Outcrop-Subcrop Sequence and Diagenesis of Upper Jurassic Arab-Hith Formations, Central Saudi Arabia

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ABSTRACT. Outcrop-subcrop of the Upper Jurassic Arab-Hith Formations in central Saudi Arabia were studied in detail. The Arab Formation is mostly poorly exposed owing to the extensive slumping, collapsing and brecciation resulted from the dissolution of the interbedded anhydrite units. Except for an excellent exposure at Dahl Hit and limited exposures to the east of Al-Hair and Al-Badi (Fig. 3), the Hith outcrop had been removed totally by underground water solution of the anhydrite.

A composite stratigraphic sequence of the Arab and Hith was established from the outcrop-subcrop relationship. Four carbonate units have been recognized; the basal unit is generally persistent and undisturbed, whereas three other units are mostly made of slumped, contorted and fractured limestones as well as of brecciated limestone. While most of the coarse-grained limestone of the Arab in the outcropping area underwent leaching and recrystallization, the rocks in the subcrop were leached, recrystallized and dolomitized.

Dissolution of the Arab-Hith anhydrite units has caused serious geotechnical problems such as slumping, brecciation, cavities, vugs and fractures of the rocks in the outcrop-subcrop areas. Presence of vertical fractures and possible presence of permeability barriers to the east of the Sulaiy (Lower Cretaceous) escarpment seem to have caused the rise of the underground water table in the Riyadh area, which may further introduce potential health hazards by vertical charging of the sewage water into the underlying Riyadh Aquifer.

Introduction
The main objective of this paper is to describe the details of the Upper Jurassic sequence (Arab and Hith Formations) on the basis of the surface-subsurface relationships.
and petrographical work. Such a study is expected to shed light on both the depositional and diagenetic aspects of the rock sequence under study, and may also lead to a better understanding of the rate of growth and of its geological problems in and around the City of Riyadh. This would help to improve the city planning. This study is a part of research covering depositional environment, basin evolution and diagenesis of the upper Jurassic Arab-Hth sequence in Saudi Arabia (Shariel et al. 1991, in prep.; and Magara et al. 1991, in prep.).

Owing to incomplete and disturbed exposures of the Arab-Hth Formations at the surface as well as in the subsample area, the study was concentrated on correlating the geological characters at surface with those of the subsurface sections penetrated by shallow wells. Detailed geological field work, petrographical study of both the surface and subsurface samples, and interpretation of wireline logs were carried out to fulfill the research objective. Composite stratigraphic sections which define formations, boundaries, thicknesses and lithologies were constructed. The diagenetic processes involved in the Arab-Hth Formations were also evaluated on the basis of petrographic study.

Bramkamp and others (1956) and Bramkamp and Ramirez (1958) mapped the Upper Jurassic Arab Formation, as well as adjacent formations of Saudi Arabia on a 1:500,000 scale geologic sheets. A geologic map of the Arabian Peninsula, including Saudi Arabia and the surrounding countries on a 1:2,000,000 was compiled from these and other maps (U.S. G.S., 1963). The Arab Formation, in general, is very poorly exposed owing to the extensive slumping caused by solution-collapse of the anhydrite intervals. For this reason, a complete outcrop section, including its description, discussion and interpretation, has not been established. Moreover, the outcropping boundary of this formation on the geological map was not truly documented at sites but merely taken from the interpretation of aerial photographs. Furthermore, the type section is taken from the subsurface data based on a complete sample and core coverage. A summary of the stratigraphy with some notes on the regional distribution of the Arab Formation was provided by Powers and others (1966) and Powers (1964). The subsurface succession of the Arab was divided by Steincke and others (1958) into four members, Arab A' at the top through Arab D' at the bottom.

Recently, stratigraphic and sedimentologic studies of the Jurassic sequence in central Saudi Arabia were reported by Enay and others (1986). Detailed geologic maps on 1:250,000 scale with the explanatory notes on the lithologic, sedimentologic and biostratigraphic interpretations as well as on the mineral prospecting in the region were published also (Manivit and others 1985; and Yaldet and others 1985 and 1988).

Geologic Setting

Bordering the Arabian Shield on the east side are the sediments of the Arabian Shelf, long arcuate belts of the Phanerzoic succession (Fig. 1). A series of mostly parallel and west-facing escarpments dominate the landscape. From the Cambrian time on, epicontinental seas moved back and forth across the lower part of the shield.
and buried it beneath a succession of nearly flat-lying strata. Sediments are of continental to shallow-marine origin. Most of the rock units of the Saudi Arabian sedimentary cover are thin and widespread, maintaining uniform lithologic character over large areas. Beds dip gently (one degree to less than a half degree) and uniformly away from the southwestern region into the Arabian Gulf and the Rub al-Khali basins. In eastern Arabia, virtually flat-lying Tertiary and younger deposits effectively mask the underlying rocks.

From late Carboniferous to early Jurassic, a very shallow carbonate platform covered large parts of Saudi Arabia. During middle Jurassic and until early Cretaceous time, the platform became more differentiated with the Central Arabian Intra-shelf basin, breaking-up the shallow carbonate platform (Murris 1980). In this intra-shelf basin euxinic conditions produced starved sequences of fine-grained lime mud and marls (Ayres and others 1982). A major inundation caused considerable thickness of post middle Jurassic to late Jurassic sequence of shallow water supratidal deposits to accumulate. In late Jurassic time, gradually increasing marine restriction resulted in characteristic carbonate-evaporite cycles of the Arab Formation deposited in shelfal shoaling-upward sequences (J. L. Wilson 1975 and A. O. Wilson 1985). Progressive
evaporite deposits formed a terminal and thick Jurassic anhydritic bed called the Hith Formation.

The area of study, covering margins of the shallow shelf and the Central Arabian intrashelf basin, comprises the outcropping/subcropping sections of the Arab-Hith in central Saudi Arabia.

### Stratigraphy

The area studied comprises the exposure of the Arab Formation with the overlying Hith/Suflay Formations and the underlying Jabaila Formation (Fig. 2), and stretches from Al-Jawayn in the north to As-Salayyil in the south for a distance of more than 700 km, covering approximately 5,600 km² in area (Fig. 3). The contacts among the

<table>
<thead>
<tr>
<th>TIME</th>
<th>ROCK UNIT</th>
<th>LITHOLOGY</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>Late Jurassic</td>
<td>SULAIY FM</td>
<td></td>
<td>Thinly bedded and nodular sandy lime mudstone with intercalation of peloidal-skeletal and sandy rhyodacite / granite.</td>
</tr>
<tr>
<td>Triassic</td>
<td></td>
<td></td>
<td>Thick and porphyry thin-bedded, black gray and intercalated bands of blue and white anhydrite with intercalation units in the lower and upper parts of limestone with some siltstone.</td>
</tr>
<tr>
<td>Haflonian</td>
<td></td>
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<td>Except the lateral (D) limestone and Arab limestone units in the grey-green mudstone are mottled, carbonized and bleached with alternation of lime mudstone / granite beds. In the subaerobic, desiccation-karst limestone units are succeeded by clay, yellowish, greenish beds of anhydrite.</td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
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<td>Lime mudstone and dolomite with subordinated lime granophyre / packstone.</td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
<td></td>
<td>Lime mudstone and granophyre / packstone with coral and Stromatopora.</td>
</tr>
<tr>
<td>Oxfordian</td>
<td></td>
<td></td>
<td>Limestone with intercalation of lime granophyre / packstone. Combs and arenaceous beds in upper part.</td>
</tr>
</tbody>
</table>

**Fig. 2.** Generalized stratigraphic section of late Jurassic of Saudi Arabia showing rock units (Formations, Members) and lithology.
FIG. 3. Geological map of the study area showing the occurrences, locations of the measured sections of the Arab-Bahia Formations and their contacts with adjacent formations (from Brunkamp and others 1995, and Brunkamp and Ramirez 1999).
Jubaila, Arab, Hith and Sulayi Formations have been assumed to be conformable in general. However, a disconformity between the latter two formations cannot be totally denied. In the north, near Al-Majn'ah (Fig. 3), pre-Middle Cretaceous Wasia erosion has affected the Jurassic sequences; where they are progressively truncated and completely overlapped by the Wasia Formation. Where the Wasia directly overlies the Arab, conglomeratic and coarse grity beds separate the two formations, possibly indicating a strand line during the deposition of the Wasia Formation. In the south, between Layla and Wadi As-Sulayyil (Fig. 3), pre-Lower Cretaceous (Hauterivian) Buwaib erosion had removed some of the Upper Jurassic and Lower Cretaceous rocks so that the Buwaib overlaps the Arab Formation directly.

Surface exposures of the outcropping Arab and Hith Formations are distributed everywhere in the region. Where the Arab Formation is found to overlie the Jubaila Formation, the latter always distinguishes itself by retaining its majestic, original and excellent horizontal bedding without any disturbances (Plate I-A).

Plate I-A: Contact between Arab and Jubaila Formations. Low range of hills is formed by the Arab, while underlying excellently bedded is representative Jubaila Formation in west section, east of Al-Hair.

Jubaila Formation

A typical geomorphic feature of the Jubaila Formation is its almost horizontal and thick-bedding, extremely resistant and dense, usually light colored as gray, yellowish to buff and light brown. It has even surfaces on which are usually littered by broken, platy limestone slabs of the overlying Arab Formation (Plate I-A). When deeply dissected by the wadis, deep canyons are formed with most of the drainage having dendritic patterns. It usually forms west-facing cliffs with beds dipping at low angles towards east. The main rock types are lime mudstone with burrows, grainstone and dolomitic limestone.
Arab Formation

Outcrop Sequence

The Arab Formation forms broad and gently undulating low ranges of hills with very gentle faces of escarpments towards the west (Plate I-B). Often, the escarpment may occur as discontinuous and isolated hills. The Arab can be distinguished from the other formations by this geomorphic features as well as by its lithology. The hills of this formation are moderately to highly weathered, leached, brecciated, stumped or contorted (Plate I-C and D) and are characterized by joints and fractures which

Plate I-B. Low hill formed of the Arab Formation. Marble cap-topped of hill is usually brecciated limestone. Lower ground of red color marks the top of the Jaba Formation which is exposed in wadi section of Mutham area (section no. 8 in Fig. 3).

Plate I-C. Breccia limestone units in the Lower Arab Formation, east of Al-Hair.
could be filled with secondary superficial deposits or by secondary calcite (Plate II-A). Where the Arab Formation is slumped, contorted and brecciated, it looks as if it is discordant with the underlying Jahalin Formation. Where there are contortions formed from local arches or swell, resembling minor folds, small to large caves are developed (Plate I-C).

The dips of bedding planes in the exposures are between 10° and 15° and in some cases more than 80°, caused by the collapse structure resulting from the removal of the anhydrite by solution. Cavities ranging from few centimeters to several meters across, either empty or filled, are encountered at several localities in the area. These cavities resulted either from the solution of limestone fragments inside the fractures of breccia units (Plate II-A), or by the rearrangement of the collapse of the original structure into a network of solutions (Plate I-D), or by the dissolution of the coarse-grained grainstone by fresh water infiltrating through cracks, joints and fractures along bedding planes resulting in the formation of solution channels (Plate II-B).
In general, the lower contact of the Arab Formation is placed at the change of colour from tan to light grey lime mudstone of the Jubaila Formation below to brown-weathering buff or to reddish, fine to medium, pelletal to skeletal grainstone of the Arab Formation above. The basal Arab unit has a sharp lithologic and topographic character. This unit (probably lower Arab 'D' limestone and also known as the Riyadh aquifer) can be distinguished from distance by having low hills of brownish to pinkish colour usually resulted from the weathering of buff coloured grainstone, free of clay, and also by pinkish to reddish colour of the dense crystalline limestone lying over the Jubaila Formation. This reddish bed can be traced for a long distance (Plate 1-B).

The middle and upper Arab units (Arab 'C', 'B' and 'A' members) cannot be distinguished easily in the outcrops but their presence is marked by zones of large brecciated, slumped and contorted, thick, massive and bedded units (Fig. 4) with thin...
grainstone beds above each unit (Plate II-C and D). The brecciated zones which cap the hills are separated by units of fine-to-coarse-grained packstone, grainstone and

![Image](image1)

**PLATE II-C.** Massive isolated breccia bed of the Lower Arab Formation exposed in a cliff section with low range of hill range of the Upper Arab Formation in the background, west of Busa Shat'a (section no. 3 in Fig. 3).

![Image](image2)

**PLATE II-D.** Massive breccia bed seen in wall section. Location same as in plate II-C.

lime mudstone. Breccia fragments range in size from 1" to 10" and whole bed is sometimes slumped and reconsolidated to form a massive breccia bed (Plate III-A). Local brecciation at outcrops may also be seen when percolating meteoric water enters through the fractures and fissures, and causes leaching, dissolution and re-crystallization of secondary calcite along such openings or along the bedding planes of rocks (Plate II-B). This resulted in brecciated rocks, particularly in the lime mudstones. In such a case, the breccia fragments exist only in the parent or host rock (Plate III-B).
Subcrop Sequence

The study of the subcrop sections of the Arab Formation and its overlying and underlying formations was carried out in the areas where both the Arab outcrops and the main Saline Ridge coincide with the major collapsed and brecciated zone. The geologic data obtained for this study include shallow cores and wireline logs such as electrical and gamma-ray-neutron of both water and piezometric wells drilled in the Riyadh area. Most of the cored wells are of depths ranging between 100 and 120 feet, whereas the water wells are to about 650 feet deep with the Riyadh Aquifer as the main target. A composite stratigraphic well log was constructed after correlating sev-
eral logs of the wells drilled (Fig. 5). Lithology from the core samples of the wells close to the water wells were overlayed onto the logs of the wells.

**Fig. 5. Composite geophysical log of the Riyadh city showing the Arab-Ithth sequence.** Relatively low neutron readings occur in high gamma-ray intervals (due to presence of residual clays left behind from the dissolution of authigenic) and can be compared from well to well.
Based on the megascopic study of the available cores and log characteristics, both the Arab and Hith Formations boundaries and the thicknesses were established (Fig. 5). The composite section was then correlated with the synthetic well log (FPOC) of location A, in which all the anhydrite beds were removed (Fig. 6). East-west correlation of columnar sections were then constructed to explain the nature and degree of collapse in the region (Fig. 7).

Fig. 6. Stratigraphic correlation diagram of the Arab-Hith Formations through outcrop-subcrop to subsurface, Central Saudi Arabia. Location A and B are oil wells.

Fig. 7. Cross-section diagram illustrates sequence and evolution of the formation thicknesses (Arab and Hith) due to solution of the anhydrite units. See Fig. 3 (A-A') for location.
From the composite log section (Fig. 5) of the Riyadh area, the thickness of the Arab Formation is about 200 feet consisting of four carbonate units. It is evident that the basal part of the Arab-D Limestone is persistent without any disturbances as can easily be seen in the exposed area as well as in the wells around Riyadh. Lithologically, the basal unit is peloidal, partially ooidal grainstone/packstone with some lime mudstone. There is much recrystallization at the surface outcrops near the contact with the underlying Jubaila Formation.

Limestone units (C to 'A') overlying the basal Arab Formation are mostly slumped, contorted and fractured, and are composed mainly of vuggy coarse- to fine-grained, peloidal grainstone and lime mudstone. Brecciated limestone units which alternate with the limestone units overlying the basal Arab Formation, are generally recemented limestone fragments of lime mudstone/grainstone with fracture fillings of calcite and gypsum, or silt size particles of limestone.

**Hith Formation**

**Outcrop Sequence**

The Hith Formation is known at only one outcrop location in the central of Riyadh area, i.e. Dahl Hit (Fig. 3 and Plate III-C). Elsewhere, the Hith had been removed by underground water solution. However, a large outcrop of this formation occurs as leached anhydrite at the Marwan Village to the east of Al-Badi Township (Fig. 3). Similarly many spots of discontinuous exposures of the formation occur in the Wadi Ash-Shutiah and south of Al-Hair (Fig. 3). Where the overlying Hith Formation is preserved, contact with the top of Arab is conformable and represented by a sharp lithologic change from grainstone of the Arab Formation to the overlying massive, bluish gray anhydrite of the Hith Formation (Dahl Hit). In other areas along the outcrop, where the uppermost part of the Arab and/or Hith sequence had been dissolved and removed by solution, the residual Arab Formation is in contact with slumped limestone of the Solayri Formation.

Plate III-C. Solution sink-hole of Dahl Hit showing contact between Hith and Solayri formations.
The Hith Formation in Dahí Híi is, in general, made of two units. The Lower Híh (about 250 feet thick) is mainly composed of bluish gray and some alternating bands of blue and white anhydrite, thick-bedded with partially thinly and regularly lami-
nated to platy. It sometimes contains nodules and network (flake wire) and wave-
flow structures and some irregular lenses of white gypsum. Thin layers of about 10
feet thick yellow, weathered lime mudstone and dolomite containing small nodules
of anhydrite occur in the lower part of the Lower Híh. The Upper Híh (about 40
feet thick) is brecciated limestone with thin beds of gray to tan lime mudstone and
grainstone. The top of the Híh where preserved is at the contact of brecciated limes-
tone and evenly bedded dolitic grainstone of the overlying Sulaiyí Formation.

Subcrop Sequence

The Híh Formation in the subcrops of the Riyád area is about 84 feet thick of
limestone lying between the Sulaiyí and Arab Formations (Fig. 5). The carbonates of
the Híh Formation are represented by the Rííthán and Mánííá Limestone (Fig. 2).
In addition, a few other thin stringers of carbonates within the Híh are stacked on
top of each other with much brecciation and slumping. To the east of the Sulaiyí
scarp, the Híh Formation is assumed to retained its thickness and is correlatable
with that penetrated by the wells in the eastern region of Saudi Arabia (Figs. 6 and 7).
Lithologically, the Híh subcrop sequence consists mainly of brecciated crystalline
limestone with some intervals of lime mudstone and grainstone.

Sulaiyí Formation

The Sulaiyí Formation occurs as two different structural units in the region stretch-
ing from north to south in the study area. Structurally and geomorphologically
speaking, it may be divided into two general distributions. The Sulaiyí Formation which
lies to the west of the main Sulaiyí Escarpments follows the structural patterns of the
underlying Híh and Arab Formations. The exposure occurs as discontinuous pyramidal-like hills and thus distinguishes itself from the other adjacent formations in
the surrounding area. Because of the removal of anhydrite beds from the Arab-Híh
sequence by solution caused by meteoric water, the Sulaiyí Formation is commonly
fractured, brecciated, foliated and contains numerous cavities, vugs and openings
(Plate III-D). The main Sulaiyí ridge is very distinct, forming an escarpment of spec-
tacular size, facing towards west with cone-like talus slopes along its entire scarp-face
resulting from slumping of the main Sulaiyí ridge. Its entire face resembles a fault-line
scarp topographic feature. To the east of the main ridge, the intensity of slumping de-
creases.

The Sulaiyí consists of thinly-bedded and nodular chalky lime mudstone with alter-
nation of packstone/grainstone. The chalky lime mudstone is, in general, light gray
to tan, light to moderately porous, and contains some pellets and shell fragments,
mainly sponge spicules. The grainstone/packstone is tan to brown, very fine to
medium- and coarse-grained, well cemented and contains pellets, ooids and abun-
dant foraminifera, peliocypod and gastropod shell debris.
Petrography

Outcropping Arab Limestone

The Arab limestone exposures consist mainly of fine- to coarse-grained grainstone/packstone and lime mudstone with zones of brecciated limestone. Detailed petrographical analysis based on textural spectra (carbonate grains or particles, matrix, and sparite) indicate that the most common rock types of the outcropping limestone are given as follow:

(A) Bio lithite (Plate IV-A)

Very tightly packed layers of algae with low intergranular porosity.

(B) Matrix (micrite) dominant rock

Mainly bio-pelmicrite including coated particles (Plate IV-B) and pelmicrite
Plate IV-B: Bio-pelmicrite. Most of the shells and buttons filled with sparry calcite while the matrix is not affected. × 20.

(Plate IV-C). At some localities, especially in the southernmost outcrop area, abundant quartz grains are characterized in the pelmicrite which was probably transported by storms at basin edges (Plate IV-D). In these matrix-dominant rocks, coarser particles and grains are easily recrystallized after leaching by solution, while the micrite part was left behind. The fine microcrystalline matrix and the pellets may be rich in magnesite since no free dolomite is present and calcitization did not occur in these fine particles and matrix.

Plate IV-C: Unusual, variable grain size pelmicrite. Note large growth of calcite in leached area, but the pellets and matrix are not affected by recrystallization. × 20.

Plate IV-D: Quartz pelmicrite. Deformed, angular, striated quartz grains of uniform size probably derived by storms at basin edges. × 20.
(C) Cement (sparite) dominant rocks

Mainly intrasparradite (Plate IV-E and F), coosparite (Plate V-A), biosparradite (Plate V-B), bio-pellosparrite (Plate V-C) and pellosparite (Plate V-D). In these sparrite-dominant rocks, coarse to medium particles and grains are occasionally leached by

**Plate IV-E.** Intra-sparradite shows clusters of ooids and pellets occurring in intrasparadic rock fragments and standing in the sea of sparry calcite as islands. When leached, the porosity becomes very high. Note that sparry calcite recrystallization is more prominent in the ooids than in the pellets and mollusks, × 20.

**Plate IV-F.** Intra-sparradite shows clusters of cemented fragments of ooids occurring as intrasparas and standing out as islands in the sea of sparry calcite and in some cases mollusque porosity is produced, × 20.

**Plate V-A.** Coosparite. Concentric layers of ooids are still clearly seen with radial calcite. In some ooids, the rims are leached upon by solution as can be seen in right upper corner. Note also the calcite crystals increase in size between the grains, × 80.
PLATE V-B. Biosparmite with recrystallization of coarse calcite where the fossils are leached forming intergranular porosity. × 20.

PLATE V-C. Bio-peloparite recrystallized mollusk shell, pellets and nodules with sparry calcite cement. × 20.

PLATE V-D. Peloparite shows sorted, uncompacted grains of pellets cemented by sparry calcite. The edges of the pellets are irregular sparry calcite which grows in intergranular pore space. The cement is fine microsparite probably derived from nitrionite. × 20.

solution and replaced by secondary calcite to produce moldsic porosity and interpores partially filled with sparry calcite; vaggy porosity may be formed in the calcite cement. Complete recrystallization as in the Plate V-E may results in the formation of crystalline limestone (sparite) with only ghost like structure remaining. In such a case, porosity becomes very low or diminished and is of the intercrystalline type.
Pl. V-E: Spurrite shows ooliths recrystallized into sparry calcite while the cement was formed by coarse calcite. Oxide forms were destroyed with only faint rims of ghost structures preserved. The center of ooids were also converted into coarse crystalline calcite, × 20.

(D) Microcrystalline (micrite) rocks

Homogenous, unlaminated and unfossiliferous micrites consisting of more than 99% microcrystalline calcite and lacking particles are common along all the outcrops. This micrite may be fractured with sparry calcite developed by recrystallization and filling of the fractures (Plate V-F). When the intensity of fracturing become

Pl. V-F: Discrete or brecciated microsparry fractures micrite with sparry calcite developed by recrystallization and filling of fractures. Fragments of micrite now resemble angular breccias. Note that sparry calcite recrystallization does not affect micrite mud but only the fractures, × 20.

great, the dismicrite will be traversed by minute veins of calcite, resembling microbreccia. Recrystallization of calcite did not occur in the microcrystalline matrix, but occurred only in the open fractures. Fractures and intercrystals may be developed in the original rock which was non-porous and non-permeable.

Subcropping Arab Limestone

Except for the presence of dolomite crystals in the subcropping rocks, the petrographic study shows the textural and compositional similarities between the surface and subcrop Arab rocks. However, the subcropping rocks are usually more complex
in lithology due to the intensive leaching, slumping and brecciation; most of them are breccias of mega-scale (Plate VI-A) to micro-scale (Plate VI-A). Unlike the outcrop areas where most of the coarse-grained limestones underwent leaching and recrystal-

**PLATE VI-A.** Brecciated limestone shows breccia of bio-occlusions, micrite and pelmicrite, × 20. Recrystalization to form secondary calcite, the rocks in the subcreeps were leached, recrystalized and dolomitized.

The most common rock types of the subcropping Arab Limestone are given as follows:

**(A) Matrix (micrite) dominant rock types**

Mainly biopelmicrite (Plate VI-B) and pelmicrite (Plate VI-C). Abundant lichoc-

**PLATE VI-B.** Bio-pelmicrite with pores filled with dolomite, × 20.

**PLATE VI-C.** Pelmicrite is commonly dolomitized and illuminated organic micrite with fine dolomite, × 20.
last mainly quartz grains are characteristic of some of the pelmicrite (Plate VI-D). In the mellite-dominant rocks, pores are mainly filled with coarse-to fine-cylindrical rhomb-shaped crystals of dolomite.

Plate VI-D. Intra pelmicrite with angular to subangular quartz fragments, × 20.

(B) Cement (sparite) dominant rock types

Bio-sparite (Plate VI-E), bio-pelopsparite (Plate VI-F), and pel-biosparite (Plate VI-G) are the main types of sparite-dominant rock types. These rocks show that fos-


Plate VI-F. Bio-pelopsparite shows pores and fossil chambers filled with calcite cement and slightly dolomitized, × 20.
sil chambers, particles and/or pores are filled with sparry calcite and partially dolomitized.

(C) Microcrystalline (micrite) rocks

In addition to the homogenous, unfossiliferous, un laminated micrites, the brescia ted micro-crystalline limestones (demicrites) showing secondary calcite filling in fracture (Plate VI-H) are common in the subcropping Arab rocks.

Diagenesis and Related Geotechnical Problems

Leaching, brecciation and fracturing of the outcropping/subcropping limestones of the Arab Formation are its common diagenetic features. Detailed petrographical study shows that cementation and recrystallization of the variable textures of limestones are additional diagenic features for outcrop samples. On the contrary, most subcropping limestones are affected by both dolomitization and recrystallization.

Cementation and Dolomitization

Whatever processes are involved, a complete recrystallization and dolomitization would cause a total loss of the original pore space. But in an intermediate stage of
dolomitization or recrystallization, porosity and permeability tend to increase (Murray 1960 and Powers 1962). Grain size, its distribution and infilling matrix control the pore geometry of a rock, which would further influence both the fluid path and its movement. Following sections discuss, in detail, the diagenetic processes involved in the outcrop-subcrop successions of the Arab Formation.

Outcrop Area

Outcropping rocks normally experience the processes of diageneric different from those in the subsurface. From Al-Jawayy in the north to Wadi As-Sulayyi in the south, the Arab section was severely affected by the recrystallization process. Significant recrystallization of sparry calcite occurred primarily in the sediment pore spaces where meteoric and ground waters were able to move freely. Joints, fractures and pore spaces parallel to bedding planes formed effective paths for such water movements. The larger the pore and throat sizes, the more effective was the movement of water. In sediments, both pore and throat sizes would change with changing average grain size, sorting and also, the presence or absence of infilling matrix. The sizes of crystals formed in such pore spaces thus decrease from biosparite-oosparite to pelmcrete. Micrite is usually not recrystallized. If assisted by fractures and joints, micrite may become partially recrystallized to produce a locally brecciated rock. Therefore, we may be able to rank the degree of recrystallization of biosparite as the highest followed by those of oosparite, pelsparite, pelmcrete, and micrite as the least.

Subcrop Area

Contrary to the outcrop area where most of the coarse-grained limestones underwent leaching and recrystallization to form secondary calcite, the rocks at subcrops were leached, recrystallized and dolomitized. Dolomitization occurred in all types of rocks from micrite to micrite and sparry dominants, and is considered to be of the secondary nature and perhaps of "late" origin. It presumably started to develop only after leaching, brecciation and fracturing of carbonate rocks. Furthermore, there is no indication of dedolomitization process occurred in the subcrop as well as in the outcrop area.

Dolomite seems to have been formed at relatively high temperatures under stagnant to static fluid conditions, which existed in rocks of relatively small pore and throat sizes, such as micrite and micrite cement-bearing rock. If the process continued in this manner, complete dolomite rhombo would be formed. During the process of leaching and dissolution by meteoric water of Mg rich carbonate near surface, Ca** and Mg** ions may be precipitated out of solution rather quickly, but Mg** ions tend to remain in the moving ground water, and would move further down dip towards east. Detailed discussion of dolomitization in the study area is made elsewhere (Sharief et al. 1991 in preparation).

In areas with vertical fluid communication through fractures, the magnesium rich water at shallower depths may move downward into low-porosity micritic rocks and station there, until all the pore spaces and fracture openings are to be filled by secondary dolomite crystals. Where any porous bed overlies an impervious bed, the latter
forests receptacles for collecting Mg\(^{2+}\) ions from ground water, and the former will become saturated with the water. Dolomitization will become more effective in such a porous bed than in the underlying impervious bed. The dolomite crystals in the coarse-grained rocks as in the pelmircite are usually large because of their larger pore sizes available during the crystal growth. The dolomite crystals in incomplete dolomitization of micrite are normally small, but become larger during the advanced dolomitization.

Dissolution of Arab-Hith Anhydrite Units

The removal of the anhydrite layers interbedded between the limestone units of the Arab Formation and the anhydrite of the Hith Formation by solution, and subsequent deposition of brecciated units caused the collapse and slump of the overlying limestone units.

A total of about 850 feet of anhydrite had been removed by solution in the Riyadh area; this includes both the Hith anhydrite and the anhydrite caps of the Arab limestone units (Table 1). This thickness is equivalent to the total collapse in this area. The total volume of anhydrite which had been removed in the area between Al-Majma'ah in the north and As-Sulayyil in the south, and further to the foothills of the Sulayl escarpment is estimated approximately at 265,000,000 tons (Fig. 7). The intensity of collapse is greatest in the west of the Sulayl escarpment, followed by that at Al-Majma'ah in the north and at Wadi As-Sulayyil in the south. To the east of Duhl Hit, only the anhydrites of the Arab 'A', 'C' and 'D' and part of the lower Hith seem to have been removed (Fig. 7). To the east of Khushum Al-Halal, normal succession prevails and continues towards oil producing areas (Fig. 6). Powers et al. (1966) reported that the water used for Al-Kharj Farms, contained high concentrations of calcium sulphate. It was also mentioned that the occurrence of the sink holes in this area shows that the Yamama Formation may also be affected by slumping as a result of anhydrite removal by solution.

The total collapse of about 850 feet in the Arab and Hith Formations seems to have caused extensive brecciation, minor folds, flexures, distortions and fractures in these formations as well as in the overlying Sulayl Formation. Part of the Sulayl often slipped off from the major outcrop of escarpment, and occurs as slumped beds which follow patterns of the underlying formations (Fig. 7).

Rise of Underground Water Table

Recently, rising ground water table has been a major problem in the Riyadh area. The present study of the Arab Formation and the adjacent formations may contribute to a better understanding of the underground water problems as well as other related geotechnical problems of the area.

Geological Factors

The Riyadh area is covered mostly by the Arab Formation and its eastern part by the Sulayl Formation. As stated earlier, both the Arab and Sulayl are characterized
<table>
<thead>
<tr>
<th>Formation</th>
<th>Member</th>
<th>Location A-1</th>
<th>Synthetic log A-1</th>
<th>Riyadh composite log</th>
<th>Collapse due to Anhydrite solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltite</td>
<td></td>
<td>393 Feet</td>
<td>30 Feet</td>
<td>20 Feet</td>
<td>35 Feet</td>
</tr>
<tr>
<td>Hith</td>
<td>Upper</td>
<td>350 Feet</td>
<td>40 Feet</td>
<td>50 Feet</td>
<td>45 Feet</td>
</tr>
<tr>
<td></td>
<td>Marble</td>
<td>40 Feet</td>
<td>Total carbonates</td>
<td>40 Feet</td>
<td>45 Feet</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>480 Feet</td>
<td>-</td>
<td>-</td>
<td>480 Feet</td>
</tr>
<tr>
<td>Arab</td>
<td>&quot;A&quot; Limestone</td>
<td>20 Feet</td>
<td>20 Feet</td>
<td>30 Feet</td>
<td>30 Feet</td>
</tr>
<tr>
<td></td>
<td>&quot;B&quot; Anhydrite</td>
<td>40 Feet</td>
<td>-</td>
<td>-</td>
<td>40 Feet</td>
</tr>
<tr>
<td></td>
<td>&quot;C&quot; Limestone</td>
<td>36 Feet</td>
<td>20 Feet</td>
<td>20 Feet</td>
<td>25 Feet</td>
</tr>
<tr>
<td></td>
<td>&quot;D&quot; Anhydrite</td>
<td>136 Feet</td>
<td>-</td>
<td>-</td>
<td>136 Feet</td>
</tr>
<tr>
<td></td>
<td>&quot;D&quot; Limestone</td>
<td>90 Feet</td>
<td>90 Feet</td>
<td>90 Feet</td>
<td>60 Feet</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total collapse due to Anhydrite removed by solution 60 Feet</td>
</tr>
</tbody>
</table>

by extensive fracturing and slumping due to dissolution of the Hith anhydrite as well as the anhydrite layers interbedded with the limestone beds of the Arab Formation.

The basal Arab 'D' Member, consisting of biotite, biotite-pyroxene and quartzite with some pelmittenite, corresponds to the so-called Riyadh Aquifer. Eastward tilt of the oil/water contact in the Arab 'D' Reservoir (Limestone) of such a close oil field as Ghawar and decreasing salinity of its formation water in the southwestward direction may indicate a possibility of fresh water movement from southwest to northeast in the geological past as well as at the present time. The movement of water may have continued since the time of the initial uplift of the Arab in the outcrop areas at the pre-Wasia unconformity stage (pre-Middle Cretaceous time).

Meteorite water which entered through this unconformity surface and also, the
pore water enclosed in the Wasia sediments of fresh water origin (Moshref and Keling 1984) would have dissolved enormous amounts of calcium sulphate from anhydrite and transported CaSO₄ to deeper levels. The Sulaibi escarpment, which had probably been developed to the west of the present position, seems to have moved eastward as the leaching caused both collapse and brecciation of limestones of the Arab-Hith and Sulaibi Formations west of it.

**Effect of Dissolution of Arab-Hith Anhydrite Units**

As stated above, dissolution of anhydrite and subsequent collapse has caused intensive brecciation, minor folds, flexures, distortions and fractures in these formations. The most intensive collapse occurred west of the Sulaibi escarpment. In the area east of Dahal Hij, most anhydrite intervals of the Arab were removed whereas the Hith anhydrite was only partially reduced. To the east of Khushnulli Al-Halal (Fig. 7) a complete succession of anhydrite and carbonate exists and continues southward the oil producing areas.

Large amounts of calcium sulphate dissolved in ground water may have passed through the aquifer down toward the basin. In the area east of the escarpment and west of the Jurassic oil field area (Fig. 6), calcium sulphate may be precipitated in the Riyadh Aquifer (Arab 'D') limestone unit, thus not only reducing its effective porosity but also forming an important permeability barrier in this region. Because of the presence of such a barrier, there has been not a single oil seepage found in the entire outcrop area of this highly prolific Arabian Formation. The oil field at Location 'A' (Fig. 6) marks a practical western limit of the oil producing region of the Arabian Formation.

The calcium sulphate content of the ground water would increase from the Arab/Jubaila contact at surface to the cast, and further cast to the Sulaibi escarpment. The level of ground water fluctuates depending on the rainfall, run-off and also by the production of ground water. The aquifer itself is subdivided by thin scals of marl or bentonite, but if they are disturbed by fracturing or solution, then the domestic aquifer may be contaminated by the sewage water above. The units which overlie the aquifer are intensely fractured in both vertical and other inclined directions as the result of collapse. On the contrary, there is virtually no effective horizontal confinement of fluid flow in the Riyadh Aquifer. In addition, the eastward movement of water may be severely disturbed by the presence of the permeability barrier mentioned above.

If the rates of the domestic water consumption and disposal are high, then it is more likely that the water table rises quickly and could aggravate foundation collapse. Furthermore, the carbonate formations may be attacked by acidic sewage disposals, causing solution channels, vugs and collapse at near surface.

**Effect of Dissolution and Recrystallization of Arabian Limestone**

Circulating surface water throughout the Arabian Formation is made easy as well because of the presence of fractures and joints caused by the Central Arabian Graben Fault Systems (Fig. 1). The percolating meteoric water, rich in carbon dioxide, attacks aragonite and calcite at both the vadose and phreatic zones above and below
the water table producing solution channels, vugs and large cavities. Along these openings, secondary precipitation and recrystallization of sparry calcite may occur either in the form of thin needles flocked there, taking the scalenohedral crystal shape, or as euhedral, rhombohedral calcite crystals. An entire five to ten feet thick bed may be recrystallized in this manner, especially in coarse-grained strata. A network of veins, due to leaching and recrystallization of calcite along fractures in the micritic re- sults in brecciation of the host rocks. In such a case, breccias consist of angular frag- ments of the host rock without any foreign rock fragments.

Control of Rising Water Table

The rise of the underground water table can be controlled by discharging the waste water in the lower unit of the Jubaila Formation which is porous and permeable. The Upper Jubaila consisting of thick dolomite and lime mudstone would act as a seal for such disposal water, and thus the Riyadh Aquifer above the Jubaila will not be af- fected. Improper disposal of sewage water at the present time should be immediately abandoned in our opinion, and the public should follow the city’s guidance or code very strictly.

In conjunction with the Riyadh’s Aquifer, it is important to note that water wells drilled in this area must be cased and cemented properly. Cement bond logs need to be run to estimate the bondage condition between the casing and formation. Proper casing and cementation are essential to avoid possible communication between the aquifer and sewage water which would cause serious health hazards.

Geotechnical Problems

The brecciated units, which have undergone underground water erosion and vari- able degrees of weathering including chemical solution cavities, vugs and openings along fractures at surface and subcrop areas, pose geotechnical problems for the foundations especially for constructing high-rise buildings and deep basement struc- tures in the Riyadh City. Rising underground water table and increase in sulphate and chloride contents of the water in the subcrop areas of the Arab Formation near Riyadh are primarily due to its high domestic water consumption and disposal. As mentioned above, due to the presence of calcium sulphate barrier in the Riyadh Aquifer (or Arab-D) in the east, lateral water flow is less likely; water would most likely move vertically. As a result, the water table will rise and cause various prob- lems, such as we are currently experiencing in the Riyadh area. This phenomenon would cause more solution channels, vugs, fractures and collapses, as described ear- lier, at near surface positions, and further continuation of this process would enlarge the existing pores and create cavities and pits. Semi-intract and hard rocks may also be reduced to highly weathered and porous rocks with relatively low mechanical strength.

Collapse, subsidence and eventual loss of the foundation supports, especially when a deep basement structure or high-rise building has been constructed, are the serious and major problems confronting the construction engineers in the Riyadh area. If there is no adequate control for rising underground water table at and around
a construction site, the engineers must pay special attentions to the sewage and groundwater problems because they are very important not only during the construction period but also afterward. In addition, they should, in our opinion, prepare for additional bearing pressures on the foundation, in case of any future collapses due to dissolution and fracturing.

Summary and Conclusion

Significant research works have been conducted on the Upper Jurassic Arab and the Hith Formations, based on the extensive field surveys and sampling, and on the analyses and interpretations of the surface-subcrop sequences. Contributions of this research project lie in the study and analysis of the outcrop-subcrop sequences including diagenetic features and their related geotechnical problems in the area, and are summarized as follows:

1. The outcropping Arab ‘D’ Member is represented by fine to medium, pelletal and skeletal grainstone with lime mudstone at the base. On the other hand, the other members of the Arab (C to A) consist of zones of thick massive and beded units which are brecciated, slumped and contorted in large scale. Each unit is overlain by a thin grainstone bed. Most of the Arab rocks have suffered recrystallization into sparry calcite. The degree of recrystallization decreases from coarse-grained bioparite, oomparite, pelparite to micrite. A complete recrystallization results in severe reductions of pore space.

2. A composite subcrop sequence of the Arab Formation was established based on the detailed study of well logs and core samples, where its thickness was estimated to be about 206 feet; it consists of four carbonatic units. The basal part of the Arab ‘D’ limestone is persistent without disturbance in the outcrop-subcrop area. The limestone units of the Arab ‘C’ to ‘A’ overlying this basal unit are mostly slumped, contorted and fractured due to the dissolution of the anhydrite intervals. They are composed mainly of vuggy coarse- to fine-grained pelletic lime grainstone and lime mudstone in the subcrop area.

3. Both dolomitization and recrystallization occurred in the Arab subcrop area. While dolomitization is confined to rocks with lime matrix which seems to have retarded fluid movement, recrystallization into sparry calcite took place in grain-supported biosparite, oomparite and pelparite in which dolomitization was negligible. Dolomitization in the subcrop area seems to have been caused by meteoric water rich in Mg$^{++}$ ions in downip locations, after dissolving and reprecipitating the original calcite in pores and vugs updp.

4. The outcropping Hith Formation in the Dahl Hat slumping area, where it is preserved (about 250 feet thick) is composed mainly of anhydrite with some brecciated lime mudstone and grainstone, and by discontinuous exposures of leached anhydrite in south of Al-Hair, and east of Al-Badi areas. In subcrop area, the Hith (about 84 feet thick) is composed mainly of brecciated microcrystalline limestone with intervals of lime mudstone and grainstone representing the Rimthan and Manifa limestone units.
5. A K50 feet of anhydritic section from the Arab-Hith has been removed by solution; which corresponds to the total collapse of the formations involved. The collapse has caused serious geotechnical problems in the Riyadh area; difficulty is particularly serious in cases of constructing deep basements and high-rise buildings. Vertical fractures formed during and after the active collapses have caused rise of the ground water table in the Riyadh area, which may further introduce potential health hazards by the vertical charging of the sewage water into the underlying Riyadh aquifer.

6. Presence of the permeability barrier, which seems to exist east of the Salaiy escarpment and west of localities A and A’ (oil fields), may be documented by drilling and coring in the area. Increasing CaSO4 content towards the barrier may be examined by other existing well data. The result of such a study would be of practical and economical value in predicting chances of stratigraphic petroleum traps in the Arab and also, a real limit of the lateral ground water flow.

7. A pilot study of vertical fluid charging near the Riyadh City and subsequent collapse of formations may be conducted for a better understanding of the city's potential and existing health and construction hazards. A method may be that by driving several shallow and intermediate wells, flow of water can be traced through examination of trace elements injected by the shallow well. The analysis of a 3-D flow pattern may be used for predicting potential flow direction of the sewage water.

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