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The Silurian Qusaiba Hot Shales of Saudi Arabia: An integrated assessment of thermal maturity

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ABSTRACT

The Lower Silurian Qusaiba Hot Shales (QHS) are proven source rocks for oil within the Paleozoic, and possibly some of the Mesozoic, reservoirs in Saudi Arabia. Moreover, these shales have oil shale potential where they are immature and shallow enough for mining, as well as unconventional shale oil and shale gas potential, in areas where they are within oil-maturity and gas-maturity levels, respectively. The QHS were deposited in relatively shallow marine environments under anoxic water conditions, resulting in accumulation of amorphous kerogen, organic-walled graptolites and acritarchs. Across the Arabian Basin, organic matter quality does not show much variation for the QHS, but the maturity varies greatly as a result of varying burial history.

Thermal maturity assessment of shale source rocks that lack vitrinite, such as the Qusaiba Hot shales, continues to be challenging, especially where conflicting measurements are obtained from different sources.

This paper presents an integrated assessment of QHS thermal maturity parameters, based on cores from 13 carefully selected boreholes that – based on regional basin models – are believed to cover a wide maturity range (ca. 0.5 to 2.0% Ro). We conducted some analyses on kerogen (maceral petrography, graptolite reflectance, UV-fluorescence, whole rock pyrolysis, Raman spectroscopy of graptolite) and other analyses on bitumen extracts (GC and GC–MS of saturate and aromatic fractions, and FTIR spectroscopy of the asphaltene fraction). We show that using many thermal maturity parameters reduces uncertainty significantly, and we therefore recommend that graptolite reflectance analyses should be conducted in support of other maturity indicators. Proper reflectivity measurements of the graptolites set the reference for comparison of other maturity parameters obtained from petrographic, geochemical, and spectroscopic techniques. Our work provides a template by which Qusaiba thermal maturity can be more accurately estimated when only a limited set of maturity parameters is available.

1. Introduction

The increasing interest in unconventional shale oil/gas resources has resulted in a greater focus on source rocks. Furthermore, globally widespread Ordovician-Silurian organic-rich shales (Klemme and Ulmishek, 1991) are attracting more attention in the US, Europe, Middle East, China, and Australia. Thermal maturity is among many key factors that play an important role in determining the viability of these shales as both source and reservoir (e.g., Curtis, 2002; Montgomery et al., 2005; Hill et al., 2007; Jarvie et al., 2007; Bruner and Smosna, 2011; Loucks et al., 2009; Alexander et al., 2011; Chalmers et al., 2012; Zhang et al., 2012; Romero-Sarmiento et al., 2013; Milliken et al., 2013; Hao et al., 2013; Romero-Sarmiento et al., 2013; O'Connor et al., 2014; Inan et al., in press). Although reflectance of vitrinite particles in coal, and carbonaceous organic matter dis@persed in sedimentary rocks, is a widely used and robust thermal maturity indicator (Tissot and Welte, 1984; Hunt, 1996; Hackley et al., 2015), pre-Devonian shales do not contain vitrinite, which originates from ligno-cellulosic tissues of higher land plants that postdated the Late Silurian, when the first vascular plants evolved (Teichmüller, 1982; Tissot and Welte, 1984; Taylor et al., 1998). Therefore, in this study it is essential to achieve reliable thermal maturity measurements (expressed as vitrinite reflectance equivalent, VRE) which are optimally suited to define oil and gas generation windows for the Qusaiba shales.

In the absence of vitrinite in Lower Paleozoic rocks, reflectance measurements have been carried out mostly on zooclasts, like graptolite, which exist in abundance with other organic matter, e.g., bitumen and vitrinite-like particles (Jacob, 1989; Suárez-Ruiz et al., 2012; Petersen et al., 2013). In several studies the reflectance of various types of

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zooclasts and bitumen were measured and compared with other maturity indicators, such as pyrolysis Tmax, Conodont Alteration Index (CAI), Thermal Alteration Index (TAI), and atomic H/C ratios of isolated kerogens (e.g., Bertrand, 1990; Bertrand and Héroux, 1987; Buchardt and Lewan, 1990; Haeri-Ardakani et al., 2015). Graptolites are the most widely used zooclast group for reflectance measurements because evolution of their optical properties is comparable to that of vitrinite (Bustin et al., 1989; Goodarzi and Norford, 1986, 1989; Goodarzi et al., 1992; Petersen et al., 2013; Hartkopf-Fröder et al., 2015). Extreme care must be exercised, however, due to inaccuracy in reflectance measurements that may arise from graptolite anisotropy, especially in samples of advanced maturities. Measurements based on bitumen reflectance are less reliable for maturity determination, because bitumen may have various origins and morphologies, and it may not be indigenous to the host rock (Petersen et al., 2013). In addition, surface quality and roughness of bitumen can significantly affect bitumen reflectance (Sanei et al., 2015). On the other hand, although experienced microscopists can easily and reliably distinguish and measure graptolite reflectance, the nature of graptolite anisotropy, especially at advanced maturities, prevents these measurements from being made and used reliably by less experienced organic petrologists.

This study offers an integrated account of this subject, comparing and calibrating a wide array of thermal maturity parameters for the widespread graptolitic Silurian Qusaiba Hot Shales (QHS) of Saudi Arabia. Oil and gas windows can then be more accurately defined.

2. Geological setting

The main tectonic phases that shaped the Arabian Plate include: 1) basement formation during Precambrian, 2) major glaciation, followed by de-glaciation in the Ordovician-Early Silurian and deposition of the organic-rich Qusaiba Hot Shales, 3) major basin inversion and erosion during mid-Carboniferous (Hercynian Orogeny), 4) fragmentation of the Gondwana Supercontinent and drift of the Arabian Plate to the equator, leading to favorable source-reservoir pairs development from Late Permian through to the Jurassic, 5) closure of the Neo-Tethys and the rejuvenation of Hercynian structures during Middle to Late Cretaceous, and 6) the Zagros Orogeny and tilt of the Arabian Plate followed by Zagros thrusting during Tertiary to present (Powers et al., 1966; McGillivray and Husseini, 1992; Alsharhan and Nairn, 1997; Wender et al., 1998; Al-Hajri and Owens, 2000; Konert et al., 2001; Sharland et al., 2001; Ziegler, 2001; Faqira et al., 2009; Cantrell et al., 2014, and references therein).

Throughout the Paleozoic era, continental and shallow-marine clastic sedimentation prevailed on a stable passive margin in northeastern Gondwana. The Hercynian events of the mid-Carboniferous affected the area, creating regional uplift, widespread erosion and basement tectonism due to rejuvenation of the pre-existing weaknesses in the basement (Konert et al., 2001). From the Permian to the Eocene, the area was a broad stable passive margin, where the deposition of mainly shallow-water carbonates with minor anhydrites and shales occurred (Cantrell et al., 2014). Since the Oligocene, the northeastern part of the basin (along the Arabian Gulf) has undergone shortening, as a consequence of collision of the Arabian Plate with Laurasia (Zagros Orogeny). The resulting flexure of the Arabian Plate underneath the Zagros fold and thrust belt created a wedge-shaped, low-angle (<2°, tilting NE) foreland basin.

With respect to Paleozoic Petroleum System (PPS) of the Arabian Basin, the Early Silurian has prime importance, due to deposition of organic-rich (hot) shales in an expansive shelf area of the Gondwana, covering present-day North Africa and Arabian Peninsula where, according to Klemme and Ulmishek (1991), Lower Silurian organic-rich shales have generated about 80–90% of the Paleozoic-sourced hydrocarbon accumulations. These hot shales represent the lowermost (basal) part of the Qusaiba Formation of the Qalibah Group (Alsharhan and Nairn, 1997). In most cases, hot shales were deposited directly above Upper Ordovician peri-glacial sandstones (Sarah Formation) during the initial Early Silurian transgression that resulted from the melting of the Late Ordovician ice cap (Lüning et al., 2000). A summary of the PPS is shown in Fig. 1. This petroleum system contains the Early Silurian basal Qusaiba "hot shale" and, to a lesser extent, the overlying warm shales, as its principal source rocks, with reservoirs extending from the Ordovician to the Early Triassic. Seals occur at different stratigraphic levels, with the evaporitic Sudair Formation of the Early Triassic age serving as the regional top seal of the PPS. Hanadir and Ra'an shales of the Ordovician Qasim Formation may also possess some source potential (Aramco internal reports).

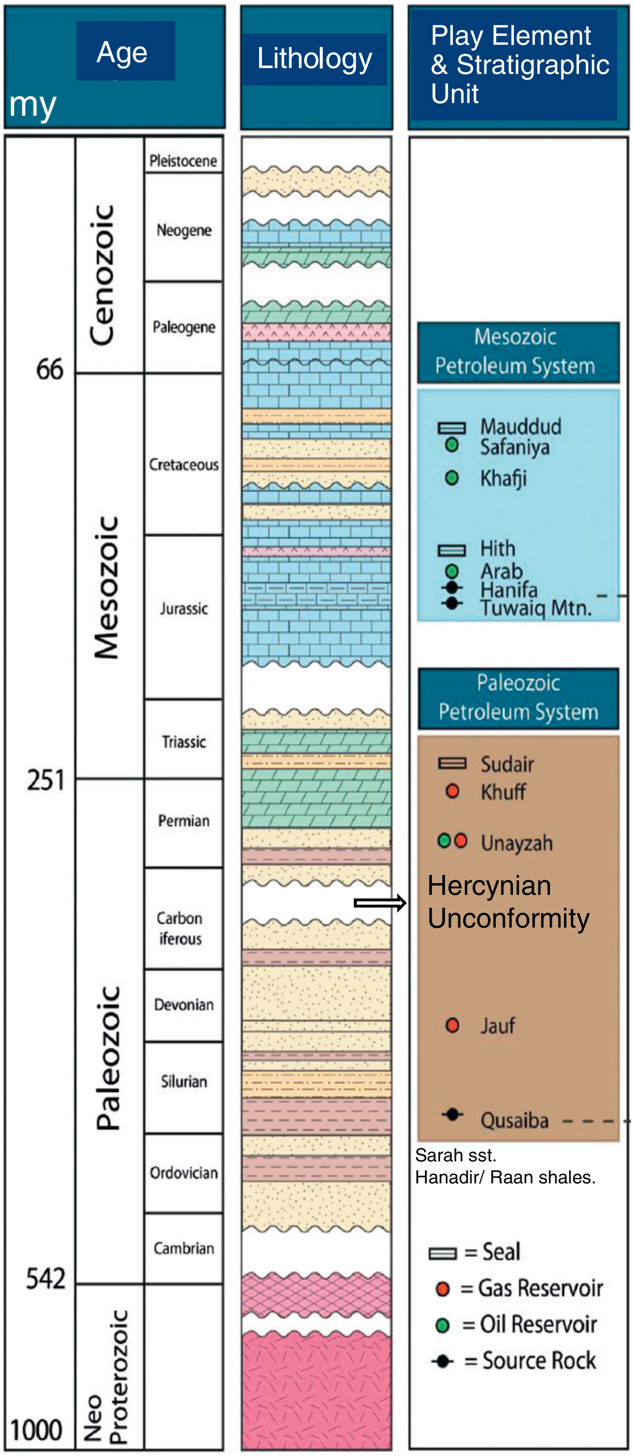

Fig. 1. Generalized stratigraphic column and the elements of the Paleozoic and Mesozoic Petroleum Systems in the Saudi Arabian Basin (modified from Cantrell et al., 2014).