

## Paleozoic Stratigraphy and Petroleum Systems of the Western and Southwestern Deserts of Iraq

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### ABSTRACT

A stratigraphic scheme for the Paleozoic of the Southwestern Desert of Iraq is proposed based upon the review of recently published data from several deep wells in the western part of the country and from outcrops in other regions in Iraq. The main formations are described in terms of facies distribution, probable age, regional thickness, and correlations with the well-reported Paleozoic successions of the adjacent countries (e.g. Jordan and Saudi Arabia), as well as with the Thrust Zone of North Iraq. The Paleozoic depositional and tectonic evolution of the Western and Southwestern Deserts of Iraq, particularly during Cambrian, Ordovician and Silurian, shows marked similarity to those of eastern Jordan and northern Saudi Arabia. However, local lithological variations, which are due to Late Paleozoic Hercynian tectonics, characterize the Upper Paleozoic sequences.

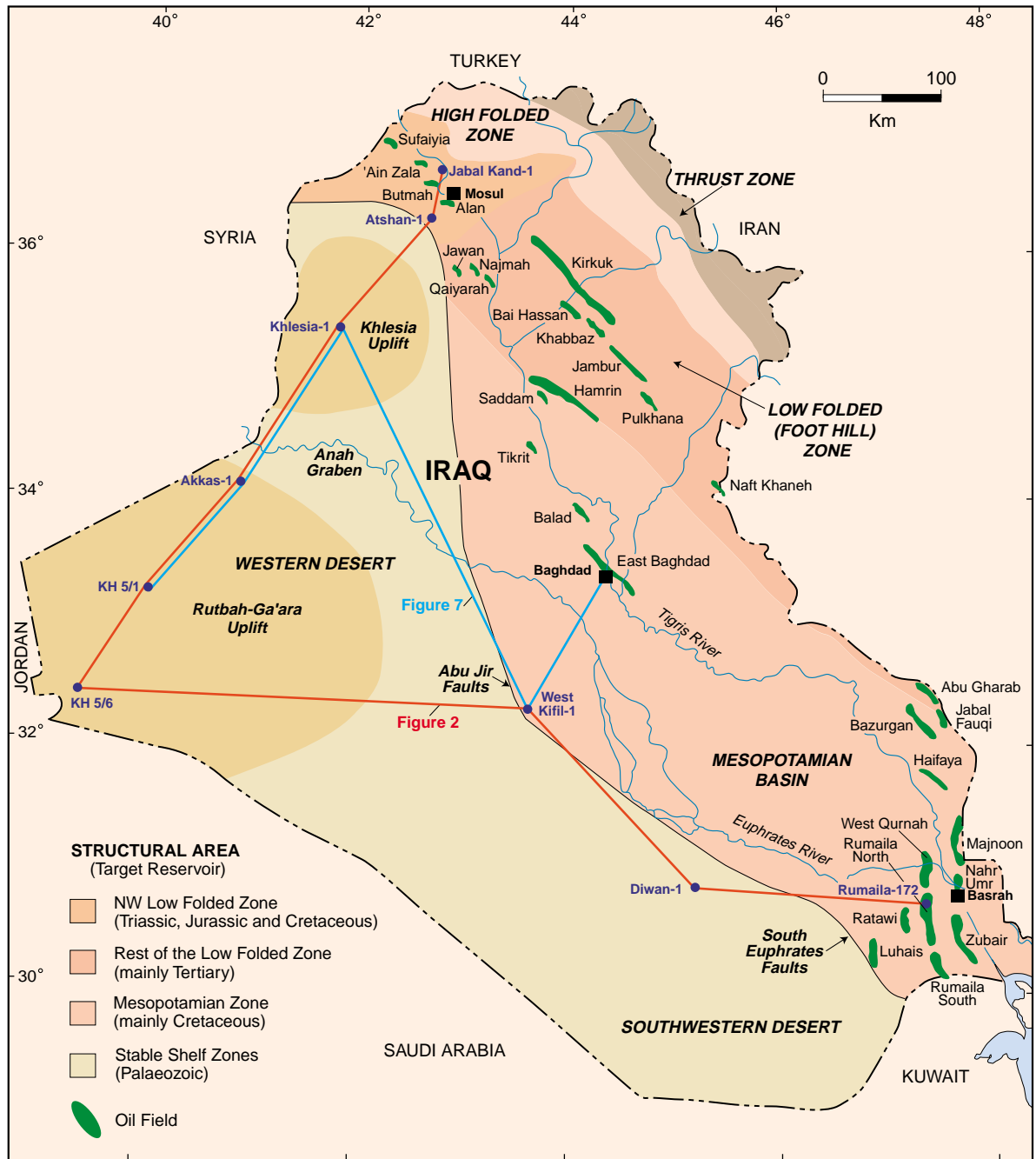
The Lower Silurian marine "hot" shale, 65 meters thick in the Akkas-1 well in the Western Desert, is believed to be the main Paleozoic source rock in the Western and Southwestern Deserts. Additional potential source rocks in this region could be the black shales of the Ordovician Khabour Formation, the Upper Devonian to Lower Carboniferous Ora Shale Formation, and the lower shaly beds of the Upper Permian Chia Zairi Formation. The main target reservoirs are of Ordovician, Silurian, Carboniferous and Permian ages. Similar reservoirs have recently been reported for the Western Desert of Iraq, eastern Jordan and northern Saudi Arabia. In addition, two main regional seals (Lower Silurian shales and Permian evaporites) of northeastern Arabia extend over most of the Southwestern Desert, together with several other local seals. These considerations render the unexplored Paleozoic Southwestern Desert of Iraq prospective.

### INTRODUCTION

Most of the oil fields and exploration programs in Iraq are concentrated in the eastern part of the country in mainly shallow Mesozoic and Tertiary reservoirs (Figure 1). The older Paleozoic sequences, however, have not been explored until the past decade (Al-Sakini, 1992; Al-Haba et al., 1994; Al-Gailani 1996). These older successions constitute promising exploration targets, particularly in the Western and Southwestern Deserts of Iraq, where their thicknesses exceed 5,000 feet (ft) and where the top of the prospective interval may occur at depths as shallow as 10,000 ft (Beydoun, 1991).

Al-Haba et al. (1994) and Al-Siddiki et al. (1994) presented important papers on the Paleozoic of Iraq, in Arabic, which describe lithological and geochemical data from several recently-drilled, deep wells in western and southern Iraq (e.g. Akkas-1, West Kifil-1, Diwan-1 and Rumaila-172 in Figure 1). One of these wells, Akkas-1, encountered good hydrocarbon shows in several Paleozoic rock-units and established Akkas field as a light oil and gas discovery. These wells indicate that the Paleozoic in Iraq is a complete petroleum system similar to the one encountered in Saudi Arabia, Oman and Jordan.

This study reviews the Paleozoic stratigraphy of Iraq by combining both outcrop and subsurface data. Much of the data and discussion is translated from the Arabic papers by Al-Haba et al. (1994) and Al-Siddiki et al. (1994). The paper also reviews the tectono-depositional model for the Paleozoic of this region which is based on comparison with surrounding countries, regional facies distribution and general biostratigraphy, particularly palynology. The paper also reviews the source rock potential and trap mechanism for the Paleozoic of the Western Desert, and suggests a stratigraphic scheme and probable hydrocarbon potential for the Paleozoic successions of the Southwestern Desert of Iraq.



**Figure 1: Location map showing the main tectonic regions and hydrocarbon systems of Iraq (modified from Al-Sakini, 1992). The stable shelf zone corresponding to the Western and Southwestern Deserts presents the best Paleozoic targets. Most of the oil reserves in Iraq are found in the eastern part of the country; mainly in Cretaceous reservoirs in the Mesopotamian Basin, Tertiary reservoirs in the southern part of the Low Folded Zone and Cretaceous to Triassic reservoirs in the northwestern part of the Low Folded Zone.**

**REGIONAL TECTONIC PROVINCES**

Iraq forms the northeastern part of the Arabian Plate which was part of the Gondwana Continent, adjacent to Africa and India, during the entire Paleozoic. It came to occupy a passive margin setting in Early Mesozoic times with the rifting of Central Iran and the formation of the intervening Neo-Tethys Ocean. The tectonic evolution of the Arabian Plate (discussed for example by Beydoun, 1991, 1993; Hussein, 1989, 1990, 1991a, b, 1992) is strongly reflected in the structural framework, stratigraphy, paleogeography and physiography of Iraq (Buday and Jassim, 1987).

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Iraq can be broadly divided into four tectonic provinces (Figure 1), each controlled by one, or more, major basement blocks (Buday and Jassim, 1987). The relative movements of these blocks affected the depositional evolution in each province (Buday, 1980; Ameen, 1992) even until the present-day when neotectonic movements are still in progress (Aqrawi, 1993). These four provinces are briefly described below.

The **Thrust (or “Geosynclinal”) Zone** is a restricted narrow strip along the northern and northeastern borders of Iraq, where the principle Paleozoic outcrop areas (down to Ordovician) are found.

The **Folded Zone** occupies the north and northeast mountainous areas and forms the outboard part of the older Mesozoic unstable shelf region of the Arabian Plate. It is contiguous with the Alpine fold belts of the Taurus and Zagros Ranges of Turkey and Iran, respectively. The Folded Zone formed during the Late Cretaceous and Tertiary.

The Folded Zone has been subdivided into a High Folded Sub-Zone (i.e. along the frontiers close to the Thrust Zone) and a Low Folded (Foot Hill) Sub-Zone by Buday (1980). The High Folded Sub-Zone is characterized by extensive exposures of sedimentary rocks down to Jurassic levels, particularly in some high-amplitude folds and overturned structures. In contrast the Low Folded Sub-Zone is dominated by outcrops of rocks younger than Neogene.

The **Mesopotamian Basin** is a flat area covered by Quaternary fluvial-plain deposits of the Tigris and Euphrates rivers, and marsh/lacustrine sediments of southern Mesopotamia, admixed with aeolian fallout deposits (Aqrawi 1995, 1997). It occupies the more inboard part of the unstable shelf region of the Arabian Plate. This zone constitutes the richest basin in Iraq with more than two thirds of the country's total hydrocarbon reserves, which are mostly contained in Cretaceous reservoirs (Sadooni, 1995, 1996, 1997; Aqrawi, 1996a; Aqrawi et al., 1998).

The **Northwestern, Western and Southwestern Deserts** are low-relief stony plateaus located within the stable shelf region of the Arabian Plate. These deserts occupy more than one-third of the country. The outcrops here include Miocene and older Palaeogene sediments, some of which were reworked during the Pleistocene. In the Rutbah-Ga'ara Uplift area, near the Jordanian border, important outcrops as old as Permian occur.

## THE PALEOZOIC ROCKS OF IRAQ

The Paleozoic rocks of Iraq outcrop in the Thrust Zone of northern Iraq and in the Rutbah-Ga'ara Uplift area of the Western Desert. As a result, most of the formal detailed lithological descriptions, which generally date from the 1950s, are based on these two parts of the country (Wetzel, 1950, 1952; Wetzel and Morton, 1952, unpublished reports in Van Bellen et al., 1959; Buday, 1980).

Buday (1980), working largely from older outcrop data (Van Bellen et al., 1959), subdivided the Paleozoic sedimentary column of Iraq into three major sedimentary cycles (Figure 2):

- (1) The Cambro-Ordovician to (?)Silurian Cycle represented by the Khabour Formation (quartzites and shales);
- (2) The Devonian (Upper Devonian) to Lower Carboniferous Cycle which consists of the Pirispiki Red Beds, Chalki Volcanics, and the Kaista, Ora Shale and Harur Limestone formations; and
- (3) The Upper Carboniferous to (?)Upper Permian Cycle represented by the Ga'ara Sandstone and Chia Zairi (carbonate/evaporite) formations.

In the subsurface, similar Paleozoic formations are described by Gaddo and Parker (1959, unpublished report) from the Khlesia-1 well (Figure 1) and more recently by Al-Haba et al. (1994) and Al-Siddiki et al. (1994) from several deep boreholes drilled in western and southern Iraq (Akkas-1, Diwan-1, West Kifil-1 and Rumaila-172; Figure 1). However, several differences in lithology and fossil contents were detected by comparing the northern outcrops with the coeval subsurface successions of western and southern Iraq (Figure 2).

**PALEOZOIC LITHOSTRATIGRAPHY OF IRAQ**

| PERIOD / STAGE       | OUTCROP NORTH IRAQ (1) | JABAL KAND-1 (2)                    | ATSHAN-1 (2)  | KHLESIA-1 (2)          | AKKAS-1 (2)            | KH 5/1 (2) | KH 5/6 (2)             | SHALLOW WATER WELLS                      | WEST KIFIL-1 (2) | DIWAN-1 (2)   | RUMAILA NORTH-172 (3) | GENERALIZED SECTION (2)             |                                     |
|----------------------|------------------------|-------------------------------------|---------------|------------------------|------------------------|------------|------------------------|--|------------------|---------------|-----------------------|-------------------------------------|-------------------------------------|
| <b>PERMIAN</b>       | TATARIAN               | Chia<br>Zairi                       | Chia<br>Zairi | Chia<br>Zairi          |                        |            |                        |  | Chia<br>Zairi    | Chia<br>Zairi | Chia<br>Zairi         | Chia<br>Zairi                       |                                     |
|                      | KAZANIAN               | Ga'ara                              | Ga'ara        | Ga'ara                 |                        |            |                        | Ga'ara                                   | Ga'ara           |               |                       | Ga'ara                              |                                     |
|                      | KUNGURIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
| <b>CARBONIFEROUS</b> | ARTINSKIAN             |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | SAKMARIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | STEPHANIAN             |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | WESTPHALIAN            |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | NAMURIAN               |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | VISEAN                 |                                     |               |                        |                        |            |                        | 550 m of undated clastics and carbonates |                  |               |                       |                                     |                                     |
|                      | TOURNAISIAN            | Harur<br>Ora<br>Kaista<br>Pirispiki | Harur         | Harur<br>Ora<br>Kaista | Harur<br>Ora<br>Kaista |            | Harur<br>Ora<br>Kaista |  |                  | Harur<br>Ora  | Harur<br>Ora          | Harur<br>Ora<br>Kaista<br>Pirispiki | Harur<br>Ora<br>Kaista<br>Pirispiki |
| <b>DEVONIAN</b>      | FAMENNIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | FRASNIAN               |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | GIVETIAN               |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | EIFELIAN               |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | EMSIAN                 |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | SIEGENIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | GEDINNIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
| <b>SILURIAN</b>      | PRIDOLIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | LUDLOVIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | WENLOCKIAN             |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | LLANDOVERIAN           |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | ASHGILLIAN             |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
| <b>ORDOVICIAN</b>    | CARADOCIAN             |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | LLANDEILIAN            |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
|                      | LLANVRNIAN             | Khabour                             |               |                        |                        |            |                        |  |                  |               |                       | Khabour                             |                                     |
|                      | ARENIGIAN              |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |
| TREMADOCIAN          |                        |                                     |               |                        |                        |            |                        |  |                  |               |                       |                                     |                                     |

**Figure 2: Correlation of the Paleozoic rocks in Iraq (see Figure 1 for locations). The number at the top of each section refers to the source: (1) the outcrop of North Iraq is attributed to Van Bellen et al. (1959) and Buday (1980); sections identified as (2) are from Al-Haba et al. (1994); and (3) Rumaila-172 (Al-Siddiki et al., 1994). The Silurian Pridolian stage is not specifically shown in Al-Haba et al. (1994) and the "Suffi" and "Akkas" are shown as informally-defined formations.**

The general subsurface Paleozoic stratigraphic column of Iraq as supported by paleontological data is shown in Figure 3. The following summaries describe the reported Paleozoic rock units, their ages, depositional environments and relationships to rocks in neighboring countries (Figure 4).

### **Precambrian and Infracambrian Rock Units**

The basement in Iraq is believed to be composed of metamorphic Upper Precambrian rocks together with partly-metamorphosed and granite-intruded Lower Infracambrian rocks (Buday, 1980). Above the basement, the platform cover in Iraq may consist of Upper Infracambrian strata similar to those in neighboring countries: Saramuj Formation in Jordan, the Fatima/J'balah groups in Saudi Arabia, the Hormuz Evaporite Series in Iran (Gorin et al., 1982; Hussein, 1989; Beydoun, 1991, 1993).

The Saramuj Formation and the Fatima/J'balah groups are composed of andesite, dacite and rhyolite flows alternating with coarse and medium-grained terrigenous clastics. The Infracambrian strata in the Western and Southwestern Deserts of Iraq probably consist of similar clastics which form a continuum with the deposits of eastern Jordan and northern Saudi Arabia. The facies of the Infracambrian sequences in the southeastern parts of Iraq may resemble the Hormuz Evaporite Series of Iran.

These Infracambrian rocks may have been deposited in basins which were influenced by a system of north-northeast to south-southwest-trending basins and their separating horsts, which run parallel to the Infracambrian Najd Fault System of Saudi Arabia (Buday, 1980). These basins may have formed in an extensional tectonic environment which prevailed during the Infracambrian throughout the Middle East (Hussein, 1989; Hussein and Hussein, 1990; Johnson and Stewart, 1994). To the west and probably the southwest of Iraq, uplifted areas might be postulated. The high position of the basement in the Rutbah-Ga'ara Uplift area (e.g. Al-Sinawi and Al-Bana, 1992) in the west of Iraq probably supports this concept.

### **Cambrian and Lower Ordovician Rock Units**

Cambrian rocks have not been reported in outcrop, nor have they been penetrated by any borehole in Iraq. However, the correlation of deep seismic sections of western Iraq (i.e. Khlesia and Rutbah-Ga'ara Uplift areas) with similar sections and deep wells in Syria and Jordan, led Al-Haba et al. (1994) to postulate the occurrence of Cambrian rocks, at least in the subsurface of the Western Desert of Iraq.

The Cambrian and Lower Ordovician sequences in the Western and Southwestern Deserts of Iraq probably resemble similar rocks in Jordan and Saudi Arabia (Figure 4). These consist of alluvial and marginal marine clastics: Saq Sandstone Formation of Saudi Arabia (Powers et al., 1966; Al-Laboun, 1986; McGillivray and Hussein, 1992) and the Ram Group of Jordan (Selley, 1970, 1996; Andrews et al., 1991; Amireh et al., 1994; Beydoun et al., 1994).

### **Ordovician: Khabour Quartzite-Shale Formation**

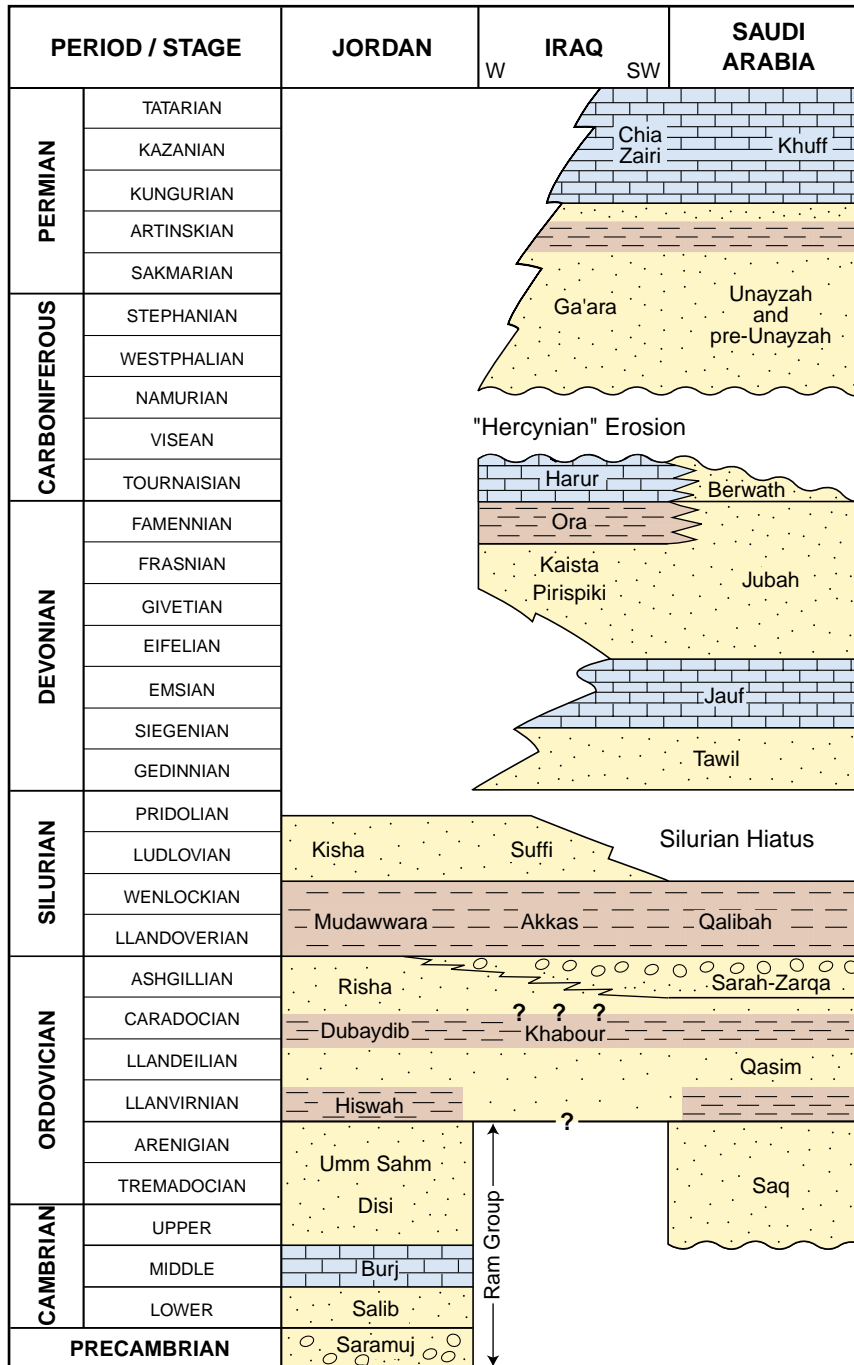
The Khabour Quartzite-Shale Formation is the oldest-known sedimentary rock unit in Iraq. It occurs in the northern Thrust Zone outcrop area and consists entirely of siliciclastics, comprising thin-bedded, fine-grained sandstones, quartzite graywackes and silty micaceous shales (Wetzel, 1950, unpublished report in Van Bellen et al., 1959).

The Khabour Formation has been dated as Ordovician (Llandeilian) in the upper part, and probably Ordovician throughout, by Wetzel (1950), Ordovician (Seilacher, 1963), and Early-Late Ordovician (Buday, 1980). Fossils reported from the northern outcrops include *Pillingsella sp.*, *Orthidae*, *Modiolopsis sp.*, *Bingula sp.*, *Orthoceras sp.*, *Endocera sp.*, *Selenopeltis buchii*, and *Cruziana furcifera*.

In Khlesia-1, the lowermost 1,500 meters (m) of section, are assigned to the Middle Ordovician and are attributed to the upper part of the Khabour Formation (Gaddo and Parker, 1959, unpublished report;

| ASSEMBLAGE OF PALYNOFORMS |              |                                       |                   | CHITINOZOA  |   |   |
|---------------------------|--------------|---------------------------------------|-------------------|---|---|---|
| SYSTEM                    | SERIES       | LITHOLOGY                             | INFORMAL BIOZONES | SPORES  | ACRITARCHS  | CHITINOZOA  |
| PERMIAN                   | Upper        | Chia<br>Zaini                         | "P1"              | S. lateralis, I. labrata, P. novicus, V. densus<br>S. richteri, P. papilionis, F. fimbriatus<br>Osmandacites spp., Campototriletes spp.<br>D. insolitus, F. zapfei, F. millichi   |   |   |
|                           |              |                                       | "P2"              | D. levis, P. incomptus, C. hartungiana,<br>G. microgranifer, C. micaceus, L. cestus,<br>E. aggrensis, M. tentula, C. saturni,<br>D. solidus, P. minutus, T. obscura   |   |   |
| CARBONIFEROUS             | Upper        | Ga'ara                                | "CP1"             | D. priddi, C. mutabilis, C. pallida L. commissuralis,<br>R. aculeata, C. plicata, Densosporites sp.,<br>A.C. rarus, S. arenaceus, S. triangulatus,<br>K. ornatus, V. vallatus, L. trileta, P. westphalensis,<br>Q. diversiformis, P. sewardii | C. pilar, D. denticulata<br>Leidofusa spp., Geron sp.   |   |
|                           |              |                                       | "DC1"             | A. splendidus, S. lybicus, D. emstenensis<br>D. muresdensis, Ambitsporites spp.,<br>Retusobiletes spp.  | N. carminae, C. pilar, L. laevigata<br>D. milliepedi, D. denticulata<br>V. dilatispinosa, L. estrecha |   |
| DEVONIAN                  | ?            | Hatur<br>Ora<br>Kaista /<br>Pirispiki | "S1"              | A. avitus, A. chultus<br>E. rotatus, A. miserabilis   | D. furcata, D. bispinosa,<br>O. eoplanktonica, Q. fantasticum,<br>D. maranhsensis, D. monterosae      | A. ancyrea, P. carminae, P. saharica<br>S. sphaerocephala, A. valentini,<br>A. echinata |
|                           |              |                                       | "S2"              | Y. subglobosum, V. irroratum,<br>V. oklahomense, E. striata, V. setosapelei   | F. fungiformis, C. armilata   |   |
| SILURIAN                  | Ludlovian    | Suffi                                 | "S1"              |   |   |   |
|                           |              |                                       | "S2"              |   |   |   |
| Wenlockian                | Llandoveryan | Akkas                                 | "S2"              |   |   |   |
|                           |              |                                       | "O1"              |   |   |   |
| ORDOVICIAN                | Ashgillian   | Khabour                               | "O1"              |   |   | A. nigerica   |
|                           |              |                                       | Caradocian        |   |   |   |
|                           |              |                                       |                   | * Expected  |   |   |

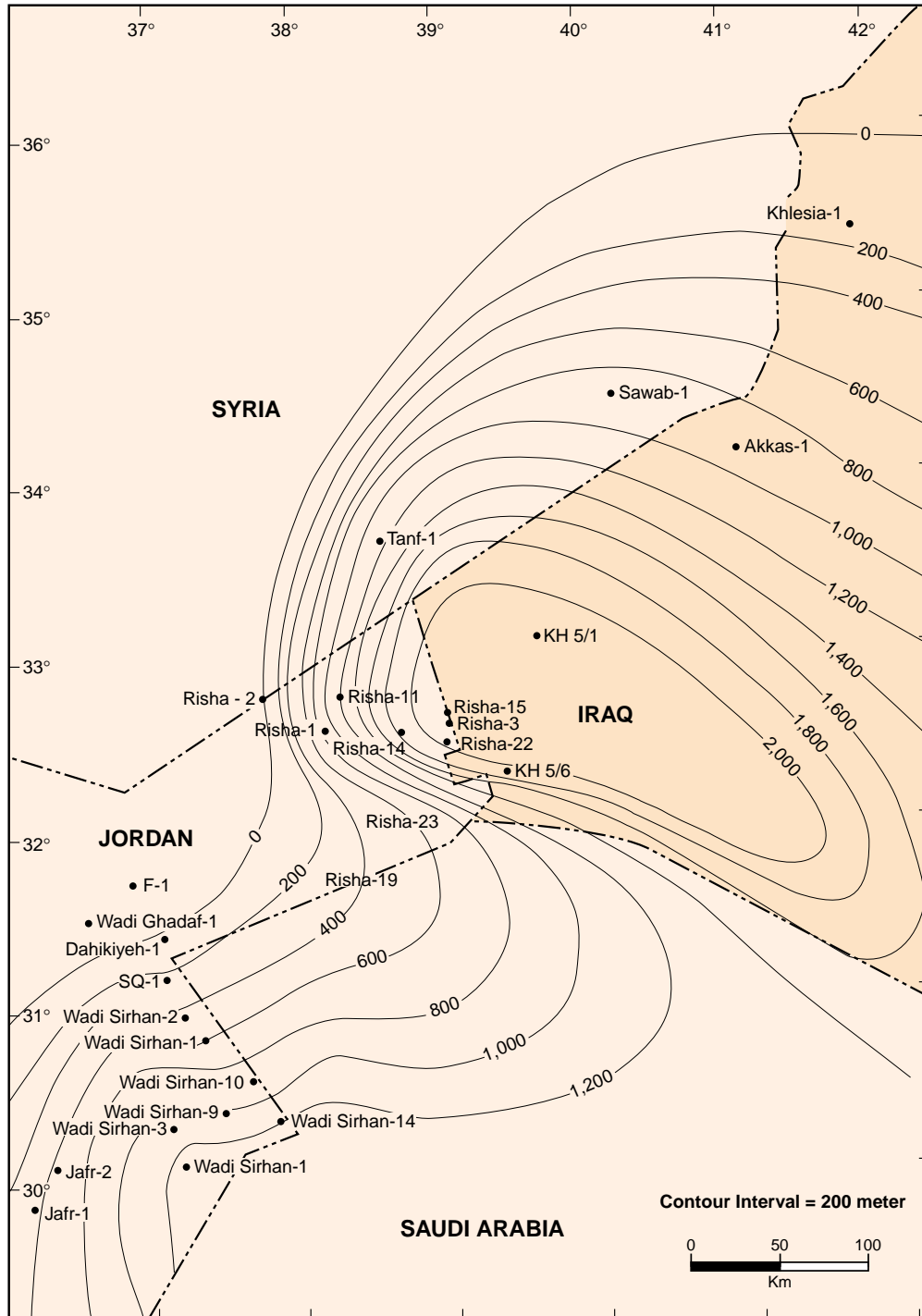
**Figure 3: General Paleozoic succession of Iraq based on published palynological data, particularly from the subsurface.**



**Figure 4: General stratigraphic scheme for the Paleozoic rocks of the Northeastern Arabian Plate: Jordan (modified from Andrews et al. 1991; Powell et al. 1994); West Iraq (after Van Bellen et al., 1959; Buday, 1980; Al-Haba et al., 1994) and Saudi Arabia (after Al-Laboun, 1986; Vaslet, 1990; McGillivray and Husseini, 1992), together with the predicted scheme for the Southwestern Desert of Iraq.**

Al-Haba et al., 1994). The lithology shows some differences with the outcrop; such as the intercalation of dolomite and limestone within the siliciclastic sequences. Ordovician rocks have also been reported in Akkas-1 (1,912 m thick; Al-Haba et al., 1994). However, both the Akkas-1 and Khlesia-1 wells did not reach the base of the Ordovician section which could therefore be much thicker (Al-Haba et al., 1994).

The Khabour Formation was deposited in an alluvial continental to shallow marine environment which prevailed over the entire eastern part of the Arabian Plate (Seilacher, 1963). The equivalent rock units in eastern Jordan are up to 3,000 m thick and correspond to the lower part of the Khreim Group (Selley, 1970; Andrews et al., 1991; Beydoun et al., 1994; Powell et al. 1994). In Saudi Arabia the equivalent rocks are the Qasim Formation (Vaslet, 1987; McGillivray and Husseini, 1992).



**Figure 5: Isopach map of the Silurian Akkas formation in the Western Desert of Iraq, and its equivalents: Mudawara Formation in Jordan, Qalibah Formation in northern Saudi Arabia and Tanf Formation in Syria (modified from Al-Haba et al., 1994).**

### Silurian: “Akkas Formation”

In Iraq, Silurian rocks are not known in outcrops: however, they have been encountered in several boreholes in the Western Desert (Al-Haba et al., 1994). Directly overlying the Ordovician Khabour Formation, this interval is informally known as the Akkas formation.



- (1) In the water well **KH5/1** (Figures 1, 2 and 5) Ludlovian rocks, 270 m thick, were penetrated without encountering the base of the Silurian sequence.
- (2) In the water well **KH5/6** (Figures 1, 2 and 5), Upper Llandoveryan and Ludlovian rocks with a total thickness of 570 m were penetrated without encountering the base of the Silurian succession.
- (3) In **Khlesia-1** (Figures 1, 2 and 5) a complete sequence of Silurian rocks was penetrated; however the thickness is reported to be only 151 m.
- (4) In **Akkas-1** (Figures 1, 2 and 5), a complete Silurian succession, 853 m thick, was encountered.

The presence of Silurian rocks in these widely-distributed boreholes indicates that the Silurian sequence was deposited over the whole of Western and, by extrapolation, many parts of the Southwestern Iraq (Figure 5). The equivalent rocks in Syria are the Tanf Formation which is up to 1,100 m thick. In northern Saudi Arabia, the Silurian Qalibah Formation also reaches thicknesses of over 1,000 m (Abu-Ali et al., 1991; Mahmoud et al., 1992; Aoudeh and Al-Hajiri, 1995). Based on correlations with eastern Jordan, Al-Haba et al. (1994) concluded that the Silurian rocks may be up to 2,000 m thick in the Rutbah-Ga'ara Uplift area of the Western Desert (Figure 5).

The lowest part of the Silurian section consists of a "hot" shale which is the main Paleozoic source rock in Saudi Arabia (Mahmoud et al., 1992). In the Akkas-1 well a 65 m thick section was identified by Al-Haba et al. (1994) and shown in Figure 6.

The Silurian "hot" shale was deposited during the transgression which followed the deglaciation of Gondwana. Deposition took place in a broad anoxic marine environment which extended over the greater part of Arabia and North Africa (Mahmoud et al., 1992; Beydoun, 1993; Cole et al., 1994; Aoudah and Al-Hajiri, 1995; Macgregor, 1996). Thick sequences of Silurian deposits, in many parts of Arabia, were subsequently eroded from elevated blocks uplifted by the Hercynian tectonic event (Alsharhan and Kendall, 1986; Hussein, 1991b, 1992).

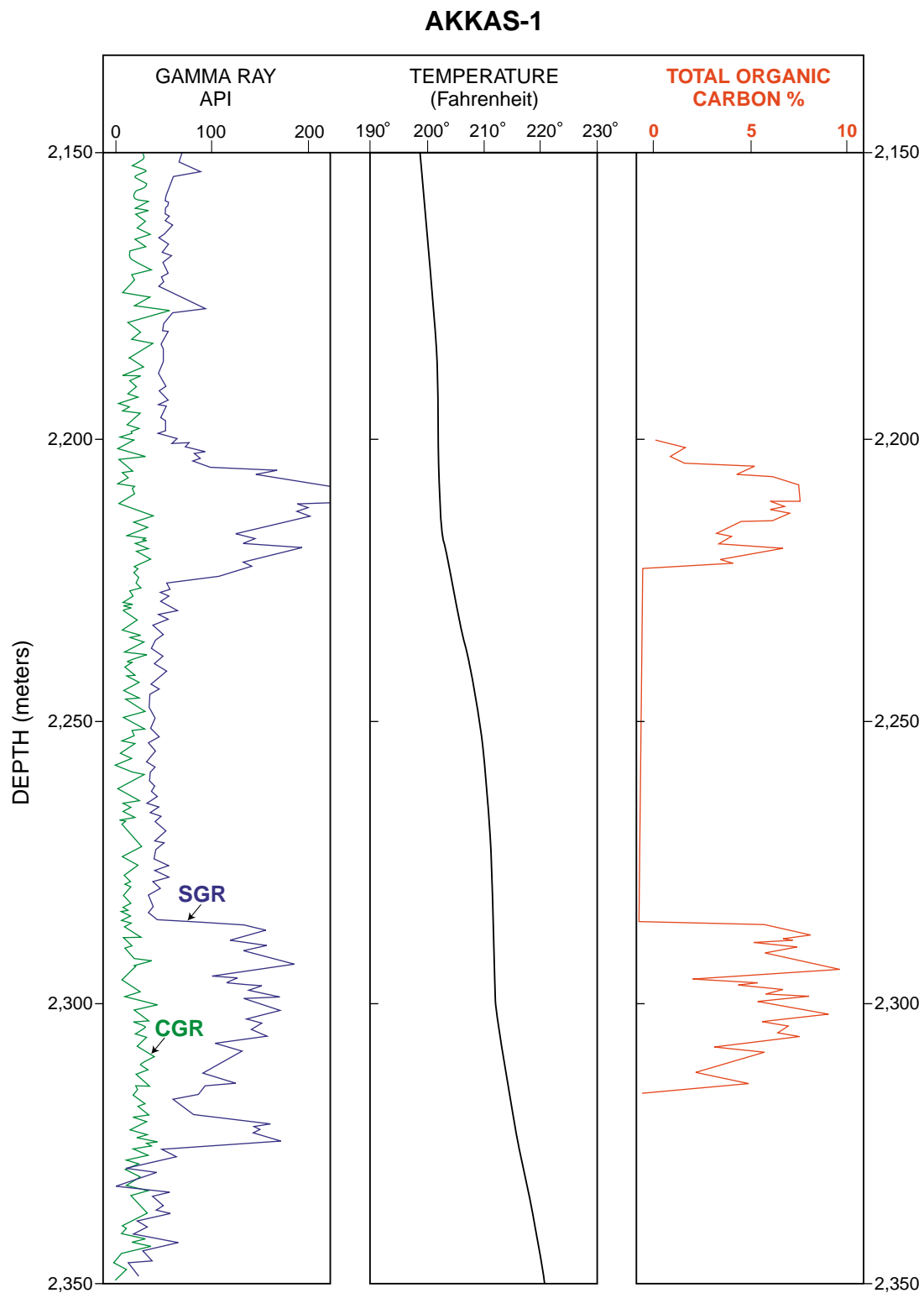
### **Devonian and Lower Carboniferous: Pirispiki Red Beds, Chalki Volcanics, Kaista, and Ora Shale Formations**

The **Chalki Volcanics** are defined as a formation; however they could also be considered a part of the **Pirispiki Red Beds Formation** (Buday, 1980). The volcanics are composed of altered olivine basalt flows (Wetzel, 1952) with intercalations of ash and some shales and siltstones (Buday, 1980). The Pirispiki Formation consists of siliciclastic deposits including quartzite sandstone, marly sandstone, siltstone, shales and conglomerates (Wetzel, 1950). The thickness of the Pirispiki Formation is about 80 m, while the Chalki Volcanics may reach up to 20 m in the northern outcrop area. The depositional environment of the Pirispiki Formation is interpreted as continental and its age is probably Devonian (Van Bellen et al., 1959), and more specifically Late Devonian (Seilacher, 1963).

The **Kaista Formation** is described by Morton (1950-1951) and Wetzel and Morton (1952, unpublished report in Van Bellen et al., 1959). It is composed of siltstones, silty shales with some quartzites in the lower part, and argillaceous limestones in the upper part. The age of the Kaista Formation is considered Late Devonian (Famennian).

The thickness of the Kaista Formation reaches 70 m in the northern outcrop area. The lower part of the formation represents a transitional facies change from continental to marine clastics, whereas the upper part is purely of shallow marine origin (Buday, 1980). Since correlative facies of the Kaista Formation are extremely rare, Buday (1980) suggested merging the lower part of the Kaista Formation with the terrigenous Devonian Pirispiki Formation and the upper part with the marine calcareous Ora Shale Formation.

The **Ora Shale Formation** is described from northern Iraq as dark calcareous shales interbedded with silty marls, lenticular organic limestones and fine-grained limestones, with a thickness of up to 220 m (Wetzel, 1952). Buday (1980) concluded that it was deposited on a shallow marine shelf and that it is widespread in northern Iraq but may not be present in the southern part of the country. Fossils are



**Figure 6: Gamma Ray log, temperature and Total Organic Carbon (TOC) contents of the Silurian “hot” shale at the base of the “Akkas” formation in the Akkas-1 well in the Western Desert of Iraq (see Figure 1 for location; modified from Al-Haba et al., 1994). The Akkas formation occurs between 1,456 and 2,326 meters below the derrick floor (870 meters thick). Geochemical analysis of the basal “hot” shale indicate a maximum TOC of 16% by weight. The “hot” shale is believed to be the source rock of the light oil and sweet gas discovered in Akkas field.**

relatively abundant (Van Bellen et al., 1959) and include *Spirifer vernenilli* in the basal parts and *Avonia praelongus* and *Spirifer julii* near the top. The Ora Shale is assigned a Late Devonian to ?early Tournasian age (Wetzel, 1952, unpublished report in Van Bellen et al., 1959).

In the subsurface, Devonian sections have been penetrated in several wells. In Khlesia-1, a section corresponding to the Kaista and Ora formations, with a Late Devonian to possibly Early Carboniferous age, is 257 m thick (Gaddo and Parker, 1959; Al-Haba et al., 1994).

In Rumaila-172, Al-Siddiki et al. (1994) correlate Devonian carbonates and clastics to the Saudi Arabian Tawil and Jauf formations and refer to them as "Jauf equivalents" (Figures 2 and 4). Overlying the "Jauf equivalents", Upper Devonian deposits may correspond to the Ora and Harur formations (Al-Siddiki et al., 1994). These may correlate to the Devonian fluvial clastics of the Jubah Formation (McGillivray and Husseini, 1992) of Saudi Arabia.

Proposed correlations by Al-Siddiki et al. (1994) of the Devonian units encountered in deep wells in southeast Iraq (e.g. Rumaila-172) with those described by Khan (1989) from the deep Burgan-399 well, in Kuwait, is doubtful. The pre-Khuff rocks in Burgan-399 are steeply-dipping (nearly 60 degrees) and are therefore most likely to be Precambrian (Carman, 1996; Al-Husseini, 1998, personal communication) rather than equivalent to the Tabuk Formation of Saudi Arabia (Khan, 1989). Any pre-Permian rocks deposited over the Burgan structure were probably eroded during the Late Paleozoic Hercynian uplift.

Other subsurface Devonian sections were reported by Al-Haba et al. (1994). These consist of clastics of Early Devonian (? Gedinian) age, 80 m thick, in KH5/6; Upper Devonian (Famennian) in KH5/1; and in Akkas-1 (Figure 2).

### **Carboniferous and Lower Permian Harur Limestone and Lower Ga'ara Sandstone Formations**

The **Harur Limestone Formation** is dated as Early Carboniferous (early Tournasian) and consists of organic detrital limestone interbedded with thin micaceous shales (Wetzel and Morton, 1952, unpublished reports in Van Bellen et al., 1959). This formation was deposited in a neritic marine environment characterized by reefs and fore-reef facies (Buday, 1980). It overlies the Ora Shale Formation conformably, but the top of the formation is marked by a break in sedimentation.

In the subsurface, sandstones, shales and carbonates of Late Devonian and Early Carboniferous (Tournasian) age have been reported by Al-Haba et al. (1994) from a few wells of the Western Desert. In KH5/1 and Akkas-1 these are 600 and 358 m thick, respectively (Figure 2) and correspond to the Kaista, Ora and Harur formations.

In Khlesia-1, Al-Haba et al. (1994) identify a section, 387 m thick, as the Ora and Harur formations. This interpretation differs from Gaddo and Parker (1959) where the thickness of the Upper Devonian-Lower Carboniferous Ora Shale Formation, in the same well, is reported as 486 m. Gaddo and Parker report the Ora Formation to have some limestone and dolomite interbeds. In addition, they report that in well Khlesia-1, the Lower Carboniferous Harur limestone is characterized by interbedded dolomite, shale and siltstones. The thickness of this formation doubles from about 60 m in the north, to 120 m in the Khlesia area. The Harur Limestone appears to be eroded towards southern Iraq due to the Hercynian tectonic event.

Upper Carboniferous rocks (Westphalian to Early Stephanian age) are only reported in KH5/1 (Al-Haba et al., 1994). These sandstones and shales are about 850 m thick and constitute the lower parts of the **Ga'ara Formation**. The latter formation is widely-distributed throughout the Western Desert, and most probably the Southwestern Desert, and extends in age up to the Early Permian (Buday, 1980).

In the water wells of the Rutbah-Ga'ara Uplift area, some parts of the Lower Permian Ga'ara Sandstone Formation occur at shallow depth intervals of 60 to 100 m (Al-Haba et al., 1994). These clastics may be similar to the pre-Unayzah and Unayzah clastics of Lower Permian age in Saudi Arabia (Al-Laboun, 1987; McGillivray and Husseini, 1992).

### **Permian: Upper Ga'ara Sandstone and Chia Zairi Formations**

In wells Atshan-1 and Jabal Kand-1, near Mosul in northern Iraq, and West Kifil-1 (Figures 1 and 2), sandstones and shales underlying carbonates of the Upper Permian Chia Zairi Formation are of Middle Permian age, and hence may be correlated with the upper parts of the Ga'ara Sandstone Formation.

The Chia Zairi Formation, in northern Iraq, is composed of limestones, sometimes cherty, and dolomites (Wetzel, 1950). The siliciclastic content in these carbonates increases in the Foot Hill Zone (e.g. Atshan-1). The upper contact is gradational with Triassic rocks. Its thickness varies between 750 m to 800 m in the northern outcrops. The age of the formation is documented as Permian according to the coral and algal faunas of the Middle-Late Permian (Hudson, 1958). However, the uppermost parts of the formation contain some Early Triassic fauna (Buday, 1980).

In southern Iraq, Upper Permian carbonates encountered in deep wells correspond to the Chia Zairi Formation. The thickness of the Chia Zairi Formation in West Kifil-1 is 502 m (Al-Haba et al., 1994) and in Rumaila-172 it is 460 m thick (Al-Siddiki et al., 1994). This formation forms a continuation of the Khuff Formation of the Arabian Gulf (Sharief, 1983; Khan, 1989; Kashfi, 1992; Alsharhan et al., 1993; Al-Jallal, 1995).

The Chia Zairi Formation (Khuff Formation) was deposited in a transgressive neritic sea with lagoonal conditions prevailing during its final stages of sedimentation (Buday, 1980). The transgression corresponds to the deglaciation of Gondwana and the rapid drift of the Arabian Plate into warmer latitudes (Husseini, 1992; Beydoun, 1993).

## **PALEOZOIC PETROLEUM SYSTEM**

The main Paleozoic source rocks in the Middle East are the Lower Silurian "hot" shales (Mahmoud et al., 1992). Other minor source rocks are believed to be shales of Ordovician, Devonian and Permian-Carboniferous ages. In Iraq, the Lower Paleozoic source rocks are expected to be restricted to the Western Desert and as-yet undefined parts of Southwestern Desert. Any Upper Paleozoic source rock potential should increase eastwards based on the overburden-cover thickness (Figure 7). The following is a brief summary of the properties of the Paleozoic source rocks encountered in Iraq.

### **Ordovician Source Rocks**

In Khlesia-1 and Akkas-1, highly-mature, marine, organic-rich Ordovician shales were encountered. These are classified as good source rocks with Total Organic Carbon Content (TOC) of 0.9 to 5% by weight. Al-Haba et al. (1994) predicted that these could generate light hydrocarbons in the Akkas-1 and Khlesia-1 area. Similar potential source rocks may be present in the western parts of the Southwestern Desert near Saudi Arabia.

### **Silurian "Hot" Shale: Main Source Rock**

The Lower Silurian "hot" shale is the main source rock within the Paleozoic succession of the Western Desert (Al-Haba et al., 1994). The "hot" shales are found in Akkas-1 and Khlesia-1 with an average thickness of about 65 m (Figure 6), although the entire differentiated Silurian rock units in Khlesia-1 doesn't exceed 151 m thickness.

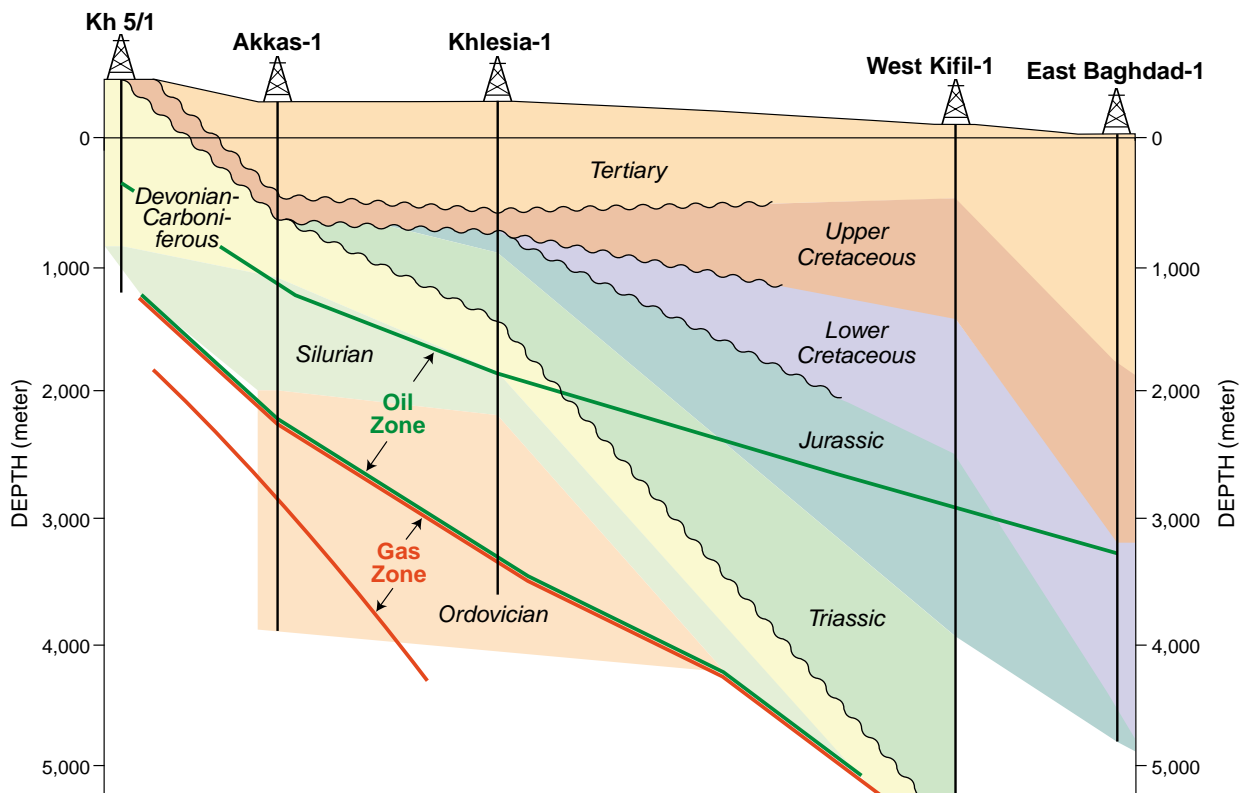
The Silurian "hot" shales contain some exceptionally high levels of TOC throughout Arabia and northern Africa. In Akkas-1, the TOC ranges between 0.96% to 16.62%, and in Khlesia-1 it ranges from 1.0% to 9.94%, with a hydrocarbon potential of about 49 kg HC/ton (Al-Haba et al. 1994). The geochemical analysis of the "hot" shales in Khlesia-1, shows similar characteristics (Salleh and Mokhtar, 1995).

The petrographic analysis of the kerogen extracted from these shales revealed their marine origin, as they are very rich in organic components such as algal amorphous, graptolites and chitins. It is also worth mentioning that the X-ray diffraction mineralogical analysis, together with Scanning Electron Microscopic study of a sample of this shale (from Khlesia-1) showed that it is rich in carbonates (particularly dolomite) and pyrite, in addition to quartz and clays. Similar petrological characteristics have also been reported from the Silurian “hot” shale of Algeria by Aqrawi (1996b).

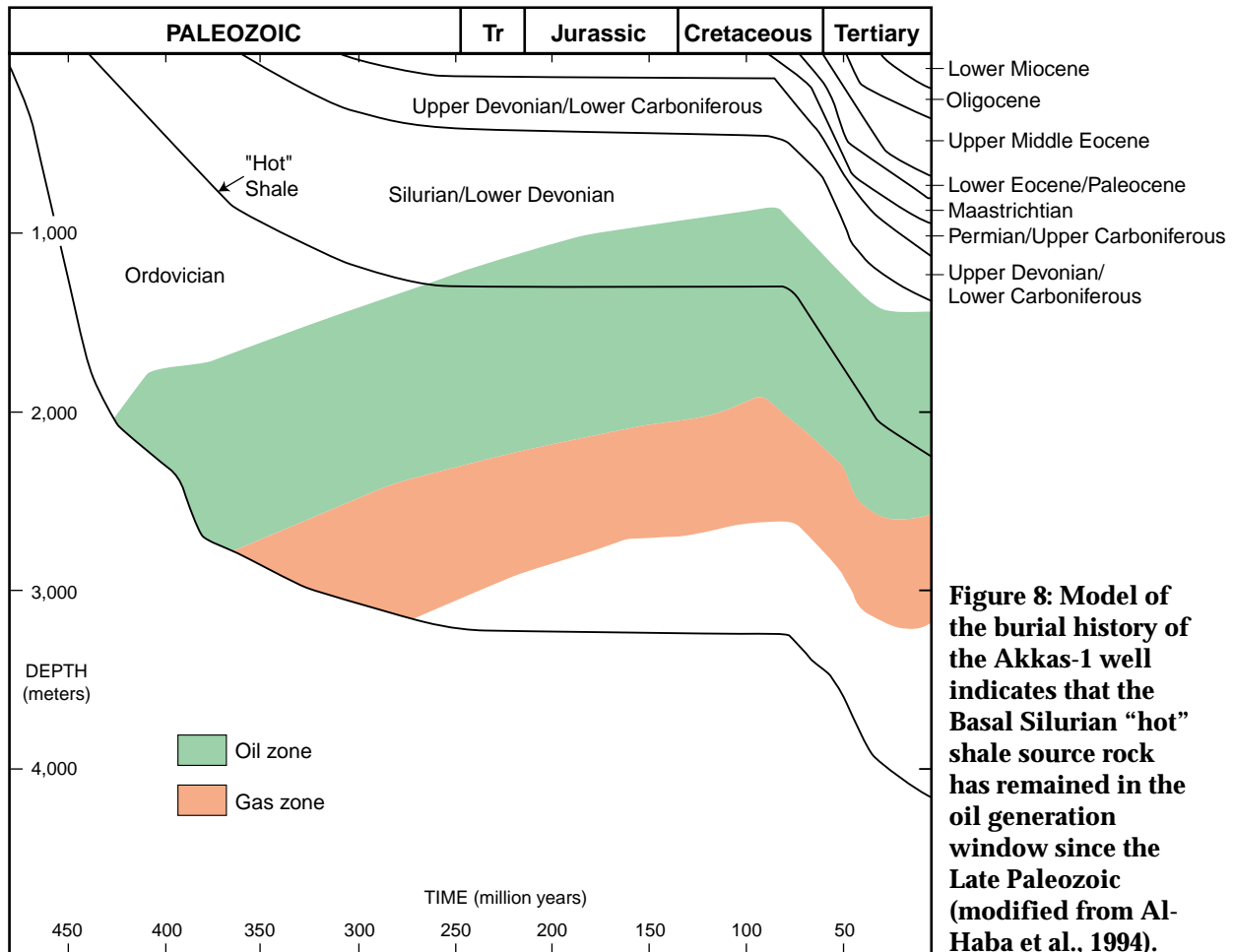
The potential for these shales to generate hydrocarbons is controlled by their burial and thermal history (Figures 7 and 8). As a result, in some deeper eastern areas of the Southwestern Desert they could be over-mature, whereas in other shallower western areas they might be premature. However, the critical factor controlling the potential presence of commercial hydrocarbons in the Paleozoic of the Southwestern Desert is likely to be the interplay between (a) Hercynian-age horsts and grabens, evidence for which can be traced northwards from Saudi Arabia to the Saudi-Iraq border (Johnson and Stewart, 1994); and (b) the presence of Silurian (and/or Upper Paleozoic) source rocks in the grabens, their maturation history, and the presence of commercial reservoirs across or adjacent to the horsts.

The Paleozoic hydrocarbons of the Western Desert of Iraq are almost free of H<sub>2</sub>S and composed of up to 85% Methane and Ethane (Al-Haba et al., 1994). Similar characteristics are reported for both the extracts of the Silurian “hot” shales (e.g. Cole et al., 1994) and the hydrocarbons being produced from the Paleozoic reservoirs of Central Saudi Arabia (McGillivray and Husseini, 1992) and Jordan (Beydoun et al., 1994).

The analysis of kerogens from the Lower Silurian “hot” shale of the Western Desert (Al-Haba et al., 1994) revealed that the saturated and aromatic hydrocarbons exceed 96% of their components, which characterize them with a very low molecular weights (C<sub>3</sub>-C<sub>20</sub>) and limited asphaltic materials (about 3.89%).



**Figure 7: Structural cross-section and hydrocarbon maturity levels for selected boreholes from west, central and southern Iraq (see Figure 1 for location; modified from Al-Haba et al., 1994).**



**Figure 8: Model of the burial history of the Akkas-1 well indicates that the Basal Silurian “hot” shale source rock has remained in the oil generation window since the Late Paleozoic (modified from Al-Haba et al., 1994).**

The marine origin of these shales increases their hydrocarbon generating potential. In addition, the high content of iron ions, in such marine siliciclastic deposits, resulted in the early diagenetic formation of pyrite and consequently reduce the sulfur contents in the generated hydrocarbons. The high levels of thermal maturity, on the other hand, probably caused the fragmentation of long-chain hydrocarbons into short-chain ones which could also have reduced the sulfur content and generated gases and very light oils in Akkas field.

### Devonian Source Rocks

The average TOC of the Devonian Ora shales is 1.48% in Akkas-1 and 3.45% in Khlesia-1. The organic matter is composed of woody fragments, lignins, chitins, pollens and spores which are mostly of continental origin (Al-Haba et al., 1994). As a result, these source rocks are gas-prone rather than oil-prone when entering the maturity zone, such as in areas to the east of the Ga’ara, Akkas-1 and Khlesia-1, and most probably in the entire central parts of Southwestern Desert.

### Upper Carboniferous-Lower Permian Source Rocks

Geochemical analysis of the shaly beds of the Upper Carboniferous-Lower Permian Ga’ara Sandstone Formation in Jabal Kand-1, Atshan-1 and West Kifil-1 indicate the occurrence of continental organic matter with an average TOC of about 1% (Al-Haba et al., 1994). The geochemical analysis of the Chia

Zairi Formation in Jabal Kand-1, Atshan-1, West Kifil-1 and Diwan-1 show reasonable hydrocarbon potential, particularly in the lower shaly part which is about 20 m thickness (Al-Haba et al., 1994). These shale beds may be good potential source rocks in many parts of the Southwestern Desert.

### **Reservoirs and Trap Mechanism**

The main Paleozoic reservoir rocks in the Western Desert of Iraq are similar in age and facies to those found in East Jordan (Risha field) and central and northern Saudi Arabia. These are the sandstones of the Ordovician upper Khabour and Silurian Akkas formations. In the Southwestern Desert, additional reservoirs may be found in the Carboniferous Ga'ara sandstones, and the carbonates of the Permian Chia Zairi Formation.

Akkas-1 discovered high gravity oil (42°API) in the Silurian Akkas sandstone reservoirs in 1993. The well also encountered sweet gas in the upper sandstones of the Ordovician Khabour Formation (Al-Haba et al., 1994). Based on the interpretation of a seismic line (Al-Haba et al., 1994) Akkas field appears to be a structural trap which is controlled by basement faulting. The faults may be the main reason for the higher thermal gradient encountered in Akkas-1 (Al-Hadithi, 1994).

The model of the burial history and thermal maturity of the Silurian "hot shale" in Akkas-1 shows that expulsion and migration of the hydrocarbons started in the Permo-Triassic, around 250 million years ago (Ma) (Figure 8, Al-Haba et al., 1994). In both Iraq and Saudi Arabia the direction of migration is towards the west (Cole et al., 1994); however, the start of oil expulsion in northern Saudi Arabia was earlier in the Devonian (360 Ma).

Al-Haba et al. (1994), based on seismic interpretations, concluded that the faulted and fractured Paleozoic strata along the eastern flank of the Akkas field, were the main pathways for these hydrocarbons to migrate downwards from the Lower Silurian source rocks to the Ordovician upper Khabour fractured sandstone reservoir. Such Paleozoic reservoirs with similar pathways are suspected in Saudi Arabia (e.g. Husseini, 1991a), and may also exist in the Southwestern Desert of Iraq.

### **Hydrocarbon Potential**

By considering an average TOC of 6% for the Silurian "hot" shale, with an average thickness of 65 m, Al-Haba et al. (1994) estimated that there would be up to 16 billion barrels of hydrocarbons generated from the areas between Akkas-1 and Khlesia-1 (an area of about 20,000 sq km).

The thermal system of both western Iraq (Al-Haba et al., 1994) and southern Iraq (Al-Siddiki et al., 1994), and northern Saudi Arabia (Cole et al., 1994) shows an increase in the maturity levels of these source rocks eastwards (Figure 7). This would restrict the prospective exploration regions to the Western and Southwestern Deserts where hydrocarbon entrapment would occur at commercial depths of less than 4,000 m, such as in the Ga'ara-Rutbah Uplift and Akkas-1 areas (Al-Haba et al., 1994).

However, in other deeper regions, younger source rocks with lower potential (e.g. Devonian Ora Shale) may have generated hydrocarbons to charge the Carboniferous and Permian reservoirs in commercial quantities.

### **CONCLUSION**

The Paleozoic evolution of the Western and Southwestern Deserts of Iraq, particularly during the Early Paleozoic, resembles that of eastern Jordan and northern Saudi Arabia, respectively. In Iraq, however, accurate mapping of the structuration resulting from the Late Paleozoic Hercynian tectonic event (and other hiatuses) will be critical in delineating exploration fairways.

The Lower Silurian marine "hot" shale is the main source rock for the Paleozoic hydrocarbons discovered in the Western Desert (Akkas-1) and it could be widely distributed throughout the western part of the Southwestern Desert. Additional potential source rocks could be shales in the Ordovician Khabour and Upper Devonian to Lower Carboniferous Ora formations.

Ordovician, Silurian, Carboniferous and Permian reservoirs, in combination with the above mentioned source rocks, and sealed by either of the two regional seals (Lower Silurian shales and the Permian evaporites) or other local seals (such as dense beds) provide numerous exploration opportunities.

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## REFERENCES

- Abu-Ali, M.A., U.A. Franz, J. Shen, F. Monnier, M.D. Mahmoud and T.M. Chambers 1991. *Hydrocarbon Generation and Migration in the Paleozoic Sequence of Saudi Arabia*. SPE Middle East Oil Show, Bahrain, November 1991, p. 819-132.
- Al-Gailani, M. 1996. *Hydrocarbon Potential of Iraq*. GeoArabia (Abstract), v. 1, p. 102.
- Al-Haba, Y., A. Al-Samarrai, F. Al-Jubori, N.N. Georgis, I.M. Ahmed 1994. *Exploration for the Paleozoic Prospects in Western Iraq, Part 1: Exploration of the Paleozoic System in Western Iraq*. Proceedings of the Second Seminar on Hydrocarbon Potential of Deep Formations in the Arab Countries (OAPEC), Cairo 10-13 October (in Arabic).
- Al-Hadithi, N. 1994. *High Thermal Grade in the Paleozoic Rocks of Western Iraq*. Third Geological Conference on the Middle East and Fifth Jordanian Geological Conference, Amman, 3-5 October, 1994, Abstract (in Arabic), p. 129.
- Al-Jallal, I.A. 1995. *The Khuff Formation: Its Reservoir Potential in Saudi Arabia and other Gulf Countries; Depositional and Stratigraphic Approach*. In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94, Gulf PetroLink, Bahrain, p. 103-119.
- Al-Laboun, A.A. 1986. *Stratigraphy and Hydrocarbon Potential of the Paleozoic Succession in both Tabuk and Widyah Basins, Arabia*. In M.T. Halbouty (Ed.), Future Petroleum Provinces of the World. American Association of Petroleum Geologists Memoir no. 40, p. 373-397.
- Al-Laboun, A.A. 1987. *Unayzah Formation: A New Permian-Carboniferous Unit in Saudi Arabia*. American Association of Petroleum Geologists Bulletin, v. 71, p. 29-38.
- Al-Sakini, J.A. 1992. *Summary of Petroleum Geology of Iraq and the Middle East*. Northern Oil Company Press, Kirkuk, (in Arabic) 179 p.



- Alsharhan, A.S. and C.G.St.C. Kendall 1986. *Precambrian to Jurassic Rocks of Arabian Gulf and Adjacent Areas: Their Facies, Depositional Setting, and Hydrocarbon Habitat*. American Association of Petroleum Geologists Bulletin, v. 70, p. 977-1002.
- Alsharhan, A.S., A.E.M. Nairn and A.A.Mohammed 1993. *Late Paleozoic Glacial Sediments of the Southern Arabian Peninsula: Their Lithofacies and Hydrocarbon Potential*. Marine and Petroleum Geology, v. 10, p. 71-78.
- Al-Siddiki, A.A., S.N. Hammodi, A.H. Al-Khersan 1994. *Exploration of the Deep Paleozoic Prospects and Design of the Drilling Programs in Iraq*. Proceedings of the second seminar on Hydrocarbon Potential of Deep Formations in the Arab countries. OAPEC, Cairo, 10-13 October (in Arabic).
- Al-Sinawi, S.A. and A.S. Al-Bana 1992. *An E-W Transect Section through Central Iraq*. Basement Tectonics, v. 9, p. 195-200.
- Ameen, M.S. 1992. *Effect of Basement Tectonics on Hydrocarbon Generation, Migration and Accumulation in Northern Iraq*. American Association of Petroleum Geologists Bulletin, v. 76, p. 356-370.
- Amireh, B.S., W. Schneider and A.M. Abed 1994. *Evolving Fluvial-Transitional-Marine Deposition through the Cambrian Sequence of Jordan*. Sedimentary Geology, v. 89, p. 65-90.
- Andrews, I.J., O. Abu Lihie, I. Makhlof, L. Abu Saad, Y. Taani, M. Al-Bashish and A. Al-Hiari 1991. *Paleozoic Lithostratigraphy in the Subsurface of Jordan*. Subsurface Geology Bulletin No. 2, Ministry of Energy and Mineral Resources, The Hashemite Kingdom of Jordan, 75 p.
- Aoudeh, M. and A. Al-Hajiri 1995. *Regional Distribution and Chronostratigraphy of the Qusaiba Member of the Qalibah Formation in the Nafud Basin, Northwestern Saudi Arabia*. In M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94, v. 1, p. 143-154.
- Aqrawi, A.A.M. 1993. *Implications of Sea-Level Fluctuations, Sedimentation and Neotectonics for the Evolution of the Marshlands (Ahwar) of Southern Mesopotamia*. In L.A. Owen, I. Stewart and C. Vita-Finzi (Eds.), Neotectonics: Recent Advances. Quaternary Proceedings, No. 3, Quaternary Research Association, Cambridge, p. 21-31.
- Aqrawi, A.A.M. 1995. *Brackish-water and Evaporitic Ca-Mg Carbonates in Holocene Lacustrine/Deltaic Deposits of Southern Mesopotamia*. Journal of the Geological Society, London, v. 152, p. 259-268.
- Aqrawi, A.A.M. 1996a. *Carbonate-siliciclastic Sediments of the Upper Cretaceous (Khasib, Tanuma and Saïdi Formations) of the Mesopotamian Basin*. Mar. Petroleum Geology, v. 13, p. 781-790.
- Aqrawi, A.A.M. 1996b. *Sedimentological Study of Some Algerian Palaeozoic Rock Samples*. PRSS Technical Service Report for the Petronas Carigali Sdn. Bhd. (PCSB), Kuala Lumpur, Malaysia (unpublished report).
- Aqrawi, A.A.M. 1997. *The Nature and Preservation of Organic Matter in Holocene Lacustrine/Deltaic Sediments of Lower Mesopotamia, SE Iraq*. Journal of Petroleum Geology, v. 20, p. 69-90.
- Aqrawi, A.A.M., G.A. Thehni, G.H. Sherwani and B.M.A. Kareem 1998. *Mid-Cretaceous Rudist-bearing Carbonates of the Mishrif Formation: An Important Reservoir Sequence in the Mesopotamian Basin*. Iraq Journal of Petroleum Geology, v. 21, p. 57-82.
- Beydoun, Z.R. 1991. *Arabian Plate Hydrocarbon Geology and Potential - A Plate Tectonic Approach*. American Association of Petroleum Geologists, Studies in Geology no. 33.
- Beydoun, Z.R. 1993. *Evolution of the Northeastern Arabian Plate Margin and Shelf: Hydrocarbon Habitat and Conceptual Future Potential*. Revue de l'Institut Français du Pétrole, v. 48, p. 311-345.

- Beydoun, Z.R., A.R.I. Futyán and A.H. Jawzi 1994. *Jordan Revisited: Hydrocarbons Habitat and Potential*. Journal of Petroleum Geology, v. 17, p. 177-194.
- Buday, T. 1980. *The Regional Geology of Iraq. Stratigraphy and Palaeogeography*. Dar Al-Kutub Publishing House, University of Mosul, Iraq. v. 1.
- Buday, T. and S.Z. Jassim 1987. *The Regional Geology of Iraq, Tectonism, Magmatism and Metamorphism*. State Establishment of Geological Survey and Mineral Investigation, Baghdad, Iraq. v. 2.
- Carman, G.J. 1996. *Structural Elements of Onshore Kuwait*. GeoArabia: Middle East Petroleum Geosciences, v. 1, no. 2, p. 239-266.
- Cole, G.A., W.J. Carrigan, S.M. Aoudeh, M.A. Abu-Ali, M.H. Tobey and H.I. Halpern 1994. *Maturity Modeling of the Basal Qusaiba Source Rock, Northwestern Saudi Arabia*. The Arabian Journal of Science and Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, v. 19, p. 249-271.
- Gaddo, J. and D.M.F. Parker 1959. *Final Report on Well Khlesia No. 1*. MPC Report, No. FWR 28, INOC Library, Baghdad.
- Gorin, G.E., L.G. Racz and M.R. Walter 1982. *Late Precambrian-Cambrian Sediments of the Huqf Group, Sultanate of Oman*. Bulletin of the American Association of Petroleum Geologists, v. 66, p. 2609-2627.
- Hudson, J.M. 1958. *Permian Corals from Northern Iraq*. Palaeontology, v. 1, Part 3, London.
- Husseini, M.I. 1989. *Tectonic and Depositional Model of Late Precambrian-Cambrian Arabian and Adjoining Plates*. American Association of Petroleum Geologists Bulletin, v. 73, p. 1117-1131.
- Husseini, M.I. 1990. *The Cambro-Ordovician Arabian and Adjoining Plates: A Glacio-Eustatic Model*. Journal of Petroleum Geology, v. 13, p. 267-288.
- Husseini, M.I. 1991a. *Potential Petroleum Resources of the Paleozoic Rocks of Saudi Arabia*. Proceedings of the Thirteenth World Petroleum Congress. John Wiley & Sons, 2, p. 3-13.
- Husseini, M.I. 1991b. *Tectonic and Depositional Model of the Arabian and Adjoining Plates during the Silurian-Devonian*. American Association of Petroleum Geologists Bulletin, v. 75, p. 108-120.
- Husseini, M.I. 1992. *Upper Paleozoic Tectono-sedimentary Evolution of the Arabian and Adjoining Plates*. Journal of the Geological Society, London, v. 149, p. 419-429.
- Husseini, M.I. and S.I. Husseini 1990. *Origin of the Infracambrian Salt Basins of the Middle East*. In J. Brooks (Ed.), *Classic Petroleum Provinces*. Geological Society Special Publication no. 50, p. 279-292.
- Johnson, P.R. and I.C.F. Stewart 1994. *Magnetically Inferred Basement Structure in Central Saudi Arabia*. Tectonophysics, v. 245, p. 37-52.
- Kashfi, M.S. 1992. *Geology of the Permian "Super-Giant" Gas Reservoirs in the Greater Persian Gulf Area*. Journal of Petroleum Geology, v. 15, p. 465-480.
- Khan, A. 1989. *Stratigraphy and Hydrocarbon Potential of Permo-Triassic Sequence of Rocks in the State of Kuwait*. Proceedings of the First Seminar on Hydrocarbon Potential of Deep Formations in the Arab Countries. Organization of Arab Petroleum Exporting Countries (OAPEC), Abu Dhabi, p. 3-29.

- Macgregor, D.S. 1996. *The Hydrocarbon Systems of North Africa*. Marine and Petroleum Geology, v. 13, p. 329-340.
- Mahmoud, M.D., D. Vaslet and M.I. Hussein 1992. *The Lower Silurian Qalibah Formation of Saudi Arabia: An Important Hydrocarbon Source Rock*. American Association of Petroleum Geologists Bulletin, v. 76, p. 1491-1506.
- McGillivray, J.G. and M.I. Hussein 1992. *The Paleozoic Petroleum Geology of Central Arabia*. American Association of Petroleum Geologists Bulletin, v. 76, p. 1473-1490.
- Morton, D.M. 1950-51. *Stratigraphic Sections in Kurdistan*. IPC report, INOC Library, No IR/DM 3-20, Baghdad.
- Powell, J.H., B.K. Mohammed and A. Masri 1994. *Late Ordovician-Early Silurian Glaciofluvial Deposits Preserved in Palaeovalleys in South Jordan*. Sedimentary Geology, v. 89, p. 303-314.
- Powers R.W., L.F. Ramirez, C.D. Redmond and E.L. Elberg 1966. *Sedimentary Geology of Saudi Arabia, Geology of the Arabian Peninsula*. U.S. Geological Survey Professional Paper No. 560D, Washington.
- Sadooni, F.N. 1995. *Petroleum Prospects of Upper Triassic Carbonates in Northern Iraq*. Journal of Petroleum Geology, v. 18, p. 171-190.
- Sadooni, F.N. 1996. *Stratigraphy and Lithological Characteristics of Upper Cretaceous Carbonates in Central Iraq*. Journal of Petroleum Geology, v. 19, p. 271-288.
- Sadooni, F.N. 1997. *Stratigraphy and Petroleum Prospects of Upper Jurassic Carbonates in Iraq*. Petroleum Geoscience, v. 3, p. 233-243.
- Salleh, Z. and N. Mokhtar 1995. *Final Results on Organic Geochemical Analysis of the Qusaiba Shale, Iraq*. Petronas Research and Scientific Services (PRSS) Technical Service Report for PCSB. (Unpublished Report)
- Seilacher, A. 1963. *Kaledonischer Unterbau der Irakiden*. Neues Jahrb. Geol. Palent. Abt. A. Monatshefte, No. 10, Stuttgart.
- Sharief, F.A. 1983. *Permian and Triassic Geological History and Tectonics of the Middle East*. Journal of Petroleum Geology, v. 6, p. 95-102.
- Selley, R.C. 1970. *Ichnology of Paleozoic Sandstones in the Southern Desert of Jordan, a Study of Trace Fossils in their Sedimentologic Context*. In T.P. Crimes and J.C. Harper (Eds.), Trace Fossils. Liverpool Geological Society, v. 2. p. 159-169.
- Selley, R.C. 1996. *Sequence Stratigraphy of Lower Paleozoic Clastic Reservoirs. A Short Course Manual*. Presented for Petronas Carigali Sdn. Bhd. (PCSB) on 10-11 July, Kuala Lumpur, Malaysia.
- Van Bellen, R.C., H.V. Dunnington, R. Wetzel and D.M. Morton 1959. *Iraq, (Mesozoic and Paleozoic)*. In L. Dubertret (Ed.), Lexique Stratigraphique International, V. III Asie. Centre National de la Recherche Scientifique, Paris, 333 p.
- Vaslet, D. 1990. *Upper Ordovician Glacial Deposits in Saudi Arabia*. Episodes, v. 13, p. 147-161.
- Wetzel, R. 1950. *Stratigraphy of the Amadiya Region*. MPC Report, INOC Library, No. TR/RW 12, Baghdad. (Internal Report)
- Wetzel, R. 1952. *Stratigraphic Survey in Northern Iraq*. MPC Report, NIMCO Library, No. 139, Baghdad. (Internal Report)

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