An assessment of the gas generation potential of the Ordovician Khabour Formation, Western Iraq

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Keywords: acritarchs, Ordovician, Khabour Formation, Iraq, maturation assessment.

Abstract: Well-preserved acritarch and chitinozoan assemblages were recovered from 106 core and cutting samples from the Ordovician Khabour Formation in the Akkas-1 and Khleisya-1 boreholes of Western Iraq. The acritarchs include 14 genera and 41 species. Common taxa include Baltisphaeridium constrictum, B. echinatum, Multiplicisphaeridium bifurcatum, M. irregulare, Orthosphaeridium rectangulare, O. ternatum, Veryhachium lairdii, and V. trispinosum. The chitinozoan assemblages are comprised of six genera and 22 species, including Conochitina intermedia, Cyathochitina campanulaeformis, Desmochitina minor, and Rhabdochitina magna. Based on the acritarch and chitinozoan species recovered, five palynozones are recognized. Amorphogen dominates the kerogen component of the palynofacies in the lower part of the Khabour Formation, changing to mainly melanogen in stratigraphically higher levels in the boreholes.

Interpretation of gas generation potential is based on maturation assessment according to the Thermal Alteration Indices (TAI) for Baltisphaeridium constrictum, Orthosphaeridium ternatum, and Dixiallophasis sp. which have a TAI of 3.8 as indicated by their dark brown color. Maturation levels indicate source potential for wet gas and condensates from Caradoc-age strata at depths between 2750-3000 m, and dry gas from Llanvirn-age strata at depths between 3570-3650 m for borehole Akkas-1 only. These gas-potential source rocks have TOC values between 0.5-1.0% by weight, highly biodegraded and abundant amorphous organic matter (70-75% amorphogen), and gas-prone type B kerogen. This organic matter is thus capable of generating wet gas and condensates that could be trapped in suitable reservoir facies within the same formation.

Based on palynologic analysis, deposition of the Khabour Formation in the Akkas-1 borehole ranged from an inner to outer neritic marine environment. Deposition of the Khabour Formation for the Khleisya-1 borehole was seemingly restricted to the outer neritic marine realm.

INTRODUCTION

The Khabour Formation comprises both the oldest exposed formation in the Amadia District, Northern Iraq (BELLEN et al., 1959) and the deepest strata reached in drilling by the Iraqi Oil Exploration Company from boreholes Khleisya-1 and Akkas-1 in the Northern and Western Iraqi Desert (Figure 1). At its type locality in the Khabour Valley, Amadia District, Northern Iraq, the Khabour Formation consists of more than 800 m (its base...
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Fig. 1 – Location map of the studied boreholes Akkas-1 ▲ and Khleisya-1 ▲, the type locality of the Khabour Formation ● near Amadia, Iraq, and borehole KHS/6 ▲.

is not exposed) of alternating olive green to brown, thin
bedded, fine-grained sandstones, quartzites, and silty
micaceous shales (Figure 2). BELLEN et al. (1959) suggested
an Ordovician age for the Khabour Formation based on
the presence of Cruziana along with a sparse trilobite
fauna and eurypterid fragments.

In the Khleisya-1 borehole, the Ordovician Khabour
Formation consists of alternating sandstones, shales, and
carbonates, and extends from a depth of 2417 m to 3791
m at its base (AL-AMERI & BABAN, 2000) (Figure 2). In
the Akkas-1 borehole, the Khabour Formation is com-
prised of alternating sandstones and shales from a depth of
2486 m to its bottom at 4238 m (Figure 2).

Regionally, the Khabour Formation can be correlated
with the Ordovician Hiswa and Dubaydib formations of
Jordan, the Saq and Qasim formations of Saudi Arabia
(AL-SHARHAN & NAIRN, 1997; AL-HAJRI & OWENS, 2000),
and the Zardkuh Formation of Iran (AL-HUSSEINI, 2000).

In the aforementioned two boreholes, the overlying
Silurian succession of alternating sandstones and grey
shales is considered by the Iraqi Oil Exploration Com-
pany to be the Akkas Formation based on recovered acritar-
chys and spores. In the Akkas-1 borehole, the Akkas For-
mation is 1026 m thick and conformably overlies the
Khabour Formation, whereas in the Khleisya-1 borehole
the Akkas Formation is unconformable with the under-
lying Khabour Formation, and is only 101 m thick (AL-
AMERI & BABAN, 2000) (Figures 2 and 7).

No detailed biostratigraphic work has been carried
out on the Khabour Formation since BELLEN et al. (1959).
They concluded that during the Silurian, non-depositio-
nal conditions prevailed in Iraq. Based on palynologic
evidence, AL-AMERI et al. (1991) and AL-AMERI (2000)
documented a Silurian succession in the Western Iraqi
Desert in borehole KHS/6 (Figure 1).

The present study documents the source potential for
gas and other hydrocarbons in the Ordovician Khabour
Formation based on recovered palynomorphs and paly-
nofacies analysis from the Akkas-1 and Khleisya-1
boreholes (Figures 1 and 2).
MATERIALS AND METHODS

The 106 samples analyzed, most of which are side wall cores, thus minimizing potential contamination from caving, were processed using standard palynological techniques of initial treatment in hydrochloric acid to remove carbonates, followed by hydrofluoric acid to remove silicates. The samples were neutralized in distilled water between each acid treatment. The remaining organic residue was sieved through a 20 µm nylon screen and slides of the >20 µm and <20 µm fraction were prepared using Celllosize and Canada Balsam as the respective mounting and embedding media. The samples were not oxidized so that maturation assessment using the thermal alteration index (TAI) could be employed.

For each sample, parallel transects of the >20 µm fraction slides were made and 500 acritarch specimens were counted per sample. The acritarch species were then placed in the appropriate group for calculation of the Inshore Index, which was used to determine shoreline proximity (Al-Améri, 1983; Richardson & Rasul, 1990).

The prepared slides are stored in the palynological laboratory of the Department of Geology, University of Baghdad, Iraq.

TOC values were determined by the titration method with subjection to chromic acid based on El-Wakeel & Riley (1957), as well as measurements by a Lego instrument.

AGE AND PALYNOSTRATIGRAPHY OF THE KHABOUR FORMATION

The recovered palynomorph assemblages from the Akkas-1 and Khleisya-1 boreholes contain numerous acritarchs, various chitinozoans, as well as scolecodonts, and graptolite siculae (Figure 3).

Comparison of the acritarch and chitinozoan assemblages recovered from the Akkas-1 and Khleisya-1 boreholes with those from within Iraq and elsewhere in the world constrain the age of the Khabour Formation to the Ordovician (Figure 3). Ordovician acritarch assemblages to which biostratigraphic comparisons were made include those of Jardine et al. (1974), Downie (1984), Bagnoli et al. (1988),...
Fig. 3 – Range chart of selected acritarch and chitinozoan species recorded from the Ordovician Khabour Formation in the Akkas-1 and Khleisya-1 boreholes, Western Iraq. Species abundance along the range line is indicated by a solid line for common occurrences, and a thick solid line for abundant occurrences. Five palynozones can be recognized based on the acritarchs and chitinozoans.
AL-HAJRI (1995), MOLYNEUX et al. (1996), MOLYNEUX & AL-HAJRI (2000), among others. Chitinozoan correlations were made with the Ordovician chitinozoan biozones of PARIS (1990, 1996) and those of JENKINS (1967).

Based on the stratigraphic distribution of acritarchs and chitinozoans within the Khabour Formation as it occurs in the Akkas-1 and Khleisya-1 boreholes, five palynozones are recognized (Figure 3). Due to the emphasis on the hydrocarbon generation potential of the Khabour Formation, and space restrictions of this paper, detailed accounts of each palynozone are not possible. Examination of the ranges of the recovered acritarch and chitinozoan taxa, indicate these zones closely correspond with the stages of the Ordovician British Series, and are primarily based on the restricted ranges of many of the recovered palynomorphs (Figure 3).

PALAEOENVIRONMENTAL AND HYDROCARBON GENERATION POTENTIAL FOR THE KHABOUR FORMATION

Palaeoenvironment and hydrocarbon generation potential can be predicted from palaeoenvironmental analysis, total organic carbon (TOC), maturation assessments, and stratigraphic variations in kerogen types.

Determination of shoreline proximity for the deposition of the Khabour Formation is based on the numerical Inshore Index of Al-AMERI (1983) as refined by RICHARDSON & RASUL (1990).

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\text{Inshore Index} = \frac{\text{sphaeromorph} + \text{tasmanitids} + \text{Microhystridium}}{\text{netromorphs, acanthomorphs, and polygonomorphs}}
\]

The counting of the above mentioned acritarch groups (based on 500 acritarch specimens per sample), and the calculation of the Inshore Index for samples from the Khabour Formation for the Akkas-1 and Khleisya-1 boreholes are shown in Figures 4 and 5.

In the Akkas-1 borehole, an outer neritic marine environment is suggested for deposition of the Khabour Formation sediments during the Tremadoc through Arenig (Figure 4). During this time, acanthomorphic and polygonomorphic acritarchs comprise up to 75% of the total acritarch assemblage. A change in the Inshore Index suggests an inner neritic marine environment during the Llandeilo, followed by a fluctuating shoreline.

Fig. 4 – Scheme of hydrocarbon generation potential for the Khabour Formation predicted from stratigraphic variations in kerogen types (sensu BUJACK et al., 1977), palaeoenvironments, maturation assessments, and total organic carbon (TOC) in the Khabour Formation of borehole Akkas-1. Abbreviations: TAI = thermal alteration index, VRo = vitrinite reflectance in oil value, and °C = degrees centigrade.
during the Caradoc where the Inshore Index indicates an inner neritic to outermost tidal marine environment.

The total organic carbon (TOC) was measured for selected samples of the grey shale from the Khabour Formation in both boreholes (Figures 4 and 5 and Table 1). In several samples, TOC exceeds 0.5% which is sufficient to generate hydrocarbons. These higher values occur in the Akkas-1 borehole at depths of 2750-3000 m and 3650-3750 m, which also mark changes in the Inshore Index (Figure 4 and Table 1).

Application of the Inshore Index to samples from the Khleisya-1 borehole, showed oscillations within the outer neritic marine environment during deposition of the Khabour Formation, but with TOC values of less than 0.5% throughout the section (Figure 5).

Maturation assessment for the Ordovician successions in this study are based on Thermal Alteration Indices (TAI) of the acritarchs Baltisphaeridium constrictum (Figure 6), Orthosphaeridium ternatum, and Diexallo-

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**TABLE 1**

Total organic carbon (TOC) and Thermal Alteration Indices (TAI) for selected samples of the Ordovician Khabour Formation in the Akkas-1 borehole.

<table>
<thead>
<tr>
<th>Forma</th>
<th>Period</th>
<th>Stage</th>
<th>Depth (m)</th>
<th>TOC</th>
<th>TAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khabour</td>
<td>Ordovician</td>
<td>Ashgill</td>
<td>2500</td>
<td>0.09</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Caradoc</td>
<td>2860</td>
<td>0.70</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Llandeilo</td>
<td>3172</td>
<td>0.15</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arenig &amp; Llanvir</td>
<td>3620</td>
<td>0.86</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3761</td>
<td>0.18</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4130</td>
<td>0.30</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tremadoc</td>
<td>4172</td>
<td>0.50</td>
<td>4.5</td>
</tr>
</tbody>
</table>

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**Fig. 5** – Scheme of hydrocarbon generation potential for the Khabour Formation using the same categories as in Figure 4, but for borehole Khleisya-1.
Fig. 6 – Selected photographs of Baltisphaeridium constrictum Kjellström, 1971 from the Khabour Formation in borehole Khleisya-1 showing the maturation variations by color changes with increasing depths. 1: Thermal Alteration Index (TAI) = 2- and depth of 2417 m (Ashgill). 2: TAI = 2 and depth of 2776 m (Caradoc). 3: TAI = 2+ and depth of 2918 m (Llandeilo). 4: TAI = 3- and depth of 2978 m (Llandeilo). 5: TAI = 3 and depth of 3271 m (Arenig/Llanvirn). 6: TAI = 4 and depth of 3414 m (Arenig/Llanvirn). Scale bar = 20µm.
phasis sp. The color measurements of these species are compared to the color standards of Pearson (1990), and show a general increase in TAI values downhole.

The types of amorphous organic matter (AOM) in this study are compared to the ideal microscopic kerogen types of Thompson & Dembicki (1986) and the sedimentary organic matter types of Bujak et al. (1977). Accordingly, based on the parameters previously discussed (Figures 4-6), the potential source rocks and generated gas and oil levels for the Akkas-1 and Khleisya-1 boreholes are summarized as follows (Figure 7).

1. Depths 2750-3000 m of the Akkas-1 borehole (Figure 4 and Table 1) have a TOC of 0.71%-1.4%. Biodegradation of the organic matter resulted in abundant amorphous organic matter (70-75% amorphogen). The composition of this material is similar to the gas-prone type B kerogen of Thompson & Dembicki (1986) and is considered to be mature. The TAI is 3.8 (Staplin, 1969; see Batten, 1996) as indicated by dark brown colored acritarchs. This organic matter is capable of generating wet gas and condensate according to thermal degradation following Brook's (1981) and Bujak's models (Bujak et al., 1977), and the characteristics of type B kerogen. This depth interval is dated Caradoc based on the constituent acritarchs and chitinozoans (Figure 3).

2. Depths 3570-3650 m of the Akkas-1 borehole (Figure 4 and Table 1) have a TOC of 0.5-0.85%. Biodegradation of the organic matter has led to abundant amorphous organic matter (amorphogen) that is similar to the gas-prone type B kerogen of Thompson & Dembicki (1986). It is considered to be post-mature with a TAI of 4 based on the brownish-black color of the acritarchs, and hence only capable of generating dry gas. This interval is dated as Llanvirn on the basis of the acritarchs and chitinozoans (Figure 3). Hydrocarbons can't be generated at deeper levels (4100-4200 m), even with high TOC, because the TAI (up to 5.0) indicates geothermal temperatures at that depth as high as 300˚ C.

3. The potential to generate hydrocarbons from Upper Ordovician (Ashgill) sediments in both the Akkas-1 borehole (Figure 4) and the Khleisya-1 borehole (Figure 5) at depths of 2486-2680 m and 2417-2550 m respectively are greatly decreased. This is due to in-

Fig. 7 – Correlation and potential source rocks diagram of the two investigated boreholes (Akkas-1 and Khleisya-1) in this study of the Western Iraqi Desert.
creasing organic matter types of mainly melanogen (sensu BUIAK et al., 1977) and type C kerogen (sensu THOMPSON & DEMBICKI, 1986). Both BUIAK et al. (1977) and THOMPSON & DEMBICKI (1986) claim that hydrocarbon generation from such organic matter types cannot occur. Furthermore, the low TOC (<0.5%) for these sediments also precludes any appreciable hydrocarbon generation from these depth levels.

4. The recorded Ordovician sedimentary successions (depths 2417-3791 m) in the Khleisya-1 borehole (Figure 5) have a very low TOC content (<0.5%) and low degradation of the organic matter, which results in poor amorphous organic matter (<50%). These two factors are indicators of no hydrocarbon potential source rocks at any maturation level according to the models suggested by BROOKS (1981), TISSOT & WELTE (1984), and AL-AMERI & BATTEN (1997).

CONCLUSIONS

It is evident from this study that some levels within the Ordovician Khabour Formation in the Akkas-1 borehole have generated condensates and wet and dry gas. Generated hydrocarbons could be trapped in the Upper Silurian rocks (Akkas Formation) along the unconformity with the Upper Devonian (Figure 7), as indicated by oil shows in the Akkas-1 borehole. These hydrocarbon levels could extend toward Jordan and Syria, and south toward the Southwestern Iraqi Desert and Saudi Arabia.

Increasing thermal alteration to temperatures greater than 170˚C (TAI=3.8) applied to the rocks containing more than 0.5% TOC could be the reason for generating gas from the Ordovician sediments in this area, whereas the condensates and the Silurian oil are from the mature zone (Figure 7). These levels of increased TOC correspond in the Khabour and Akkas formations with changing marine environments from the outer to the inner neritic zone. Such conditions provide the best environment for higher organic matter accumulation, and combined with increasing temperatures, provide the mechanism for generating hydrocarbons in this area.

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REFERENCES


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