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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 us to a better understanding of the rise of ground water and of its geotechnical 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-Hith sequence in Saudi Arabia (Sharief *et al.* 1991, in prep.; and Magara *et al.* 1991, in prep.).

Owing to incomplete and disturbed exposures of the Arab-Hith Formations at the surface as well as in the subcrop 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 formational boundaries, thicknesses and lithologies were constructed. The diagenetic processes involved in the Arab-Hith 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 1:500,000 scale geologic sheets. A geologic map of the Arabian Peninsula, including Saudi Arabia and the surrounding countries on 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 boundaries 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 (1968). The subsurface succession of the Arab was divided by Steineke 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 Vaslet and others 1985 and 1988).

Geologic Setting

Bordering the Arabian Shield on the east side are the sediments of the Arabian Shelf, long arcute belts of the Phanerozoic 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

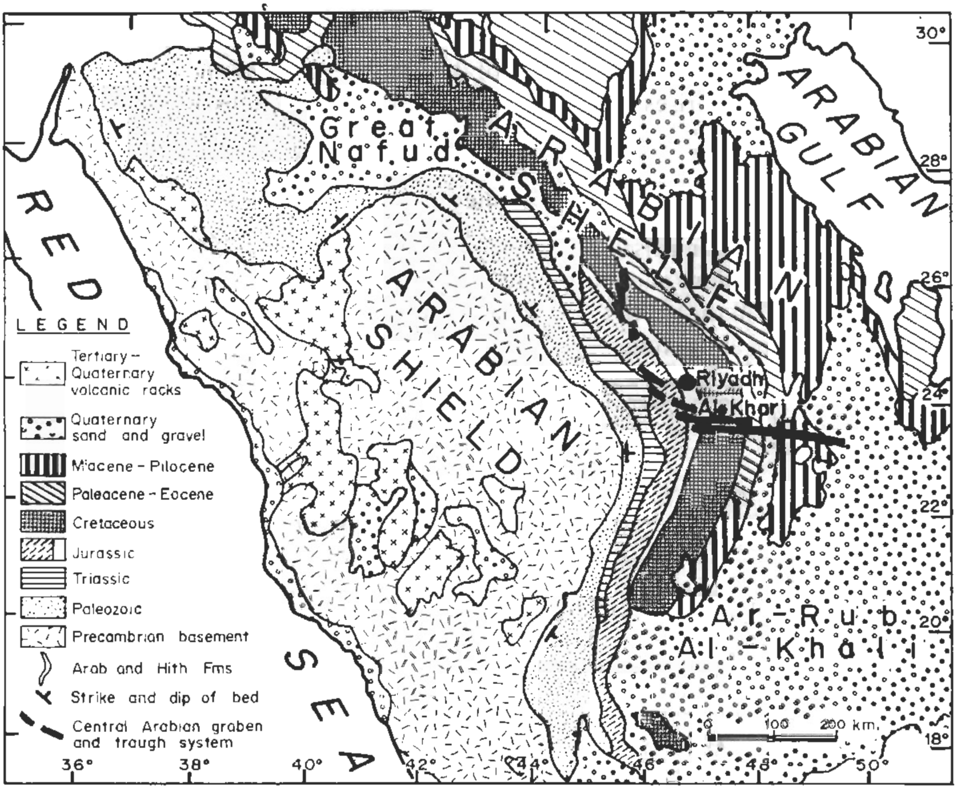

FIG. 1. Generalized geological map of Saudi Arabia and adjacent areas showing the study area.

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 escarpment 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 a considerable thickness of post middle Jurassic to late Jurassic sequence of shallow to 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 anhydrite 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/Sulaiy Formations and the underlying Jubaila Formation (Fig. 2), and stretches from Al-Juwayy in the north to As-Sulayyil in the south for a distance of more than 700 km, covering approximately 5,600 km^2 in area (Fig. 3). The contacts among the

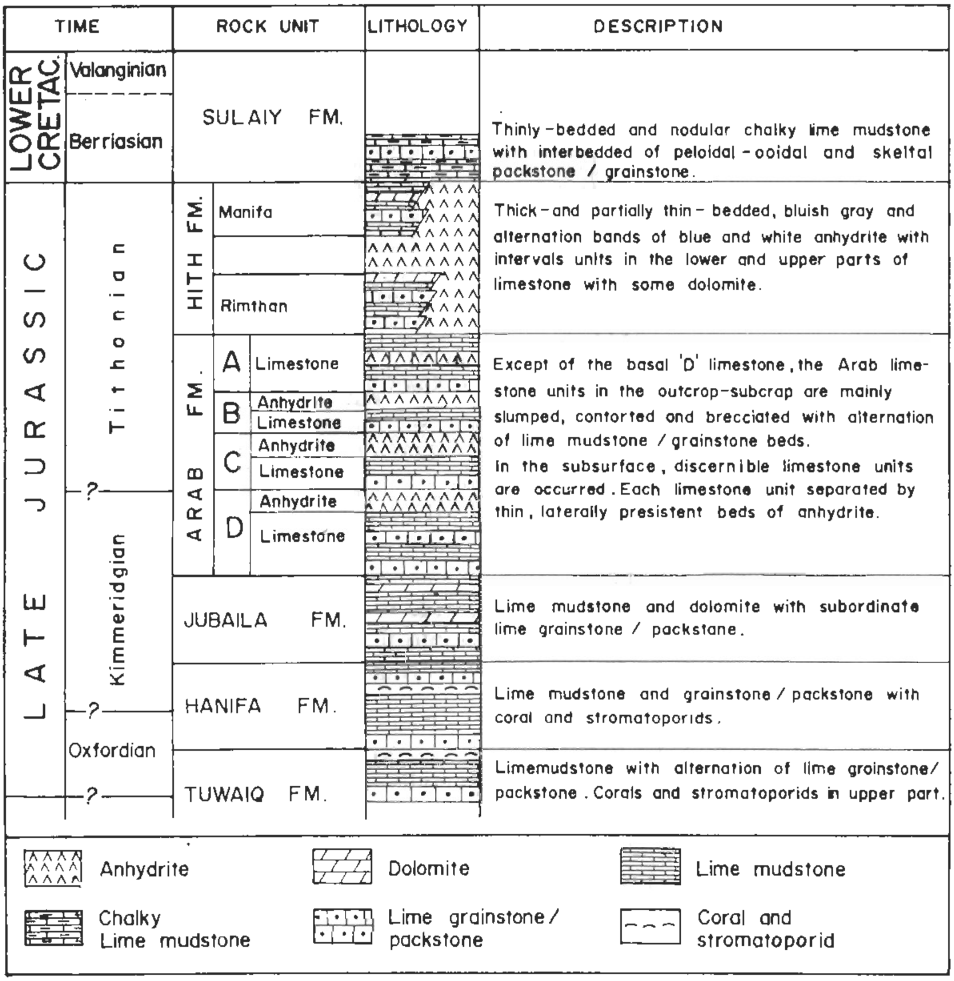

FIG. 2. Generalized stratigraphic section of late Jurassic of Saudi Arabia showing rock units (Formations, Members) and lithology.

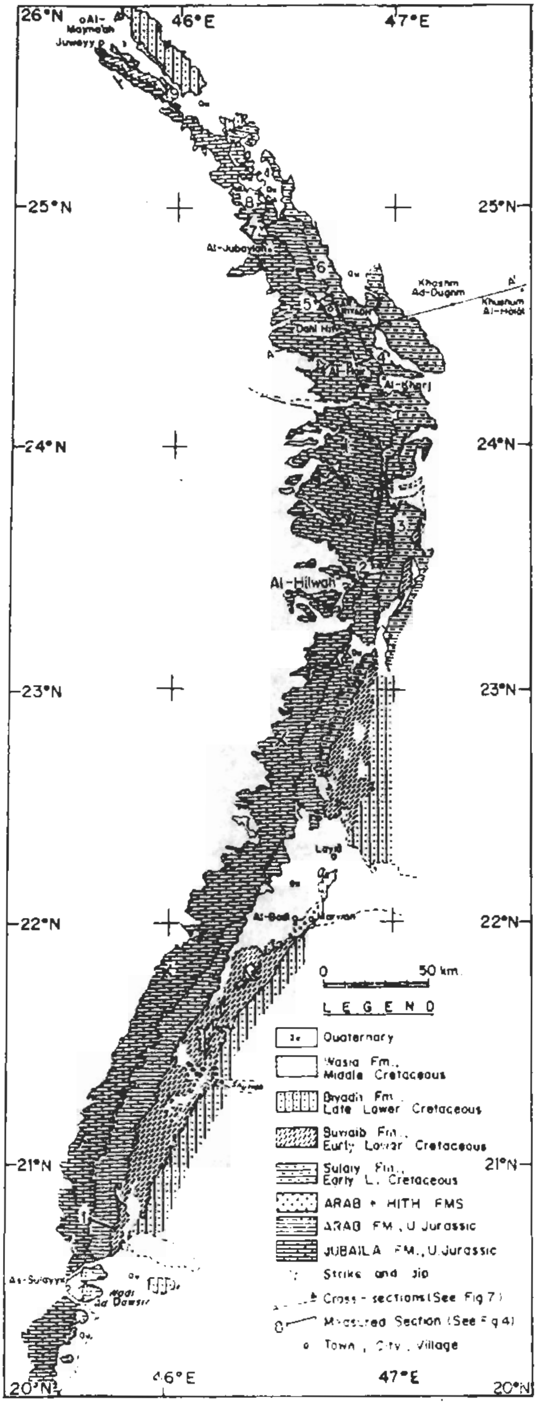

Fig. 3. Geological map of the study area showing the occurrences, location of the measured sections of the Arab-Hith Formations and their contacts with adjacent formations (from Bramkamp and others 1956; and Bramkamp and Ramirez 1958).

Jubaila, Arab, Hith and Sulaiy 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-Majm'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 gritty 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 (Hautervian) 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).

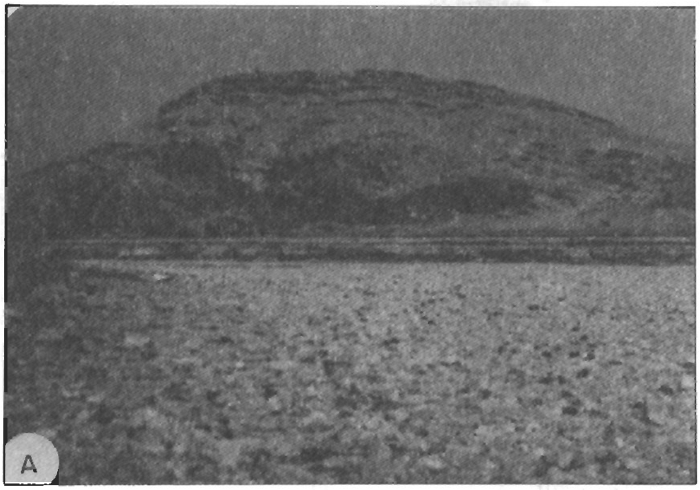

PLATE I-A. Contact between Arab and Jubaila Formations. Low range of hills is formed by the Arab, while underlying excellently bedded is represented Jubaila Formation in wadi section, east of Al-Hair.

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

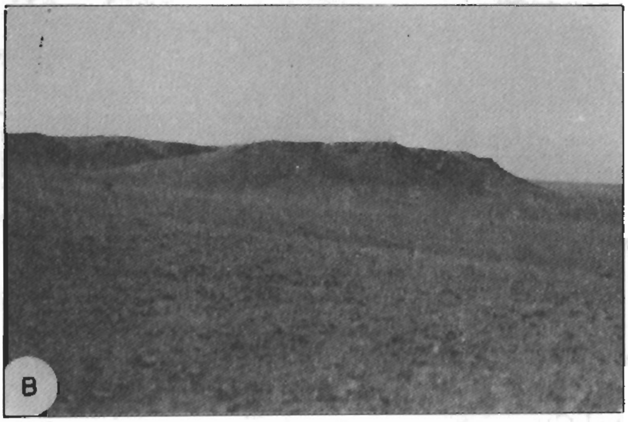

PLATE I-B. Low hill formed of the Arab Formation. Massive cap bed on top of hills is usually brecciated limestone. Lower ground of red color marks the top of the Jubaila Formation which is exposed in wadi section of Malham area (section no. 8 in Fig. 3).

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, slumped or contorted (Plate I-C and D) and are characterized by joints and fractures which

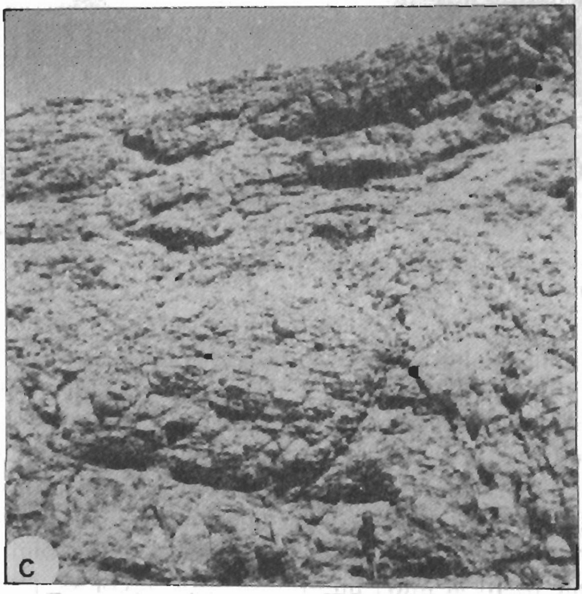

PLATE I-C. Breccia limestone units in the Lower Arab Formation, east of Al-Hair.

PLATE I-D. Slumping, foliation with cave in the Lower Arab Formation, west of Bani Shara (section no. 3 in Fig. 3).

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 Jubaila Formation. Where there are contortions formed from local arches or swells, resembling minor folds, small to large caves are developed (Plate I-C).

PLATE II-A. Cavities and recrystallization of secondary calcite crystals in massive and brecciated Arab Formation, Riyadh area.

The dips of bedding planes in the exposures are between 10° and 15° and in some cases more than 40°, 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 foliations (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).

PLATE II-B. Part of grainstone bed in the Arab Formation replaced by growth of secondary calcite crystal. Salbouk-Gassim-Riyadh fly-over bridge, north of King Saud University, Riyadh area.

In general, the lower contact of the Arab Formation is placed at the change of colour from tan to light gray lime mudstone of the Jubaila Formation below to brown-weathering buff or to reddish, fine to medium, pelletic 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 I-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

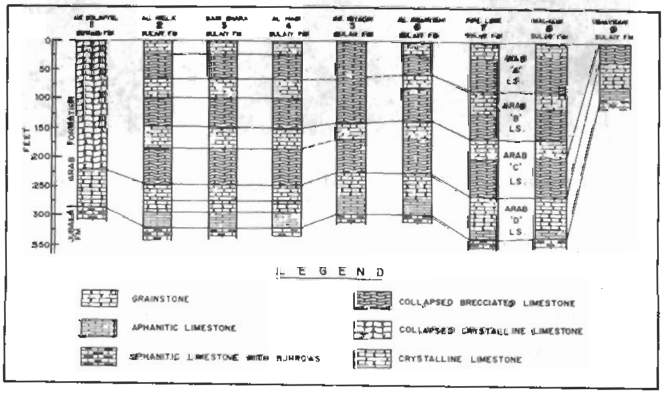

FIG. 4. Schematic stratigraphic correlation diagram along strike of the Arab Formation outcrop area, Saudi Arabia. See numbers on Fig. 3 for location of the sections.

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

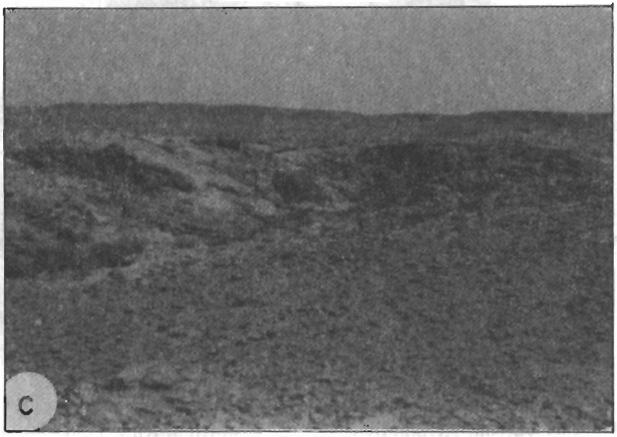

PLATE II-C. Massive foliated breccia bed of the Lower Arab Formation exposed in wadi section with low range of hill range of the Upper Arab Formation in the background, west of Bani Shara (section no. 3 in Fig. 3).

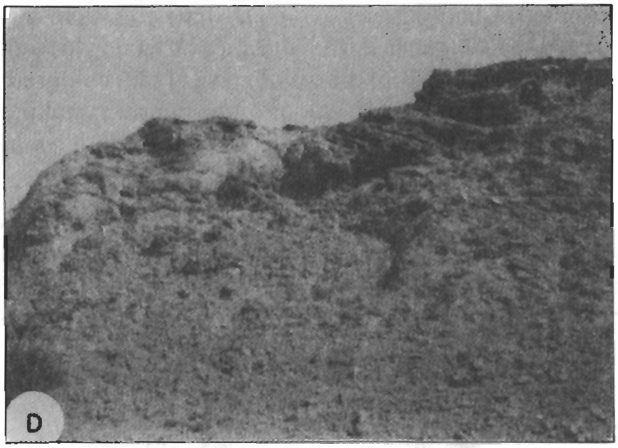

PLATE II-D. Massive breccia bed seen in wadi section. Location same as in plate II-C.

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 recrystallization 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).

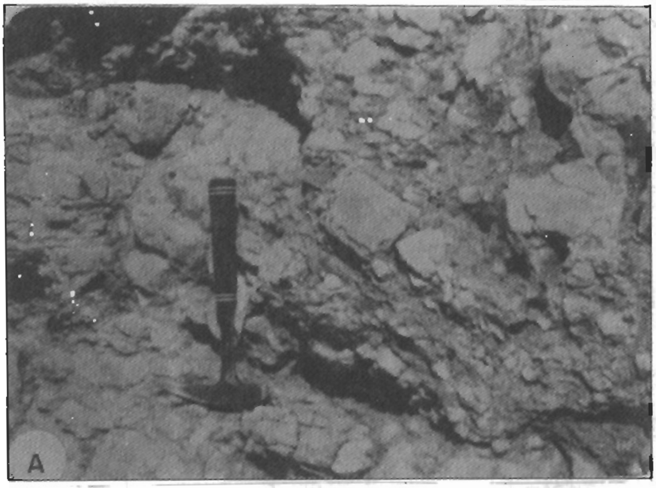

PLATE III-A. Close-up view of the brecciated limestone unit in Arab Formation, east of Al-Hair.

PLATE III-B. Close-up view of the brecciated bed, originally lime mudstone with numerous cavities developed, resulting from leaching, east of Al-Hair.

Subcrop Sequence

The study of the subcrop sections of the Arab Fromation and its overlying and underlying formations was carried out in the areas where both the Arab outcrops and the main Sulaiy Ridge coincide with the major collapsed and brecciated zone. The geologic date 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 130 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 several 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.

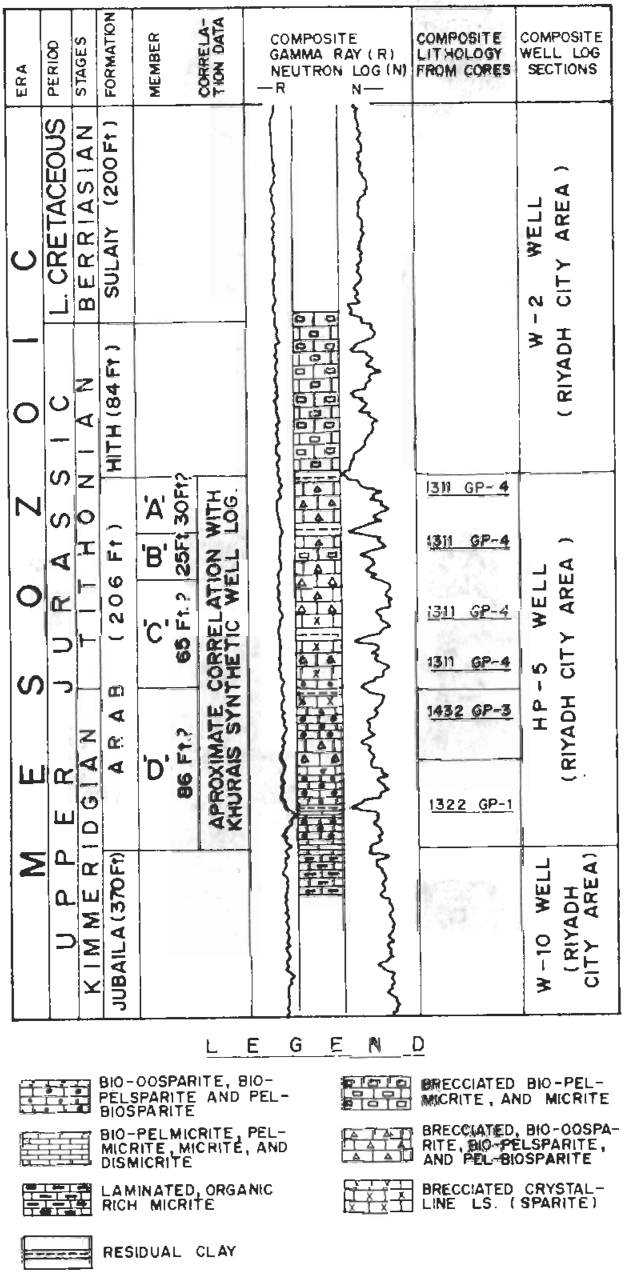

FIG. 5. Composite geological log of the Riyadh city showing the Arab-Hith sequence. Relatively low neutron readings occur in high gamma-ray intervals (due to presence of residual clays left behind from the dissolution of anhydrite) and can be correlated from well to well.

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 (FDC) 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).

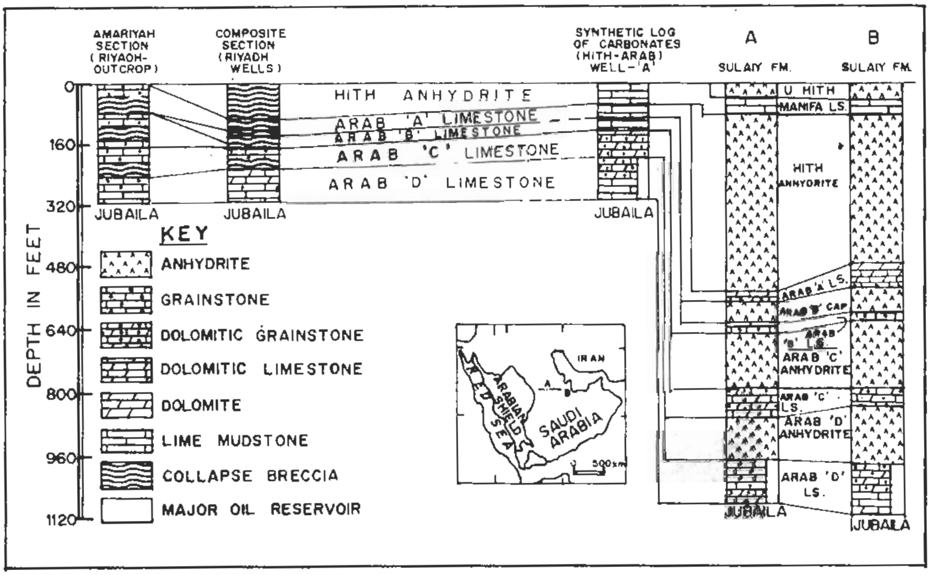

FIG. 6. Stratigraphic correlation diagram of the Arab-Hith Formations through outcrop-subcrop to subsurface, Central Saudi Arabia. Location A and B are oil wells.

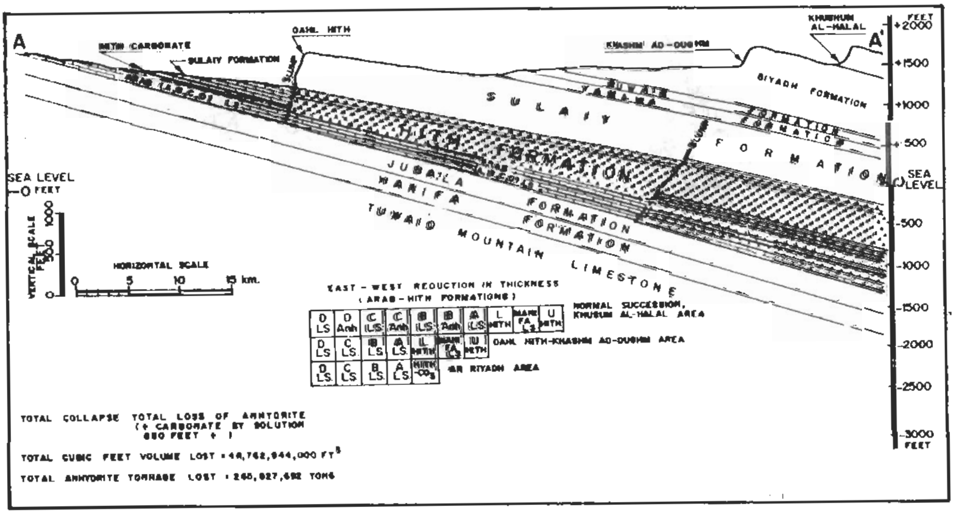

FIG. 7. Cross-section diagram illustrates sequence and reduction of the formation thicknesses (Arab and Hith) due to solution of the anhydrite units. See Fig. 3 (A-A') for location.

From the composite log section (Fig. 5) of the Riyadh area, the thickness of the Arab Formation is about 206 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 pelloidal, 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 fructured, and are composed mainly of vuggy coarse- to fine-grained, pelloidal 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

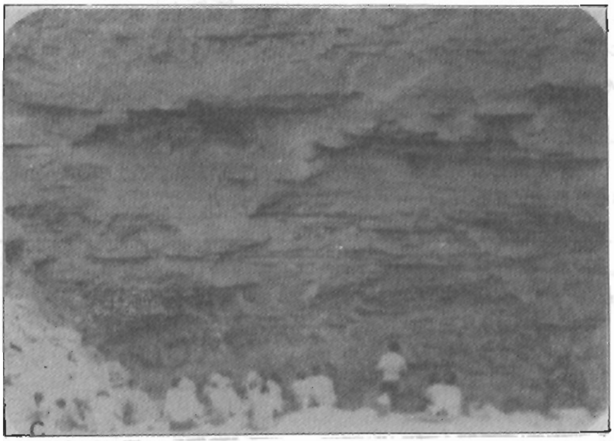

Plate III-C. Solution sink-hole of Dahl Hit showing contact between Hith and Sulaiy Formations.

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 Sulaiy Formation.

The Hith Formation in Dahl Hit is, in general, made of two units. The Lower Hith (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 laminated to platy. It sometimes contains nodules and network (chicken wire) and waves-flow structrues 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 Hith. The Upper Hith (about 40 feet thick) is brecciated limestone with thin beds of gray to tan lime mudstone and grainstone. The top of the Hith where preserved is at the contact of brecciated limestone and evenly bedded oolitic grainstone of the overlying Sulaiy Formation.

Subcrop Sequence

The Hith Formation in the subcrops of the Riyadh area is about 84 feet thick of limestone lying between the Sulaiy and Arab Formations (Fig. 5). The carbonates of the Hith Formation are represented by the Rimthan and Manifa Limestones (Fig. 2). In addition, a few other thin stringers of carbonates within the Hith are stacked on top of each other with much brecciation and slumping. To the east of the Sulaiy scarp, the Hith 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 Hith subcrop sequence consists mainly of brecciated crystalline limestone with some intervals of lime mudstone and grainstone.

Sulaiy Formation

The Sulaiy Formation occurs as two different structural units in the region stretching from north to south in the study area. Structurally and geomorphologically speaking, it may be divided into two aerial distributions. The Sulaiy Formation which lies to the west of the main Sulaiy Escarpments follows the structural patterns of the underlying Hith and Arab Formations. The exposure occurs as discontinuous pyramid-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-Hith sequence by solution caused by meteoric water, the Sulaiy Formation is commonly fractured, brecciated, foliated and contains numerous cavities, vugs and openings (Plate III-D). The main Sulaiy ridge is very distinct, forming an escarpment of spectacular size, facing towards west with cone-like talus slopes along its entire scarp-face resulting from slumping of the main Sulaiy ridge. Its entire face resembles a fault-line scarp topographic feature. To the east of the main ridge, the intensity of slumping decreases.

The Sulaiy consists of thinly-bedded and nodular chalky lime mudstone with alternation of packstone/grainstone. The chalky lime mudstone is, in general, light gray to tan, tight 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 abundant foraminifera, pelecypod and gastropod shell debris.

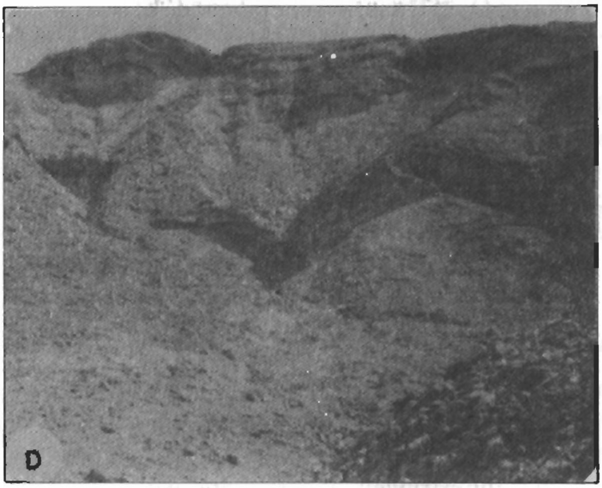

PLATE III-D. West-facing scarp formed by slumped Sulaiy Formation, east of Bani Shara.

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) Biolithite (Plate IV-A)

Very tightly packed layers of algae with low intergranular porosity.

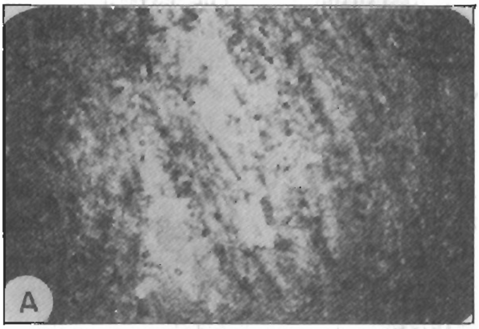

PLATE IV-A. Biolithite composed mainly of encrusting layers of red algae, very tightly packed together with low intergranular porosity, × 20.

(B) Matrix (micrite) dominant rock

Mainly bio-pelmicrite including coated particles (Plate IV-B) and pelmicrite

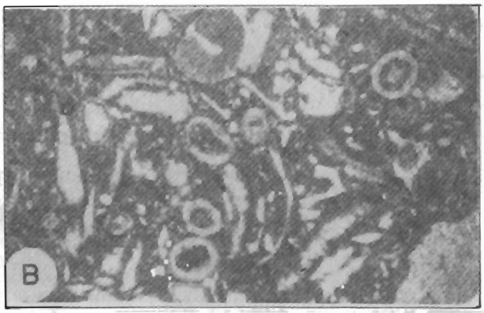

PLATE IV-B. Bio-pelmicrite. Most of the shells and burrows filled with sparry calcite while the matrix is not affected, × 20.

(Plate IV-C). At some localities, especially in the southern most 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 magnesium since no free dolomite is present and calcitization did not occur in these fine particles and matrix.

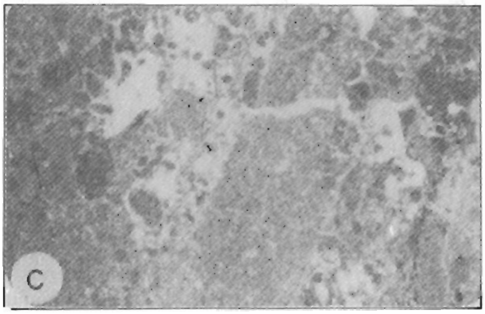

PLATE IV-C. Unsorted, variable grain size pelmicrite. Note large growth of calcite in leached area, but the pellets and matrix are not affected by recrystallization, × 20.

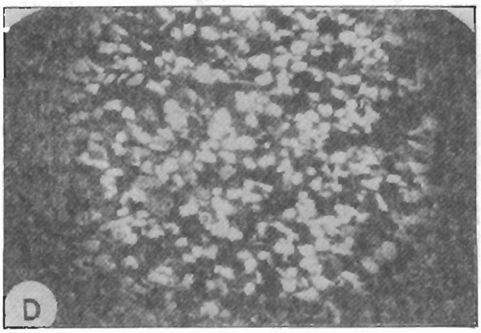

PLATE IV-D. Quartz pelmicrite. Dominant, angular, strained quartz grains of uniform size probably derived by storms at basin edges, × 20.

(C) Cement (sparite) dominant rocks

Mainly intrasparrudite (Plate IV-E and F), oosparite (Plate V-A), biosparrudite (Plate V-B), bio-pelsparite (Plate V-C) and pelsparite (Plate V-D). In these sparite-dominant rocks, coarse to medium particles and grains are occasionally leached by

PLATE IV-E. Intra-sparrudite shows clusters of ooids and pellets occurring in intraclastic 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 oolites than in the pellets and micrite, × 20.

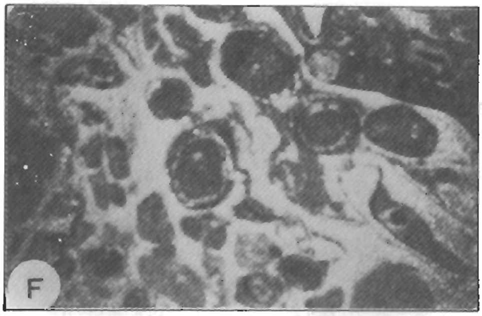

PLATE IV-F. Intra-sparrudite shows clusters of cemented fragments of ooids occurring as intraclastics and standing out as island in the sea of sparry calcite and in some cases moldic porosity is produced, × 20.

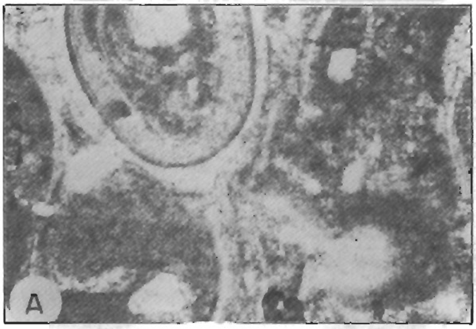

PLATE V-A. Oosparite. Concentric layers of oolites are still clearly seen with radial calcite. In some ooids, the rims are leached upon by solution as can be seen in right upper corner. Note also the calcite crystals increase in size between the grains, × 80.

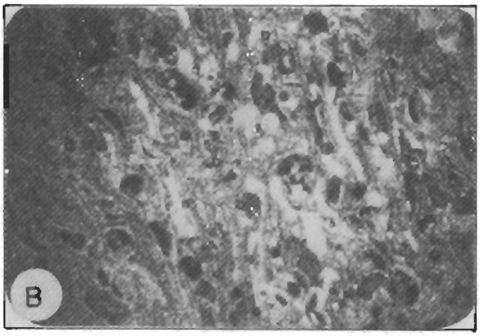

PLATE V-B. Biosparrudite with recrystallization of coarse calcite where the fossils are leached forming intergranular porosity, × 20.

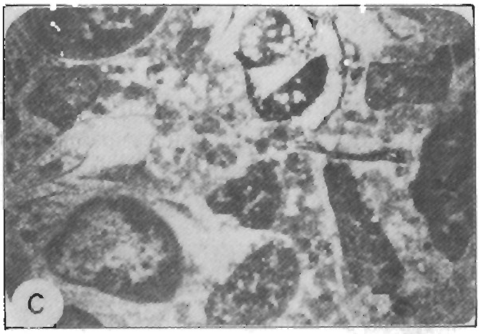

PLATE V-C. Bio-pelsparite recrystallized mollusk shell, pellets and ooids with sparry calcite cement, × 20.

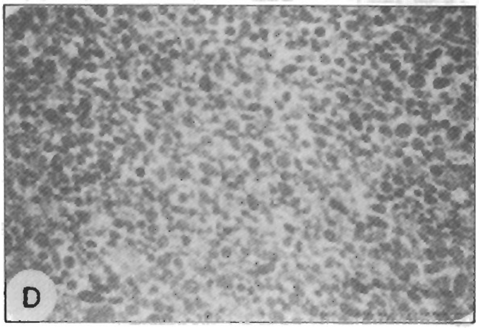

PLATE V-D. Pelsparite shows unsorted, uncompacted grains of pellets cemented by sparry calcite. The edges of the pellets are irregular sparry calcite which grows in intergranular pore space. The cement is fine micro-sparite probably derived from micrite, × 20.

solution and replaced by secondary calcite to produce moldic porosity and interpores partially filled with sparry calcite; vuggy 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.

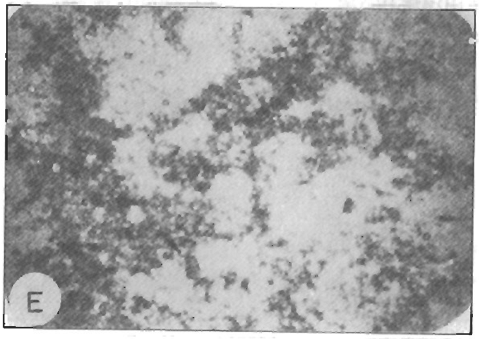

PLATE V-E. Sparite shows oolites recrystallized into sparry calcite while the cement was formed by coarse calcite. Oolite forms were destroyed with only faint rims of ghost structure preserved. The center of ooids were also converted into coarse crystalline calcite, × 20.

(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 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.

PLATE V-F. Dismicrite or brecciated micrite. Highly fractured 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 micritic mud but only the fractures, × 20.

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 II-A) to micro-scale (Plate VI-A). Unlike the outcrop areas where most of the coarse-grained limestones underwent leaching and recrystal-

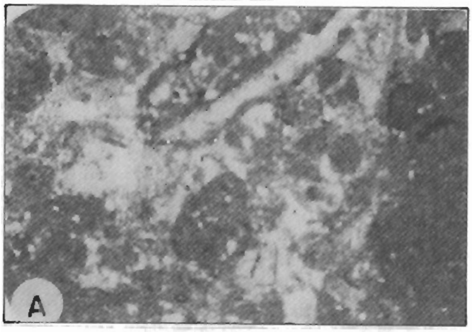

PLATE VI-A. Brecciated limestone shows breccia of bio-oosparite, micrite and pelmicrite, × 20.

lization to form secondary calcite, the rocks in the subcrops were leached, recrystallized 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 lithoc-

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

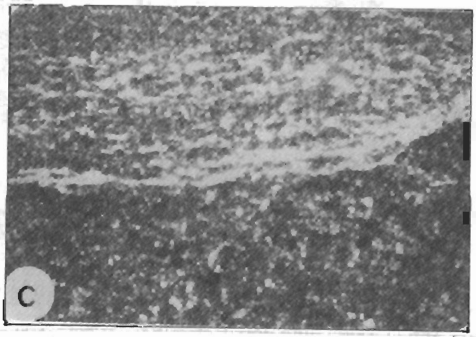

PLATE VI-C. Pelmicrite is commonly dolomitized and laminated organic micrite with fine dolomites, × 20.

lasts mainly quartz grains are characteristic of some of the pelmicrite (Plate VI-D). In the micrite dominant rocks, pores are mainly filled with coarse-to fine-euhedral rhomb-shaped crystals of dolomite.

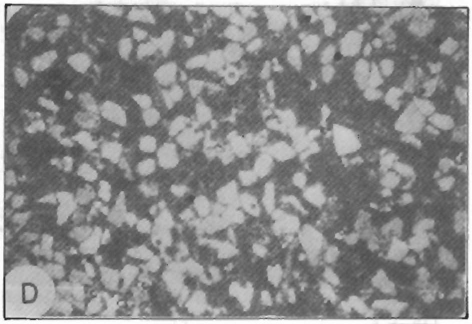

PLATE VI-D. Intra-pelmicrite with angular to subangular quartz fragments, × 20.

(B) Cement (sparite) dominant rock types

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

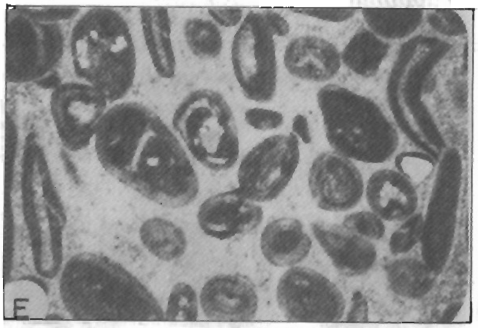

PLATE VI-E. Bio-oosparite loosely formed with microsparite, calcite cementation and fossil chambers filled with calcite, × 20.

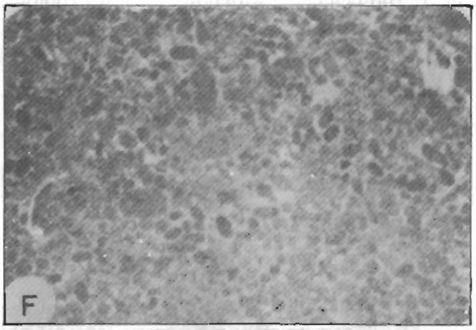

PLATE VI-F. Bio-pelsparite shows pores and fossil chambers filled with calcite cement and slightly dolomitized, × 20.

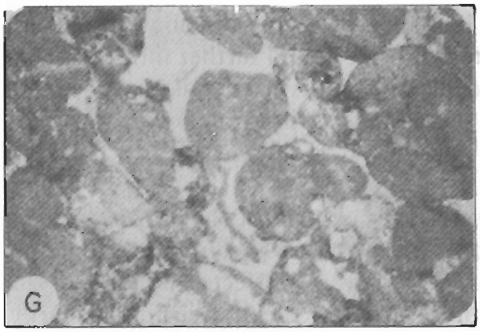

PLATE VI-G. Pel-biosparite, loosely arranged with sparry calcite filling, × 20.

sil chambers, particles and/or pores are filled with sparry calcite and partially dolomitized.

(C) Microcrystalline (micrite) rocks

In addition to the homogenous, unfossiliferous, unlaminated micrites, the brecciated micro-crystalline limestones (dismicrites) showing secondary calcite filling in fracture (Plate VI-H) are common in the subcropping Arab rocks.

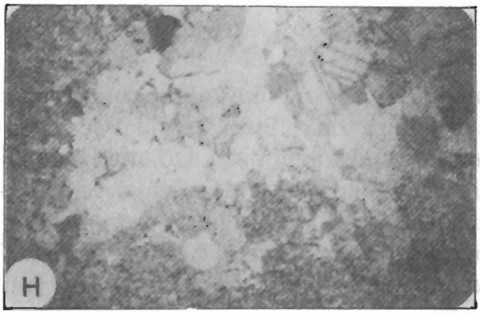

PLATE VI-H. Microcrystalline limestone breccia with secondary calcite filling in fracture showing Carlsbad twinning, × 20.

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 diagenetic 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 diagenesis different from those in the subsurface. From Al-Juwaiyy in the north to Wadi As-Sulayyil 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 pelmicrite. 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, pelmicrite, 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 sparite 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 rhoms would be formed. During the process of leaching and dissolution by meteoric water of Mg rich carbonate near surface, Ca^{++} 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 forms receptacles for collecting Mg^{++} 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 pelmicrite 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 slumping 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 Sulaiy escarpment is estimated approximately at 265,000,000 tons (Fig. 7). The intensity of collapse is greatest in the west of the Sulaiy escarpment, followed by that at Al-Majma'ah in the north and at Wadi As-Sulayyil in the south. To the east of Dahl Hit, only the anhydrites of the Arab 'B', 'C' and 'D' and part of the lower Hith seem to have been removed (Fig. 7). To the east of Khashum 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 intensive brecciation, minor folds, flexures, distortions and fractures in these formations as well as in the overlying Sulaiy Formation. Part of the Sulaiy often slipped off from the major outcrops 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 problem 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 Sulaiy Formation. As stated earlier, both the Arab and Sulaiy are characterized

TABLE 1. Changing thickness and collapse of the Arab-Hith Formations, Riyadh area.

Formation	Member	Location A - 1		Synthetic log A - 1		Riyadh composite log		Collapse due to Anhydrite solution
Sulaiy	·	393 Feet		393 Feet		± 200 Feet		
Hith	Upper Anhydrite	555 Feet	35 Feet	60 Feet	–	86 Feet	–	35 Feet
	Manifa LS		40 Feet		Total carbonates = 60 Feet		Total carbonates = 86 Feet	
	Lower Anh.		480 Feet		–		–	480 Feet
Arab	"A" Limestone	542 Feet	20 Feet	208 Feet	20 Feet	206 Feet	30 Feet	
	"B" Anhydrite		40 Feet		–		–	40 Feet
	"B" Limestone		36 Feet		36 Feet		25 Feet	
	"C" Anhydrite		156 Feet		–		–	156 Feet
	"C" Limestone		58 Feet		58 Feet		65 Feet	
	"D" Anhydrite		138 Feet		–		–	138 Feet
	"D" Limestone		94 Feet		94 Feet		86 Feet	
Total collapse due to Anhydrite removed by solution								849 Feet
Jubaila								

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 biolithite, biopelsparite and oosparite with some pelmicrite, 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).

Meteoric water which entered through this unconformity surface and also, the pore water enclosed in the Wasia sediments of fresh water origin (Moshrif and Kelling 1984) would have dissolved enormous amounts of calcium sulphate from anhydrite and transported $CaSO_4$ to deeper levels. The Sulaiy 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 Sulaiy 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 Sulaiy escarpment. In the area east of Dahl Hit, most anhydrite intervals of the Arab were removed whereas the Hith anhydrite was only partially reduced. To the east of Khushum Al-Halal (Fig. 7) a complete succession of anhydrite and carbonate exists and continues towards 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 petroliferous Arab Formation. The oil field at Location 'A' (Fig. 6) marks a practical western limit of the oil producing region of the Arab Formation.

The calcium sulphate content of the ground water would increase from the Arab/Jubaila contact at surface to the east, and further east to the Sulaiy 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 seals of micrite 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 Arab Limestone

Circulating surface water throughout the Arab 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 oosparite strata. A network of veins, due to leaching and recrystallization of calcite along fractures in the micrite results in brecciation of the host rocks. In such a case, breccias consist of angular fragments 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 affected. 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 variable 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 structures 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 the 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 problems, such as we are currently experiencing in the Riyadh area. This phenomenon would cause more solution channels, vugs, fractures and collapses, as described earlier, at near surface positions, and further continuation of this process would enlarge the existing pores and create cavities and pits. Semi-intact 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 samples. 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, pelletic 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 bedded 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 biosparite, oosparite, pelsparite 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 carbonate units. The basal part of the Arab 'D' limestone is persistent without disturbance in the outcrop-subcrop areas. 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, oosparite and pelsparite in which dolomitization was negligible. Dolomitization in the subcrop area seems to have been caused by meteoric water rich in Mg^{++} ions in downdip locations, after dissolving and reprecipitating the original calcite in pores and vugs updip.

4. The outcropping Hith Formation in the Dahl Hit 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 850 feet of anhydrite 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/or 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 Sulaiy escarpment and west of Locations A and A′ (oil fields), may be documented by drilling and coring in the area. Increasing $CaSO_4$ 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 drilling 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.

Acknowledgement

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التتابع السطحي – تحت السطحي وعمليات النشأة المتأخرة لمتكوني العرب – الهيت (الجوراسي العلوي) في وسط المملكة العربية السعودية

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المستخلص . أجريت دراسة تفصيلية على الصخور السطحية وتحت السطحية لمتكوني العرب والهيت الممثلة لصخور الجوراسي العلوي في وسط المملكة العربية السعودية ، وذلك لاستنتاج السجل الصخري الكامل لهما وتأثيرات عمليات النشأة المتأخرة عليهما . والتي قد تساعد على فهم مشكلة انحلال وإذابة وانهيارات صخورهما ، وكذلك مشكلة ارتفاع منسوب المياه الجوفية في مدينة الرياض .

يُظهر متكون العرب عدم وجود تتابع صخري متكامل في منكشفاته السطحية وذلك بسبب الهبوط والبنيات الانهياريَّة الحادثة على نطاق واسع والناجمة من إذابة وحدات الأنهيدريت المتواجدة ضمن صخور المتكون . وفيما عدا المنكشف الواضح والظاهر لمتكون الهيت في منطقة دحل هيت والمنكشفات المحدودة والموجودة إلى الشرق من منطقتي الحائر والبديع (شكل ٣) فإن صخور الهيت أُزيلت من المنطقة نتيجة لإذابة الأنهيدريت بوساطة المياه تحت السطحية .

ومن خلال دراسة علاقة التتابع الطبقي لصخور المتكونين في المنكشفات السطحية والتتابعات التحت السطحية ، تم استنتاج التتابع الطبقي المركب والذي أظهر وجود أربع وحدات من صخور الكربونات في متكون العرب . أحتفظت الوحدة السفلية منها بالاستمرارية في حين أن الوحدات الثلاث الأخرى العلوية غالبًا ما تتكون من صخور الحجر الجيري المهشم والملتوي والمتشقق ورواهص من الركام المتلاحم . وتتكون التتابعات تحت السطحية لمتكون الهيت من رواهص جيرية دقيقة التبلور وعقدية تحتوي على أصداف أحافير . وتعرضت غالبية صخور الحجر الجيري الحبيبي لمتكون العرب الظاهرة على السطح لعمليات الشطف وإعادة التبلور ، في حين تعرضت الصخور تحت السطحية للمتكون لعمليات الشطف وإعادة التبلور والدلمتة . وتكاد تكون عملية الدلمتة محصورة على الصخور التي تحتوي على نسبة عالية من الراسب الأرضي الجيري الناعم .

وقد سببت إزالة وحدات الأنهيدريت من متكوني العرب والهيت بوساطة المحاليل مشاكل في عمليات تغير خصائص التربة والصخور بمنطقة الرياض . كما أن تواجد الانكسارات الرأسية والتي تكونت أثناء وبعد الانهيارات والانخفاضات في التتابع الصخري للمتكونين ، وكذلك احتمال وجود حواجز مانعة للنفاذية إلى الشرق من جرف متكون السلي – الطباشري السفلي – سبب في ارتفاع منسوب الماء تحت السطحي لمدينة الرياض . والتي قد تخلق العديد من المشكال الجيوتقنية والمخاطر البيئية من جراء الاختلاط الرأسي لمياه الصرف بمياه خزان الرياض الجوفي .