Paleozoic sandstones are now the most exciting oil exploration target in Arabia. Oil and gas have recently been discovered in large quantities in these ancient rocks in Saudi Arabia, Oman the United Arab Emirates. Slightly younger Mesozoic sands are also important targets in Yemen, Syria and Egypt.

Roy Nurmi examines the recent discoveries in the Paleozoic and explains why these sandstones hold great promise for the future. Eric Standen also shows how the high-resolution Formation MicroImager (FMI®) tool helps in understanding these sandstones. Moujahed I Husseini of Saudi Aramco describes in detail the geology of the Permian marine sandstones around Riyadh in which oil was first discovered two years ago.

Contributions by Don Hadley, United States Geological Survey, Al Ain, UAE and Jaap Focke, Shell, Rijswijk, The Netherlands. Many of the photographs in this article were kindly supplied by Don Hadley.
The search for hydrocarbons in the deeper and older Paleozoic rocks intensified as the number of supergiant discoveries in Cretaceous and Jurassic carbonates declined. The first step was to drill into the uppermost Paleozoic carbonate Khuff Formation—a move that led to the discovery of a wealth of gas reserves. More recently, drilling around the margins of Arabia’s prolific oil provinces has enabled explorationists to find oil in rocks older than the Khuff.

In the past few years, Petroleum Development Oman (PDO) and ELF have found oil in Oman’s Paleozoic sandstones. However, the heavy grade oil and the complexity of some fields make development of these reserves a technological challenge.

Major gas discoveries have been made in the Paleozoic Haima sandstones under central Oman’s preexisting and shallower carbonate reservoirs. Hydrocarbons have been located in the Saih Nihayda and Saih Rawl fields at depths greater than 14,000 ft and 16,000 ft, respectively.

The discovery of oil in Saudi Arabia’s Paleozoic sandstone by the Al Hawtah 1 wildcat well in June 1989 was the first firm indication of possible oil reserves. Subsequent large oil finds in these Permian marine sandstones southeast of Riyadh, Saudi Arabia, have prompted further evaluation of the Paleozoic system.
Fig. 2.2 (Above): The red curve shows the latitudinal position of the City of Muscat, Oman during geologic time (calculated by M. W. Hughes Clark of PDO). During much of Paleozoic time, the Arabian Peninsula lay south of the equator. Little carbonate sediment would have accumulated, thus explaining the predominance of quartz sandstone reservoirs. Later in geologic time when the Arabian Plate approached its present position, carbonates and carbonate reservoirs became dominant.

Fig. 2.3 (Right): Location of Paleozoic sandstones in Arabia (green dots). The red dot shows the site of the Nabatean tomb (on the opening pages of this article) which is cut into Siq sandstone at Mada in Salih, Saudi Arabia. This is the oldest Paleozoic sandstone in Arabia.
Recent discoveries of several billion barrels of Paleozoic oil in the previously unexplored sandstones of Central Province of Saudi Arabia highlight the prospective nature of the Paleozoic rocks on the Arabian Peninsula. The oil is of very high quality (Arabian Super-light) and is sulphur free with gravity exceeding 43° API.

The Unayzah Formation (see figure 2.4) is the main sandstone reservoir and this lies immediately underneath the youngest Paleozoic rock unit - the carbonate Khuff Formation - which is also of Permian age. The Unayzah Formation comprises two sandstone reservoirs with highly variable porosities which average about 20%. However, permeabilities of several darcies are relatively common.

Older Paleozoic sandstone reservoirs are present to the northeast of Riyadh and the lateral continuity of these clastic sequences, combined with the good reservoir quality, suggests that these sandstones will be a prime exploration target in central Arabia for many years.
**Paleozoic - the prime target**

The uppermost Paleozoic carbonate Khuff Formation was producing gas in Saudi Arabia years before the discovery of oil in the underlying sandstones. The oil discovery at Qirdi-2 well in 1979 marked the first significant find in a Saudi Arabian Paleozoic sandstone. Later that year, sweet gas was found in even older Paleozoic (Devonian) sandstones in the Shedgum area of the supergiant Ghawar complex.

A far more prolific discovery was drilled shortly later, in 1982, at Abu Jifan Field, which flowed more than 8,000 BOPD of sweet, high-gravity oil from Lower Paleozoic sandstones at 13,500 ft. In 1982, the deepest discoveries of oil and gas were made in Paleozoic sandstones in Saudi Arabia (oil in Tinat Field at 14,800 ft and gas in Abu Safah Field at 14,500 ft).

A petroleum potential for Paleozoic sandstones across central Saudi Arabia was indicated by these encouraging results in eastern Saudi Arabia’s deep wells together with hydrocarbon shows encountered, in 1984, in Paleozoic sandstones in water wells west of Riyadh at Wadi Birk.

Shortly afterwards, in late 1986, the Saudi Arabian Oil Company (Saudi Aramco) began exploring central Saudi Arabia and has since discovered seven fields south of Riyadh, including the giant Hawtah Field. Other Paleozoic sandstone reservoirs have also been discovered to the northeast of Riyadh where wells were drilled deeper to test the sandstone beneath the established fields.
**Let’s talk traps**

In Saudi Arabia, the Paleozoic, Khuff and underlying sandstone traps are predominantly structural and vary in size and complexity. Some have a broad, low-relief, overlying deeper fault blocks while others are complex, highly faulted, rift-type blocks.

The typical Unayzah structural trap is moderate in relief due to basement faulting. The vertical closure of the Unayzah structures is generally less than 100m.

The structural traps grew during several tectonic pulses in the Cretaceous and Triassic. But the movements were most significant in the Late Paleozoic Hercynian event. A variety of possible stratigraphic traps have also been recognized and successfully tested.

The general cross-section (figure 2.4 on page 14) of the Paleozoic in central Arabia shows two stratigraphic traps - at Shedgum and Wadi Birk. At Shedgum, the Devonian sandstone pinches out on the flank of the structure forming a trap between the Khuff cap rock and the Silurian source rock. In the discovery well, sulphur-free gas and condensate flowed at a rate of 26.8MMSCFD and 760BCPD at 2,300psi from a 3/4in choke from a depth of 13,563ft.

At Wadi Birk, a sandstone pinchout between a tight basal Khuff interval and Precambrian basement was defined by water wells. Both these pinchout observations are important as they provide a guide to other exploration targets that may exist along the flanks of large structures where the Paleozoic sandstones pinchout. This occurs at the Khurais, Ain Dar and Abqaiq fields.

The combined structural/stratigraphic trap at Abu Jifan Field can also be seen on the generalized cross-section across central Arabia. These stratigraphic traps prove that reservoirs older than the Permian-Carboniferous Unayzah and Khuff reservoirs should be targets in Paleozoic exploration. For all the traps discovered to date, the regional seals are the tight Upper Permian Khuff.

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Fig. 2.8: The Paleozoic stratigraphic column is modified after Powers (1968); El Khayal and Wagner (1985); El Laboun (1987); Miessner et al (1988); Vaslet (1990); Mahmoud et al (in press); McGillicray and Husseini (in press).
Sweet and sour in Saudi

Two types of Palaeozoic hydrocarbons are found in Saudi Arabia. The first is located in central Saudi Arabia’s Palaeozoic sandstones and is a sweet, high-gravity oil and gas. The second, in contrast, is sour gas found in large Khuff reservoirs to the northeast.

The source rock of the sour Khuff gas has not been firmly established but the two most likely candidates are the Qusaiba Shale or Precambrian carbonates which are buried deep beneath eastern Arabia, onshore and offshore. These appear to be the only sequences with sufficient thickness to provide the prolific quantities of Khuff gas. This is particularly true of large gas accumulations such as the Qatar Dome which has estimated reserves of about 100 Tcf.

Fig. 2.9 (Below and right): Red siltstone from flood plain deposits of the Unayzah Formation. The core is from the Unayzah Formation in the Hawatub-1 well.
There are strong indications that the Silurian Qusaiba Shale is the source rock of the hydrocarbons in Paleozoic sandstones. The main indications are the isotope and biomarker distributions between oils from the Paleozoic sandstone and bitumen extracted from several possible source rocks.

In addition, the Qusaiba Shale is the richest of all the possible source rocks with a maximum total organic content of 6.15%. It is followed by the Jauf Formation with 3.7%, the Unayzah Formation with 2.1%, the Khuff Formation with 1.34%, and the Hanadir and Ra’an Shales with 1.13% and 0.68%, respectively.

The Qusaiba Shale is relatively thick and is present throughout most of central Saudi Arabia’s basins. Today, the Qusaiba Shale is buried at depths of 10,000ft to 15,000ft throughout Saudi Arabia and this implies that it is in the hydrocarbon-generating window. In northwestern Saudi Arabia, the Silurian Shale is thought to have been ‘frozen’ at depths conducive to oil generation since the Late Paleozoic. At this time, the Hercynian orogeny uplifted the area and effectively reset the subsidence curve of these rocks back to shallow depths. Moreover, the early entry of oil into the pore systems of Paleozoic sandstones appears to have helped to preserve the reservoir character.
Focus on the Unayzah Formation

The Unayzah Formation in central Arabia comprises a succession of siliciclastic fluvial, coastal and shallow marine sediments. In southern Arabia, these range in age from Late Carboniferous to Late Permian and are the equivalent of the Al-Khlata Formation glacial clastics in Oman. Younger marine sediments from the same sequence also correlate well with Oman’s Gharif Formation which is Early Permian in age.

Sedimentological and biostratigraphical evidence shows that there is a regional marine incursion which sits above fluvial sediments of the lower depositional sequence. This incursion, which is marked by transgressive lag deposits, indicates that a large sea once entered the region from east and northeast, covering central and southeast Arabia.

A regionally extensive progradational succession lies above these transgressive lag deposits and this can usually be divided into three depositional zones - a basal red siltstone, a middle sandstone and an upper layer of interbedded mudstones and sandstones. This rock sequence shows that the Permian Sea covered Saudi Arabia before the major transgression which deposited the Khuff Formation.

The middle sandstone is fine-to-medium grained, moderately well sorted, laterally continuous and, in places, of good reservoir quality. In some areas, it is over 150ft thick. This is the reservoir rock for the newly-discovered Hawtah, Dilam and Raghib fields and was deposited in a variety of paralic environments - shoreface, foreshore and delta channel.

The top unit of the three was deposited in a coastal or delta plain environment and is made up of channel and splay sandstones. It also contains variegated mudstones and some soil profiles. This rock sequence shows that the Permian Sea over Saudi Arabia receded before the major transgression which resulted in the deposition of the Khuff carbonates.

There are also other Paleozoic sandstone sequences on the Arabian Peninsula which have exploration potential and in Oman, some of these have already been found to house oil. But to understand these exploration targets, it is necessary to review the entire Paleozoic System.

Further reading on Saudi Arabia


The Paleozoic in a nutshell

During the early part of the Paleozoic, in Cambrian and Ordovician times, central Arabia formed part of a stable shelf at the edge of the Gondwana land mass in which the Saq and Qasim clastics were deposited. Later, during the Late Ordovician and Early Silurian periods, polar glaciers and related fluvio-marine systems deposited the Zarqa and Sarah formations unconformably above older rocks, including the Precambrian basement. As these glaciers melted, the sea rose rapidly and this led to the deposition of the upward-coarsening Qalibah Formation.

At the end of the Silurian, the sea level dropped and the Tawil Formation sandstones were deposited. During the Middle Devonian, Hercynian mountain-building movements uplifted and tilted central Arabia towards the east, exposing older rocks to erosion. In the Late Carboniferous, glacio-fluvial conditions led to the deposition of the Unayzah Formation clastics in central Arabia which now contain oil.

By the Late Permian and Early Triassic the Arabian Peninsula, which had been eroded to a peneplane, was flooded by a warm-water regression and this led to the deposition of the Khuff Formation carbonates.

These Paleozoic deposits were altered extensively by later tectonic forces, changing areas where oil could be trapped and creating new migration pathways. During the Triassic, rift tectonics along the Zagros mountain belt transmitted extensional stresses across Arabia. These produced localized folded and faulted areas such as those seen in the Hawtah Field. Faulting produced at this time may have provided a conduit for oil migration from the Qalibah Formation to the Unayzah Formation sandstones. The Triassic faults rarely disturb the Khuff Formation which is the regional seal for the Unayzah reservoirs.

More recently, during Tertiary and younger times, central Arabia was again uplifted and tilted eastwards. This led to rapid and widespread erosion of both Mesozoic and Cenozoic rocks. However, unlike eastern Saudi Arabia, these central Arabian structures do not appear to have been structurally reactivated during the Cretaceous.

Focus on grabens

The discoveries in central Arabia have led to the evaluation of the hydrocarbon potential of sandstones in other scarcely investigated Paleozoic basins of Saudi Arabia. Seismic reconnaissance surveys and regional studies indicate that many of these basins contain the same petroliferous source rocks and sandstone reservoirs of central Saudi Arabia. In fact, some of these areas also exhibit significantly greater structural development than central Saudi Arabia.

A major Precambrian half-graben system can be seen in regional surface seismic sections across the Western Rub al-Khali in Saudi Arabia. This half-graben was formed at the same time as those in southern Oman and the Najd Rift when extensional forces dominated the Arabian Plate.

The Western Rub al-Khali grabens contain both NS-SE trending faults and basins in addition to the more common N-S trending horsts and grabens. Seismic data revealed a rock sequence similar to that found in Oman’s Huqf Group carbonates which are thought to be the source rocks for the Ghaba and South Oman Intra-Cambrian salt basins. Future exploration wells will test the possibilities of these basins.
Exploration in Oman has almost doubled the country’s reserves since 1980. In just over a decade, the reserves have increased from 2,484Mb to 4,250Mb with a steady increase of about 50Mb each year over the past five years. Gas reserves have also increased significantly since gas exploration began in 1985. More recently, drilling deeper beneath known oilfields has yielded a number of significant gas finds including those at Saih Nihayad, Saih Rawl and Barik. Oman’s total gas reserves are now estimated to be greater than 9.91Tcf.

This gas search has yielded some surprising light oil finds. These include the Khuff discovery in 1985 under Yibal Field and a more recent find in a deeply buried Precambrian carbonate reservoir rock in Al-Noor Field. The amazingly high porosity found at a depth of 4,800m now opens up several deep carbonate prospects in South Oman.

Production from a thick interval of ‘shales’ in the same well has further alerted explorationists to be aware of all possibilities. In October 1991, PDO began drilling its first offshore well - only the fourth well to be spudded in the Arabian Sea portion of the Indian Ocean. The well is located in the south, some 63km offshore at a depth of 105m.

PDO is concerned about the hard limestone on the sea bed in this area and the well may have difficulty reaching its target. However, almost all the oil produced by PDO from Paleozoic sandstones of South Oman, in addition to that from younger overlying carbonates, appears to have come from the Precambrian source rocks. Geochemical and geological evidence indicates that the source rock was the carbonate/evaporites of the Cambrian Huqf Group. At the Middle East session of the 1991 AAPG International Meeting in London in October, Geert Konert presented PDO’s evidence for an elaborate history of early maturation and migration in Huqf carbonate reservoir zones such as in the Al-Noor Field.

Over much of South Oman, the dissolution of Huqf salt units has resulted in the upwards migration of this Precambrian oil into the overlying Paleozoic sandstones and Cretaceous carbonates.

The Precambrian oil is classified as either Huqf or ‘Q’ crude depending on its geochemical characteristics. A plot of the sterenes contained in Oman Huqf and ‘Q’ crude oils shows them to be markedly different from the Saudi Aramco Paleozoic crude oil. The Khuff oil of Yibal Field appears to be of the same origin whereas Saudi Arabia’s Paleozoic oil seems to have its source in a Silurian Phase northeast of Hawtah Field. The organic-rich Silurian shales of the Safiq Formation are also a source rock for the Haima Group sandstones which are found in the El Sahmah Field near the Saudi/Oman border and the pre-Khuff sandstones of the UAE.
Yemen - the new frontier

Yemen has been a focus of attention since Ian Maycock led Hunt Exploration Company to the discovery of oil in the sandstones of the Maarrif/Jawl graben basin. This find was a surprise because explorationists believed that the targets were Jurassic carbonate reservoirs which had source rocks and evaporite seals reminiscent of the prolific Arab Formation to the north.

Since its first discovery, Yemen Hunt Oil Company has found 11 oil and gas fields, all of which have been found in Jurassic sandstones. About 200,000b/d of sweet crude are currently being produced. Three recently discovered gas condensate fields - Al-Raja, Dostour Al-Wihdan and Al-Saidah - will add to the gas production from the Asaad Al-Kamil Field.

These sandstones range from fluviodeltaic in the Alif Formation to deeper marine, possibly turbidite, in the Lam Formation (Upper Amran Group). The Alif sandstones usually exhibit good reservoir qualities with porosities in the range of 20-25% and permeabilities exceeding one darcy. The reservoir seal is the Sabatayan (Safer) Formation which includes a number of thick Jurassic salt units (Upper Tithonian age).

Oil was later found in Jurassic Amran carbonates (Amal, East and West Ayan fields), southwest of the Yemen Hunt Oil Company concession, by a Soviet-led effort. Dolomitization, vugs and fractures have enhanced the reservoir character of some of the shallower water carbonate deposits and there is evidence to suggest depositional variation.

Canadian Occidental Petroleum Ltd is leading explorationists still further east in Yemen. Five of six wells have been successful and as a result Canadian Oxy has more than tripled its planned spending in this relatively unexplored country - drilling 13 wells this year in their 6.8M acre block. The first discovery well for Canadian Oxy, the Sunah-1, flowed 3,767b/d 36 degree gravity oil for 12 hours through a 7/8in choke with 378psi flowing tubing pressure. It has been suggested that the Sunah Field may be nearly as large as the 500Mb Alif Field although more wells are needed to determine the field’s potential. A well in another structure, Camaal, in the same block recently produced 4,900b/d during an extended production test.

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![Fig. 2.17: Location of Yemen discoveries.](image-url)  
![Fig. 2.18: The Paleozoic and Lower Mesozoic stratigraphic column for Saudi Arabia, Yemen and Oman (modified after Beydoun, 1991).](image-url)
Channel deposits and their geometry can often be interpreted on outcrops by analysing the cross-bedding within the sandstone. Occasionally, dipmeters provide enough dip information for this analysis but often the size of the cross bedding is too small to be analyzed using dipmeter data alone. However, the detailed images provided by Formation MicroScanner* (FMS) images allow the analysis of even the smallest cross-beds within fluvial channels.

Schlumberger-Doll Research (Luthi et al 1990) has demonstrated that it is possible to analyze and model the fluvial cross-bedding within Upper Paleozoic and Lower Mesozoic sandstones of the Western Desert of Egypt using FMS images. The FMS images detected around 100 individual cross-beds over a vertical interval of 120 ft, with an average cross-bed thickness of less than one foot.

The cross-bed distribution exhibits an azimuth scatter well in excess of 180 degrees. A large number of models were tested (350 combined models) with the best result being obtained for semi-circular bedforms in a sinuous river channel with a slight oblique migration of 5° to account for the data’s asymmetry.

According to the interpretation, the mean channel flow is towards NNW which is similar to the modern flow of the Nile River. As there are virtually no floodplain deposits over the entire interval, it is further interpreted that a wide braided-river system of sinuous channels existed in which crescentic (lunate) subaqueous dunes prevailed.

Fig. 2.19 (Above left): Fluvial cross-bedding data from FMS imagery which indicated from modelling that the ancient river flow was N to NE in direction with a channel migration of 5° and a low (S=0.5) sinuosity.

Fig. 2.20 (Above right): Probable appearance of the Late Paleozoic-Jurassic river system in the Western Desert of Egypt.

**Dipping into fluvial channels**

Fig. 2.21 (Top): Sketch of the Early Paleozoic (Ordovician) channels associated with glaciation in central Arabia (from Denis Vaslet, 1990).

Fig. 2.22 (Above): Late Paleozoic channel in the Gharif Formation outcrop in southern Oman.
At the 1991 Annual AAPG Meeting, the Jules Braunstein Memorial Award was presented to a team of geologists, which included Prof. Paul Potter, Mike Grace and Dr. Gordon Pirie, who used images as well as dips to analyze channel reservoirs in the USA.

Channels occur in nearly every type of Middle East sandstone reservoir and are present in most depositional settings. They are common in the reservoirs associated with glacial deposition in both Oman and Saudi Arabia.

Large erosional valleys, up to 8km wide, and channels associated with glaciation which occurred during the Lower Paleozoic of Saudi Arabia, can be seen on outcrops and in subsurface seismic data acquired by Saudi Aramco in northwest Saudi Arabia. The channels are cut into the Qasim Formation and are overlain by the source rock, Silurian Quasiba Shale. Perry Dobson of Texaco Research suggested that gas is being produced from the equivalent sands in Jordan’s Risha structure.

Outcrops of similar channels associated with a later glaciation (Carboniferous) can be seen in Gharif Formation outcrops in southern Oman (figure 2.22). Subsurface channels in this sandstone were identified using FMS imagery from a well in the Thuleilat Field in Oman. The geometry and orientation of the channels could be directly interpreted from the images. Also identified in the FMS image were caliche soil horizons and calcite cemented fractures in a porous sandstone.
Filling in channel data

In addition to using cross-bedding for analysing channels, it is often possible to see other features which may reveal, even more directly, the shape and orientation of the channel system. In analysing a submarine shelf deposit, cores and FMS images indicated that cut and fill troughs, which are very common in channels, can be seen in the images.

Channel fills associated with submarine shelf and slope deposits along India’s southeast coast have also been analyzed using FMS images. These revealed the orientation of some of the clay-filled troughs within the deposits.

Examination of the borehole images indicated that the sands and shale within the lower part of the interval (3,497m to 3,507m) were deposited as channel fills. The trough-like shape of the thicker shale bodies suggests that they were the final fill after erosion and sand deposition. The texture of some of the fill is sufficiently coarse to be directly visible in the images. The particles range in size from pebbles to small cobbles.

Similar coarse pebbles were observed during the later examination of the core and can be seen in the core photographs of figure 2.23. Note that the scale of the photograph is approximately twice the size of the accompanying FMS image. Most of the associated shale is discontinuous and may include shale clasts carried by the channel currents.

The shale wedge-like geometry, interpreted as channel fills using FMS imagery, were matched with the core. Although the detrital clasts within these channel-like troughs were found to be oyster fragments, it is thought that these fragments were carried into this deep-water setting. This is supported by the presence of deep-water fossils in the non-channel deposits.

The orientation of the axes suggests that the channels were affected by N-S oriented basement ridges. The channels were buried by either prodelta shales or part of a submarine fan.

Thin shale beds in the sequence above the channel deposits indicate a very different depositional geometry. The interval contains eight individual shale beds which are thin, relatively parallel beds of high conductivity (seen as black in FMS imagery). These are less well detected by the Gamma Ray shown to the right which has poorer vertical resolution.

The information on shale geometry, depicted so clearly by the FMS, indicates that these shales extend over a large area away from this well and could possibly be correlated with a nearby well.
**Riding on the storm**

With enough bedding information, it is often possible to understand the direction of current movement, whether water or air, so that the geometry of the reservoir body can be determined. In the past, the geometrical limitations of the dipmeter made it difficult to reliably define the cross-bed types and geometry as they are often too small to be correlated from button-to-button or pad-to-pad. FMS images now present a wealth of bedding information much like a core but with the added advantage of having the dip of the well, the formation, and continuous orientation of the bedding features.

Early research work on the dipmeter analysis of bedding demonstrated that it was possible to determine the dune type origin for the ancient dune deposits in the Nugget reservoirs in Wyoming. The dip and azimuth distribution of the cross-bedding and the relationship of azimuth to the dip angle was used to determine the dominant dune types. It was found that dune geometry is revealed by separating the dip data into different dip magnitude: low-angle (0°-5°), medium-angle (5°-10°) and the high-angle (10°-30°) dips. The change in dip magnitude with changes of azimuth revealed the crescent shape of the dune slip faces.

It was interpreted that barchan-like (crescent-shaped slip faces) were dominant, but also present were some longitudinal-type dune features. The dip within these longitudinal features is to the SE and NW. However, the vector average of these two modes is to the SW, which is the same as the crescent-shaped dune faces.

**Reference**