The Paleozoic and Mesozoic petroleum systems of Saudi Arabia

Mahdi AbuAli, Saudi Aramco

Summary

The Paleozoic petroleum system is principally sourced by the early Silurian Qusaiba Member, with some contributions from algal beds in the Permian Khuff, Devonian and Ordovician shales (AbuAli, 2012a, b, c; Abu-Ali and Littke, 2005; and Abu-Ali et al., 1999, 1991). The main reservoirs, from oldest to youngest, include the Ordovician Sarah, Devonian Jauf, Carboniferous-Permian Unayzah and Permian-Triassic Khuff. Seals for this petroleum system include the Triassic Sudair Shale at the top of the Khuff, interbedded anhydrites within the Khuff, basal Khuff carbonates above the Unayzah reservoirs, shales at the top of the Devonian, and the Silurain source rock shale at the top of the Sarah Reservoir. The Mesozoic petroleum system is composed of organic-rich carbonate mudstone source rocks of the Tuwaiq Mountain, Hanifa, Shuaiba and Wasia formations. The main reservoir units are the Arab, Manifa, Hanifa, Hadriya, Fadhili, Shuiaba and Wasia. The medium-light, sulfur-rich crude oil and associated gas generated within this system are generally in structural traps, with regional Hith evaporite seals above the Arab main reservoirs. Other seals include intra-Arab evaporites and tight argillaceous carbonate rocks of the Dhruma, Tuwaiq Mountain and Hanifa formations.

Introduction

Saudi Arabia holds significant amounts of the world's oil reserves. These reserves are predominantly found in Jurassic and Cretaceous carbonate and, to a lesser extent, clastic reservoirs. The hydrocarbons in these reservoirs are uniquely different from the older Paleozoic, mostly clastic, petroleum system that is responsible for the unassociated gas, condensate and high quality oil that has been discovered to date. Chronologically, the first hydrocarbon discovery in Saudi Arabia took place when the Dammam-7 well struck oil in the late Upper Jurassic Arab Formation in 1938. Other Jurasic discoveries soon followed with the discovery of Abqaiq Field in 1940, and the discovery of the world's largest oil field, Ghawar, in 1948. The full extent of Ghawar Field was delineated in stages beginning with the Ain Dar Field in the north, found in 1948, and ending with the Hawiyah Field, in the south, discovered in 1953. These discoveries were primarily in the Jurassic Arab Formation. Other fields followed including the world's largest offshore field, Safaniyah, with oil in Tertiary and Cretaceous reservoirs. The Paleozoic petroleum system was first recognized when Khuff gas was discovered in the Dammam structure in 1957. Exploration in the older Paleozoic section in the 1980s resulted in the discovery of extra-light oil in the Carboniferous-Permain Unayzah Formation of central Arabia. This latter petroleum system is characterized by a clastic source rock-reservoir pair that is governed by a complex lateral and vertical migration. The migration fairway is significantly different from the early Jurassic and Cretaceous discoveries, which are mainly charged vertically.

Theory and Method

Hydrocarbons generated from the Paleozoic petroleum system are extra-light, almost sulfur-free and have a Carbon-13 (C_{13}) isotopic range of -28 to -31 per mil. The isotopic gas profile is less steep than the Mesozoic petroleum system and the pristane/phytane ratio is much higher than one. Depending on depth of burial, exploration below the Jauf Reservoir can be very high risk, as porosity and permeability are drastically reduced and producing these reservoirs requires unconventional methods for economic deliverability. Major risks for exploitation of reservoirs found in this petroleum system are reservoir continuity and quality for deeper targets, lateral seal for stratigraphic traps, closure integrity in areas of lesser seismic data quality, and trap timing with respect to hydrocarbon migration. Jurassic-generated hydrocarbons are identified by a C_{13} isotopic range falling between -25 and -29 per mil PDB (Peedee Formation Belemnite) while the Cretaceous has a range of -24.5 to -27 per mil measured on the saturate and aromatic oil fractions. The associated gas displays a steep C_{13} isotope signature for the C1-C2 gas components. Unlike the Paleozoic system, the pristane/phytane ratio is much less than one. Major exploration risks within this system include maturity of the source rock for Cretaceous and Tertiary targets, closure integrity, top seal breach and access to charge.

Examples

Paleozoic and Mesozoic petroleum systems can be classified using both carbon isotopes and biomarkers. Table 1 lists the major differences between both systems (AbuAli, 2012a, b, c; Abu-Ali and Littke, 2005; Abu-Ali et al., 1999, 1991; Carrigan et al., 1994; and Cole et al., 1994).

Parameter	Paleozoic System	Mesozoic System
C_{13}/C_{12} (PDB)	-29.5	-26.5
% Saturates	> 80%	60 - 70%
Pristane/Phytane	1.6-1.8	0.5-0.6
Hopanes/Steranes	Trace	Normal
H_2S mol% in Gas and Condensates	Trace	> 2%

Table 1: Classification of Paleozoic and Mesozoic petroleum systems, Saudi Arabia.

Another useful classification between Paleozoic and Mesozoic petroleum systems is a correlation between carbon istopes of the hydrocarbon fractions (oils and condensates) versus that of the source rock extracts. Figure 1 displays the values for both source rocks and the generated hydrocarbons, signfying the positive correlation between both systems and their respective source rocks.

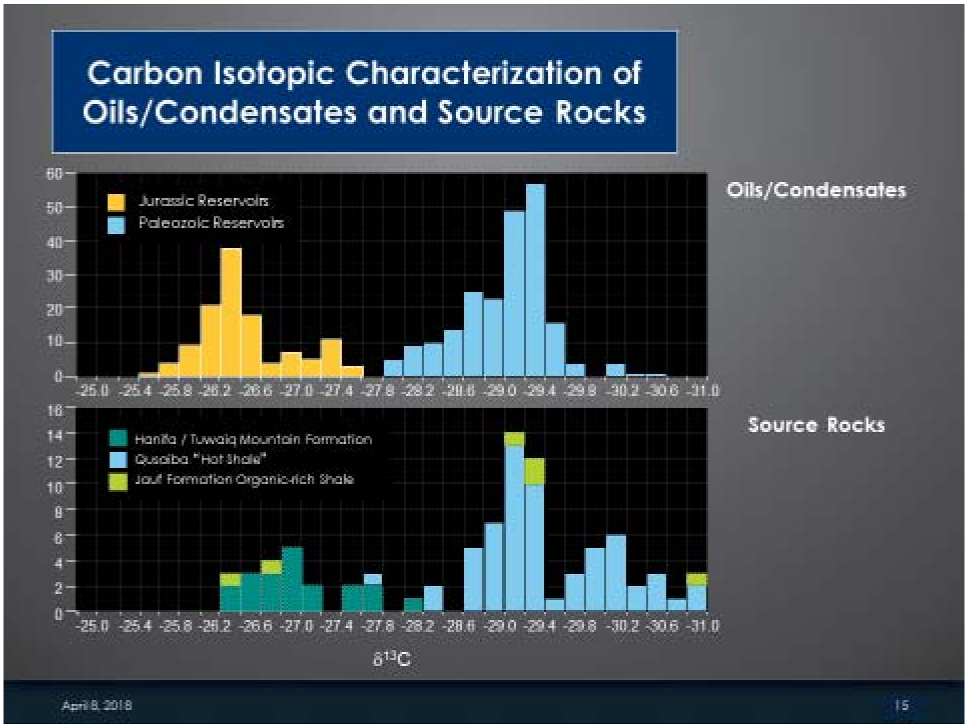

Figure 1: Carbon isotopic characterization of oils/condensates and source rocks, Saudi Arabia (AbuAli, 2012a, b, c; Carrigan et al., 1994; and Cole et al., 1994).

Conclusions

The Paleozoic petroleum system is uniquely and geochemically distinct from the Mesozoic system. The Mesozoic petroleum system is dominantly a carbonate source-reservoir system, while the Paleozoic system is mostly clastic. Hydrocarbons from the Paleozoic system are extra light, sulfur-poor, while the Mesozoic hydrocarbons are light-medium, sulfur-rich. Mixing between the two systems is possible where seal/fault breach is evident. Both systems are generally under-explored unconventionally in the rest of the Kingdom, therefore significant potential still exists for unconventional shale gas, tight sand gas and shale oil resources.

Acknowledgments

The author would like to thank Saudi Aramco for permission to present and publish this work. I acknowledge the support of Bill Carrigan and Sami Abdelbagi for providing some of the isotope and Rock-Eval data.

References

AbuAli, M.A., 2012a, Major Petroleum systems of Saudi Arabia, 8th International Conference on Petroleum Geochemistry and Exploration in the Afro-Asian Region, Oral Presentation, 2-4 November 2012, Hangzhou, Zhejiang, China.

AbuAli, M.A., 2012b, A new Regional Co-Source Rock for Paleozoic Khuff Gas Condensates in the Arabian Gulf. AAPG 2012 Annual Convention and Exhibition, Oral Presentation, April 22-25, Long Beach, California, USA.

AbuAli, M.A., 2012c, The Khuff Algal Mats: A new Regional Co-Source Rock for Paleozoic Khuff Gas Condensates in the Arabian Gulf. Geo 2012 Oral Presentation, March 5-7, Bahrain.

Abu-Ali, M.A., 2005, Organic Petrology, Maturation, Thermal and Burial History Analysis, and Hydrocarbon Generation and Migration Modeling of the Saudi Arabian Paleozoic Petroleum Systems, PhD Thesis, Aachen University of Technology (RWTH Aachen), Germany.Abu-Ali, M. A., and R. Littke, 2005, Paleozoic petroleum systems of Saudi Arabia: A basin modeling approach: GeoArabia, v. 10, no. 3, p. 131–168.

Abu-Ali, M. A., J. L. Rudkiewicz, J. G. McGillivray, and F. Behar, 1999, Paleozoic petroleum system of Central Saudi Arabia: GeoArabia, v. 4, no. 3, p. 321–335.

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: Society of Petroleum Engineers, SPE 21376, p. 345–356.

Carrigan, W.J., Cole, G.A., Colling, E.L., Jones, P.J., 1994, Geochemistry of the Upper Jurassic Tuwaiq Mountain and Hanifa Formation Petroleum Source rocks of Eastern Saudi Arabia. In: Katz, B.J. (Eds.), Petroleum Source Rocks. Springer Verlag, pp. 67-87.

Cole, G.A., M.A. Abu-Ali, S.M. Aoudeh, W.J. Carrigan, H.H. Chen, E.L. Colling, W.J. Gwathney, A.A. Al-Hajji, H.I. Halpern, P.J. Jones, S.H. Al-Sharidi, and M.H. Tobey, 1994, Organic Geochemistry of the Paleozoic Petroleum System of Saudi Arabia. Energy & Fuels, Vol. 8, No. 6, p. 1425-1442.