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Research paper

Hydrocarbon potential and palynological study of the Latest Ordovician – Earliest Silurian source rock (Sarchahan Formation) in the Zagros Mountains, southern Iran

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ABSTRACT

Source rock studies are one of the key issues of petroleum exploration activities. In the supercontinent of Gondwana, ice ages related to the Upper Ordovician (Hirnantian) and rising sea levels caused by glacial melting at the end of the Ordovician and Early Silurian (Llandoverian) created excellent source rocks along the margin of Gondwana. Investigations conducted in the Arabian Peninsula have been indicated indicating that the lower Qalibah Formation (the so-called Qusaiba Member or Hot Shale) is a good source rock for the Paleozoic petroleum system in this area. Likewise, the Sarchahan Formation was recently introduced as a source rock in the Zagros Basin of Iran, which is probably equivalent to the Qalibah Formation in the Arabian Peninsula. In this study, samples were prepared from surface and subsurface Paleozoic rock units in Iran's Zagros Basin. The emphasis of the paper was on the Sarchahan Formation in Kuh-e Faraghan, ranging in age from the Late Ordovician (Hirnantian) to Lower Silurian (Llandoverian) to determine whether the high richness of organic matter in the Sarchahan Formation is related to the Late Ordovician or Lower Silurian. The basal part of the Sarchahan Formation belongs to the Late Ordovician (Hirnantian) because of the presence of the persculptus graptolite biozone, while the remainder belongs to the Lower Silurian. The Ordovician and early Llandoverian parts of the Sarchahan Formation contain type II and III kerogen with TOC ranging from 2.94 to 7.19, but the rest of the Sarchahan Formation (late Llandoverian) has TOC ranging from 0.1 to 0.58. Therefore, the Hot Shale in Iran falls within the Hirnantian and early Llandoverian (Rhuddanian), and not the latest Llandoverian (Aeronian and Telychian). Utilizing organic petrography, kerogen type was found II/III. The carbon stable isotope studies revealed that the source rock of hydrocarbons in Dalan and Kangan reservoirs has been the Sarchahan Formation. Based on analytical data, the kerogenous shales in the lower part of the Sarchahan Formation are at end of gas window, and the gamma ray amount is approximately 180 API. This research indicates the differences between the source rocks in the southern and northern Persian Gulf and suggesting, the Hot Shale should be considered in different views and used in modeling studies of sedimentary basins for future exploration targets.

1. Introduction

The Paleozoic rock units and its petroleum systems are important in North Africa and the entire Middle East. Since the early 1970s, an increasing number of gas accumulations have been discovered in Permo-Triassic siliciclastic and carbonate reservoirs in the Unayzah and Khuff formations in the Arabian Peninsula (Saudi Arabia, Abu Dhabi and Qatar) and siliciclastics and carbonates in the Faraghan, Dalan and Kangan formations in Iran. The current gas reserves of the Middle East are more than 1500 trillion cubic feet (Tcf), represent 25% of the global reserves (Bordenave, 2008). According to Iran's Petroleum Ministry, the proved natural gas reserves of Iran are about 1046 trillion cubic feet or about 15.8% of world's total reserves (33% as associated gas and 67% as non-associated gas). So far, the only important source rock in Iran's Zagros Basin for Late Paleozoic - Late Triassic successions is the organic-rich, radioactive shales in the Sarchahan Formation (Bordenave, 2008, 2014; Le Heron and Dowdeswell, 2009; Luning

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et al., 2005, 2000). Based on studies of palynomorphs and graptolites, the Sarchahan black shales are diachronous throughout the Zagros Basin, ranging from the Hirnantian to Llandoverian (Ghavidel-syooki and Winchester-Seeto, 2004; Ghavidel-syooki et al., 2011, 2014; Rickards et al., 2000). The Sarchahan Formation is part of a widespread Paleozoic shelf system extending across northern Gondwana (Ghavidel-syooki and Winchester-Seeto, 2004; Ghavidel-syooki et al., 2011, 2014; Konert et al., 2001; Sharland et al., 2001). During the Late Ordovician to Early Silurian, a strong eustatic sea level rise occurred (Ghavidel-syooki et al., 2011; Loydell, 1998) that flooded wide areas, triggering the deposition of black, organic-rich shales in many places in Iran, North Africa and the Arabian Peninsula. The Sarchahan Formation represents a good hydrocarbon source rock and has generated large amounts of oil and gas for various Paleozoic and Triassic units (Konert et al., 2001; Macgregor and Walk, 1996).

The present paper attempts to fill the gaps and update the information regarding structural setting, paleoenvironment, organic richness and thermal history of the Paleozoic successions in Iran by using Rock–Eval pyrolysis, chitinozoan reflectance and palynological study. Most previous evaluations have focused on individual formations and members with no emphasis on the regional geographic or stratigraphic positioning and the source rock potential and regional age equivalents of viable source rocks in Iran and neighboring countries.

Our research showed that the Sarchahan Formation can be divided into two main zones, a poor organic matter zone with low gamma-ray response and a rich organic matter zone with high gamma-ray response, each with their own organic geochemical signatures. In the Arabian Peninsula, the poor organic matter and low gamma-ray zone has almost no source potential and is called the Sharawra Member of the Qalibah Formation. The rich organic matter and high gamma-ray zone consists of dark gray to black, oil-prone, marine shales and is called the Qusaiba Member of the Qalibah Formation. This member contains abundant amorphous organic matter, marine algae, acritarchs, chitinozoans and graptolites (Ghavidel-syooki et al., 2011).

The aims of this study are twofold:

1 Evaluation of the Sarchahan Formation for Paleozoic petroleum systems in Iran's Zagros Basin and a comparison with neighboring countries.
2 Determination of the organic rich part of the Sarchahan Formation (Hot Shale) in relation to either the Late Ordovician (Hirnantian) or Lower Silurian by using paleontological and geochemical data.

2. Geological setting

The Zagros Mountain Range extends from NW to SE Iran and is located in the northeastern margin of the Arabian Plate. The Zagros mountain system in SW Iran can be divided into the western, central and eastern sectors by the Balarud and Qatar-Kazerun faults (Fig. 1) (Alavi, 2004; Falcon, 1974; Motiei, 1995; Rabbani, 2013; Sherkati and Letouzey, 2004).

In this area, the north-south trending Qatar-Kazerun fault has exerted a strong control on the sedimentation and regional deformation patterns from the Infracambrian onwards (Bahroudi and Talbot, 2003; Bordenave, 2008; Koop and Stoneley, 1982; Murris, 1980; Sepehr and Cosgrove, 2004). Together with the adjacent offshore region, the eastern part of the fold belt is one of the world's most prolific hydrocarbon provinces (Galimove and Rabbani, 2001).

The Paleozoic petroleum system provides an example of a complex system involving long migrations of Late Ordovician (Hirnantian) or Lower Silurian (Llandoverian) source rocks, the formation of large accumulations of oil and gas on regional highs long before the formation of the Zagros folds and the late re-accommodation of some of the gas in anticlines, which occurred from the Late Miocene to Pliocene Orogeny (Bordenave, 2008; Rabbani, 2013).

Throughout the Paleozoic, the northeast margin of the Afro-Arabian plate evolved as an extensive, stable, slowly subsiding continental shelf along the margin of Gondwana (Cole et al., 1994).

The older sediments known in the Zagros fold belt and offshore are thick halite in the Hormoz Formation (late Precambrian to Cambrian), which formed early deep-seated salt-pillows and salt-plugs (Fig. 2) (Setudehnia, 1976). This formation was deposited as a result of the Late Proterozoic to Early Cambrian “Najd” rifting (Al-Husseini, 2000). Following the Najd rifting, post-rift continental to deltaic siliciclastics derived from the interior of the Gondwana landmass were deposited unconformably either on Late Proterozoic/Early Cambrian evaporitic rocks or on the basement of the Arabian Platform (Al-Husseini, 2000).

During the Middle Cambrian, a sea-level rise led to the deposition of shallow-water carbonates throughout northern Saudi Arabia, Jordan, Syria and Iran. The Late Cambrian was marked by the deposition of dominantly argillaceous siliciclastics and subordinate limestones in a deltaic to shallow-marine environment (Konert et al., 2001). After a regressive episode at the end of Cambrian, predominately marine argillaceous sedimentation continued during Ordovician, with more distal conditions to the NE of the Arabian Platform. In SW Iran, Cambro-Ordovician rocks crop out at the base of thrust units in the High Zagros from Zard-Kuh to Kuh-e Dinar, while Ordovician-Silurian rocks crop out only in two massifs north of Bandar Abbas, namely, Kuh-e Faraghan and Kuh-e Gahkum (Hubert, 1978; Setudehnia, 1976).

The Ordovician sequence (Seyahou and Zardkuh formations) is composed of black and greenish gray clays alternating with intercalations and members of sandstones, conglomerates and calcareous mudstones. The Seyahou Formation crops out in Kuh-e Faraghan (Stratotype) (Ghavidel-syooki & Khosravi, 1995). Based on the abundant fauna and flora, these sediments accumulated over a long period from the Early (Floian) to Late Ordovician. Black shales occur throughout the entire section, but they are most abundant in the Middle Ordovician interval, where they are accompanied by siltstones with high P_2O_5 contents and low organic carbon content (Ghavidel-syooki et al., 2011, 2014). At the end of Ordovician, the northern margin of Gondwana, including north Africa and the Arabian platform, was located at a latitude of 60° south (Bordenave, 2014).

The Late Ordovician (Hirnantian) was influenced by a major, short-lived (0.5–1 m.y.) glaciation, with the center of the ice sheet located in central Africa (Le Heron and Dowdeswell, 2009) (Fig. 3). Features commonly attributed to the pro- and subglacial processes reported from North Africa, Mauritania, Mali, the Arabian Peninsula, Turkey and Iran include glacial striations, glacial pre-lithification tectonics, diamictites and micro conglomeratic shales (Ghavidel-syooki et al., 2011, 2014; Ghienne and Deynoux, 1999; Husseini, 1990; Monod et al., 2003; Powell et al., 1994; Vaslet, 1990).

In the Iranian segment of the Zagros mountainous system, the Middle Ordovician black shales in the Seyahou Formation are overlain by erosion at its top and the basal part of the Dargaz diamictite sequence. The relatively wide distribution of diamictites in the Zagros Mountains and their cyclic patterns reflect several phases of expansion and degradation of the ice shield, which covered spacious areas of northern and central Gondwana in the Late Ordovician. This region exhibits a glacial trough (up to 40 m deep) filled with sandy drift. According to Ghavidel-syooki et al.