. Thin section petrographic studies showed that the reservoir lagoonal facies is the only one in which the original rock texture is virtually unaffected. Point counting of samples from the Bi1 shelf facies showed that its rocks are composed of 30 per cent bioclasts. The remainder is lime mud which was neomorphosed to micrite or partially replaced by dolomite rhombohedrons with no significant change in particle size. The bioclastic grains have two types of size range: 30 per cent of the total grains are in a 60 to 200 microns size range. The remaining 70 per cent of the total grains range in size from 200 to 600 microns. No larger grains are recorded.

The rock bioclasts are poorly sorted, and were obviously preserved near the places where the organisms originally lived. Some of these particles were moderately recrystallized, but those not fragmented by scavengers can be recognized by their original shape and size.
Alterations of the Reservoir

Original Texture

The original sediments texture of the Dahra (B) reservoir was subjected to two types of alterations: (1) Alterations caused by diagenesis, including dolomitization and neomorphism, and (2) Alterations caused by organic community in the depositional basin. Both alterations caused a significant change in the reservoir rock's texture which consequently determined the reservoir quality.

Diagenetic Alterations of the
Original Texture

1. **Textural Alterations Caused by Dolomitization**

Four degrees of altered texture caused by dolomite replacements, are observed in the Dahra (B) reservoir:

a. **Insignificantly altered texture**

   Observed in rocks in which the originally deposited sediments were replaced by no more than 20 per cent dolomite. This texture was also subject to aragonite-calcite inversion and other minor replacements. This type of alteration is observed in the pelecypoda wackestone facies, which is described from the marginal shelf facies.

b. **Moderately altered texture**

   Rocks having this type of altered texture are those containing 30-50 per cent dolomite (Pl. 22, A-B).
c. **Strongly altered texture**

Is recognized in the reservoir rocks in which 50–70 per cent of the original texture was replaced by the growth of the dolomite rhombohedrons. Crystals of dolomite appeared to "consume" the lime mud particles which partially or totally constituted the rock's original texture. The "merging texture" is characterized by larger equigranular crystals of sucrose dolomite. The end result is an improvement in the reservoir quality caused by permeability.

d. **Extremely altered texture**

The original texture of the rock is nearly or completely obliterated. It characterized rocks of the supratidal and the intertidal facies of the reservoir. Dolomite rhombohedrons replaces 70–100 per cent of the rock. The segment of the Dahra (B) reservoir which has excellent reservoir quality was subjected to this type of alteration.

2. **Textural Alterations Caused by Neomorphism (Chalk Formation)**

Notable change in original texture in carbonate sediments was brought about by the rearrangement of calcium and carbonate ions through processes which involve inversion and/or recrystallization. Carbonate particles are neomorphased, if they were influenced by one or both of these processes. In rocks which were originally composed of lime mud, a strong alteration of their original texture issues when the cryptocrystals of lime mud changes to micrite particles of 2 – 3 microns. As discussed earlier some of these micrite particles grow to larger grains
having a diameter of several microns characteristic of chalky texture (Pl. 23,A-B). The evolution of chalk from micrite is caused by coalescent growth of the micrite particles as a result of surface tension between grains boundaries and/or by rim cementation of the micrite particles. Chalky texture in the Dahra (B) reservoir is also evolved by a strict chemical process resulted in growth of cryptocalcite crystals to larger crystals characteristic of chalk texture. Chalks evolved by this process is characterized by a dense crystallinity. The chalk of the Dahra (B) reservoir is purely diagenetic and was not caused by the accumulations of coccoliths or microplanktonic foraminifera. The chalk in the Dahra (B) reservoir has an average porosity of 30 per cent; however, its permeability does not exceed 10 millidarcy. It is logged from the reservoir shallow-shelf facies. This environment permitted little cementation, perhaps caused by a very slow water movement or water leaches Ca$^{2+}$ and CO$_3^{-2}$ ions.

3. Textural Alterations Caused by Burrowing Organisms

Petrographic thin section studies of the rocks of the Dahra (B) reservoir facies revealed that the original texture of these facies was altered progressively by the burrowing community which inhabited the depositional basin. The intensity of burrowing has been explained. Marine epifauna and infauna feed on the organic matter which is in sea water and in the depositing sediments. Hence, they burrow in it and fragment the tests and shells of mortal organisms, resulting in a decrease in the sediment's size. These organisms also agglutinated the cryptocrystals of lime mud in the form of silt and/or sand-size fecal pellets.
The result of their activity is a modification of the texture of the originally deposited sediments. The intensity of the textural alteration depends on their activity and abundance in the depositional environment of the particular facies.

Supratidal facies of the reservoir is the least altered by this process; this facies is only slightly burrowed. The burrowing seems to have taken place at the time the sediments were partially consolidated. The abandoned burrows were filled with sediments having a different texture and higher permeability. The burrows appear to have been more susceptible to dolomitization.

The originally deposited sediments of intertidal facies were intensely burrowed and bioturbated, hence the original rock texture was intensely altered. The fabric of the bioturbated sediments appeared sensitive to dolomitization processes. Thus, the rocks of the intertidal facies are strongly dolomitized and have an excellent reservoir quality caused by creation of a remarkably high permeability.

The reservoir shelf facies have suffered a moderate textural alteration caused by the organic community. The reason for the moderate alteration is because this facies was composed of skeletal grains whose abundance exceeded the fragmentation activity of the scavengers.
PLATE 22

A. Scanning electron microphotograph, shows the insignificantly altered texture, in lime mudstone. Notice the distribution, shape and sizes of the dolomite rhombohedrons. B11 (3702-03), 3000X.

B. Scanning electron microphotograph, shows calcite and dolomite crystals in moderately altered texture in lime mudstone. Notice the perfect development of the calcite crystal faces. B9 (3769-70), 3000X.
PLATE 23

A. Scanning electron microphotograph shows chalky texture in strongly altered lime mudstone. This texture is not caused by the fabric of the "pelagic chalks". Notice the size, shape and distribution of the diagenetically originated pore spaces. C1 (3667-68), 1500X.

B. Scanning electron microphotograph, shows a chalky texture in strongly altered lime mudstone. Notice the denser fabric than seen above. Large grains are probably recrystallized skeletal fragment. B11 (3781–82), 750X.
RESERVOIR COMMUNICATION

Porous reservoir rock is the essential element of a petroleum reservoir. The rock must contain pores, or voids, of such size and character to permit the storage of oil and gas in pools that are large enough to justify exploitation. Porosity, however, is not enough; the pores must be interconnected to permit the passage of oil and gas through the rock – the quality termed permeability. The Dahra (B) reservoir's average porosity is 24 to 30 per cent, and 4.5 to 70 millidarcy is its average permeability (figs. 15 and 16).

Origin and Distribution of Porosity in the
Dahra (B) Carbonate Reservoir

Introduction

Porosity is defined as the ratio of pore space to total volume of the reservoir rock and is commonly expressed in a percentage (Leverson, 1967, p. 100).

\[
\text{Percentage of Porosity} = \frac{\text{Pore Volume}}{\text{Rock Volume}} \times 100
\]

The ratio of total volume of pore space to total volume of rock is called absolute porosity or total porosity. It includes all the interstices or voids whether interconnected or not. The porosity measurement used in reservoir studies, however, is the ratio of
interconnected pore spaces to the total bulk volume of the rock, and is termed the effective porosity. It is commonly 5 to 10 per cent less than the total porosity (Leverson, 1967, p. 101).

The literature bearing on the classification of porosity in carbonates has taken two general trends: one focused on the purely descriptive physical properties of pore system, and the other has had a more geologic or genetic emphasis. Classifications of the first type include those of Archie (1952), Stout (1964), and Jodry (1966). Classifications of Howard (1928), Murray (1930) and Imbt and Ellison (1946) emphasize the genetic developments of pore system.

Because of the importance of carbonate rocks for the oil industry, literature concerning them has noticeably increased in the past decade. However, only a small percentage of the published literature considered the porosity in great detail. The treatment by Thomas (1962, p. 204) is considered by several good geologists as the most detailed and genetic. It calls attention to the effect of carbonate matrix sorting on porosity, a consideration generally overlooked. Some of the most valuable recent literature which contributed to the understanding of the occurrence and the origin of pore space rather than classification are those of Choquette and Pray (1970), Illing et al. (1967), Lucia (1962), Lucia and Murray (1967), Murray (1960), Murray and Lucia (1967), Roehl (1967) and Schmidt (1965). Choquette and Pray (1970) presented the most complete and extensive treatment for the genetic development and modifications of the pore system is carbonate rocks.

Pore space can be created, modified or destroyed at many stages
in the history of sedimentary carbonate. Important changes in porosity within particles can occur between the time the sedimentary particles first form and the time when these particles, or aggregates of fragments derived from them, come to rest at their site of deposition and later burial. Afterward, the creation, modification, and/or elimination of porosity can occur at any time or continuously during the post depositional period, which may last millions of years (Choquette and Pray, 1970, p. 215).

From a genetic point of view, porosity in carbonate rocks is classified as primary and secondary. Primary porosity refers to pore spaces in the original sediment, or those that were created during the depositional processes; whereas the secondary pores are those that were formed during the subsequent diagenetic history of the rock. From the descriptive standpoint, separation of porosities into vuggy, inter-grain, inter-crystal and fracture types is found to be a workable system when used in conjunction with other observable parameters such as crystal and grain size. The vuggy group can be further broken down when the cause of the discrete cavities - leaching, inter- and intra-skeletal pores, etc. is determinable.
Primary Porosity

Petrographic thin section studies and electron scanning microscope observations of the Dahra (B) reservoir rocks, revealed that porosity and permeability framework is effected by (1) borings, burrowings, dessications, shrinkage factors and solution processes, and dolomitization in the supratidal facies; (2) burrowings, churned fabric, extensive dolomitization and solution in the intertidal zone; and (3) by a remarkable increase in skeletal constituents in the lagoonal facies. Except for the vugs and channel porosities, all the pore spaces developed in the Dahra (B) reservoir are fabric selective. Fabric selective primary porosity of the Dahra (B) reservoir rock are the following:

1. **Interparticle porosity**
   
The most important in the shelf facies. The pore spaces were developed between the textural components of the rocks and were not modified by diagenetic processes. Since the main two types of rocks of this facies are wackestones and mudstones, two types of pore system based on size, are observed:

   a. **Macrointerparticle pore system**
      
      Found between grains of sand size where the grains are closely packed, or the lime mud matrix has been leached out. This type of porosity is not the chief type in the rocks of the marginal shelf and lagoon subfacies; however, it is important in the deeper water shelf facies of B57, B4 and B2.
b. Microinterparticle porosity

The most dominant in rocks which are composed of 100 per cent micrite and/or composed of sand-size non-skeletal particles. These are micro-pore system with a radius dimension of less than 2 microns, which exists between micrite cryptograins of the matrix and in pellets. Chalky textured lime mudstones have an intricate pore system with pores ranging in dimension between 1 and 10 microns. This pore system is of diagenetic origin and it seems that they are controlled by gradual growth and eventually coalescence of the micrite cryptocrystals during a neomorphic process which caused the creation of the chalky texture. This has been discussed above. (Pls. 14, 15 and 23).

Pray and Choquette (1966), and Ginsburg (1957) have measured the porosity of recent lagoonal lime mud in excess of 50 per cent. The close measurements of porosity values between the mudstone rocks (\(\sim 30\) per cent) of the Dahra (B) reservoir and that of the recent lime mud suggests that compaction of the reservoir sediments was not important in the reduction of pore spaces. This porosity is caused by re-arrangement of original mud sediments.

2. Intraparticle Porosity

This porosity occurs within indvidual particles or grains and is represented mainly by the micropores which exist within individual pellet intraclasts and pores within the tests of the organisms. It is an important porosity type in the pelleted lime mud rocks and wackestones,
packstones and grainstones of the shelf facies. However, it is less important than the interparticle porosity reported from the same facies (Pl. 24,A-B).

Secondary Porosity

In this thesis, the secondary porosity includes all pore system which was not developed during the original depositional processes of the reservoir sediment and did not exist in the particles before they were deposited. Secondary porosity is created mainly during the processes of diagenesis, and is either fabric selective or non-fabric selective. Fabric selective porosity is that in which pore position and boundaries are determined by the fabric elements of the rocks, such as moldic, chalky and intercrystalline porosity. Non-fabric selective porosity is that in which the pore system development is not confined by the rock fabric elements, such as vuggy and fracture porosity.

1. Moldic Porosity

Moldic porosity is not an important porosity type of the reservoir. It is formed by selective removal, normally by solution of a former individual constituent of the rock such as pellets or bioclasts. Molds are observed in the dolomites of supratidal and intertidal facies, as well as in the fairly dolomitic pelleted lime wackestones (Pl.25,A-B). The contribution of the moldic porosity to the total porosity of the reservoir is less than 5 per cent.
2. Chalky Porosity

Rocks of chalky texture in the Dahra (B) reservoir showed pore system of various shapes and sizes. It resulted mainly from the stacking effect of the various micrograins in relation to each other. Though the micropores are fabric selective, they were of secondary origin and were created during the diagenetic history of the rock. Some of the pore spaces which attain a considerable large pore radius (>10 microns), they may be created by leaching of calcite cryptoparticles by meteoric water. No chalky porosity of primary origin is observed in the Dahra (B) reservoir rocks.

3. Intercrystalline Porosity

In this thesis it refers to the pore spaces which are located between the microcrystalline dolomite rhombohedrons. It is an effective porosity type and is the most important. Supratidal and intertidal facies of the reservoir are characterized by the intercrystalline porosity. The pore spaces between the dolomite microcrystals are created by the growth of each individual rhombohedron on a plane different from the one adjacent to or above it (Pl. 26,A-B). This process resulted in a slit-like void space between the rhombs. The stacking effect of the differently oriented microrhombs also resulted in the microtriangular void spaces of a few microns in radius. Larger voids in 100 per cent dolomite were created either by dissolution of previously existing cryptocrystalline calcite or as a result of the growth of dolomite rhombohedrons around pre-existing void spaces (Pl. 19,B). Pore systems
created by dolomitization not only vary in shape, but also have various sizes. They range in diameter from 1 to 15 microns (Pl. 26, B).

The specific relation of porosity to dolomitization has long been debated (Hohlt, 1948, p. 26) and the problem was summarized by Fairbridge (1957, p. 159). The progressive textural and chemical changes that accompanied dolomitization of the Dahra (B) reservoir rocks confirm Murray's "local source" diagenesis (Murray, 1960), meaning that the extra $\text{CO}_3^-$ ions necessary for the reaction are supplied by solution of calcium carbonate itself. The process can be summarized as:

$$2\text{CaCO}_3 + \frac{\text{Mg}}{20} + 2\text{H}_2 \rightarrow \text{CaMg(CO}_3)_2 + 2\text{H}_2$$

Discrete dolomite rhombohedrons preferentially replaced the cryptocrystalline aragonite at the early stages of dolomite evolution. No dissolution of calcite constituents is observed if the dolomite rhombohedrons have not replaced 70 per cent of the rock constituents. It has long been reported that dolomitization on a molecule for molecule basis will bring about a 12 to 13 per cent increase in the rock's original porosity. However, according to Schmidt (1965) only 5 per cent volume reduction result from the replacement of aragonite particles by dolomite rhombohedrons. Hence, no significant porosity increase issue. The porosity map of the Dahra (B) reservoir does not show any significant change in porosity measurements as the percentage of dolostones in the reservoir increased, inferring that the replacement is volume for volume.
4. Vuggy Porosity

Vuggy porosity is important in the Dahra (B) reservoir. Vugs are frequently logged from all the reservoir facies, but are remarkably abundant in the supratidal and intertidal rocks facies. The reservoir communication was remarkably improved by the creation of vugs. This observation is based on the fact that the reservoir's high permeability readings are correlatable to the abundance of vugs (see cross-sections A-A', B-B', Appendix). Vuggy porosity in the Dahra (B) reservoir was caused by several processes:

1. by selective dissolution of replacement and void filling anhydrite. This process is responsible for the creation of excellent vug porosity in the supratidal and the intertidal facies. The author believes that dolomitization and vugs created by dissolution of anhydrite are principal processes which gave the Dahra (B) reservoir its potential quality.

2. Vuggy porosity has also been created in rocks in which the dolomite rhombohedrons replaced about 70 per cent of the rock constituents. Probably these vugs occupy areas which were originally aragonitic bioclasts. This process provides the carbonate ions necessary for dolomitization, a phenomena observed by Murray (1960). Vugs created by this process are observed in the supratidal and the intertidal rock facies.

3. Vuggy porosity created by dissolution of calcite grains by percolating meteoric water during periods of subaerial exposure. This process is believed to be responsible for the creation of vugs which
were caused by dissolution of lime mud and aragonitic bioclasts. Vugs of the shelf facies are originated by this process.

Vugs are observed to have various shapes and sizes, especially those which were created by dissolution of anhydrite and lime mud. The size range of vugs is from less than a micron up to several centimeters (Pl. 27, B). Compound porosity is a porosity type observed to be created by solution enlargement of molds (Pl. 27, A).

5. Fracture Porosity

It is not fabric selective and is logged from wells B8, B11 and B18. Fractures are of microscale and seem to be created during late diagenesis. Fracture porosity is not a significant porosity type in the Dahra (B) reservoir.
PLATE 24

A. Lime wackestone, composed of 50 per cent grains, 10 per cent dolomite and 40 per cent micrite. B57 (3690-91) deep-neritic shelf facies. Notice the presence of porosity in a foraminifera test. Porosity = 30 per cent; Permeability, \( V = 61 \text{md.} \), \( H = 61 \text{md.} \), 100X.

B. Scanning electron microphotograph illustrates the geometry of a pore in the foraminifera in illustrated above, 3000X.
PLATE 25

A. Microphotograph illustrates the sizes, shapes and distribution of moldic porosity in pelleted dolostone, B8 (3703-04). Cross nicols, 40X.

B. Microphotograph shows the development by solution effect of intraparticle porosity in nummulitic lime grainstone (deep-neritic shelf facies), B57 (3718-19). Cross nicols, 40X.
PLATE 26

A. Dolostone (B14, 3776-77), Sucrose fabric. Intercrystalline pore-spaces were caused by dolomite rhombohedrons random growth on different planes. (Scanning), 2000X.

B. Dolostone (B18, 3672-73), Sucrose fabric, intercrystalline porosity. Pores size and geometry were controlled by the stacking effect of the dolomite rhombohedrons. Porosity = 34.6 per cent; Permeability, V = 63md. and H = 39md., 3000X.
PLATE 27

A. Dolostone (B11, 3736-37). Shows pellet mold porosity. Notice the solution enlargement of the pellets molds, and the development of vuggy porosity. The white patches are anhydrite replacement. Cross nicols, 40X.

B. Dolostone (B18, 3648-49). Shows solution vugs. The vugs are partially filled by calcite spar. Cross nicols, 40X.
DAHRA (B) RESERVOIR PERMEABILITY

Introduction

Permeability is the property that permits the passage of a fluid through the interconnected pores of a rock without damage to or displacement of the rock particles (Leverson, 1967, p. 104).

The permeability of an average reservoir rock generally ranges between 5 and 1,000 millidarcy. A carbonate reservoir rock whose permeability is 5 md. is called a dense limestone. According to Leverson (1967, p. 105), a field appraisal of reservoir permeability is:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Permeability Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair</td>
<td>1 - 10 md.</td>
</tr>
<tr>
<td>Good</td>
<td>10 - 100 md.</td>
</tr>
<tr>
<td>Very Good</td>
<td>100 - 1000 md.</td>
</tr>
</tbody>
</table>

The permeability of the Dahra (B) reservoir rocks was determined in the laboratory by testing cores in a premeameter and the fluid used was a dry air. Permeability value of the reservoir rock types ranged from 0 to 400 md.

Nodular anhydrite beds have zero permeability, and the pelecypoda-wackestone facies and lime mudstone rocks have a fair permeability. It is noticeable that the reservoir permeability increases with dolomitization and abundance of grains; however, it decreases with the increase of micrite composition. The reservoir textural parameters and the permeability maps (Figs. 16,17) illustrate this relationship.
The creation of vugs caused the interconnection of the pore system of the reservoir. It gives the reservoir the good and very good permeability measurements. The vertical and horizontal permeabilities of the reservoir are about equal. This is believed to be caused by the burrowing effect of the organisms which lived in the depositional environment. The organisms by homogenizing the sediments have caused obliteration of the rocks' depositional fabric, including the beddings.

Influences on the Reservoir Permeability

The Dahra (B) reservoir permeability appeared to be improved by the following:

(1) Increase of dolomite replacement of rock particles beyond 50 per cent.

(2) Abundance of sand-size grains.

(3) Abundance of vugs which resulted from leaching of void filling and replacement anhydrite as well as by the dissolution of calcite.

The reservoir permeability is observed to be low because of the following:

(1) Abundance of micrite in the rocks with no appreciable dolomite replacement.

(2) Presence of clays.

(3) Presence of calcite cement.

(4) By anhydrite plugging.
RELATION BETWEEN THE RESERVOIR
POROSITY AND PERMEABILITY

It has been reported that the relation between a reservoir rocks porosity and permeability is obscure and variable (Botset and Reed, 1935). Beyond the fact that a permeable rock must also be porous, there seems to be only a general connection (Leverson, 1967, p. 133). The relationship between the porosity measurements and the horizontal and vertical permeability of the Dahra (B) reservoir rock types is graphically illustrated in the cross sections (A-A', B-B', Appendix). There is not even a general connection between the reservoir porosity and permeability (figs. 15, 16). The porosity of the reservoir rocks seems to be constant (mean = 30 per cent) and does not seem to vary noticeably by abundance of grains, micrite, or by intensity of dolomite replacement, cementation, existence of vugs or by abundance of clay minerals. However, the permeability seems to vary with the variation of these factors, as previously explained and illustrated (figs. 16, 17).
SUMMARY AND CONCLUSIONS

1. In summary, the Dahra (B) reservoir is a calcilutite, calcisiltite, dolomite and anhydrite rock unit of Danian age, Lower Paleocene.

2. The specific particle types which contributed to the reservoir rocks include foraminifera, Pelecypoda, calcareous algae, and Ostracoda as the main skeletal elements. "Fecal" pellets are the principal non-skeletal particle. Micrite, dolomite and anhydrite are the significant authogenic constituents.

3. The diagenetic processes to which the reservoir rocks were subjected have influenced the reservoir rock quality.

4. Pelleted lime mud was the principal carbonate sediment at the time of deposition. During early diagenesis, lime mud was replaced by dolomite rhombohedrons or was neomorphosed to micrite micrograins.

5. Four types of micrite particles were distinguished:
   (a) 1/4 to 3 1/2 micron platy, irregularly shaped particles; growth of these cryptocrystals to larger crystals by coalescent neomorphism was driven by surface tension of grain boundaries, and resulted in intra-particle micropores having a diameter of 1/5 to 1/3 micron.
   (b) Anhedral platy particles of 1/2 to 3 microns size. These grains grow in size by rim cementation to larger grains up to 15 microns in diameter, with the 1/2 to 3 micron cryptograins virtually preserved. They are termed by the author as micrite aggregates.
(c) Anhydral crystals having 1/4 to 10 microns size. These have denser crystallinity than type (a) and show no preferred orientation.
(d) Anhydral grains of 1/4 to 1/2 microns originated from recrystallization of skeletal constituents such as ostracods and foraminifera.

6. Cementation of the reservoir rocks is virtually absent. Sparry calcite cement exists only, and rarely between, the sand-size particles. It does not exceed 5 per cent of the reservoir composition.

7. Compaction is also absent. Skeletal grains show no evidence of crushing, and no pressure-solution effect was observed.

8. The distribution of replacement dolomite indicates that the dolomite replacement took place during the end of the early stage of diagenesis. Dolomitization was controlled by vagaries in fabric permeability. Dolomite rhombohedrons primarily replaced the lime mud particles. Pellets were progressively replaced by dolomite as the intensity of dolomitization increased and after the lime mud matrix was replaced. However, skeletal particles resisted the dolomite replacement.

9. Environmental parameters which seem to have promoted early diagenetic dolomitization are: (a) high Mg/Ca ratio of supernatant sea water, (b) high salinity, (c) high temperature, and (d) long lasting and easy communication between interstitial water and supernatant sea water.

10. Stylolites in the reservoir rocks were caused by the increase of overburden, and at a stage after the oil had migrated into the reservoir.

11. The reservoir structure is an anticline of about 85 km²,
having a NS fold axis and gentle plunge toward the south.

12. The structural growth of the reservoir was contemporaneous with sedimentation. Restricted shoal water and intertidal/supratidal facies occur principally on structurally high parts of the area.

13. Reservoir structure might have essentially been controlled by normal faults which were growing in the sediments below. Thus, the folding may be due to the higher beds having bent rather than fractured.

14. The reservoir is composed of three distinctively rock units. From base to top, they are: (a) massive nodular anhydrite ranging in thickness from one to ten feet, (b) dolostone beds in which the dolomite rhombohedrons replaced the burrowed and churned lime mud, and (c) mud supported rocks having an appreciable amount of bioclasts.

15. The three rock units are representative of a transgressive cycle which was brought about as a result of the gradual increase in the tectonically influenced water depth. The tectonic instability was caused by the gradual subsidence of the Sirte basin.

16. The reservoir rocks are interpreted to have been deposited in a very shallow marine environment. Within this environment, three subenvironments are recognized; they are: (a) supratidal zone to (b) intertidal zone to (c) subtidal environment. The latter is subdivided on the basis of faunal content into: (1) shallow-restricted shelf, and (2) deep-neritic shelf with normal marine fauna.

17. Supratidal zone was restricted to low-lying carbonate islands which existed in a broad, shallow shelf. The nodular anhydrite beds were deposited in a shallow saline playas across the (Sabkha)
plain during periods of widespread aridity. The sediments of supratidal flat lack fossils and are preferentially dolomitized.

18. Similarity is established between the Dahra (B) intralagoon fossil islands and the present day Crane and Sugarloaf Keya in the Florida Bay.

19. Intertidal facies overlies the supratidal beds into which it grades. The originally deposited sediments of this facies were churned, bioturbated and otherwise reworked.

20. Relation is established between a progressive increase in rock susceptibility to dolomitization with an increase of burrowing intensity. Hence, rocks of the intertidal zone were the most intensely dolomitized and constitute the major segment of the potential reservoir.

21. Rocks of the shelf facies overlies the intertidal facies into which it grades. It was deposited in the shallow water environment which existed between the intralagoonal islands and around the major anticlinal structure. Rocks of this facies contain an appreciable amount of foraminifera, calcareous algae, pelecypoda and Fayeina.

22. The sediments of the subtidal environment escaped intense dolomitization because they were deposited in a deeper water, were laterally remote from any possible gravity head caused by downward refluxing of brines, and were too far beneath the periodic surface brines trapped in very small intergranular capillaries under the control of climate and tidal rhythm. The rocks of this facies are not considered as a potential reservoir because of their low permeability.

23. Alteration of the reservoir rocks original textures was
caused by two processes: (a) diagenetic, including dolomite replace-
ment and neomorphism; and (b) burrowing communities which inhabited the
depositional basin. This process includes aggregation of mud particles
into sand-size pellets and fragmentation of skeletal particles.

24. Chalky texture of the reservoir is diagenetic, and caused
by rim cementation of micrite particles and/or by neomorphism.

25. The effective reservoir porosity is diagenetic. It is an
intercrystalline microporosity which was evolved by the growth of
each dolomite rhombohedron on a plane different from the one adjacent
to or above it, or by different stacking effect of the grown rhombo-
hedrons. Vuggy porosity also developed as a result of leach out of
void-filling and replacement anhydrite and dissolution of aragonite
particles.

26. Replacement of dolomite strongly effected reservoir
behavior. Permeability increases for rocks which are 50 per cent
dolomite.

27. The creation of vugs in the reservoir rocks apparently
contributed to the reservoir's fluid conductivity.

28. No general connection is established between porosity and
dolomitization.

29. No general relation is present between the reservoir porosity
and permeability. The reservoir porosity seems to be constant. It is
not influenced by abundance of grains, intensity of dolomite replace-
ment, or existence of vugs. However, the permeability seems to vary
with the variation of these factors.
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APPENDIX
### Well B-57-32

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Graphic Log</th>
<th>Texture</th>
<th>Porosity</th>
<th>Vertical Permeability</th>
<th>Horizontal Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,000</td>
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<tr>
<td>5,000</td>
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<tr>
<td>6,000</td>
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<tr>
<td>7,000</td>
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</tr>
</tbody>
</table>

Legend:
- Vugs
- Vugt

*Note: Diagrams and tables represent data specific to the well and its formations.*
VITA

The author was born in Tripoli, Libya, on September 29, 1942. He is the son of Mr. and Mrs. Razzagh E. Khoja. In 1964 he obtained the B.S. in geology and chemistry with excellence and first certificate of honor from the University of Libya in Tripoli. In 1967 he received his M.A. in geology (Ore Deposits and Mineralogy) from Columbia University in New York City, U.S.A. He also attended Stanford University and the University of New Mexico. In 1970 Dr. Khoja received a diploma from the Rosentiel School of Marine Atmospheric Sciences, University of Miami. His Ph.D. was granted in 1971 in geology (Reservoir Petrography and Petroleum Geology) from Rice University, Houston, Texas.

He is a member of the faculty of the Geology Department, University of Libya. He is also a member of several scientific organizations including the American Association of Petroleum Geologists and the Society of Economic Paleontologists and Mineralogists. His ambition is to contribute to geological science, hoping someday to be an international scientific figure. (His hobbies are sports and music.)
Sh, gr, sm gr-grm, abt.
Lochmartig.

Lo, no sh., ch sp.,
Otopusina.

DCT No.1, Boo.45' mud.

Lo, gr., no sh., w/C'sar, tp-bf, p fr por, v num., sm
talgodien ron, strong adj.
Flux, p.out.
Sh, eool-gr, brn-gr, n-dk gr, calc, cn clg v/la, C"arbon, Lt
gr, v f x, sm fss frsg.

Le, C'lat, v f x, bf-bf gr, p-nil por.

DF No.2, packer failure
DF No.2, packer failure

Sh, dl, grn gr, eli calc, spl, fiss, brittle

DF No.3, Poo.155', drig mud.
Le, st C'aron, Lt gr-bf, eli
coet, v f x, fss, bg, st.

Le, l gr, mott, v f x, dne,
hly.
Dahra Reservoir.

Deep, lt (x), natt, v f x, oil sand, oil arg.

Res. no. 4, Pro. 7679. 3% (32,000 ppm)

Deep, ol. calc, tn, lt brm, 5 ft,
ssp-sud, mm spar calc, incl.

Fr: inter-z por, amby.

Dol, un ab, no enby.
Dol, an ab, no anhy.

Dol, cald, mott, lt-dk brn, v f x, mm th, chky, orty, mm cft.

Le, dol, v f x, tn-brn, mott

Siderolites, alnt.

La w/anhy

Dol, sli calo, bf-thn, v f x, semi-sulc, anhy.