

## Geology and hydrocarbon occurrences of the clastic Permo-Carboniferous in the central and eastern Arabian Basin

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### Abstract

The siliciclastic lower part of the Permo-Carboniferous in the Arabian Basin represents a cyclic transgressive and regressive unit, consisting of sandstones, shales and thin beds of argillaceous limestone. This unit crops out in small exposures in central and northwest Saudi Arabia, but is widespread in the subsurface of central and eastern Arabia. It is known as the Unayzah Formation in Saudi Arabia and in the western and southern Arabian Gulf region, and as the Haushi Group in Oman.

The Permo-Carboniferous clastics in the Arabian Basin proved to be prospective for hydrocarbons. Oil and gas were encountered in Saudi Arabia, Qatar, the United Arab Emirates (U.A.E.) and Oman.

The Unayzah Formation in the subsurface of the U.A.E. ranges in thickness from 140 to 206 m. The relatively thin upper section consists of pyritic siltstone and terrigenous mudstone with minor sandstone, whereas the lower section is dominated by a thick sequence of very fine to coarse-grained, subangular to subrounded, moderately to poorly sorted quartzitic sandstones with minor interbeds of siltstone. Minor quantities of clay minerals, plagioclase, dolomite and pyrite occur in the sandstones. The formation is interpreted to be of fluvial origin.

Six lithostratigraphic units were identified in the U.A.E. Three units have moderate to good reservoir potential, while others act as seals over these reservoirs. Porosity in the reservoir units ranges from less than 1 to 27%, and permeability from less than 1 to 75 md.

The sediments in the U.A.E. are highly affected by diagenesis. The main diagenetic events include silica cementation (which occurs as quartz overgrowths), precipitation of illite and minor kaolinite, carbonate cementation (calcite and dolomite) filling pores around the quartz grains, and locally a partial dissolution and leaching of feldspar grains.

### Introduction

The Late Carboniferous–Early Permian siliciclastic rocks, described in Saudi Arabia by Al Laboun (1986, 1987) and Ferguson & Chambers (1991), and known as the Unayzah Formation, are one of the deepest exploration targets in the central and eastern Arabian Basin (Figs 1, 2). Gas was tested in this formation or its lateral equivalents in the fields of Ghawar, Abu Safah, Berri and Qatif of Saudi Arabia, in the Matbakh-2 and Ras Qirtas-1 wells of Qatar, in Hair Dalma in the United Arab Emirates and in the Yibal Field of Oman. New discoveries of oil and condensate were reported from

this formation in central Saudi Arabia (Ferguson & Chambers 1991, McGillivray & Hussein 1992). The laterally equivalent Haushi Group is a well-known oil producer from a few fields in Oman (Focke & Van Popta 1989; Levell et al. 1988).

The Haushi Group in Oman consists of a Late Carboniferous–earliest Permian glacial sequence, the Al Khlata Formation, overlain by a fluvial–coastal plain sequence of early to mid Permian age, the Gharif Formation. In Saudi Arabia the formation was divided into three members; the Unayzah C (with its floating granules and pebbles) is most likely the glacio-marine equivalent of the Al Khlata, whilst the Unayzah B and

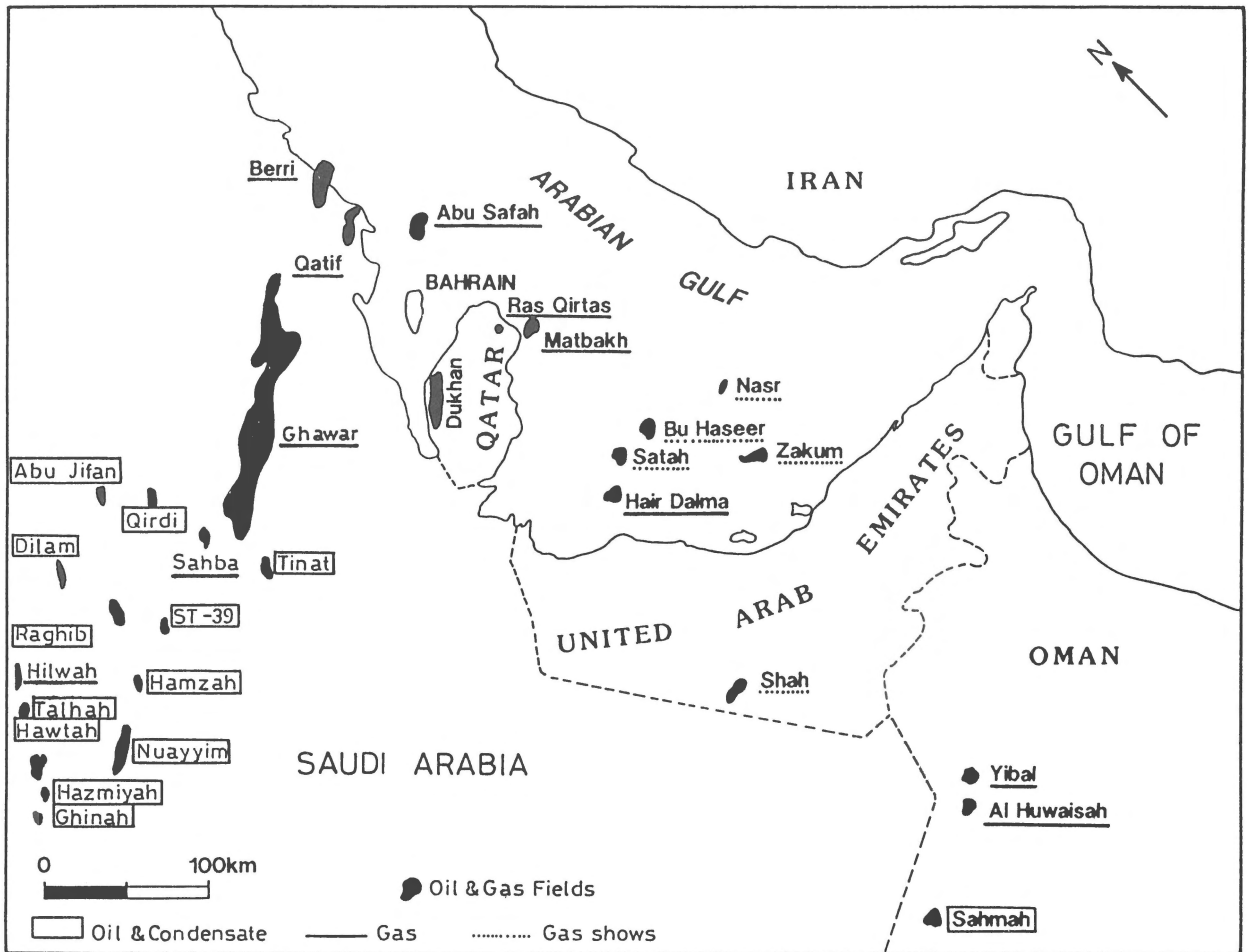


Fig. 1. Location map of the Arabian Basin showing some of the oil and gas fields producing from Mesozoic sediments. Names of fields producing from Permo-Carboniferous clastics are also shown. Oil and condensate, gas and gas shows in the legend refer to the Unayzah Formation and its equivalents.

A are the equivalent of the Gharif. The validity of the 'layer-cake' model of the Unayzah, based on data of closely drilled fields in Oman and Saudi Arabia, is highly unlikely in other regions of Arabia. Since there is no evidence of glacial deposits in eastern Arabia (the United Arab Emirates, Qatar and Bahrain; Alsharhan et al. 1993) an equivalent of the Al Khilata of Oman or the Unayzah C of Saudi Arabia seems unlikely in these areas. Therefore, contrary to previous ideas, the six units of the Unayzah in the United Arab Emirates (U.A.E.) and the three in Saudi Arabia (Unayzah A, B, and C) are not likely to be continuous and constant elsewhere. A similar subdivision of the Unayzah is not made in Qatar or Bahrain.

After reviewing the regional stratigraphic setting and hydrocarbon occurrences of the Unayzah Forma-

tion in central and eastern Arabia, this paper intends to describe details of the lithostratigraphy, petrography, geological age and depositional setting of the formation in the subsurface of the U.A.E.

### Regional stratigraphic setting in Arabia

The lower part of the Permo-Carboniferous in the Arabian Basin consists exclusively of terrigenous siliciclastic sediments which were derived from the exposed Precambrian of the Arabian Shield, from the Lower Paleozoic clastics of western Saudi Arabia and the Hadhramout Arch, and also from the Cambro-Ordovician clastics of southern Oman (Beydoun 1989; Alsharhan et al. 1991; Ferguson & Chambers 1991;

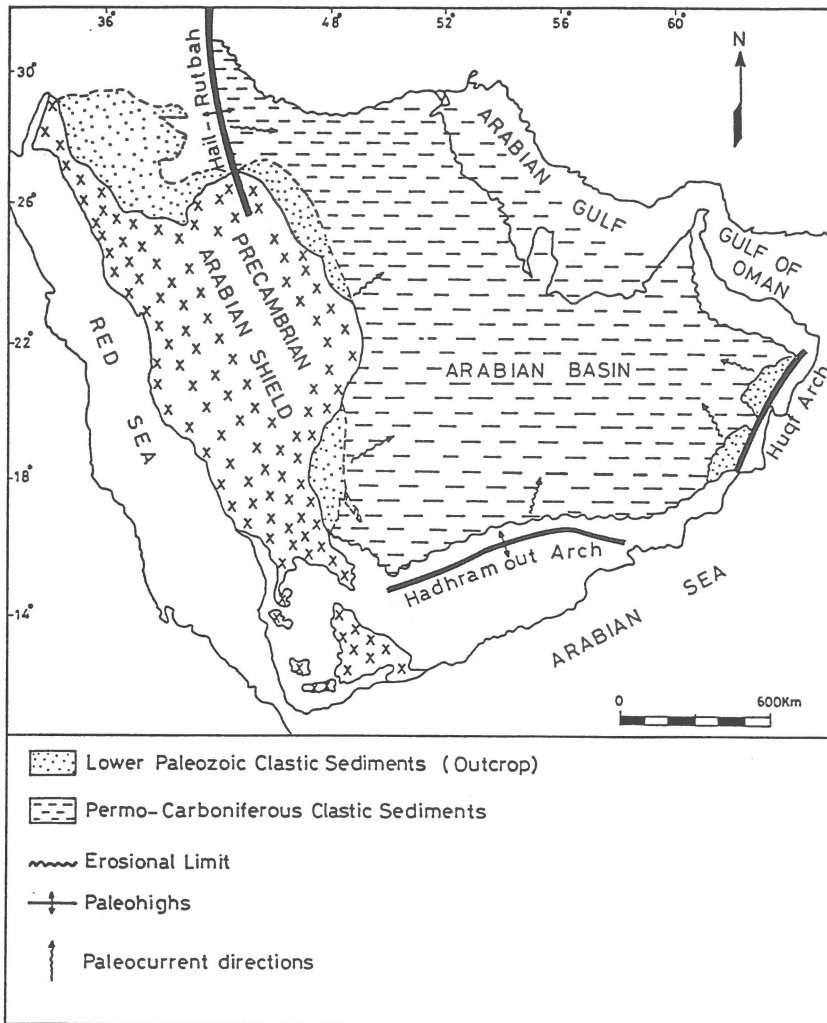


Fig. 2. The distribution of siliciclastic sediments in the Arabian Basin during Permo-Carboniferous time.

Fig. 2). These terrigenous sediments spread from Saudi Arabia to the east, toward the Arabian Gulf across a relatively stable platform in depositional settings ranging from alluvial-fan to coastal-plain fluvial and shallow marine. The periodic transgressions and regressions of broad and shallow epicontinental seas, associated with uplift and erosion in the source areas, explain the predominance of clastic facies as well as the presence of sedimentary breaks over much of the Arabian Basin.

In the early days of petroleum exploration in Saudi Arabia, Powers et al. (1966) adopted the name of Wajid Formation for the clastics below the Late Permian Khuff Formation. Different formation names and ages were assigned by different authors. The recovery

of Late Carboniferous–Early Permian palynomorphs on the one hand and the presence of *Tigillites* and other Lower Paleozoic trace fossils on the other in various locations, resulted in the recognition of two outcropping formations, viz. the Cambro-Ordovician Wajid and the Permo-Carboniferous Bani Khatmah formations. The Wajid sandstone is not in the scope of this paper; it was described by Powers et al. (1966), Dabagh & Rogers (1983) and Alsharhan et al. (1991). The palynological age assigned to the Bani Khatmah makes it equivalent to the Unayzah and Haushi sediments in eastern Arabia (Alsharhan et al. 1991). The Bani Khatmah Formation was described and measured by Hadley & Schmidt (1975) in the vicinity of Bani Khatmah at Khashm Khatmah and also at Jibal Umm

Ghiran, about 50 km east of Jibal al Wajid in south-western Saudi Arabia (Alsharhan et al. 1991). The Bani Khatmah clastics occur as a series of fining-upward sediments which pass upwards from coarse-grained sandstone to fine-grained and slightly argillaceous sandstone (Fig. 3).

The Unayzah Formation, named by Al Laboun (1986), occupies a well-defined stratigraphic position in central and northern Saudi Arabia. The lower and upper contacts are marked by regional unconformities. The Unayzah rests on the Hercynian unconformity which constitutes a major sequence boundary due to sea-level rise associated with the post-glacial transgression that followed the Late Carboniferous–Early Permian glacial period. The top of the Unayzah prograding cycle was terminated by a regional relative sea-level fall, resulting in significant erosion which caused deeply incised valley systems (Ferguson & Chambers 1991; Figs 3, 4). The Unayzah consists mainly of continental and shallow marine siliciclastics. The name was derived from the type locality in the town of Unayzah in central-western Saudi Arabia and is widely accepted in Saudi Arabia and other Arabian Gulf regions. Al Laboun (1986, 1987) who designated the type section, described in great detail the formation and its distribution in Saudi Arabia. His regional surface and subsurface studies indicate that the Permo-Carboniferous clastic sediments of the Unayzah Formation and its equivalents are widespread over much of the Arabian Gulf area (Fig. 3). In Saudi Arabia the formation mainly consists of cycles of cross-bedded fine to coarse-grained quartzitic sandstone, interbedded with siltstones, varicoloured claystones and shales. The claystones and siltstones are locally very calcareous. Al Laboun (1987) concluded that the Unayzah sediments in north-central Arabia were deposited in a swampy delta plain subject to some shallow marine incursions.

In the subsurface of central Saudi Arabia, Ferguson & Chambers (1991) applied the name Unayzah Formation to the clastic succession between the Hercynian unconformity and the carbonates of the Khuff (Fig. 4). The depositional history of the Unayzah is complex and involves periods of extensive erosion and local structural complications. The formation contains three sandstone units informally known in ascending order as the Unayzah C, B and A members (Fig. 4; Ferguson & Chambers 1991; McGillivray & Hussein 1992). The C-Member, dated as Early Permian, forms part of the basal Unayzah sequence that filled in a paleotopographic low on the eroded Pre-Unayzah

surface. It is characterized by poorly sorted, medium to coarse-grained sandstone with floating granules and pebbles of marine origin. The B-Member consists of medium to coarse-grained, rounded to well-rounded, cross-bedded sandstone of braided-stream to general alluvial origin. It is dated no younger than Kazanian. The A-Member consists of a thin transgressive lag deposit in the lower part, followed by regressive marine siltstones, shoreface sandstones and coastal-plain sediments of early Late Permian age.

In Qatar, similar rocks of Permo-Carboniferous age were locally named as the Haushi Formation. This formation rests unconformably on the pre-Hercynian Tawil Formation (Devonian–Early Carboniferous) and is unconformably overlain by the transgressive Late Permian Khuff carbonates (Fig. 3; Schlumberger 1981). The formation is encountered in deep wells such as Matbakh-2 and Ras Qirtas-1 and in the Dukhan Field (Fig. 1). It consists of intercalated fine to coarse-grained, well-sorted and cross-bedded quartzitic sandstones, and subordinate conglomerates, breccias, siltstones and variegated shales, with occasional thin beds of anhydrite, lignite and silty coal. The Haushi was deposited in a shallow marine nearshore to terrestrial alluvial setting (Schlumberger 1981; Hamam & Nasrulla 1989).

In the U.A.E., the terrigenous clastic sequence underlying the carbonates of the Permo-Triassic Khuff Formation is known as the 'Pre-Khuff clastics'. Alsharhan (1989) introduced the name Unayzah Formation to designate this sequence in the U.A.E. (Figs 3, 5). The sequence consists of fine to coarse-grained quartzitic sandstones (coated by secondary quartz), with thin interbeds or argillaceous siltstone and shale which are slightly dolomitic and partially pyritic. The uppermost part of the formation consists of dark-grey siltstone, mudstone and claystone. The Unayzah Formation is generally bounded at the top by a gradational contact except in some places where a minor erosional hiatus separates the Unayzah clastics from the Khuff carbonates. Below the Unayzah Formation is an unconformable surface clearly picked from the cores at a sharp lithological change and also from wireline log characteristics (see Ali & Silwadi 1989; Fig. 5). This represents the latest Hercynian tectonic phase. It separates the Middle Devonian–Early Carboniferous 'Pre-Unayzah Formation' from the Unayzah.

In Oman, the Haushi Group contains in its lower part glaciogenic deposits which occur extensively in outcrops as well as in the subsurface to the west and south of the Oman Mountains (Hughes Clarke 1988).

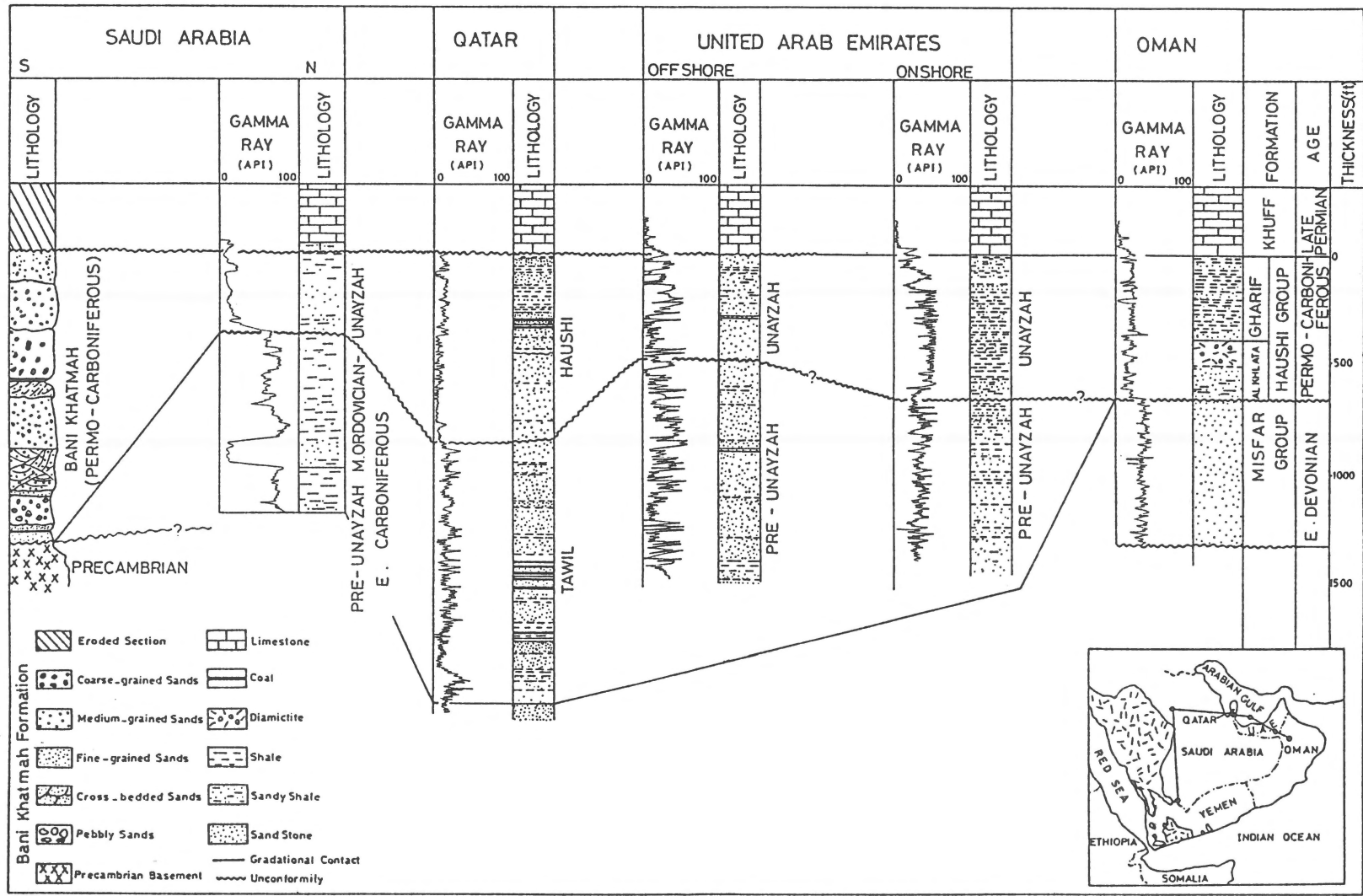


Fig. 3. Correlation of the Permo-Carboniferous clastics in the Arabian Basin (sources: Sugden & Standring 1975; Al Laboun 1987; Hughes Clarke 1988; Ali & Silwadi 1989; Alsharhan et al. 1991).

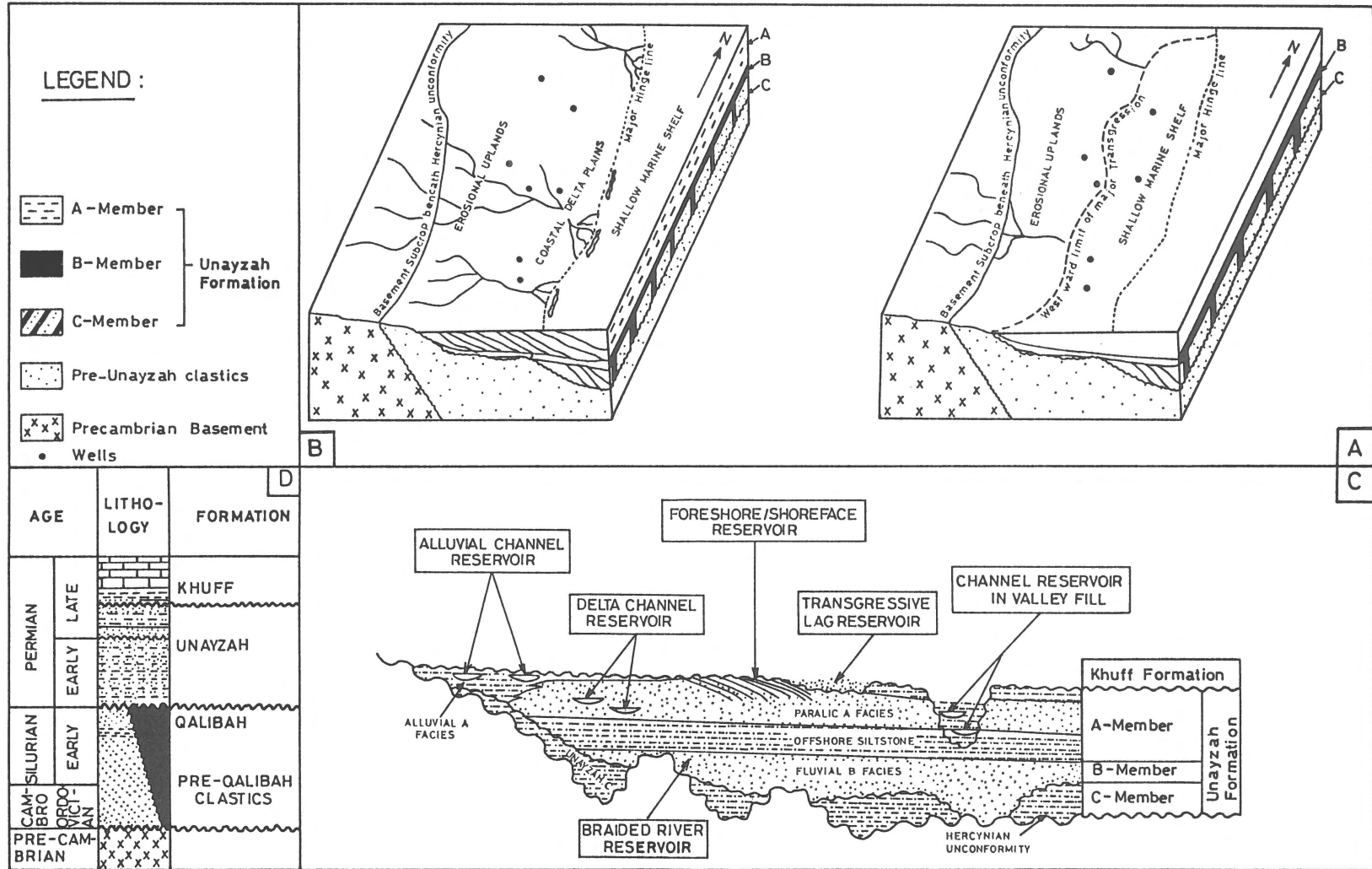


Fig. 4. Depositional setting and reservoir facies of the Unayzah Formation in central Saudi Arabia (in the vicinity of the Hawtah Field, see location on Fig. 1; compiled and modified from Ferguson & Chambers 1991). A – Facies distribution and paleogeography at the maximum extent of the Unayzah A to B marine transgression. B – Facies distribution and paleogeography during clastic progradation of the Unayzah A-Member. Both A and B are drawn not to scale but cover an area of approximately 51650 sq. miles (135000 sq. km). Thickness of Unayzah Formation in east of area shown is approximately 50 m. C – Reservoir facies identified in the Unayzah Formation (not to scale). D – Generalized Paleozoic stratigraphy.

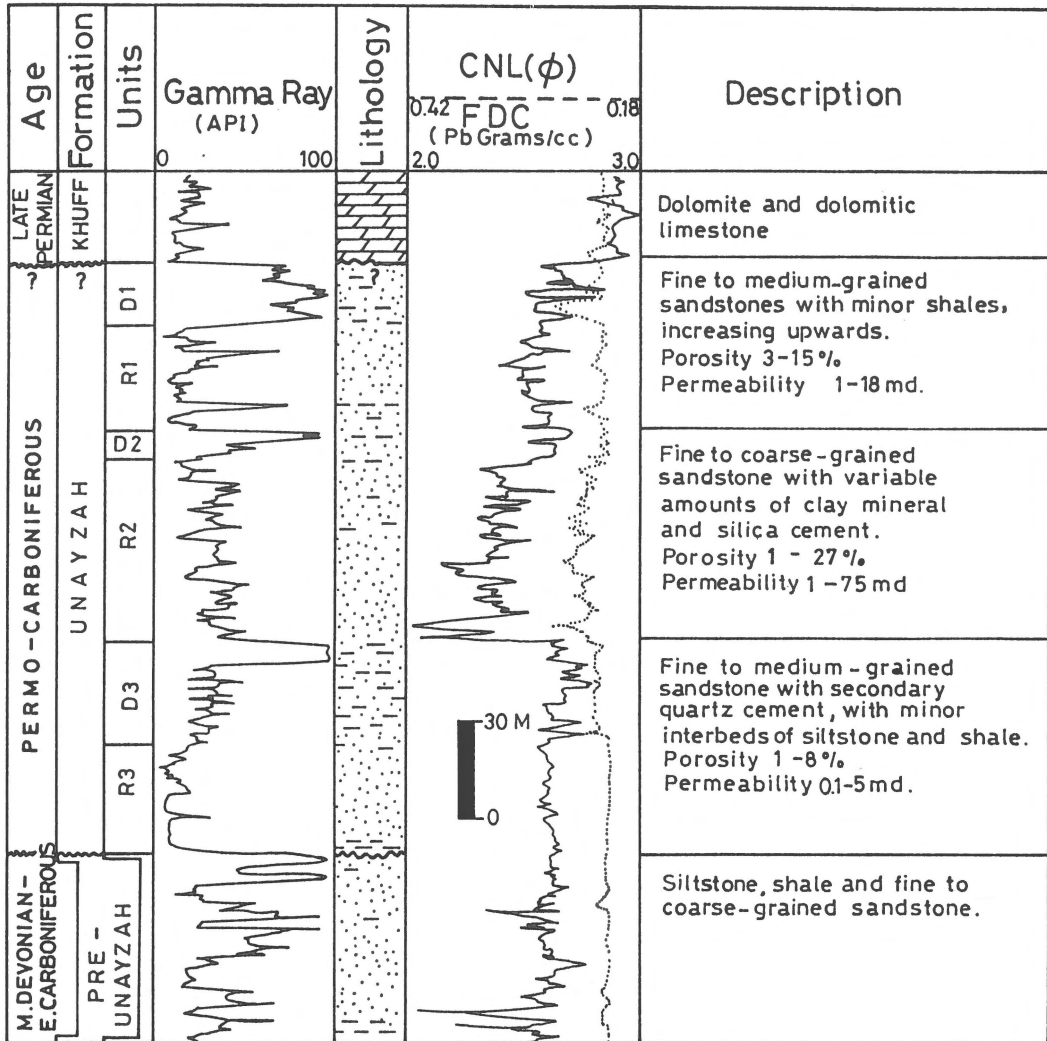


Fig. 5. Lithostratigraphy and log characteristics of the Unayzah Formation in the United Arab Emirates.

This lower part of the Haushi is named the Al Khlata Formation and is of Westphalian to Sakmarian age. The upper part of the Haushi is made up by fluvial and coastal sediments with some marine limestones. It is known as the Gharif Formation and is of Sakmarian to Artinskian age (Hughes Clarke 1988). The Khuff carbonates conformably overlie and interfinger with the Gharif Formation in most areas (Fig. 3).

The Al Khlata Formation is composed of more or less indurated clastic rocks ranging from coarse to fine-grained diamictites, conglomerates, pebbly sandstones, cross-bedded sandstones, siltstones, silty shales and varved shales. These sediments were deposited in various environments forming fluvial channels, out-wash sands, fluvio-glacial and glacial sands, shales

with varve-like laminations and dropstones in subaqueous glacial deposits (Rahab Shale; Levell et al. 1988, Hughes Clarke 1988). The Gharif Formation consists predominantly of clastic deposits of coastal plains and alluvial subenvironments. It represents an alternation of sandstones (arkosic and quartzose), shales and claystones. Towards the northeast of central Oman a marine limestone develops in the lower part of the Gharif. The composition of the Gharif clastics shows that they are most probably derived from glacial Al Khlata rocks. The fluvio-marine reworking of these rocks made the clastics more mature (Hughes Clarke 1988).

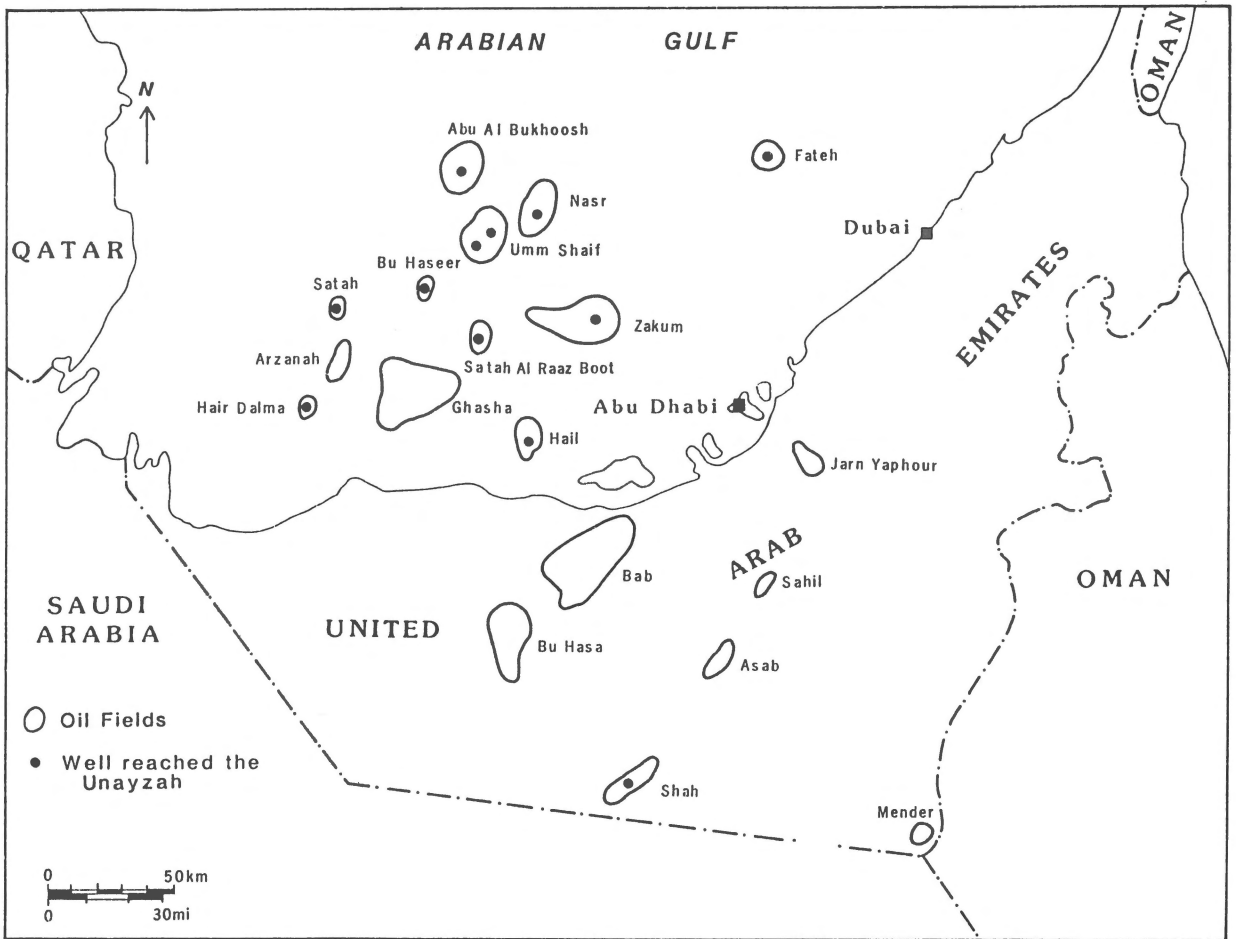


Fig. 6. Location map of the United Arab Emirates showing the wells reaching the Unayzah Formation. The Hair Dalma Field produces gas from the Unayzah Formation; other oil fields shown produce from formations younger than the Unayzah.

### Hydrocarbon occurrences in Arabia

Oil occurrences in the Permo-Carboniferous of the Arabian Peninsula are known only from the Haushi and Unayzah formations in small structures in Oman and Saudi Arabia. As only a limited number of structures in the region have so far been drilled for this objective, it can be argued that a high potential remains for hydrocarbon exploration in these reservoirs. Because of the depth, the hydrocarbons would probably be mainly gas (Fig. 1). Gas and condensate discoveries were reported from Oman, the U.A.E., Qatar and Saudi Arabia in recent years. Details on the oil and gas occurrences are given in Hemer & Hatch (1983), Levell et al. (1988), Ali & Silwadi (1989), Hamam & Nasrula (1989), Focke & Van Popta (1989), Sykes & Abu Risheh (1989), Ferguson & Chambers (1991), Abu Ali et al. (1991) and McGillivray & Hussein (1992).

Gas was tested in the Unayzah Formation in the Ghawar, Abu Safah, Berri and Qatif fields of Saudi Arabia. Ferguson & Chambers (1991) and McGillivray & Hussein (1992) reported that oil and condensate were produced from some new discoveries in central Saudi Arabia, such as Nuayyim, Hazmiyah, Hawtah, Stratigraphic well-39, Talhah, Dilam, Hilwah, Raghieb, Hamzah and Tinat (Fig. 1). Hydrocarbons were encountered in six reservoir facies (Fig. 3), viz. braided-river, shoreface-foreshore, delta-channel, coastal-plain channel, valley-fill channel and transgressive lag (Ferguson & Chambers 1991). The Silurian Qusaiba Member of the Qalibah Formation is considered to be the source rock of the oil and condensate in these fields (Abu Ali et al. 1991).

In the Permo-Carboniferous clastics of Qatar, hydrocarbon shows were reported during drilling in the Dukhan Field. Tests of the relevant sections, however,

yielded no formation fluids due to very poor reservoir qualities. Offshore, gas was discovered in the Matbakh-2 and Ras Qirtas-1 wells.

In the U.A.E., some gas shows were encountered in the sandstone and siltstone sections of the Unayzah Formation in the Zakum, Nasr and Bu Haseer fields (Figs 1, 6). Gas was tested in the Satah Field. Some gas shows (mainly methane) were reported during the drilling of the Unayzah Formation in the Shah Field. The Hair Dalma Field is the only field producing gas from reservoir units 1 and 3 of the Unayzah Formation; the production rates are between 1.70 and 4 mmscf/d (approximately 48000 and 116000 m<sup>3</sup>/day) per well. The gas is composed of 21–23% N<sub>2</sub>, 8.5–8.7% CO<sub>2</sub> and 67–69% methane and contains no H<sub>2</sub>S. An unpublished geochemical study of the Abu Dhabi National Oil Company (ADNOC), cited in Ali & Silwadi (1989), concludes that the organic matter contained in the thin and argillaceous siltstones and shales interbedded within the Unayzah sands, is probably the source of the gas, even though these clastics are incapable of generating significant volumes. Geochemical analysis reveals that the total organic carbon content ranges from 0.94 to 1.4%. It seems more likely that, like in Saudi Arabia, the principal origin of the Unayzah gas is to be sought in the Silurian shales. In the U.A.E., these shales would occur at great, unpenetrated depths.

Hydrocarbon occurrences in the Permo-Carboniferous clastics are also known from a number of small to medium-sized accumulations in central and southern Oman (Fig. 1). The oil from the Sahmah Field is produced from the Gharif Formation. It has a low sulphur content and a 36–39.6° API gravity. This oil most likely originated from the Silurian Safiq shale (Grantham et al. 1988). Oil and gas-condensate recovered from the Haushi reservoirs in the Al Huwaisah and Yibal fields are believed to have been derived from the Infracambrian Huqf source rocks (Sykes & Abu Rishah 1989).

### **The Unayzah Formation in the United Arab Emirates**

Exploration drilling, aimed at the Paleozoic clastics in the U.A.E., started in 1979 when the first well (Umm Shaif-88) penetrated approximately 66 m (217 ft) of the Unayzah Formation (Fig. 6). These deeply buried sediments have caused drilling problems due to high pressure and temperature, and the high cost of drilling deeper than 6000 m has limited the drilling activity.

Only thirteen wells have reached the Unayzah with penetrated thicknesses ranging from 17 to 206 m (Fig. 6). Only three deep wells completely penetrated the Unayzah Formation and defined the contact with the underlying Early Carboniferous 'Pre-Unayzah Formation' (Ali & Silwadi 1989; Fig. 7). Based on the information from these wells, the thickness of the Unayzah Formation in the U.A.E. ranges between 141 and 206 m. It is encountered at depths varying from 4642 m in northwest offshore Abu Dhabi in the Abu Al Bukhoosh Field to about 6120 m in southeast onshore Abu Dhabi in the Shah Field. Ali & Silwadi's (1989) regional depth contour map of the top of the Unayzah shows the deepest burial of the Unayzah Formation to occur in a northeast-southwest striking through from Abu Dhabi city to the Bab Field. It gradually shallows toward Oman in the southeast and toward Qatar in the northwest.

### *Lithostratigraphic units*

As described above, the Unayzah Formation of the U.A.E. is fully penetrated in three wells only and can be divided into six lithostratigraphic units which can be recognized from wireline log shapes, lithology, grain size, and petrographic and petrophysical characteristics (Fig. 5). Three units are non-reservoirs which act as seals. They are designated as Pre-Khuff Dense Units (PK-D1 to PK-D3). The other three units, named as Pre-Khuff Reservoir Units (PK-R1 to PK-R3), are considered to have reservoir potential (Table 1).

#### *Pre-Khuff Dense Unit 1 (PK-D1)*

This unit is 13–19 m thick and forms the uppermost part of the Unayzah Formation. It has a gradational contact with the overlying Khuff carbonates in most wells drilled, except for Hair Dalma-3 and Satah-19 in the extreme western offshore of Abu Dhabi where the contact is unconformable. Most of the unit is dark-grey siltstone with minor interbeds of silty claystone and thin bands of silty to very fine-grained sandstones. Non-calcareous grey flaky shales and siltstones constitute about a third, and very fine-grained siliceous sandstones with thin intercalations of silty shales form about two thirds of the unit. Load casts are developed in the middle of this unit. The porosity ranges from 1 to 3% while the permeability is usually less than 1 millidarcy (md).

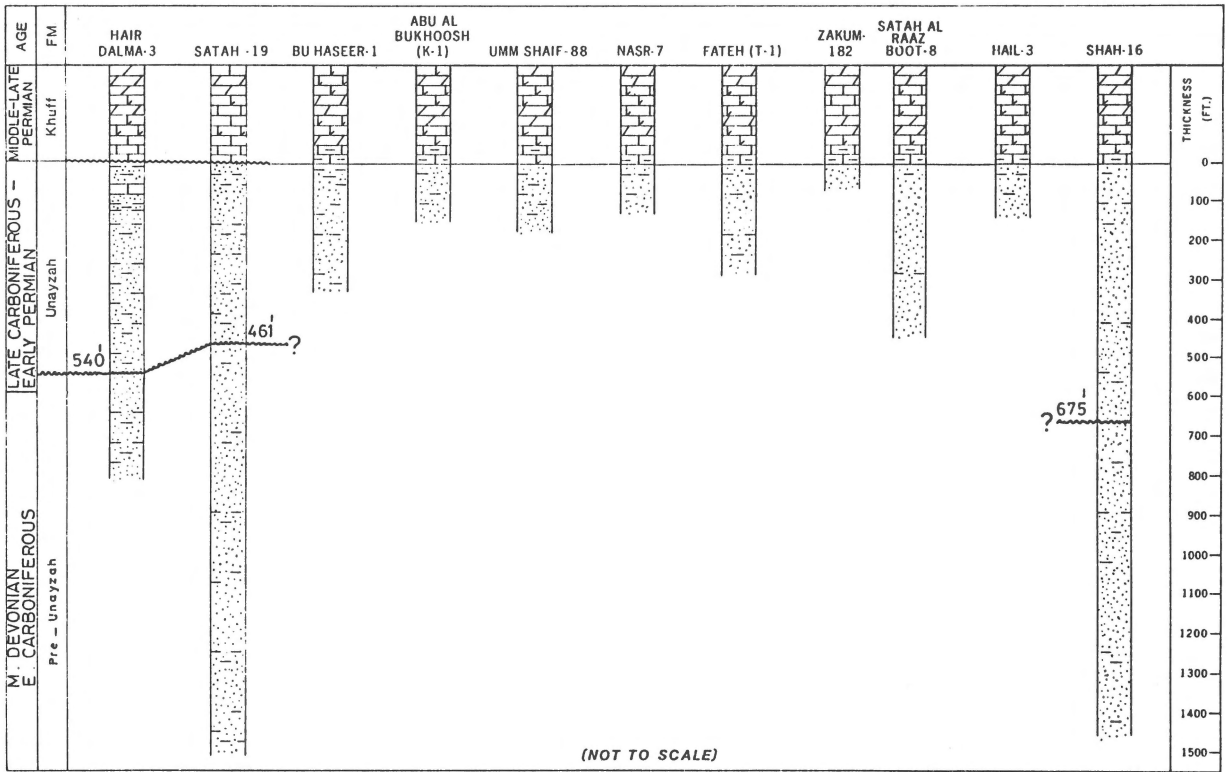


Fig. 7. Lithostratigraphic correlation of the wells reaching Carboniferous sediments in the United Arab Emirates (datum at top of Unayzah). Locations of these wells are shown in Fig. 6.

Table 1. Reservoir characteristics of the Unayzah Formation in the United Arab Emirates

Unit	Lithology	Thickness (m)	Porosity (%)	Permeability (md)	Reservoir quality
PK-D1	Siltstone with minor interbeds of silty claystone	13-19	1-3	1	Probably source rock, seal
PK-R1	Quartzitic sandstone	23-32	1-14	1-18	Moderate reservoir
PK-D2	Argillaceous siltstone	7-8	< 1	< 1	Seal
PK-R2	Quartzitic sandstone, minor argillaceous sandstone	48-63	2-27	2-75	Moderate-good reservoir
PK-D3	Siltstone & argillaceous sandstone	9-32	1-5	< 0.1	Seal
PK-R3	Quartzitic sandstone & siltstone	25-50	3-8	< 0.2	Poor reservoir

#### Pre-Khuff Reservoir Unit 1 (PK-R1)

This unit is 23-32 m thick and consists of fine to medium-grained, occasionally coarse-grained, poorly to moderately sorted, subangular to subrounded quartzitic sandstones. In thin section the quartz grains are closely packed and slightly distorted due to compaction (Plate 1A), thus reducing the interparticle

porosity drastically. Syntaxial quartz overgrowths further reduce the porosity. The presence of pyrite is limited to certain intervals. Well-developed, dark-grey, compacted sandy siltstones are found in the uppermost part of the unit, which has a gradational contact with unit PK-D1. The sandstone fines upward and is dominated by cross-bedding, with local horizontal lamina-

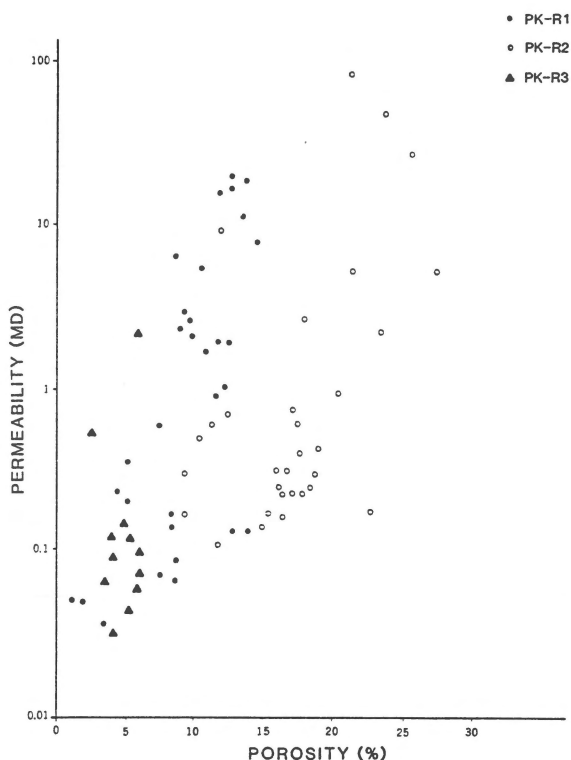


Fig. 8. Porosity (%) versus permeability (md) measured on cores from potential reservoir units in the Unayzah Formation in the United Arab Emirates.

composed of monocrystalline quartz grains cemented by secondary quartz. Pyrite exhibits euhedral crystals, probably precipitated by the reaction of  $H_2S$  with iron. Small amounts of dolomite, which appears as euhedral to subhedral crystals of secondary origin, corrode the margins of the quartz grains and in some cases replace the whole grain.

The fine to very fine-grained argillaceous sandstones in the lower part are generally poorly sorted and subangular to subrounded (Plate 1D), with a clay-mineral content of 10–15%. The authigenic clays coat the detrital grains. Monocrystalline quartz is dominant; plagioclase, pyrite and haematitic cement are rare.

The common sedimentary structures are cross-bedding and cross-lamination, with occasional horizontal and flaser-bedding. Fractures are rare in this unit.

Pre-Khuff Reservoir Unit 2 exhibits the best reservoir characteristics. The porosity measured from cores ranges from 9 to 27% and averages 17% (Fig. 8). The higher porosity values are generally associated with medium to coarse-grained and moderately sorted sandstones. The permeability ranges from 2 to 75 md and is associated with sandstones in which good interparticle porosity is preserved. Lower porosities (less than 10%) and permeabilities (less than 1 md) are due to the partial filling of the interparticle pores by clay minerals.

#### *Pre-Khuff Dense Unit 3 (PK-D3)*

This unit ranges in thickness from 9–23 m and consists of argillaceous, slightly dolomitic and dark-grey siltstone with thin interbeds of fine to very fine-grained argillaceous, partly pyritic, sandstones. The porosity ranges from 1% to a maximum of 5%; the permeability is less than 1 md.

#### *Pre-Khuff Reservoir Unit 3 (PK-R3)*

This unit is 25–50 m thick and consists of very fine to coarse-grained (mostly fine to medium-grained), subangular to subrounded and poorly to moderately sorted quartzitic sandstone, cemented with siliceous material (Plate 1E). Interbeds of siltstone sometimes occur in the upper part of this unit (Plate 1F), in which feldspar grains, clay minerals and carbonate cement are rare. Secondary quartz is common and drastically reduces the reservoir quality. Small-scale stylolites, generally parallel to the bedding are present in some intervals. This unit has a fairly low porosity which ranges from 3 to 7% and averages 5%. The permeability is extremely low (less than 0.2 md for most samples; Fig. 8). The

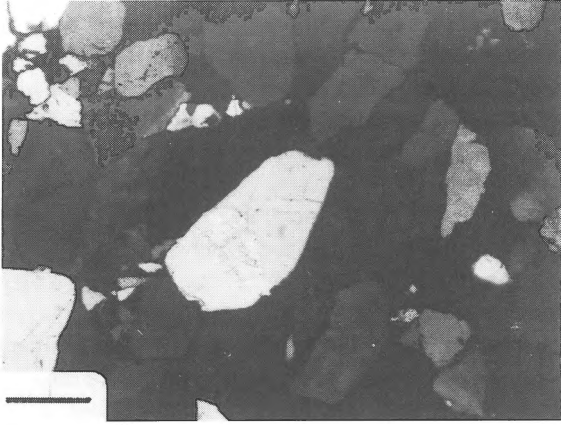
tion. The porosity ranges from 1 to 14%, averaging about 8.5%. The horizontal permeability is between 1 and 17.5 md for nearly one half of the samples, while for the remaining half it is less than 1 md (Fig. 8).

#### *Pre-Khuff Dense Unit 2 (PK-D2)*

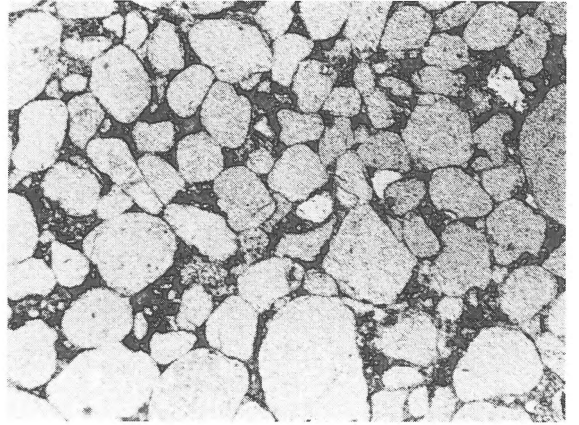
This unit is 7–8 m thick and is composed mainly of light-grey, argillaceous siltstones and shales with minor interbeds of claystones (illite and kaolinite) and fine to medium-grained sandstones. The porosity is less than 1% and the permeability is very low (less than 1 md).

#### *Pre-Khuff Reservoir Unit 2 (PK-R2)*

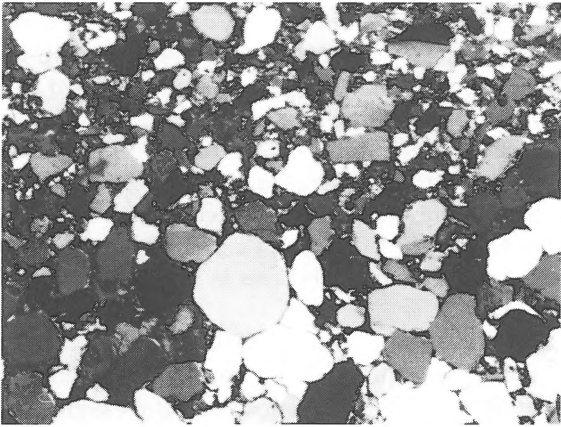
With a thickness ranging from 48–63 m, this is the thickest of the three reservoir units (Fig. 5). The lower part consists of fine to very fine-grained argillaceous sandstones, and the middle part of medium to coarse-grained quartzose sandstones. The upper part consists of brown, moderately to well-sorted and subrounded, generally medium-grained to occasionally coarse-grained sandstones (Plates 1B, C). They are



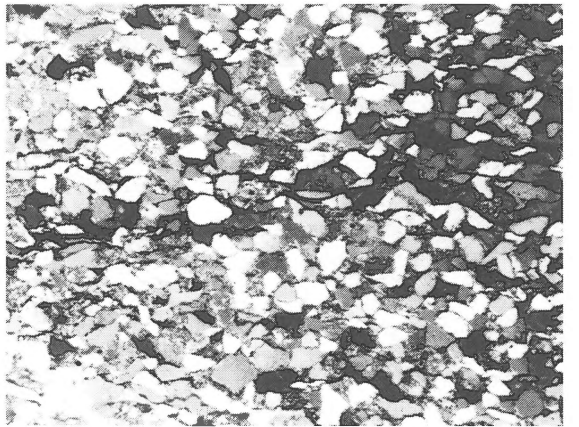
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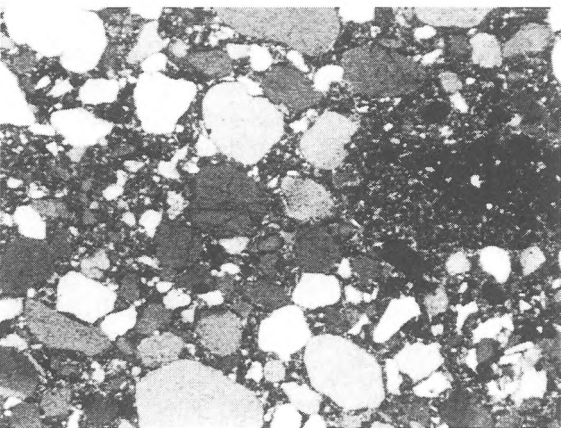
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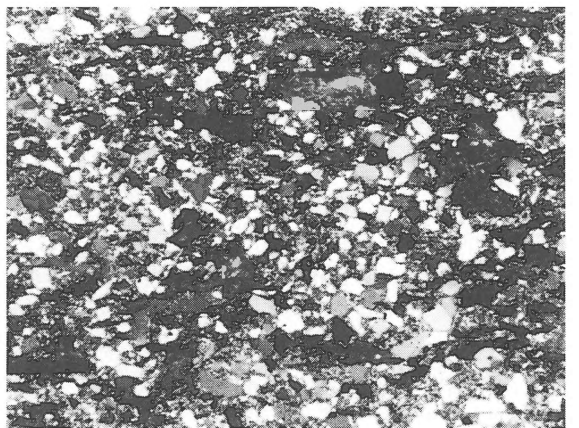
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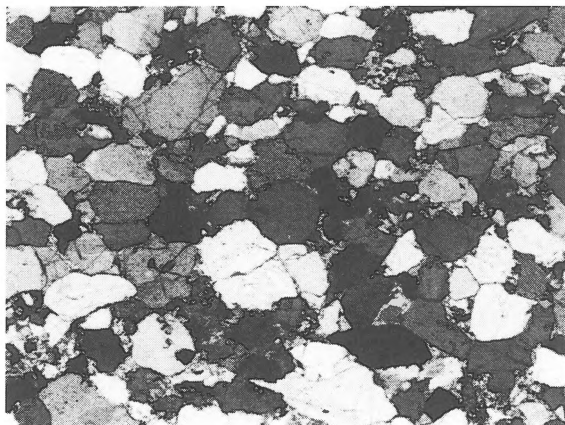
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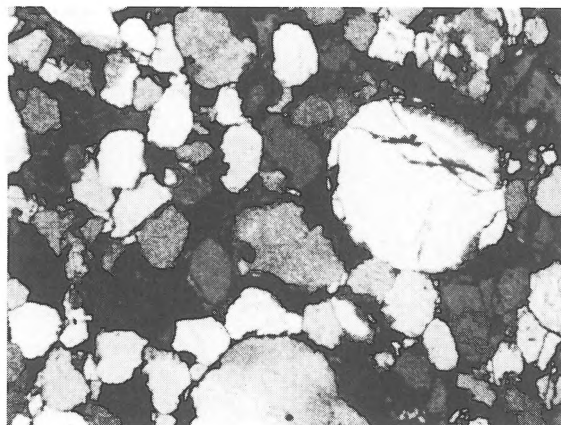
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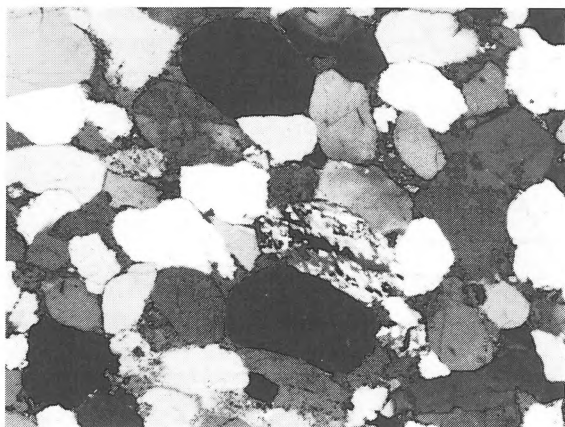
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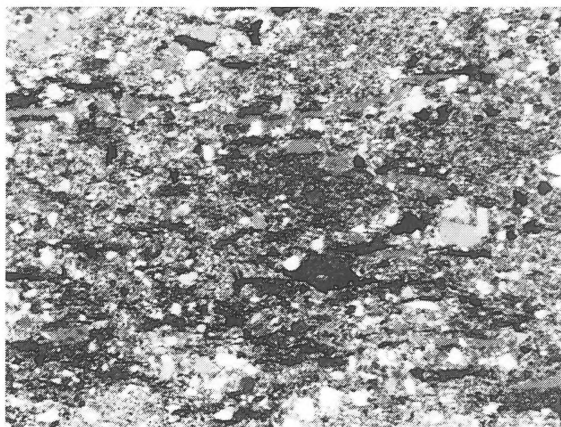
G



H



I



J

Plate 1: Photographs of thin sections from the Unayzah Formation in the United Arab Emirates. Scale bar = 0.2 mm as shown in photo A applies to all photographs

- A – Orthoquartzite: Medium to coarse-grained, moderately sorted, highly compacted, straight and sutured contacts, quartz overgrowth and traces of calcite cement.
- B – Orthoquartzite: Coarse to medium-grained, moderately to well-sorted with abundant quartz overgrowth, authigenic clay and intergranular porosity.
- C – Protoquartzite: Fine-grained, laminated, poorly-sorted, moderately to poorly rounded quartz grains.
- D – Protoquartzite: Well sorted, fine to medium-grained quartz, semi lamination, pyrite, iron oxides; authigenic clay coats grains and fills pore space.
- E – Medium to fine-grained, poorly sorted quartzwacke sandstone with quartz overgrowth and rare feldspar grains.
- F – Fine-grained, poorly sorted greywacke sandstone with abundant lithic fragments, pyrite and siltstone interbeds.
- G – Orthoquartzite: Medium to fine-grained, showing quartz overgrowth, compaction, fractures and linear orientation.
- H – Quartzose sandstone showing fractured quartz grains indicating high stress, corroded grains.
- I – Orthoquartzite: Quartz overgrowth, monocrystalline quartz, rare polycrystalline quartz.
- J – Sandy siltstone with claystone laminae.

poor reservoir quality is due to the precipitation of secondary quartz which partially occludes the interparticle pores.

#### *Petrographic analysis*

Petrographic study of the potential reservoir sections of the Unayzah Formation shows that the majority of

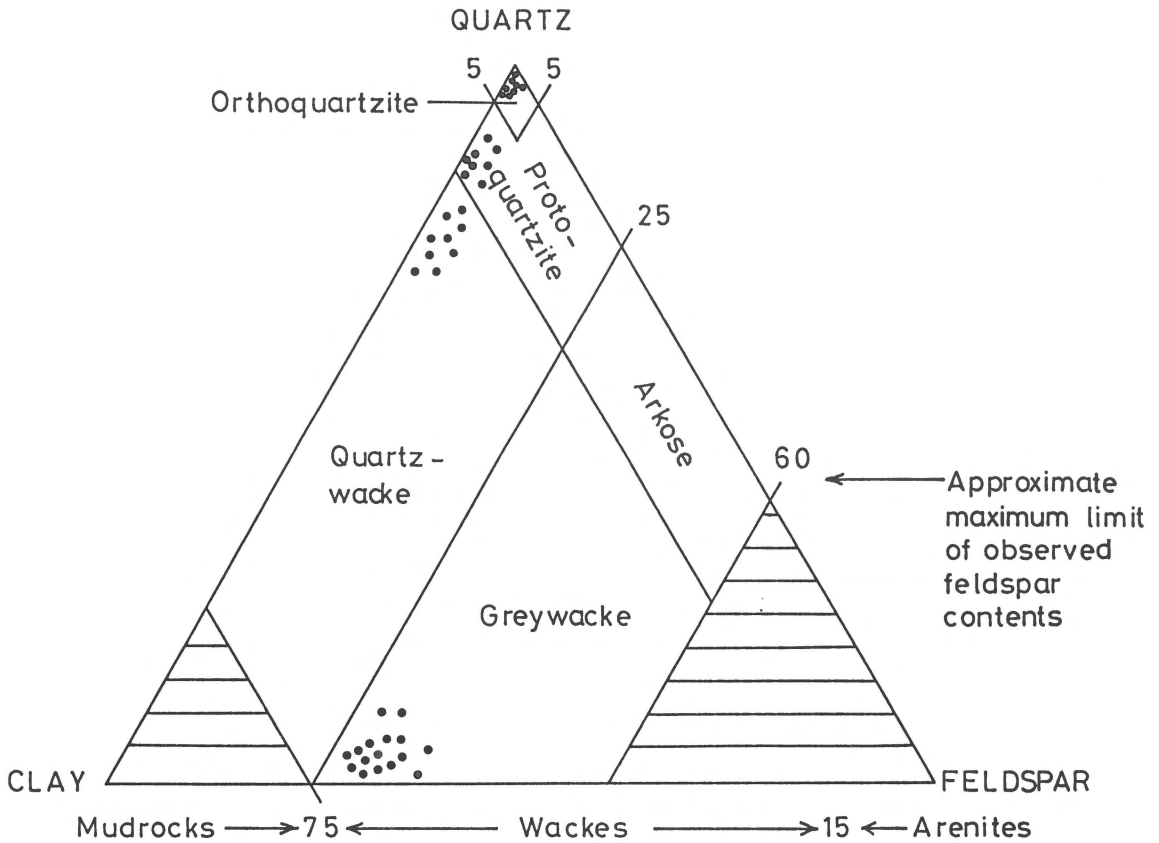


Fig. 9. Triangular plot (after Selley 1982) showing the main rock types of Unayzah sandstones in the United Arab Emirates.

the sandstones are orthoquartzites and protoquartzites. Some sandstones, however, fall in the quartzwacke and greywacke areas (Fig. 9).

Most sandstones are physically and chemically very mature (Plate 1B), generally light-grey to off-white in colour, highly cemented (Plate 1A), and very well indurated (Plate 1G). The dominance of quartz indicates chemical maturity. Furthermore, the quartz grains are mostly monocrystalline (Plate 1A) and rarely polycrystalline. According to the grain size, the sandstones of the Unayzah Formation are subdivided into two main groups:

A) Medium to coarse-grained, mostly moderately to well-sorted but occasionally poorly sorted sandstones. The grains are subrounded to rounded but occasionally well-rounded (Plates 1B, C, G), and highly cemented with siliceous and calcareous material. Quartz constitutes 95 to 98% of the rock material (orthoquartzite) with very minor amounts of feldspar, claystone, siltstone, mica, iron oxides,

calcite and even rare dolomite. The reservoir quality is moderate to poor.

B) Very fine to fine-grained sandstones (protoquartzite), composed of moderately sorted, subangular to subrounded (Plate 1D) and rarely rounded grains. The quartz content ranges from 84 to 90%, the clay mineral content is approximately 7–12%, and feldspar accounts for no more than 3%. Traces of mica, calcite, iron oxides and very rare dolomite occur. The grains of mica and quartz show lamination which reduces permeability in certain directions.

Soon after deposition, the sandstones of the Unayzah Formation were subjected to compaction due to deep burial that resulted in a very close packing (Plates 1C, G). Straight and sutured grain contacts were caused by pressure solution (Plate 1A). During subsequent deeper burial, porosity and permeability were further reduced or completely destroyed by authigenic clay development and quartz overgrowth (Plate 1A), often followed at a later stage by calcite filling. It is also evident that

the Eh and pH of the connate water changed during burial and caused leaching and corrosion of selected grains (Plate 1H). At later stages the Unayzah sediments were subjected to more stress and heat resulting in fractures (Plate 1G) and wavy extinction in many quartz grains. Horizontal re-orientation due to rotation of quartz grains, mica and iron oxides is seen in many thin sections (Plates 1D, J).

The feldspar is partially or wholly altered into authigenic clays (Plate 1J). Locally, these clays are totally or partially dissolved, which resulted in secondary moldic, interparticle and rarely intraparticle porosity (Plates 1B, J). Also, the quartz grains are partially to slightly dissolved, leading to corroded surfaces that locally enhance the porosity. The calcite cement is also affected by dissolution, but this, in general, does not enhance the permeability.

#### *Age and contact relationships*

The presence of spores and pollen allows an age assignment for the generally unfossiliferous Unayzah Formation in the U.A.E. An assemblage including *Hamiapollenites medium*, *Endosporites pappilatus*, *Vittatina* sp., *Punctatisporites* sp., *Densosporites* cf. *spinifer* and *Lycospora* sp. suggests an age ranging from Visean to Sakmarian (Early Carboniferous to Early Permian; ADNOC unpublished report cited in Ali & Silwadi 1989). Other species such as *Thymospora thiesseni* and *Punctatosporites minutus* also occur but cannot be used to date the Unayzah. Based on the regional stratigraphic correlation and areal distribution of the clastics in Arabia, Alsharhan (1989) assigned a Late Carboniferous–Early Permian age to the Unayzah in the U.A.E.

The nature of the Khuff–Unayzah contact within the U.A.E. varies from one area to another (Fig. 7). Wells drilled in central offshore and onshore Abu Dhabi show a conformable Khuff–Unayzah contact, whereas those drilled in extreme western offshore Abu Dhabi seem to suggest that the contact may be erosional (Ali & Silwadi 1989). The contact between the Unayzah and the ‘Pre-Unayzah formations’ is unconformable and marks the latest Hercynian tectonic phase. It separates Early Carboniferous and older rocks from the Late Carboniferous–Early Permian clastics. This regional unconformity was detected in many deep wells drilled in the Arabian Gulf region.

#### *Depositional setting*

The lithostratigraphic, petrographic and sedimentological studies led us to the interpretation that the Unayzah Formation in the U.A.E. was laid down in a fluvial to deltaic setting. The facies variation is controlled by the inherited Carboniferous topography, the structural configuration, and possibly climatic variation. The surface morphology of the quartz grains and the presence of coal seams suggest deposition in a littoral swamp, either in a delta or in a coastal barrier zone. The interpretation of the fluvial origin is based primarily on the overall absence of fossils, the occasional presence of pollen and spores, the presence of carbonaceous material, the local presence of upward fining sequences, and also the absence of glauconite. The sand-clay ratios and the sedimentary features suggest low to moderate-energy, moderate to high-sinuosity meandering streams, in which the sandstones were deposited as point bars.

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