Petroleum 9 (2023) 499–507

Contents lists available at ScienceDirect

Petroleum

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Shale gas potential of the lower Silurian hot shales in southern Iran and the Arabian Plate: Characterization of organic geochemistry

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A R T I C L E I N F O

Article history:
Received 30 November 2021
Received in revised form
20 December 2021
Accepted 14 March 2022

Keywords:
Silurian hot shale
Shale gas
Southern Iran
Arabian plate
Favorable shale gas areas

A B S T R A C T

A significant phase of global warming appeared during the Llandovery and productive Silurian hot shale was preserved all over the world. The lower Silurian shale is the main effective source rock for most of the Paleozoic hydrocarbon in Iran and the Arabian platform. Silurian hot shales have become prospective resources for new energy such as shale gas. The regional distribution and shale gas potential of the lower Silurian hot shale in southern Iran and the Arabian plate are determined using outcrops and exploration well samples data from previous studies. The studied area has a high organic content (on average more than 2%), maximum burial depth is 5300 m, shale thickness of 30–200 m, organic matter maturities (most comparable), clay minerals content ranging from 20% to 57%, quartz content ranges from 20% to 49%, feldspar content ranges from 10% to 15% and calcite content ranges from 1.48% to 5% which all favor shale gas generation and accumulation. We concluded that southern Iran and east-central Saudi Arabia are two of the most sustainable and favorable locations for shale gas exploration and production for lower Silurian hot shale after assessing all of the key characteristics.

1. Introduction

The growing interest in unconventional resources has turned the priority to source rocks. Moreover, Silurian hot shales, which are found all over the world, are getting interested in China, the US, Europe, and Australia [1]. However shale gas exploration is in the early stage in Iran and the Arabian platform and due to the difficulties of geological conditions and resource evaluation, more studies are needed. In the Middle East during the Llandovery, a significant phase of global warming appeared due to the retreat of the glaciers. The sea level began to increase gradually [2,3]. The flood of fresh water from the melting ice cap induced anoxia, which was caused by oceanic layering [4]. A noticeable transitional marine shale that extends over much of the northern Gondwana margin may be observed in the early Silurian strata. The shale accumulated throughout the late Silurian in some regions, while it developed into fluviodeltaic shallow-marine siliciclastic in other areas [5]. Major hiatuses nevertheless occur in parts of Iran, the Arabian platform, the eastern Mediterranean, and the strata are absent on the eastern margin in Oman and Yemen due to late erosion in the mid-Carboniferous. However, the productive Silurian shale was preserved in numerous areas [5–8] due to anoxic sea bottom conditions in the sediment-starved basin. The Silurian shales are called hot shales because of their high uranium concentration, which makes them highly radioactive (up to 400 API units), equating to approximately 3 wt% total organic carbon (TOC) [6–9]. Source rock hydrocarbons, such as shale oil, shale gas, and coal bed gas, are self-generation and self-storage hydrocarbons primarily produced from reservoirs inside source rocks. Shale gas is a type of natural gas generated from organic-rich black shale [10,11]. When permeability and porosity were both low, shale may have been an effective natural gas reservoir [12]. Shale gas can be stored in several ways, including free gas in natural fissures and intergranular porosity, gas dissolved onto kerogen and clay surfaces, and gas solubilized in kerogen and bitumen [13].

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Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.petlm.2022.03.004
2405-6561/

Organically enriched intervals in lower Silurian shales across North Africa, the Arabian Peninsula, and the Persian Gulf have been proposed to represent the source of 90% of the region's early Paleozoic oil [3,7,8,14]. Because these hot shales can be used as hydrocarbon source rocks and shale gas reservoirs [15–17] recently, an increasing number of studies have been demonstrated in the Middle East to assess the existence of shale gas potential. In addition, the lower Silurian hot shale formations have been regarded as prolific unconventional shale gas reservoirs.

This study is an evaluation of the lower Silurian hot shales using an organic geochemical and geological approach, including burial depth of shale, TOC, organic matter maturity, mineral composition, and porosity and permeability with the aim of shale gas exploration in southern Iran and the Arabian Plate and carries out the comparison between Longmaxi Formation in China and the lower Silurian hot shales in southern Iran and the Arabian Plate as well as providing a foundation and motivation for future research.

2. Geological setting

2.1. Stratigraphic and sedimentary features

Silurian hot shales are essential for the production of 9% of the world's petroleum reserves [1]. The Arabian Platform, the Zagros Basin, and the Oman Oil Basin are the three main hydrocarbon habitats in the Middle East [18,19]. Stratigraphically, Sarchahan Formation in southern Iran, Qusaiba Shale in Saudi Arabia, Akkas Formation in Iraq, Mudawwara Formation in Jordan, Sahmah Formation in Oman, Tanf Formation in Syria, and Dadas Formation in southeast Turkey are examples of Silurian hot shales that can be found in many parts of the Arabian Plate and southern Iran [6](Fig. 1). Based on geochemical fingerprinting, they are considered to be the source of gas in Iran, the North Field of Qatar, and oil in central Saudi Arabia [4,18,20–22]. The Arabian Peninsula's lower Silurian shales represent a major source rock, a fact recognized only in the last two decades [18].

2.1.1. Sarchahan Formation in Iran

In the Zagros Mountains, Sarchahan Formation is exposed locally [3]. Ghavidel-syooki [23] presented the Sarchahan Formation, which ranges approximately from 56 to 90 m in Kuh-e Faraghun and 170 m in Kuh-e Gahkum. In Iran, the presence of hot shale is equivalent to the Qusaiba member, defined by higher Gamma-Ray response and organic richness [21]. Stratigraphically, Sarchahan Formation is divided into two parts: an organic-rich section and an organic poor part [21]. In several wells in Coastal Fars, the Sarchahan Formation has been discovered [21,23]. The organic matter content of these sediments is low [4]. Lack of sedimentation on pre-Silurian paleohighs or/and erosion contributed to the disappearance of an organic-rich section of the Sarchahan Formation in the Coastal Fars [21,24,25].

2.1.2. Qusaiba Formation in Saudi Arabia

The lowermost (basal) part of the Qalibah Group's Qusaiba Formation is represented by hot shale. Lower Silurian organic-rich shales are able to take responsibility for around 80%–90% of Paleozoic hydrocarbon accumulations in Saudi Arabia [18]. Qusaiba's type location and type sections are in the Tabuk Basin in Saudi Arabia's northeast part [30,31]. The Qusaiba is approximately 290 m thick in its type locality in the Qalibah area, and it reaches up to 482 m thick near Tabuk City in northwest Saudi Arabia at its reference section. The Qusaiba is subdivided into two different parts, one upper and one lower in terms of stratigraphy. Regional marine transgression deposits generated the lower part, whereas a coarsening upward deltaic shale formed the upper part [8,32]. The thickness of the Qusaiba hot shale is within 10–70 m [33–35].

2.1.3. Akkas Formation in Iraq

The Akkas Formation, comprising of black fissile shale with intercalation of sandstone and siltstone, represents the Silurian sequence in Iraq. Due to Devonian erosion, the Silurian Akkas Formation is not exposed in outcrops in Iraq; nonetheless, the

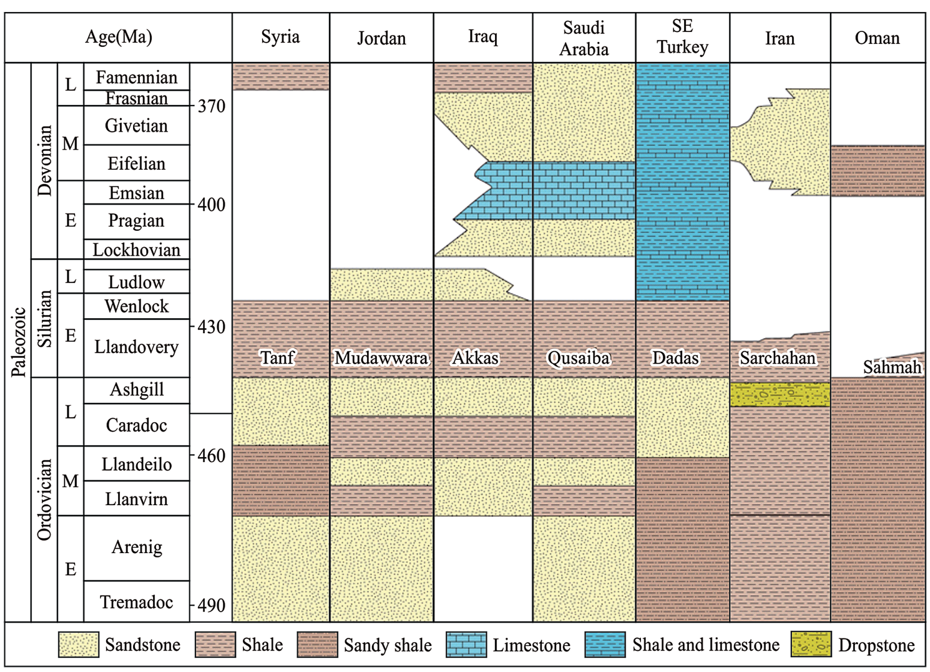

Fig. 1. Stratigraphic summary diagram of the Paleozoic in the southern Iran and Arabian Plate [3,6,9,26–29].

formation has been penetrated in many exploration wells in Iraq's Western Desert [36]. The upper and lower hot shales in Akkas-1well are approximately 25 and 41 m thick, respectively. The gamma-ray radiation in these two hot shales beds is quite high. There are 25 m of gray shale with normal gamma radiation between these two beds [26,27]. Al-Hadidy [27] subdivided the formation into two members based on gamma-ray and organic-matter content: the lower Hoseiba and the upper Qaim.

2.1.4. Mudawwara Formation in Jordan

The Mudawwara Formation, Batra Formation [37], and Batra or Mudawwara Mudstone Member of the Mudawwara Sandstone Formation are all names for the Silurian shale unit in Jordan [38]. A significant Tethys marine transgression occurred on the basin from the Middle Ordovician to the Early Upper Silurian, resulting in the deposition of 1700 m of marine clastic sediments in Jordan [7,8]. Mudawwara shale outcrops in Jordan are restricted to the Mudawwara region in the Southern Desert [7,39,40]. The lower hot shale unit is characterized by pale green, gray, and blue-gray graptolite-rich shales with thin red siltstone laminae in surface exposures [7,8,37]. Oxidation has changed the dark colors of the originals and partially or completely destroyed the organic content. The lowermost section of the Mudawwara shale is dark gray to black in shallow boreholes in the same location, with organic materials preserved [7,8].

2.1.5. Sahmah Formation in Oman

The Sahmah Formation extends from the western edge of the Rub' Al-Khali Basin to eastern Saudi Arabia. The Sahmah Formation consists of the lower Shale and upper Sandy member and reaches a thickness of more than 500 m The formation is thinner to the south and east because of erosion [41].

2.1.6. Tanf Formation in Syria

The Paleozoic section is consists of Ordovician shallow-marine clastic and lower Silurian shales from the Tanf Formation [42]. The Tanf Formation in Syria is located in the lower Silurian in two hot Shale zones separated by lean shale strata [43,44]. The hot Shales investigated from a Syrian well are quite rich in organic content to be characterized as oil shale [44]. The Tanf Formation is one of the two major source rocks in Syria that charge Paleozoic reservoirs [18,28,43,44]. Because of a proposed regional uplift, the Upper Silurian and Devonian formations are completely absent in eastern Syria [43].

2.1.7. Dadas Formation in Turkey

The Dadas Formation represents the Silurian–lower Devonian succession. The Dadas I Member represents the Silurian (Llandovery) hot shales of the succession [29]. The Silurian hot shale of the northern Arabian plate in southern Turkey are being eyed as a prospective unconventional oil and gas opportunity [29,45]. Mudstone, sandstone, and carbonates are found in the Silurian–lower Devonian Dadas II and Dadas III members. Black to dark-gray, laminated pyrite-rich shales indicates the hot shale. Anoxic conditions existed in the depositional habitat, which was an open marine but temporally restricted [29].

2.2. Tectonic features

2.2.1. Tectonic evolutionary features

Sedimentation, diagenesis, and sediment composition are considered to be influenced by the depositional environment's tectonic features [46,47]. The Arabian Plate is a tectonostratigraphic term that has been widely used in early Paleozoic palaeogeographic reconstructions, however, the "plate" only occurred in the Oligocene. Because of rifting along the margin of northeast Africa and the opening of the Red Sea and Gulf of Aden, the rocks that now comprise the Arabian Peninsula, Syria, Jordan, Iraq, and the Iranian Zagros began to separate from the African continent. The Arabian "Plate" was part of Gondwana from the Neoproterozoic until the end of the Paleozoic. Throughout the Neoproterozoic, the Zagros was near the equator, and during the Cambrian–Ordovician, it followed the southward (and poleward) drift that characterized West and East Gondwana, reaching as far south as 60°S latitude during Silurian times (Fig. 2) [3,48].

2.2.2. Present-day tectonic features

The present-day Arabian Plate's borders encompass a wide range of tectonic regimes. They include rifting and sea-floor spreading in the Red Sea and Gulf of Aden, collision along the Zagros and Bitlis sutures, subduction along the Makran zone, and transform movement in the Dead Sea and Owen-Sheba fault zones. The Arabian Plate is separated from the microplates of inner Iran by the Makran and Zagros convergence zones (Fig. 3) [6].

3. Material and methods

Major factors for evaluating shale gas potential include mineralogical composition, total organic content (TOC), and thermal maturity of shales. A total of 221 cutting and outcrops shale samples from the Paleozoic strata were discussed. The great majority of the data comes from readily available English-language sources and compiled from all currently available depth maps and source rock information (Fig. 4, Table 1). These study investigated total organic carbon (TOC wt%), pyrolysis (S1, S2, S3, HI, PI, OI), and vitrinite reflectance (% R_o) (Table 1), mineral composition and porosity and permeability. Many earlier published and unpublished investigations produced similar data [7,8,20–22,24,29,36,41,43]. All available information was analyzed and used to generate a detailed regional mapping of the source rocks and their characteristics. In general, determining the thermal maturity of lower Silurian shales is difficult since vitrinite did not exist at the time due to the general lack of land plants. Alternative approaches such as graptolite reflectance, chitinozoan coloration, and determination of the

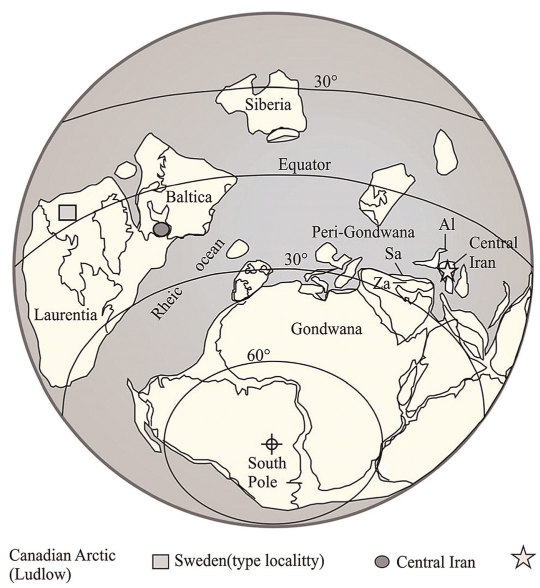

Fig. 2. Paleogeographic position of the Arabian Plate and Iran in the Wenlock–Ludlow (Silurian time) Modified from Ref.49].

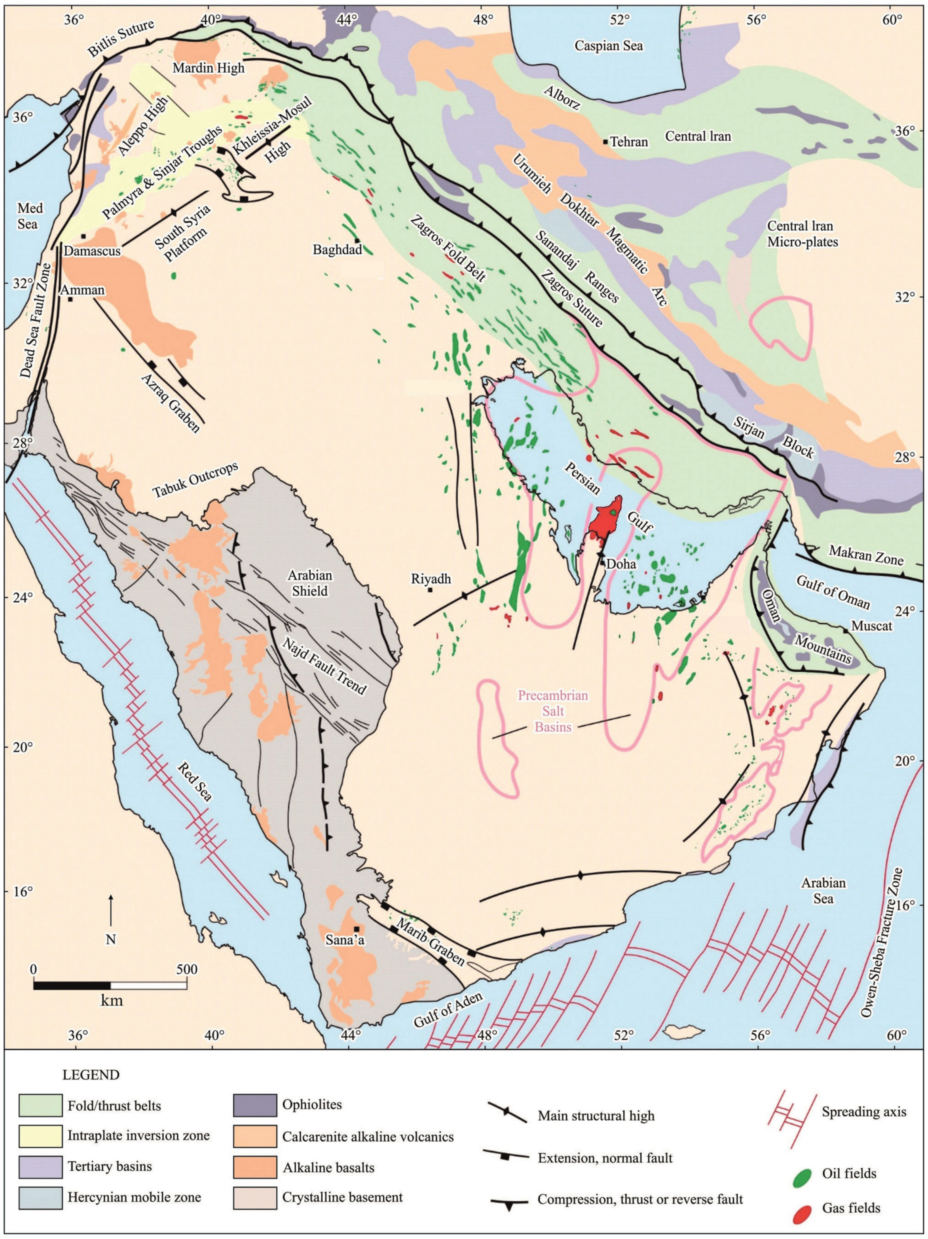

Fig. 3. Present-day tectonic features of the Arabian plate and Iran. Modified from Ref. [6].

pyrolysis-derived temperature of maximum hydrocarbon generation (T_{max}) are commonly used to estimate the vitrinite reflectance parameter (R_o).

4. Results and discussion

4.1. Total organic carbon (TOC) and kerogen types of hot shales

According to several types of researches, the preliminary evaluation of shale gas zones required that the shale fulfill specific geochemical characteristics, such as organic matter abundance (TOC) of over 2% and maturity (R_o) of higher than 1.1% [10]. In areas where all of these parameters are mostly achieved, shale gas exploration and production risks can be substantially reduced. Table 1 shows that TOC values of Silurian hot shale in the study area range from 0.14% to 16.68%, with an average of 5%. According to the TOC histogram, most of the data is in the range of lean shale with organic carbon values of 0.1%–2%. The highest frequency of TOC values is between 2% and 12%. In the range of oil shales, a few data have TOC values of more than 12% (Fig. 5). As shown in Fig. 6, the TOC versus S2 plot was used to determine the kerogen types in the studied area. The lower Silurian hot shale kerogen types are extremely varied, ranging from type II through type IV and organic matter in Iran and Saudi Arabia is mostly type III, humic type kerogen, which mostly generates gas during the maturity evolution phase.

4.2. Thermal maturity

The natural gas conversion rate may reach over 40% when the R_o value reaches 1.0% and over 95% when the R_o value reaches 2.5%. The main gas generation stage of coal bed organic matter is

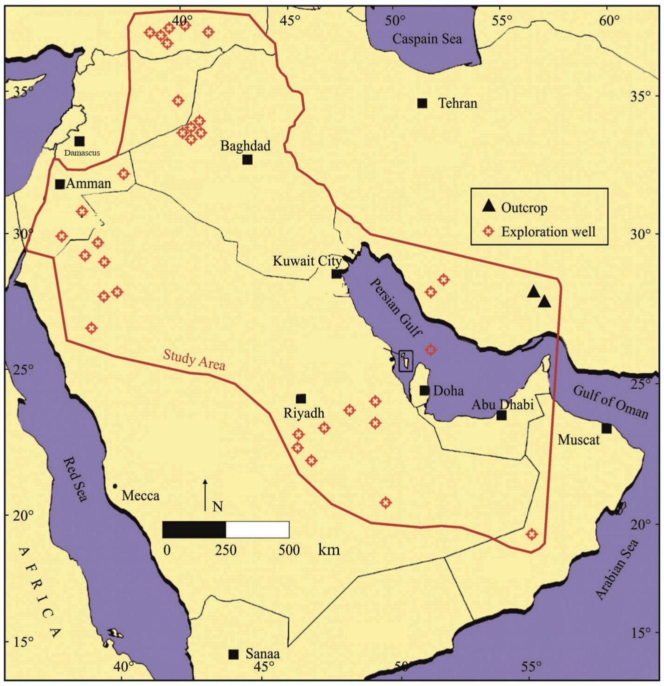

Fig. 4. Map of the study area, indicating the location of hot shale samples from both outcrops and exploration wells.

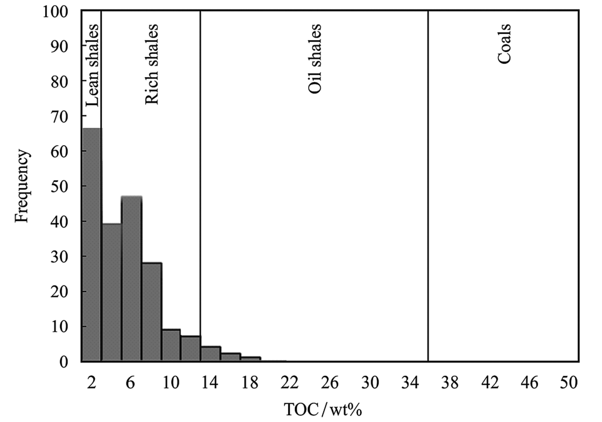

Fig. 5. Histogram for the TOC data.

between 0.8% and 2.5% R_o [50]. Table 1 contains a summary of R_o values. The R_o values in the samples range from 0.55% to 2.2%, with an average of 1.2%, indicating that the organic matter has been thermally matured/over-matured in Iran and east-central Saudi Arabia. Pyrolysis analysis (PI and T_{max}) can be used to measure the thermal maturity of organic material. Samples from the lower Silurian hot shale had T_{max} values ranging from 414°C to 510°C. The maturity of the majority of samples is within the late range of the oil generation window to the gas generation window in Iran and east-central Saudi Arabia as shown in the PI-T_{max} plot (Fig. 7). Earlier published research concluded that lower Silurian hot shale in Iran is currently in the gas window and this formation has entered the gas window since 75 million years ago [51]. The T_{max} of these shales, as obtained by Rock-Eval pyrolysis tests, likewise indicates a high level of maturity in Iran and east-central Saudi Arabia (Fig. 8) (Table 1).

Table 1
Average organic geochemical data for the hot Shale used in the current study and their sources.

Country	Well or outcrop name	No. of samples	TOC	S1	S2	T_{max}	HI	OI	R_{equ}	Data source
Iran	Kuh-e Farghun	12	4.00	0.58	6.88	458.89	149.44	6.33	ND	[21]
Iran	Kuh-e Farghun	17	5.29	0.48	5.47	458.95	154.3	4.2	1.9	[21]
Iran	Kuh-e Siah#1	8	0.83	0.01	0.08	444	10	60	ND	[21]
Iran	Golshan#3	7	0.26	0.27	0.21	429.14	83.14	686.86	ND	[21]
Iran	Zirreh#1	7	0.30	0.53	0.50	422	151	262	ND	[21]
Saudi Arabia	A	2	8.70	1.12	1.29	484	15	3	1.78	[22]
Saudi Arabia	B	2	1.50	0.145	0.48	444	40	37	0.98	[22]
Saudi Arabia	C	4	5.84	0.25	0.66	453	48	10	1.51	[22]
Saudi Arabia	D	3	5.65	1.00	1.00	473	22	6	2.03	[22]
Saudi Arabia	E	4	6.02	0.98	11.00	453	103	3.5	1.3	[22]
Saudi Arabia	F	1	12.6	2.52	63.80	414	508	4	0.68	[22]
Saudi Arabia	G	2	5.20	1.06	2.17	455	51	5.5	1.78	[22]
Saudi Arabia	H	4	6.52	2.35	12.42	441	210	2.75	1.7	[22]
Saudi Arabia	I	1	3.17	0.07	0.20	510	6	10	2.2	[22]
Saudi Arabia	J	2	1.61	0.30	0.55	455	35	16.5	1.33	[22]
Saudi Arabia	K	3	8.27	2.25	32.16	417	399	1.3	0.76	[22]
Saudi Arabia	L	3	2.10	0.05	0.56	429	35	8.3	ND	[22]
Saudi Arabia	M	2	1.61	0.025	0.24	427	24	12	ND	[22]
Iraq	Akkas-1	27	3.60	1.83	13.76	438	393	ND	0.9	[36]
Iraq	Akkas-2	7	4.75	1.78	16.39	439	373	ND	ND	[36]
Iraq	Akkas-3	13	4.10	2.04	14.55	439	361	ND	ND	[36]
Iraq	Akkas-4	6	3.60	0.80	5.87	436	289	ND	ND	[36]
Jordan	Risha	1	4.00	ND	ND	ND	ND	ND	1.2	[8]
Jordan	Wadi Sirhan	1	7.00	ND	ND	ND	ND	ND	0.8	[8]
Jordan	Al Jafr	1	9.00	ND	ND	ND	ND	ND	0.55	[8]
Oman	Rija-1	4	6.40	1.73	20.01	427	288	17.25	1	[41]
Syria	Ratka	9	7.00	0.20	5.00	465	71	11	1.35	[43]
Turkey	Gulf Kevan-1	14	7.51	2.20	30.00	433	413	ND	0.63	[29]
Turkey	TP Dogan-1	12	8.37	2.92	28.35	437	349	ND	0.71	[29]
Turkey	TP Soguktepe-1	10	3.07	1.30	6.80	466	213	ND	0.87	[29]
Turkey	TP K. Migo-2	10	4.39	2.80	8.60	444	184	ND	0.84	[29]
Turkey	TP G. Hazro-2	4	2.21	0.78	1.50	459	76	ND	1.1	[29]
Turkey	TP-Arco Abdulaziz-1	18	6.24	0.51	4.40	466	105	ND	1.23	[29]

TOC = total organic carbon (wt%); S1 = the amount of free organic compounds (mg HC/g rock); S2 = the amount of hydrocarbon compounds generated from thermal cracking of the kerogen (mg HC/g rock); T_{max} = pyrolysis temperature at the highest amount of HC released (∘C); HI = hydrogen index (mg HC/g TOC); OI = Oxygen index (mg HC/g TOC); R_{equ} = vitrinite reflectance equivalent; ND = no data available.

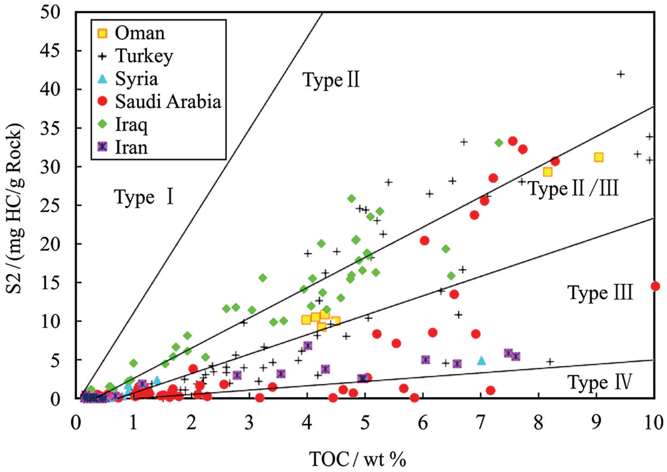

Fig. 6. A plot of S2 vs. TOC of the lower Silurian hot shale samples in the study area.

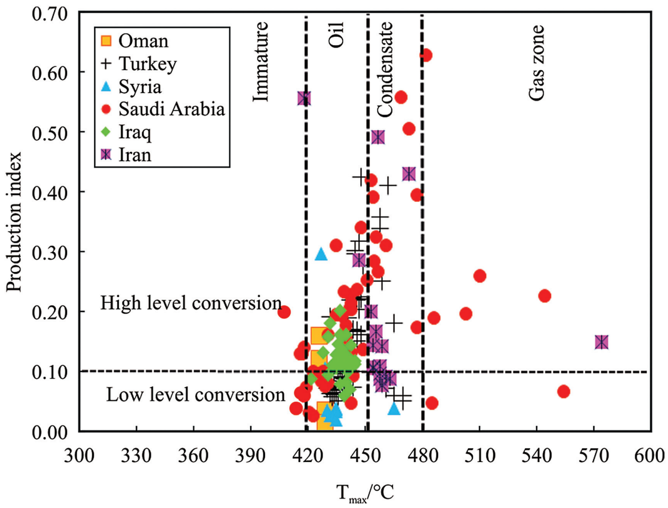

Fig. 7. Production index (PI) versus Rock-Eval T_{max} temperature of the lower Silurian hot shale samples in the study area.

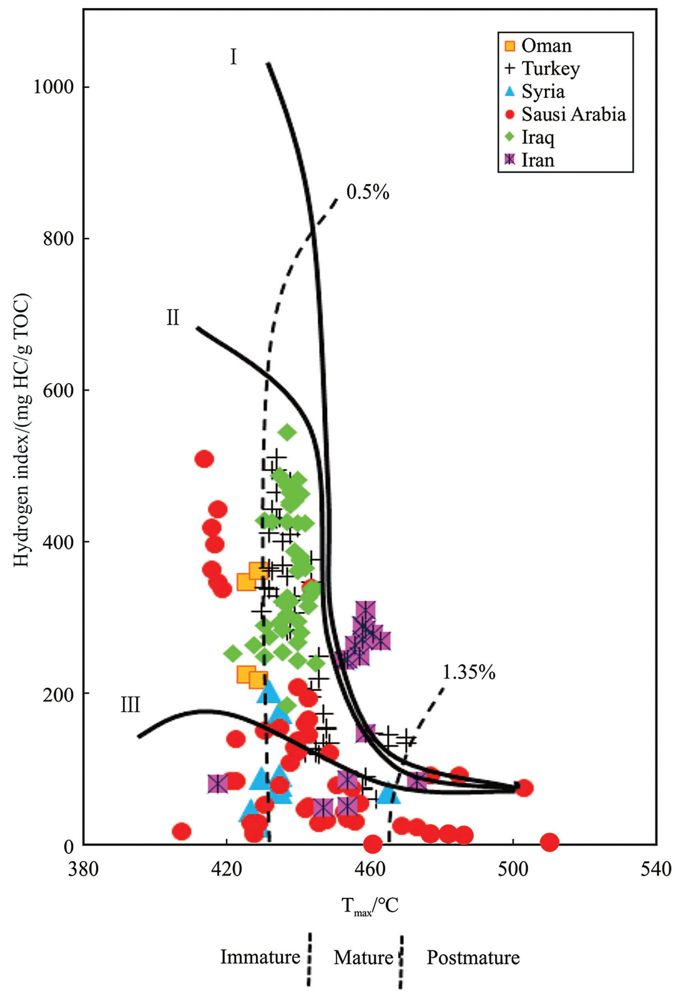

Fig. 8. Hydrogen index (HI) versus Rock-Eval T_{max} temperature of the lower Silurian hot shale samples in the study area.

4.3. Mineral composition

Lower Silurian shale in southern Iran and the Arabian Plate has clay minerals content ranging from 20% to 57% (average: 40%). Illite, illite-smectite mixed layer mineral, and chlorite are the most common clay minerals. Illite has a relative content of 30%–60%, illite-smectite mixed layer has a content of 20%–45%, and chlorite has a content of 2%–9%. quartz content ranges from 20% to 49% (average: 35.5%), whereas feldspar content ranges from 10% to 15%. (average 13%). calcite content ranges from 1.48% to 5% (average 2.67%) [52–54]. According to previous research, shales with a high percentage of brittle mineral particles, such as quartz, feldspar, and carbonate, have lower tensile strength and shear resistance. Natural and artificial fracture development consequently favors black shales rich in brittle minerals [12,55].

4.4. Porosity and permeability

The Arabian plate's lower Silurian hot shale contains about 25% of the total porosity, which is mainly composed of organic particles. The sample's overall mean porosity is 7.8%. However, organic particles with a high maturity has significant micro-porosity, with pore size distribution ranging from 0.2 to 0.6 μm, as well as a high level of pore connectivity, which is expected to contribute significantly to potential permeability. The permeability of the shale matrix is 1.6×10^{-6} mD [53]. Furthermore, silica cement is the most common cement type in southern Iran, resulting in porosity reduction and increased brittleness of the Sarchahan Formation [56].

4.5. Comparison of lower Silurian hot shale, southern Iran and the Arabian Plate and Longmaxi Formation in China

A set of fine clastic rocks, mostly black shale, deposited at the depositional stage of the early Silurian Longmaxi Formation as a result of tectonic movement and transgression. In South China, the lower Silurian Longmaxi Formation is a major target for shale-gas exploration [57]. The similarities and contrasts between the lower Silurian hot shale Formations in southern Iran and the Arabian Plate, as well as the Longmaxi Formation, are provided to show the lower Silurian hot shale in southern Iran and the Arabian Plate's unconventional reservoir potential. Organic geochemical features and thermal maturity, sedimentary setting, and thickness are the main comparative criteria. A high gamma-ray log response indicates organic-rich, basal hot shale strata in both formations. Total organic carbon (TOC) values are high in both formations. Both formations contain oil-prone zones and have started to gas-prone zones. The kerogen type of the Longmaxi Formation, on the opposite side, is mostly Type I [57], whereas the kerogen types of the lower Silurian hot shale Formation in southern Iran and the Arabian Plate are extremely varied, ranging from type II to type IV. The effective thickness of the Longmaxi Formation is notably considerable, increasing from northwest to southeast to approximately 120 m [57], whereas the lower Silurian hot shale Formations in southern Iran and the Arabian have a maximum thickness of 200 m. The sedimentary environment of the Longmaxi black shale is comparable to that of the basal Silurian hot shales in the Middle East and North Africa, and they are both the result of a major regional flooding event in the early Silurian. The Longmaxi shale was deposited on top of thick Ordovician limestones, whereas the Silurian hot shales were deposited on top of Ordovician sandstone [57]. Furthermore, no commercial discoveries have been made from Paleozoic unconventional reservoirs in southern Iran and the Arabian Plate to date. Nevertheless, because Silurian hot shales are still an undiscovered target, this is an advantage in researching their unconventional reservoir potential.

4.6. Favorable areas for exploration and development of shale gas

Because shale gas exploration and development in southern Iran and the Arabian Plate is still in the early stages, there is only a limited amount of data that can be utilized to determine resource potential. We considered a variety of parameters before determining ideal regions for shale gas potential of the lower Silurian hot shale. These factors included the total organic carbon (TOC), vitrinite reflectance (% R_o), kerogen types, burial depth of hot shales and pyrolysis (S1, S2, S3, HI, PI, OI), mineral composition and porosity and permeability. The burial depth of the shale gas has a significant impact on the costs of exploration and production. Some areas like Kuh-e Faraghun in Iran and NW Saudi Arabia are outcrop in the study area. Shale gas exploration and production has indicated that shale burial depths generally range from 180 to 3600 m, with a minimum hot shales thickness of 9 m [10,11,13,58]. The thickness of commercially sustainable hot shale has been reported to be higher than 30 m [10]. Lower Silurian hot shale is buried quite deep in a significant part of southern Iran and the Arabian Plate (Fig. 9).

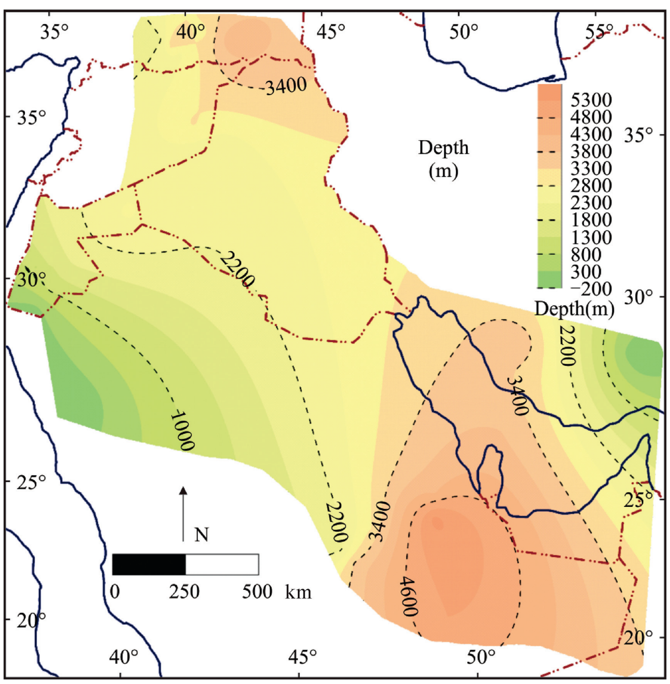

Fig. 9. Map showing depth below sea level to the top of the lower Silurian hot shale. Negative values represent depth above sea level (Contour intervals are 1200 m).

The lower Silurian hot shale's thickness varies from 3 to 200 m. In Turkey, the maximum thickness reaches 200 m. As shown in Fig. 10, in the study area the thickness of lower Silurian hot shale are generally higher than 30 m.

A TOC threshold of >2.0% has been recommended for commercial shale gas exploitation [10,11,13,58]. This number might be higher/lower in numerous sites [10]. It should not, however, be less than 0.3% [58]. As shown in Fig. 11, in the study area total organic carbon (TOC) levels are generally high.

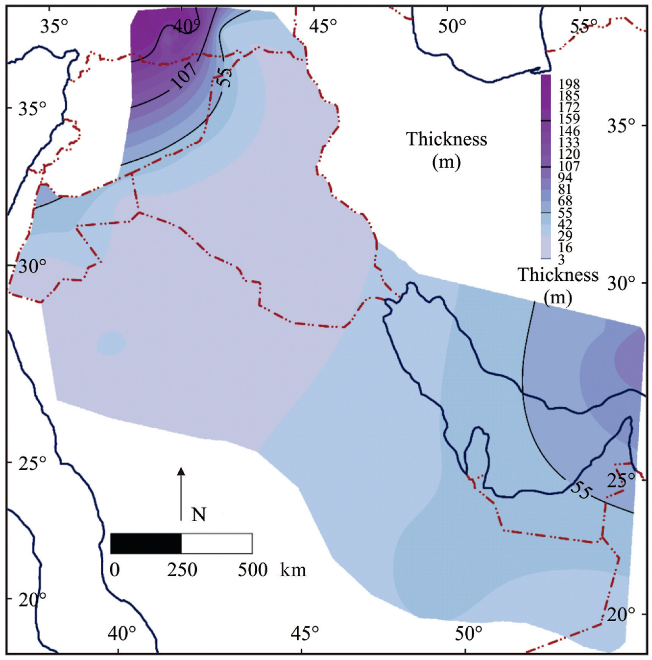

Fig. 10. Generalized isopach map of the lower Silurian hot shale in the study area.

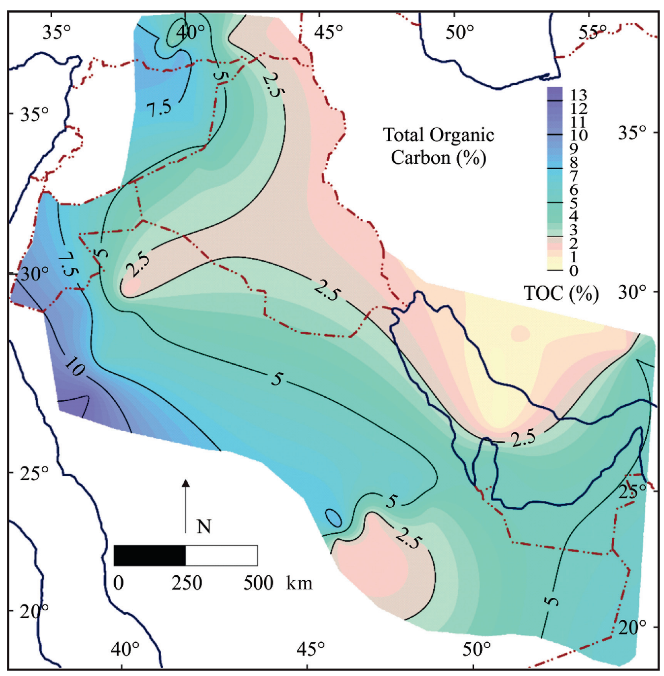

Fig. 11. Map illustrating the generalized distribution pattern of total organic carbon (TOC) in the study area.

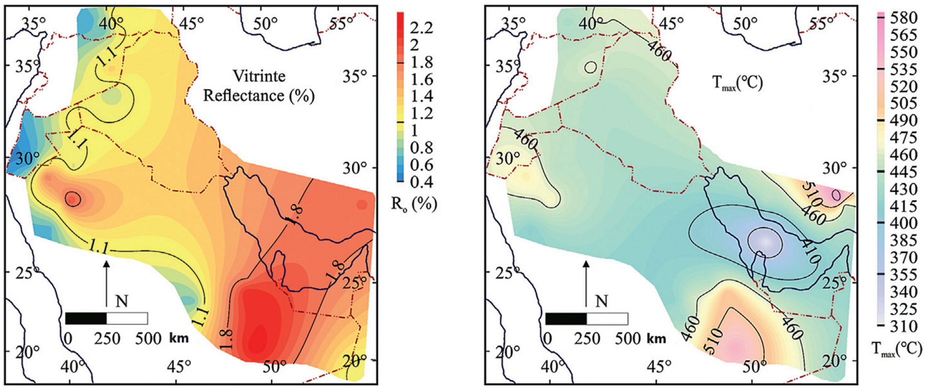

Fig. 12. Map illustrating the generalized distribution pattern of organic matter maturities as measured by R_o and T_{max} in the study area.

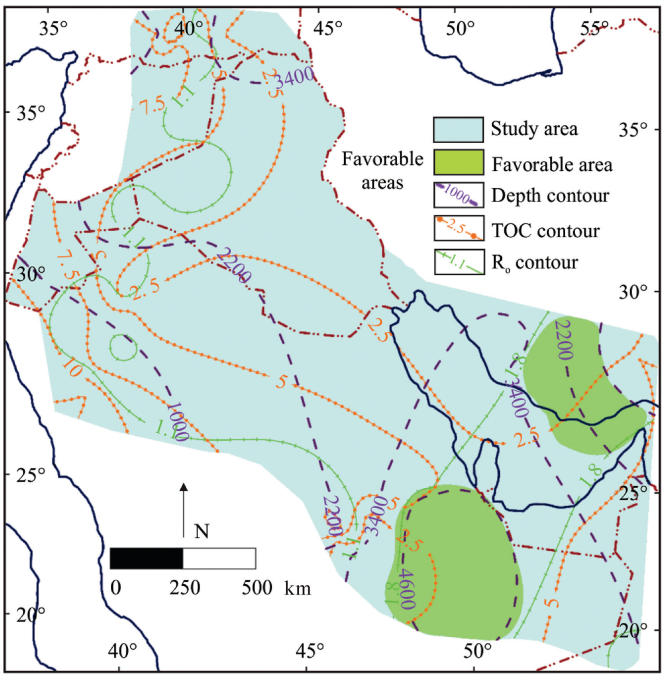

Fig. 13. Illustration of favorable shale gas zone of the lower Silurian hot shale in the study area.

R_o is estimated to be between 1.1% and 3.0% based on the shale gas development technique [10,13]. A minimum R_o value of >0.4% has been considered for shale gas production [58]. Organic matter maturities, as determined by R_o and T_{max} in this study, are relatively comparable to the requirement for gas production in southern Iran and east-central Saudi Arabia and the other parts of the study area is just 1.1%, concluding that they are not equal to the gas production requirement as shown in Fig. 12.

As a result, after considering all of the key parameters, we determined that southern Iran and east-central Saudi Arabia are the most ideal areas for shale gas exploration and production in the study area for lower Silurian hot shale, as shown in Fig. 13.

5. Conclusions

The lower Silurian shale is well developed in southern Iran and the Arabian Plate. In this study the essential elements of the productive Silurian shale are analyzed in southern Iran and the Arabian Plate. Our results indicate that key parameters are mostly achieved in some areas. These results include:

(1) The lower Silurian shale is particularly thick in the Southern Iran and east-central Saudi Arabia. A maximum burial depths of lower Silurian hot shale in southern Iran and the Arabian Plate is 5300 m, while A maximum thickness of 200 m is present in the study area.
(2) The lower Silurian hot shale kerogen types are extremely varied, ranging from type II through type IV and organic matter in Iran and Saudi Arabia is mostly type III, humic type kerogen, which mostly generates gas during the maturity evolution phase.
(3) Production index values in lower Silurian hot shale samples ranging from 0.01% to 0.6%, indicating that the organic matter are in the late range of the oil generation window to the gas generation window.
(4) Samples had R_o values ranging from 0.55% to 2.2%, with an average of 1.2%, indicating that the organic matter in Iran and Saudi Arabia had been thermally matured/over-matured.
(5) TOC values of Silurian hot shale range from 0.14% to 16.68%, with an average of 5%.
(6) T_{max} values in lower Silurian hot shale samples ranged from 414°C to 510°C.

According to burial depth, hot shale net thickness, TOC, and R_o values were plotted and mineral composition and porosity and permeability Southern Iran and east-central Saudi Arabia are both favorable areas for investigating shale gas and maybe significant locations for future exploration and production.

Acknowledgements

We would like to thank two anonymous reviewers for their constructive critiques. We also would like to extend our appreciations for the efforts of Dr. Jinzhou Zhao, Editor-in-Chief of the Journal in the course of review process.

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