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RESEARCH PAPER

Reconstruction of Depositional Environment of Sarchahan Formation (Silurian) in the Persian Gulf

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Abstract
Sarchahan Formation (Silurian) consists of shale and sandstone interbeds in the studied well in the Persian Gulf. Based on petrographic and wire line logs studies, five petrofacies and three facies associations were identified in the Sarchahan Formation. It is composed of fine-grained shale with a high amount of TOC and very thin interbeds of sandstone representing both marine and terrestrial deposits. This facies association comprises the lower parts of the Sarchahan Formation and was deposited in a prodelta sub-environment. Facies association 2 is composed of alternation of sandstone and shaley sandstone with dominance of shaley sandstone. It is deposited in a less deeper and nearer to beach environment compared to facies association 1 with fining upward sequences and represents delta front sub-environment. Facies association 3 is composed of sandstone and shaley sandstone with sandstone dominance and some red mudstone interlayers and anhydrite grains. It is mostly representing coarsening upward sequences which is assigned to delta plain sub-environment. Variations in facies association in combination with palynological studies represent that deposition of the Sarchahan Formation took place in different sub-environments of a delta environment from prodelta to delta plain. The lower part of the formation is represented by a high amount of black shale and higher total organic carbon values which are the result of deposition in the deeper parts of the basin. Meanwhile, the upper part is composed of sandstone and red mudstone which are the result of deposition in the shallower part of delta environment. Cementation, compaction, and dissolution are the main diagenetic features that affected the Sarchahan Formation. Silica and sericite cements are the most abundant cement types in quartzarenite and subarkose petrofacies the development of which resulted in porosity reduction. The comparison with the Arabian plate, the deposition took place in a southward deepening basin into which sediments were introduced from the northern parts.

Keywords: Sarchahan Formation, Delta environment, Persian Gulf, Arabian Plate, Silurian source rocks.

Introduction

As time passes by, the exploration of hydrocarbon in older rocks becomes inevitable due to the necessity of finding new prolific petroleum systems. In the Persian Gulf, seeking hydrocarbon reservoirs in the Paleozoic rocks have come to the center of attention (Kashfi, 2000; Bordenave, 2008). According to the latest investigations in the Iranian sector of the South Pars/North Dome (as it is called in Qatar) field (Fig. 1), the evidence of new potential reservoir are found in the Permian rocks and Silurian source rocks are considered as one of the major source rocks of

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Permo-Triassic reservoirs (Bordenave, 2008, 2014; Le Heron and Dowdeswell, 2009; Luning et al., 2005; Luning et al., 2000). Studying this source rock is important from two standpoints: firstly it is important to set up a lithostratigraphic correlation between this source rock with the ones studied in the other parts of the Persian Gulf; secondly, the role of this source rock in the generation of petroleum is of great importance.

Silurian shales in the Middle East are considered as major source rocks (Luning et al., 2000; Beydoun et al., 1992). This formation is called Sarchahan Formation in the Zagros, Iran (Ghavidel-Syooki, 1990, 1995; Motiei, 1993), Qusaiba and Sharawra formations in Saudi Arabia (Jones and Stump, 1999; Konert et al., 2001), Sahmah Formation in Oman, and Abba group in Syria (Abu-Ali et al., 1991; Mahamoud et al., 1992) (Fig. 2). In the latter countries, this formation is almost well studied and described in the outcrops (Saberi et al., 2016; Mahmoud et al., 1992; Senalp et al., 2001; Al-Husseini, 2000) and some wells in the Persian Gulf (Al-Saad and Sadooni, 2016). In the Iranian section of the Persian Gulf, no study has been carried out on these shales since they were located in great depths and so were not accessible in the wells.

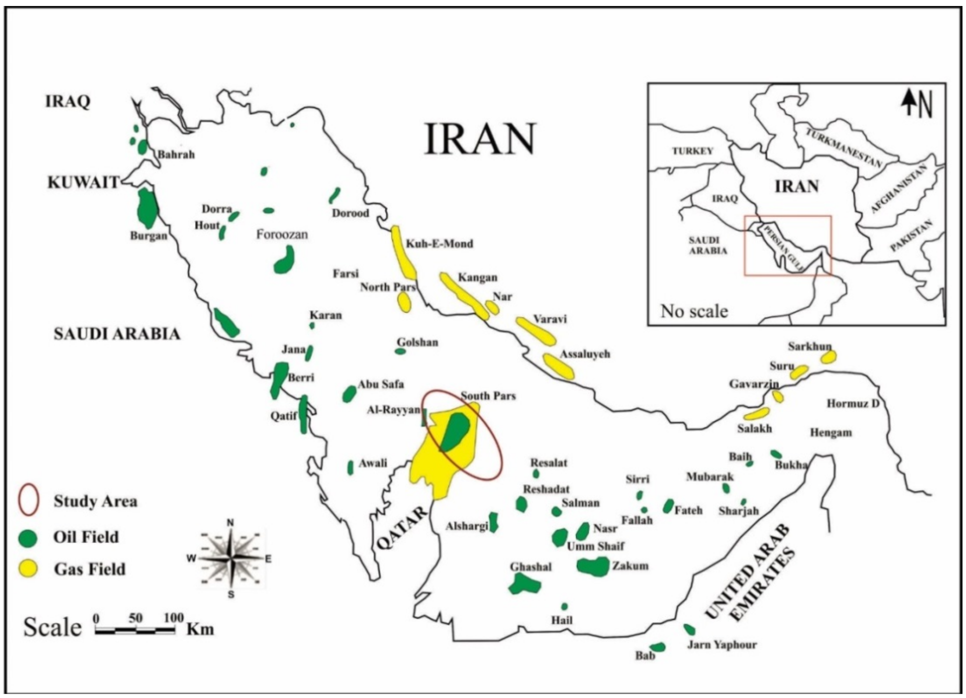

Figure 1. Location map of South Pars Field in the Persian Gulf

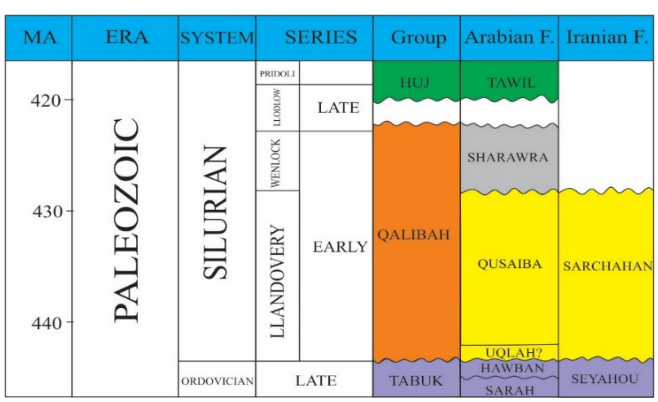

Figure 2. General lithostratigraphic chart for the Paleozoic sedimentary rock units in the South Pars and Arabian Plate (modified after Ghavidel-Syooki, 1997 and Halawani et al., 2013)

Sarchahan Formation in Iran was just studied in its outcrops in the Zagros Mountains. Almost all of these studies included paleontological and geochemical ones (Ghavidel-Syooki, 1995, 1996; Saberi et al., 2016; Rabani et al., 2007) and sedimentological characteristics of this formation have not been studied in details yet neither in the outcrops nor in the wells. During recent years, some wells were drilled into the upper and lower Paleozoic rocks in onshore and some offshore fields in Iran. Only one of these wells penetrated Silurian rocks in the Persian Gulf and consequently presented a chance of detail sedimentological studies on the Sarchahan Formation (Silurian). Here we are going to ~~re~~present the results of sedimentological studies of the Sarchahan Formation in the latter well in the Persian Gulf for the first time. Since this work is focused on sedimentological studies, we propose that one of the future studies can be the palynological studies for setting up a stratigraphic correlation with other parts of the Arabian Plate. On the other hand, the studied well is the first drilled well penetrating Sarchahan Formation; the data gathered from this well have a significant importance. At the time of this study, the available data included cuttings, logs, and geochemical data.

Geological setting

Deposition of Silurian shales occurred immediately after a period of glaciation (i.e. Hirnantian glaciation) and retreat of glaciers which resulted in a sea level rise (Rong and Harper, 1998; Owen and Robertson, 1995). This rise in sea level inundated low relief margins of continental area and resulted in development of shallow marine environment. As this shallow marine environment transgressed and covered vaster areas (Mahmoud et al., 1992; Jones and Stump, 1999) (Fig. 3), a chemical layering occurred which resulted in development of widespread anoxia which in turn caused preservation of organic matter in shales and ultimately formation of source rocks in the Middle East (Mahmoud et al., 1992; Bordenave, 2008).

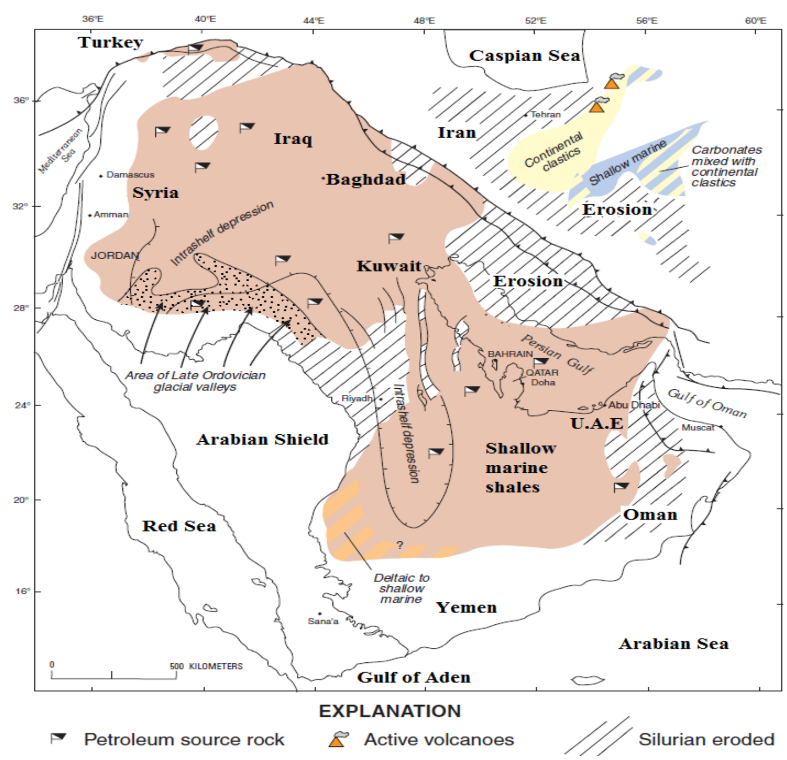

Figure 3. Paleogeographic map of early Silurian representing distribution of Khasibeh shaley member of Qaliba Formation in the Arabian depression and depositional and erosional areas on the Arabian plate and central Iran zone (Konert et al., 2001)

As it is investigated in other parts of the Arabian plate, these shales were deposited in a shallow marine environment when the sea level was rising. Afterwards, when sea level was at highstand, the predominant depositional environment changed into a prograding deltaic environment (Konert et al., 2001) (Fig. 2). In southern Persian Gulf states these Silurian shales are lithostratigraphically divided into two formations (i.e. Qusaiba and Sharawra formations) (Jones and Stump, 1999; Konert et al., 2001). However, in Iran in the Zagros Mountains, all Silurian deposits are named only as one formation called the Sarchahan Formation (Ghavidel-Syooki, 1990, 1995).

The study area is located in the Persian Gulf, i.e. South Pars Field (Fig 1). This formation has a lower Silurian age (Llandovery) and consists of shale and sandy layers (Ghavidel-Syooki and Winchester-Seeto, 2004). Iranian Silurian rocks generally have a variable thickness (70-700 m) and are composed of dark gray shales with abundant mica and Graptolithina with interlayers of sandstone and limestone. The Sarchahan Formation unconformably overlies on Ordovician Seyahou and Dargaz formations in their outcrops in Faraghan Mountain and lies unconformably on Seyahou Formation in Gahkum Mountain (Ghavidel-Syooki, 1996). On the other hand, Sarchahan Formation lies unconformably under Zakeen Formation (Devonian) almost all over the Zagros in the outcrops and subsurface sections. In the Zagros, the upper part of the Sarchahan Formation is composed of red siltstone and claystone in the outcrops (Ghavidel-Syooki, 1996).

Materials and methods

Cuttings and petrophysical logs from the first offshore well penetrated into the Sarchahan Formation in the Persian Gulf were available for this study. First of all, the cuttings which were obtained from 190 meters drilled interval were carefully studied under binocular; to provide a basic lithological description of the samples. Afterwards, 167 thin sections were prepared from shale and mostly from sandstone cutting samples and then were studied under petrographic microscope in detail (every 2 meters for shale samples and one meter for sandstone samples). For classification of sandstone facies Pettijohn's scheme (Pettijohn, 1975; Pettijohn et al., 1987) was used. These studies resulted in determination of petrofacies. To study the shaley cuttings, X-ray Diffraction (XRD) and Scanning Electron Microscope (SEM) analyses were performed to determine mineralogical composition of the samples especially the clay minerals. Also, 48 samples from the shaley section were selected for geochemical analysis. Elemental and organic geochemistry analyses were carried out the results of which were used to help in sedimentary environment reconstruction. By considering the results of petrographic, SEM and petrophysical studies a total number of four facies were identified. Besides, a palynofacies study was carried out mostly on shaley samples. Finally, based on combining petrofacies, firstly four facies were determined and afterwards by combining different facies the facies associations of different sub-environments in the Sarchahan Formation were found out. According to these facies associations and combining all palynofacies, petrophysical and geochemical studies, the depositional sub-environments were reconstructed. For palynological studies, some 58 samples were chosen and prepared for separation of palynofacies and studying relative abundance of palynological elements such as amorphous materials (AOMs), marine palynomorphs (Mps) and phytoclasts (Phs) in geological lab of Research Institute for Applied Science (RIAS).

Results

To reconstruct the sedimentary environment of the Sarchahan Formation, petrographic studies of cuttings, well logs response and the results of palynological and geochemical studies were combined. Based on these results, a total of five petrofacies could be identified and defined

(Table 1). Afterwards, by combining petrofacies and log responses, equivalent sedimentary facies and facies associations were introduced. Eventually the results of facies associations were used for reconstruction of depositional environment model and meanwhile geochemical and palynological evidence were introduced for cross-checking.

Facies

In this formation totally five petrofacies were recognized based on petrographic studies on cuttings (macroscopy) and thin sections (microscopic). By combining the results of petrographic and XRD studies with geochemical results four facies (S1-S4) were recognized in the Sarchahan Formation (Table 1). For identification of sub-environments in the Sarchahan Formation, it was necessary to determine facies associations. In this regard 3 facies associations were determined based on association and repeating of special facies on each other. These facies associations represent offshore, delta front and delta plain Sub-environment. Figure 2 illustrates the lithological column and vertical distribution of the recognized facies in the Sarchahan Formation.

Facies S1 (Sandstone)

This facies is composed of sandstone with dominant quartz grains (with syntaxial overgrowth), k-feldspars (Fig. 7C), tourmaline (Fig.7L) and zircon minerals (Fig. 7B and 8). Under binocular, it is composed of white and limpid grains (Fig. 4A) and under the microscope it is classified as quartz arenite and subarkose petrofacies according to the classification scheme of Pettijohn (Pettijohn and Potter, 1987) (Fig. 5). Most parts of this facies consist of well-sorted subarkose. Grain size in this facies range from fine to medium sand. From both mineralogical and textural maturity standpoints, this facies is considered as submature. Feldspar content in this facies varies so that in some places it is represented as quartz arenite and in other places with arkose petrofacies. Various types of cements are observed: silica overgrowth, intergranular pyrite, calcite and dolomite cement. The dominant porosity type is of intergranular one. Most of clay minerals are of illite-muscovite type as represented by SEM studies. These clays are observed as pore-filling and lining the pore space. XRD results also verify the presence of illite-muscovite in subarkose petrofacies (Fig. 5).

Table 1. Petrofacies and Facies in Sarchahan Formation

Facies	Petrofacies	Description
S1: Sandstone	Quartzarenite Subarkose	The major mineral is quartz. Most of the samples are supermature quartzarenite with well-rounded and well sorted grains
S2: Shale	Shale	The grains are silt to clay sized. Due to the presence of high content of organic carbon this facies is black in color
S3: Sandy Shale	Sandy Shale	This facies is very similar to shaley facies but it contains sand-sized quartz grains which sometimes represents a vague orientation. Sometimes alternating sandy and shaley laminations are observed.
S4: Red Mudstone	Red Mudstone	This facies is very similar to shaley facies but it is red in color which represents a prolonged subaerial exposure which resulted in oxidation of ferric iron to ferrous and alteration of other grains such as feldspars to clay minerals such as kaolinite.

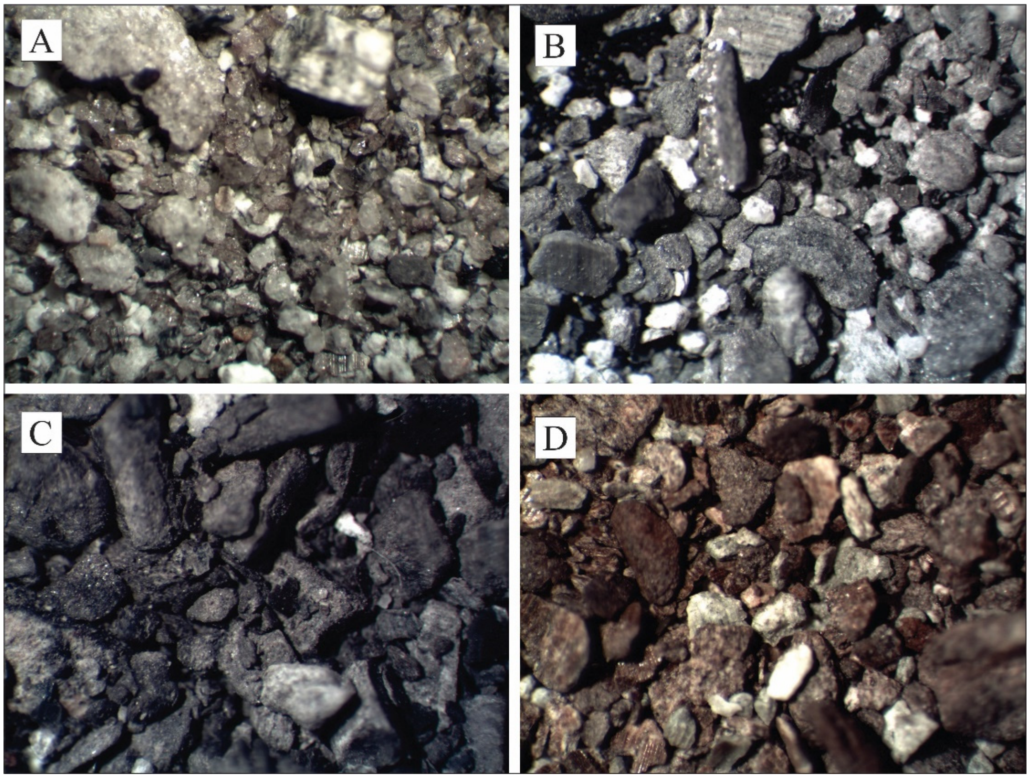

Figure 4. Cuttings samples from different facies under binocular: A: gray and white Sand, B: Sandy Shale, C: Shale, 4: Red Mudstone

Facies S2 (Shale)

This facies is represented by black and shiny grains under binocular (Fig. 4C) and under the microscope, it is represented as siltstone to claystone which contains very fine clay minerals and very scarce fine quartz grains (Fig. 5). XRD analysis of these samples indicates the presence of clay minerals such as kaolinite and illite. The latter analysis also represents the presence of muscovite and albite minerals (Fig. 5). Geochemical analyses indicate that TOC of this facies is more than the other ones (Fig. 8).

Facies S3 (Sandy Shale)

This facies comprises a major part of the Sarchahan Formation. It is represented by dark grey grains under binocular (Fig. 4B). From sedimentological point of view, it is very similar to the shale facies (Facies S2). The prominent difference is the presence of grains including quartz, chert and feldspar (mostly k-feldspar). In some parts fine to medium grains are observed (Fig. 5). The grains in this petrofacies are angular. Sometimes a clear orientation is observed in grains. In most parts alternation of quartz-dominated and clay minerals dominated layers is observed. SEM analysis of the samples represents the presence of small pore spaces between the grain boundaries and clay minerals. XRD analysis of the samples represents that the major clay minerals are kaolinite and illite in this facies (Fig. 5).

Facies S4 (Red Mudstone)

This facies is readily recognized from the other facies by its red weathered color (Fig. 4D). It is very similar to sandy shale facies (S3) from grain size and other sedimentological characteristics viewpoint. Its constituent grains are silt and clay sized. This facies is more dominant in the upper part of the studied section. The dominance of iron oxide in some intervals resulted in horizons with dark red color. Based on XRD studies, the present clay minerals in this facies are mostly of illite-muscovite type and kaolinite to a lesser extent. SEM studies also represent a high content of clay minerals besides quartz and dolomite grains (Fig. 5)

Diagenesis

Diagenesis and its controlling factors are essential concepts in understanding the evolution of sediments through time.

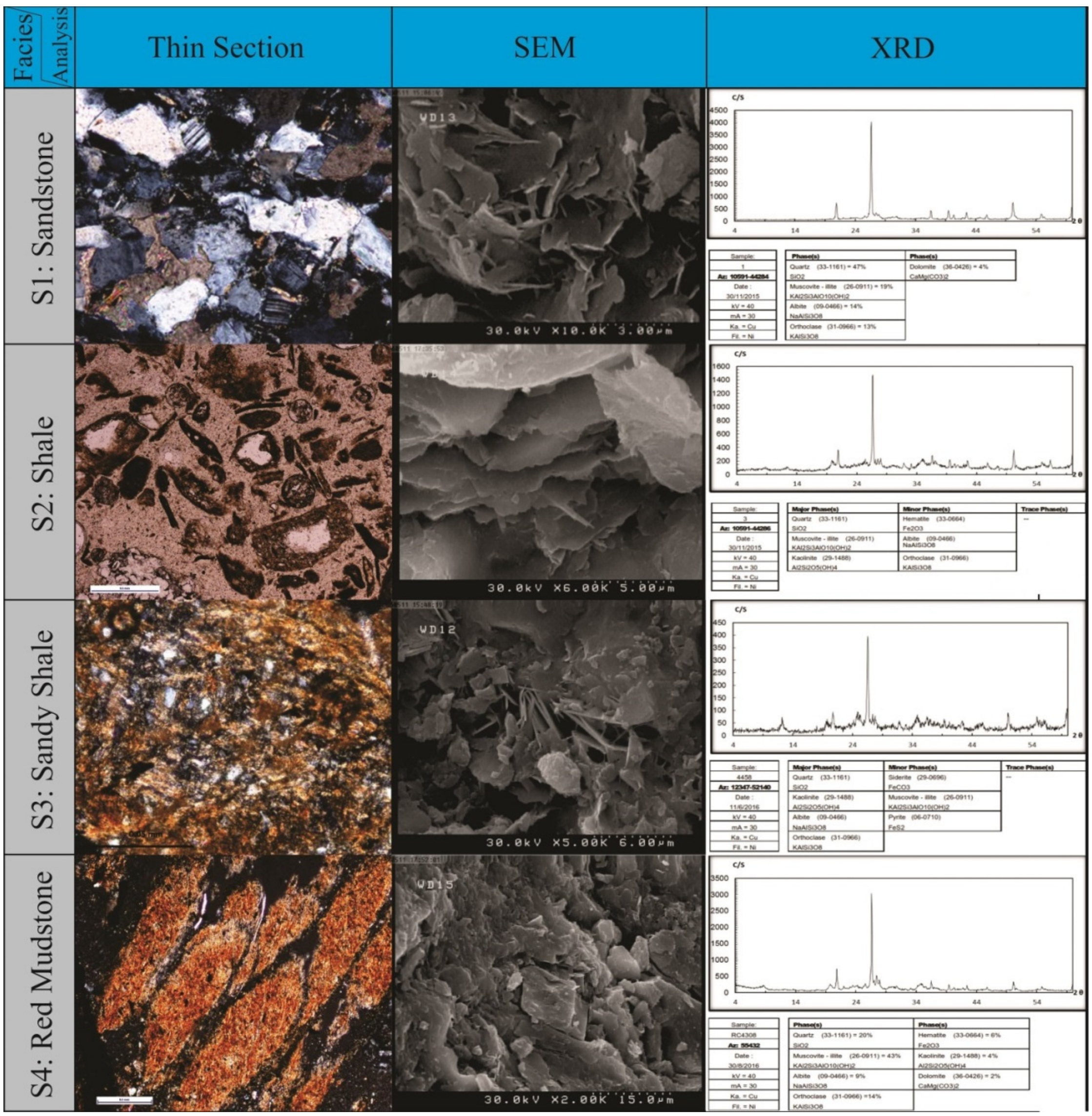

Figure 5. Different facies from top to bottom respectively: S1: including subarkose petrofacies along with carbonate cement, feldspar grains and illite clay in SEM image; quartz and illite-muscovite represented by XRD graph. S2: including black organic matter bearing grains, illite clay in SEM image; illite-muscovite along with kaolinite represented by XRD graph. S3: including shaley along with quartz grains in thin section; kaolinite and quartz minerals in SEM and kaolinite clay represented by XRD graph. S4: including: red mudstone grains under the microscope; quartz and dolomite minerals in SEM and illite-muscovite represented by XRD graph.

Diagenetic processes are mainly controlled by different factors such as mineral composition of sediments, chemical composition of pore waters and geological history of sediments such as burial depth, uplift, sea-level fluctuations and climatic controls (Morad et al., 2000). Some of the important diagenetic processes and products of the Sarchahan Formation are described below.

Silica cement: Silica cement is mostly observed as overgrowth cement on quartz grains in petrographic studies (Fig. 6A-B). Other forms of this cement include microcrystalline, intergranular cement resulted from pressure solution of quartz grains, subhedral-euhedral quartz crystals, and fracture-filling silica cement. Since quartz grains are more abundant in sandstones of the Sarchahan Formation (in quartz arenite and subarkose petrofacies), the source of silica for cementing the grains can be the dissolution of quartz grains available in the formation due to pressure dissolution, feldspar alteration and clay minerals transformation into each other (e.g. kaolinite to illite). Similar probable sources providing silica for sandstone cementation were reported by researchers previously (Morad et al., 2000).

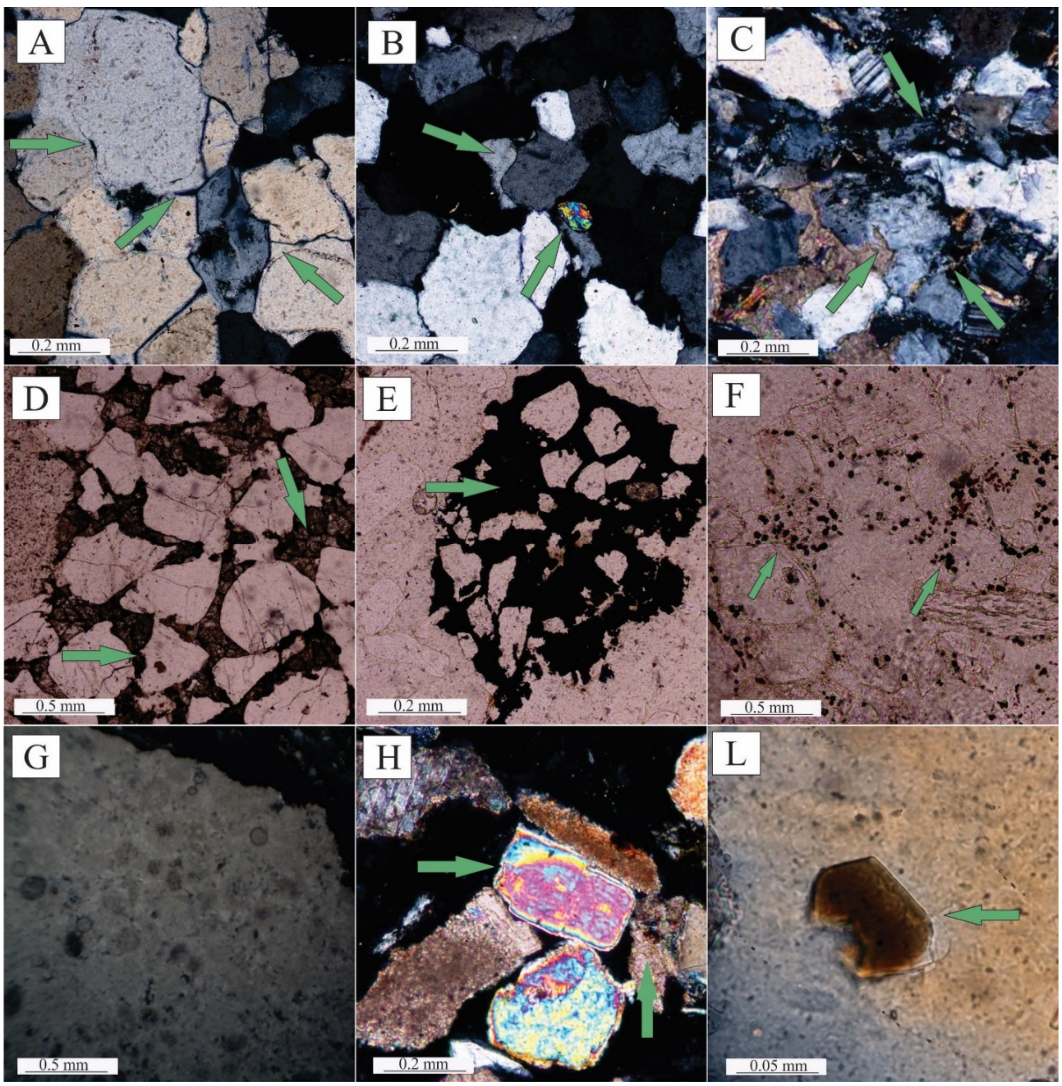

Figure 6. A: syntaxial silica cement, compaction and dissolution (arrows); B: silica cement, grains compaction and dissolution with zircon mineral (arrows); C: calcite and sericitic cement with dissolution of grains (arrows); D: dolomite cement and corrosion of grains (arrows); E: pyrite cement (arrow); F: iron oxide cement (arrow); G: calcite cement; H: anhydrite grain and calcite cement (arrows); L: tourmaline grain (arrow)

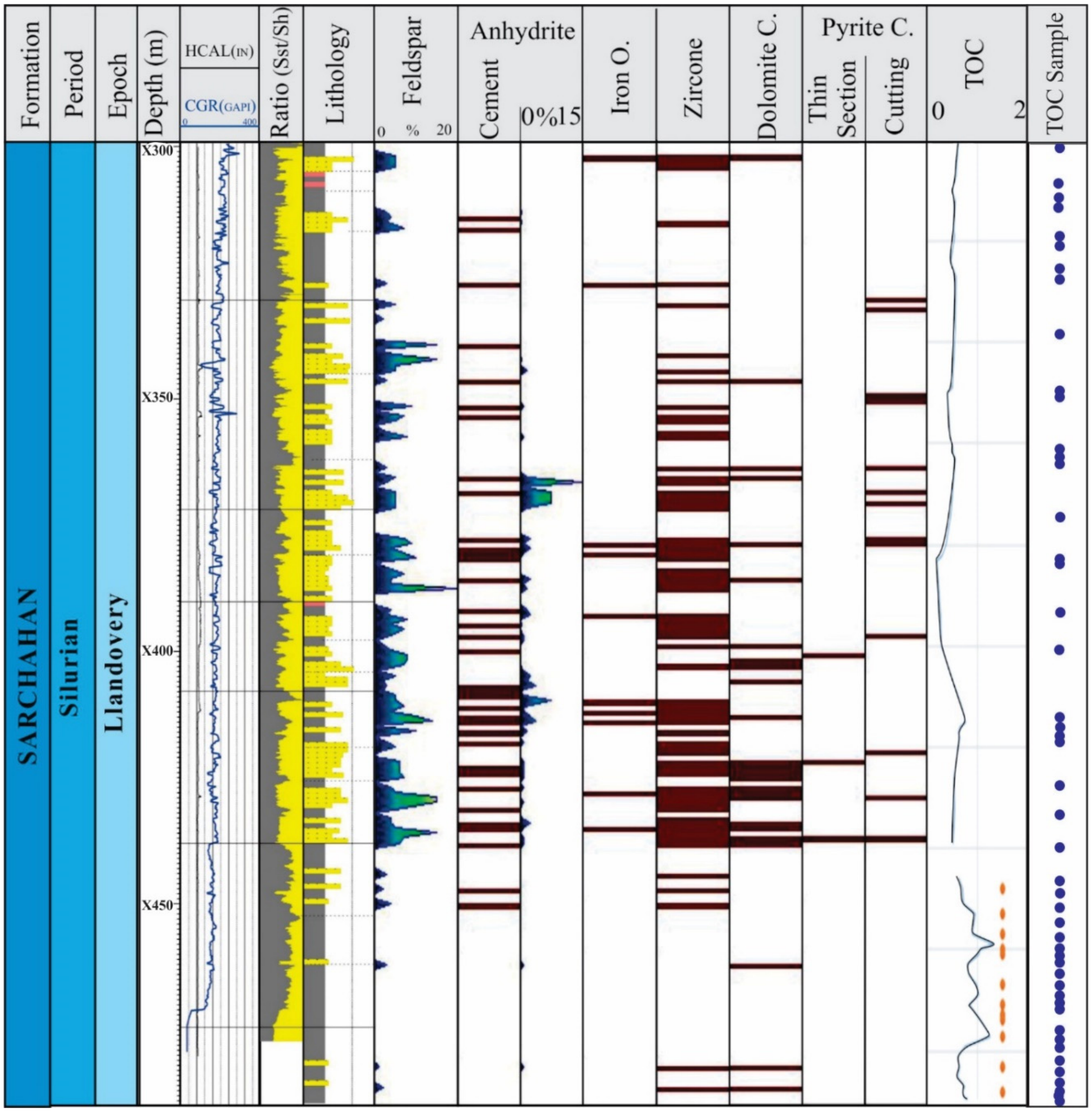

Figure 7. The lithology of the Sarchahan Formation along with distribution of feldspar content, GR and TOC changes and distribution of some diagenetic products of this formation

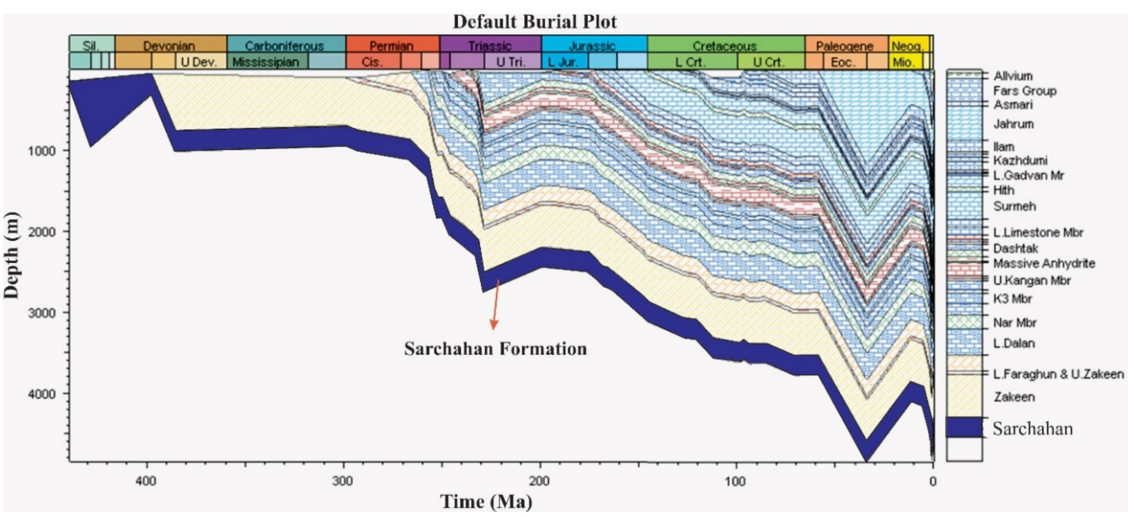

Figure 8. Burial history of Sarchahan Formation

Carbonate cements: Carbonate cements are the most important and abundant cements in the Sarchahan Formation. The abundance of these cements varies in different parts of the studied formation in the well. They mostly comprise calcite and dolomite cements which are discussed below.

Calcite cement: When the water is supersaturated with respect to calcium and bicarbonate ions calcium carbonate is precipitated as calcite cement in intergranular pores in sediments or fractures in the rocks (Tucker, 2001). Early diagenetic cement is observed as patchy forms and late diagenetic calcite cements are observed as poikilotopic and pore-filling cements in sandstone and siltstone petrofacies (Fig 6C-G-H). Sometimes precipitation of calcite cement caused partial dissolution of quartz grains because a basic (pH> 7) condition prevailed.

Dolomite cement: Dolomite cement is mostly observed as pore filling, poikilotopic or patchy forms (Fig 6D). It was possibly developed as a result of replacement of micritic calcite grains. The distribution of dolomite cement in the Sarchahan Formation is shown in Figure 7.

Fe-oxide cement: Iron oxide cement (with red to brown color) is observed in both sandstone and mudstone petrofacies. This cement is usually seen as pore-filling and iron oxide seams between quartz grains and their overgrowths (Fig. 6F). This cement is an indication of precipitation under oxidizing conditions in vadose zone or telogenic environments. Sometimes this cement is observed as patchy cement between grains. The distribution of Fe-oxide cement is shown in Figure 7.

Pyrite cement: Pyrite cement is sporadically observed in small amounts in the Sarchahan Formation. This cement is observed as intergranular and framboidal forms in sandstones (Fig. 6E). Development of this cement took place as a result of reaction between iron ions with H_2S especially by sulphate reducing bacteria or development of reducing conditions (Vieira and Ros, 2006). The distribution of pyrite cement is shown in Figure 7.

Sericite cement: Sericite cement is mostly observed in arkose and subarkose petrofacies. Its development greatly impacted porosity and permeability of the sandstone. Sericite cement developed as a result of feldspar alteration (Fig. 6C). Its abundance in feldspar bearing petrofacies (i.e. arkose and subarkose) is the evidence showing the role of feldspar alteration in development of sericite cement. Compaction: compaction usually takes place immediately after deposition of sediments (Fig. 6A-B). This phenomenon causes a reduction in sediments volume and consequently reduction in porosity and reservoir quality. Its intensity depends on rate of deposition, burial depth and the volume of fine-grained sediments. The more sediments are buried, the more intense compaction is. It is usually associated with dissolution and cementation. Cementation of grains before compaction caused reduction in compaction of grains. An increase in compaction finally results in development of fractures which are usually filled with cements.

Dissolution: Dissolution of grains in the Sarchahan Formation occurred as a result of sandstone grain compaction (Fig. 6A-B-C-D). The result of this compaction and dissolution of grains in this formation is illustrated in development of concave-convex boundaries and precipitation of silica cement on quartz grains as overgrowths.

Figure 7 illustrates the distribution of diagenetic factors in stratigraphic column.

Paragenetic sequence in the Sarchahan Formation

The first diagenetic phenomenon which affected the Sarchahan Formation sediments was compaction. It started almost immediately after deposition and continued up to mesogenesis stage. During this time the intensity of compaction changed from the more intense at the beginning of eogenesis and lessened gradually with more burial and cementation as well. Development of silica cement occurred in two stages. The first stage happened at the beginning of burial before the sediments underwent severe compaction. The second stage took place after intense compaction in deeply buried sediments which represents pressure solution phenomenon.

The silica released from this pressure solution precipitated as overgrowth or intergranular silica cements in sandstone layers in later stages (i.e. late eogenesis to mesogenesis stage). Since carbonate cements precipitated in the pore spaces on previously precipitated silica cements, carbonate cements are considered as a late diagenetic phenomenon. These carbonate cements have large crystals and both of these evidence represent that this type of carbonate cements developed during mesogenesis stage. Another carbonate cement that is observed in the Sarchahan Formation is Fe-dolomite cement. Since this ferroan dolomite is formed under reducing conditions (Worden and Burley, 2003), this type of cement can be inferred to be formed in mesogenesis stage. According to precipitation of Fe-dolomite on silica cement, its development in mesegenesis stage is understood. There are also poikilotopic calcite and saddle dolomite cements which are formed on silica cements. Both of these cements are considered to form in deep burial mesogenetic environments (Worden and Burley, 2003). Pyrite cement is also observed in sandstones in the Sarchahan Formation. Development of pyrite took place in reducing conditions, besides it filled the remained pore spaces after compaction. As stated before pyrite cement is observed in two forms of framboidal and patchy. Framboidal pyrite is mostly considered to be a diagenetic product of bacteria that are active in reducing conditions. Because development of reducing conditions especially in sandstone takes place in conditions out of reach of oxygen (i.e. after eogenesis and before telogenesis stages), so development of reducing conditions mostly occurs in mesogenetic environments. The latter environments provide best condition for activity of sulphate reducing bacteria (producing framboidal pyrite) and also precipitation of pyrite in patchy forms. According to all these evidence, development of pyrite cement mostly took place in burial mesogenetic environments. Fe-oxide cement is the last cement that is formed on silica, carbonate and pyrite cements. This shows that Fe-oxide cement postdated all of the previous cements. Based on its position and its development under oxidizing conditions, it can be assumed that Fe-oxide cement developed in telogenetic condition. This condition prevailed during uplift causing the sediments to be exposed to oxygen in near surface environments. According to burial history diagram prepared for the studied well (Fig. 8), development of telogenetic conditions happened during Devonian period. Consequently, we can propose that the development of Fe-oxide cement took place during this uplift stage.

Feldspar alteration took place when the feldspar grains were subjected to freshwater input. This situation happened two times. The first time was immediately after deposition during eogenesis. The second time could be during uplift in Devonian time (i.e. telogenesis). sericite cement in Sarchahan Formation is usually observed in feldspar-rich sandstones. Usually, sericite cement develops from illite recrystallization during mesogenesis, it can be deduced that feldspar alteration which resulted in clay minerals development (e.g. kaolinite and illite) took place in eodiagenesis stage. Afterwards these clay minerals recrystallized into sericite cement during mesogenesis when the sediments were buried. Accordingly, the paragentic sequence of these sediments can be represented in Figure 9.

Facies Associations

A facies association is defined based on genetic relations of facies with each other. In this study for recognizing the facies associations, all petrography, geochemical analyses and repeating of the facies on each other were taken into account. The Sarchahan Formation represents three facies associations which are discussed below:

FA1: Offshore

This facies association comprises shale and sandy shale facies which comprise most part of the studied sequence.

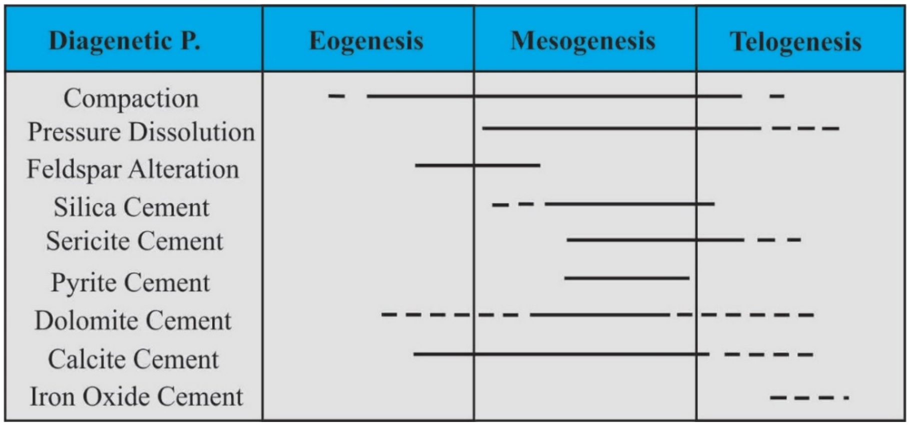

Figure 9. Paragenetic sequence of the diagenetic products in the Sarchahan Formation

This facies association is mostly observed in the lower 40 meters of the studied interval. It has a dark color indicating a high amount of organic matter content (TOC, Fig. 7) deposited in a deep environment with limited water circulation in an open sea. The latter situation resulted in a suitable organic matter preservation condition which is caused by weaker circulation of water in shallower basins (i.e. semi-confined environment). According to the observations, this facies association represents deposition in an offshore prodelta environment. Its coarsening upward nature represents deposition under a changing depositional condition through time toward a shallower environmental setting where energy level changes from a lower level to a higher one. However, changes in lithology from shale to sandy shale can be assigned to fluctuation of energy level in shallower parts caused by high energy events (e.g. turbidity currents) and resulted in shedding sandy grain into deeper environments. In addition, fossil content and TOC level indicate that this facies association was deposited in a deeper condition with respect to the other facies associations in the Sarchahan Formation.

FA2: Shoreface (delta front)

This facies association is composed of sandy shale (dominant) and sandstone facies. This facies association represents terrestrial sediment input and a higher energy flow into the environment. In some parts an obvious preferential orientation is observed in constituent grains. Sometimes an alternation of quartz grains and shaley layers is observed (Fig. 5). This alternation shows changes in energy level of the environment so that in more calm situations shaley layers were deposited and by increasing energy level silty or sandy layers containing quartz deposited. This facies association was deposited in a delta front environment where most of the facies were sandy shale and sporadically sandy facies were introduced into the environment. When sea level fluctuation was at the minimum or when sea bed deformation was little, a more stable condition developed and resulted in deposition of quartz arenite facies near foreshore (beach) environments.

FA3: delta plain

This facies association is composed of sandy shale and sandstone lithologies similar to FA2, but in FA3 sandstone lithology dominates over sandy shale and it also has red mudstone facies. Sorting is good in sandstone facies representing higher level of energy in the environment (beach) and larger transportation time. Abundance of feldspars and more angular grains in sandstone facies are indication of proximity to source area or a high energy condition resulted from input of the rivers.

This facies association includes a small sequence of sandstone, sandy shale and red mudstone. Higher level of energy in the environment is represented by well sorted sandstones. According to the changes in grain size in the sequence and presence of the red mudstone, it can be inferred that the depositional environment sometimes underwent subaerial exposure and oxidation of Fe in sediments and leading to development of red mudstone. The latter evidence besides lower value of Fe^{2+}/Fe^{3+} (representing oxidizing environment) (POGC internal report, 2017), deposition of this facies association is assigned to the upper limits of the delta plain to the seaward of which a sandy beach developed (Fig. 10). Also in this facies association, some anhydrite grains were observed representing temporary subaerial exposure of the sediments (Fig. 6H).

palynological evidence

The results of palynological studies indicate that from bottom of the Sarchahan Formation to the top, changes of sea level resulted in relative abundance of marine palynomorphs and terrestrial materials input.

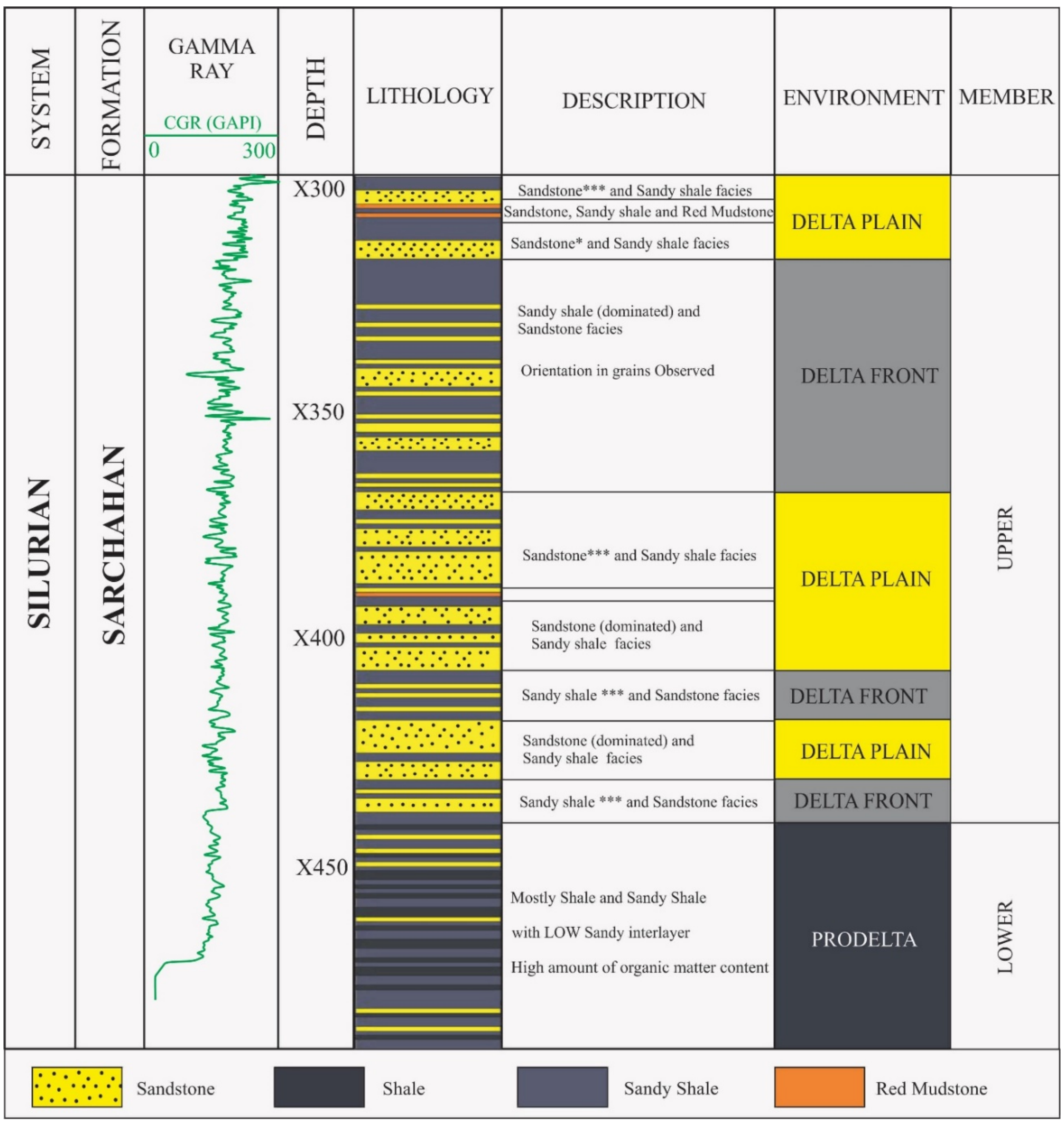

Figure 10. lithological column, facies distribution and facies association of the Sarchahan Formation

In equidimensional opaque palynomacerals (P1) against blade-shape opaque palynomacerals (P2), relative abundance of blade-shape opaque palynomacerals is indication of relative deepening of depositional environment (Tyson, 1995; Van der Zwan, 1990). An increase in relative abundance of opaque equant palynomacerals in the uppermost 50 meters of upper Sarchahan Formation represent short-term regression of the sea and relative decrease in the depth of the environment. Based on this study, 140 meters of the Sarchahan Formation at the base represents deposition in a relatively deeper and less oxygenated environment. The upper 50 meters of this formation deposited in a relatively proximal and shallower foreshore environment with low to moderate level of oxygen (Fig. 11).

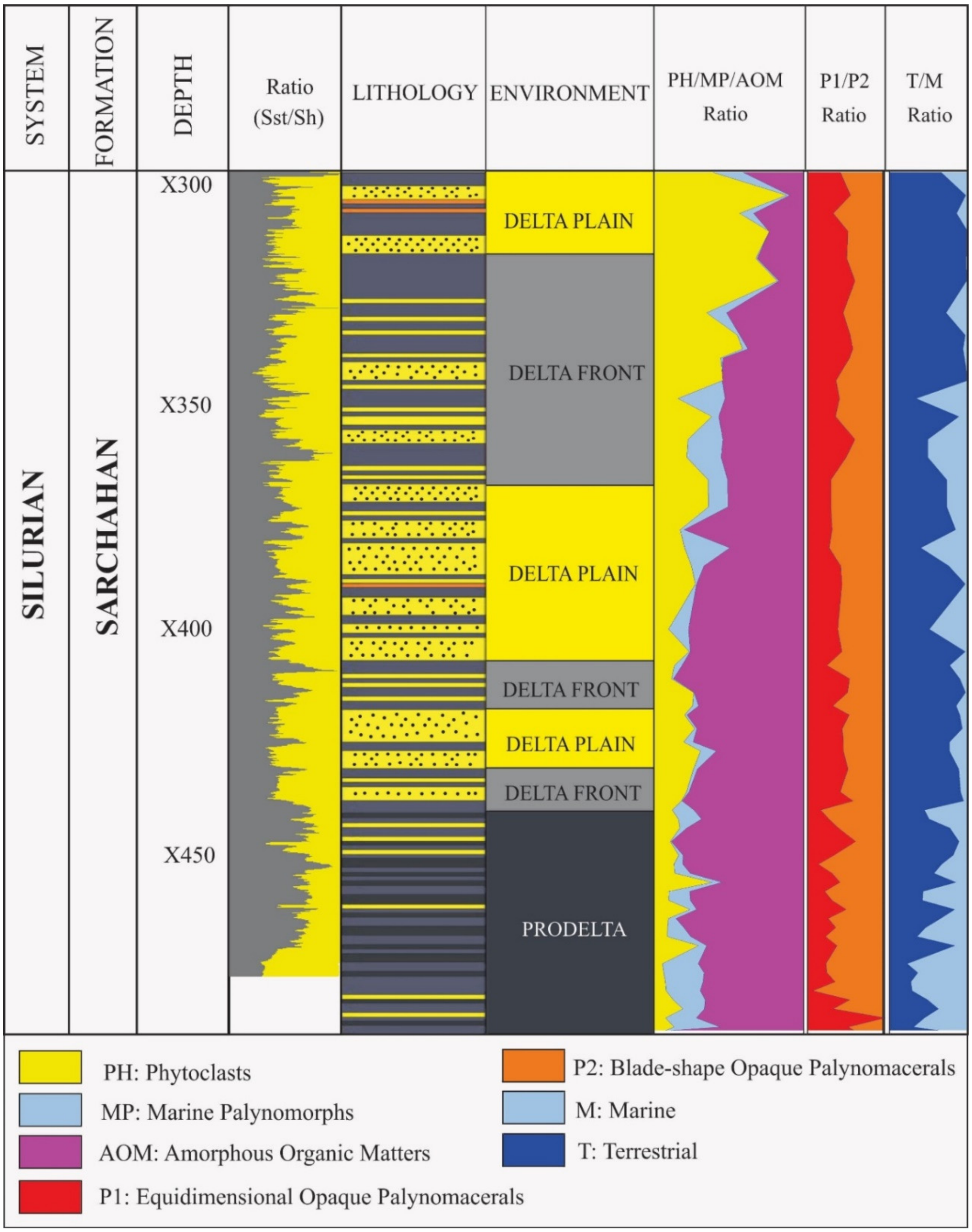

Figure 11. Changes of Palynological Factors in the Samples of the Sarchahan Formation, South Pars Field

Discussion

The Sarchahan Formation deposited during the Early Silurian (Llandovery) (Ghavidel-Siooky, 1997). According to the results of palynological studies, Qusaiba Formation is considered as the time equivalent of the Sarchahan Formation, i.e. Early Silurian (Llandovery) (Halwani et al., 2013; Jones and Stamp, 1994; Konert et al., 2001).

Almost all over the world, the Early Silurian is represented by a global sea-level rise (Luning et al., 2000), but this time interval in Iran coincides with the onset of Caledonian epeirogenic events (Ghavidel-Syooki, 1997), so that deposits of the Early Silurian are limited to Llandovery stage (Fig. 3). This epeirogenic event in some parts of the Zagros resulted in occurrence of Permian deposits lying disconformably on Ordovician deposits e.g. in the Kuh-e-Surmeh area (Ghavidel-Syooki, 1997). On the other hand, in contrast to the Arabian time equivalent (i.e. Quasaiba Formation) which is more shaley, this event caused that the Sarchahan Formation has a more sandy content (Fig. 10) regardless of its general description in Iran that is indicated as Silurian Shales.

Generally speaking, it is believed that this formation was deposited in an eastward deepening basin into which the sediments entered from the southern and southwestern parts of the Arabian plate (Jones and Stump, 1999). However, the comparison made in this study along with sedimentological (Zamanzadeh, 2008) and palynological studies (Ghavidel-Syooki, 1986) on Zakeen and Faraghan formations (Devonian and Permian in age respectively) and the Sarchahan Formation represent that in the northeastern part of the Arabian plate (i.e. the Zagros Mountains) the deposition took place in southward deepening basin and sediments were introduced from the northern parts (Fig. 12).

Our study shows that the Sarchahan Formation is composed of shale and sandstone beds, by contrast the Qusaiba Formation is mostly composed of shaley beds and scarce sandstone interlayers (Al-Saad and Sadooni, 2016; Paris et al., 2007; Konert et al., 2001). Although different ideas about depositional environment of this formation are suggested by different researchers, e.g., open shelf (Paris et al., 2007), shallow or open marine (Konert et al., 2001), marine transgressive shale (Al-Saad & Sadooni, 2016) and mostly offshore sub-environment in open marine or shelf (Mahmoud et al., 1992; Jones and Stump, 1999), the common idea among all of them is deposition in a marine environment (though under different conditions). According to the results of our study, a delta environment is proposed for depositional environment of the Sarchahan Formation (Fig. 13).

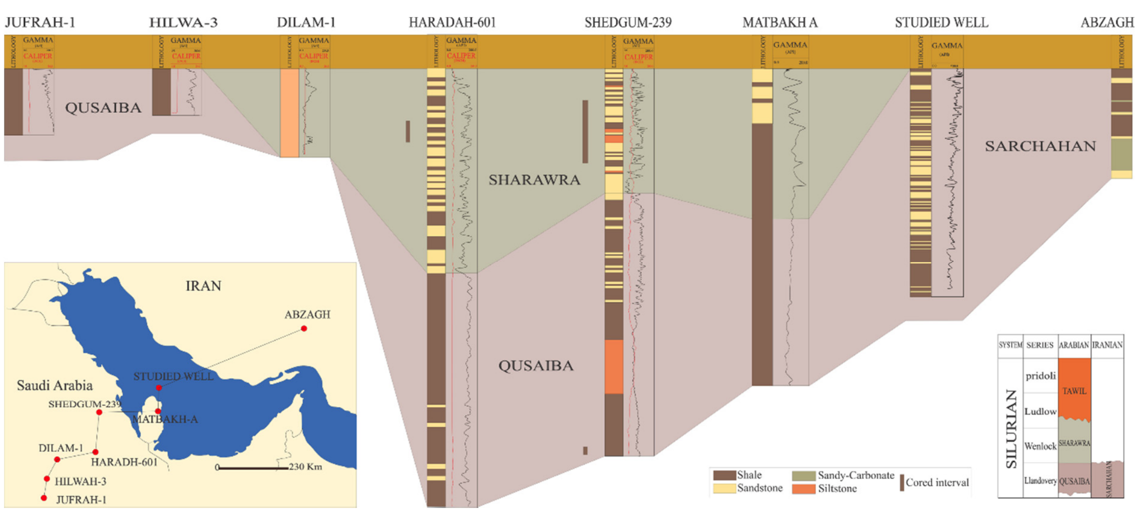

Figure 12. Correlation chart of outcrop, offshore wells in the Persian Gulf and onshore wells of Saudi Arabia for the Sarchahan Formation and its time equivalents

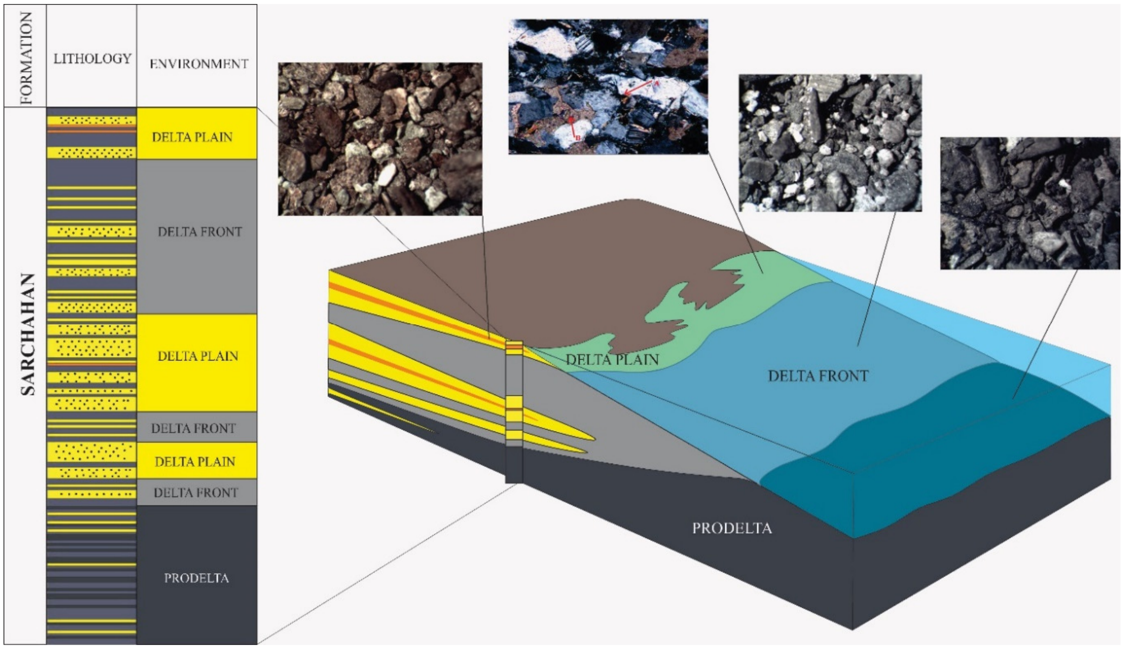

Figure 13. Depositional Environmental model of Sarchahan Formation in the South Pars Field

Sedimentological studies show that facies association 1 is composed of fine-grained shale with a high amount of TOC and very thin interbeds of sandstone. According to palynological studies (POGC internal report, 2017) this facies association represents both marine and terrestrial deposits. This facies association comprises the lower parts of the Sarchahan Formation and was deposited in a prodelta sub-environment.

Facies association 2 is composed of alternation of sandstone and shaley sandstone petrofacies, but shaley sandstone dominates. This facies association is deposited in a less deeper and nearer to beach environment compared to facies association 1 and represents fining upward sequences. Depositional environment of this facies association is regarded as delta front sub-environment.

Facies association 3 is composed of sandstone and shaley sandstone petrofacies, but sandstone dominates. Besides, some red mudstone interlayers and anhydrite grains occur. This facies association mostly represents coarsening upward sequences and occurs in the upper 50 meters of the Sarchahan Formation. Palynological studies represent the dominance of terrestrial elements over the marine ones. According to the sedimentological evidence, this facies association is assigned to delta plain sub-environment.

Sedimentological study of the Sarchahan Formation represents a voluminous amount of sandstone and sandy shale beds (Fig. 10) representing deposition in a near-shore marine environment. In this formation red mudstone layers and anhydrite grains are also observed (Fig. 7). Both evidence indicate that deposition took place under subaerial well oxygenated condition. Also palynological studies represent that deposition occurred in a range of environment from open marine to shallow marine oxygenated conditions (Fig. 11). Accordingly lower part of the formation is assigned to deeper marine and the upper 50 meters of sediments were deposited in a relatively proximal and shallower environment with a low to medium levels of oxygen. Consequently, it can be proposed that deposition of the Sarchahan Formation occurred in an intermediate to open marine environment representing a shallowing upward condition. Based on the sedimentological and palynological evidence, deposition took place in a transgressive delta environment, so that a coarsening upward trend which ends up in deposition under subaerial condition of red mudstone can be obviously seen.

The results of sequence stratigraphy studies indicate that a rapid global sea level rise occurred in the Early Silurian due to glacial retreat at the end of Ordovician and followed by almost a rapid fall of sea level (Sharland et al., 2001). This rapid sea level rise in the Arabian plate is represented by vast deposition of shale beds (e.g. Qusaiba Formation in the southern Persian Gulf states and the Sarchahan Formation in Iran) almost all over the plate and even in the north of Africa (Beydoun et al., 1992). In the studied area deposition of the Sarchahan Formation took place in a delta environment which temporally was under the influence of sea level fluctuations. Due to rapid sea level rise in the Early Silurian, a rapid transgression and deepening of the environment took place. Consequently a deep anaerobic condition developed and it was suitable for deposition of prodelta black shales with a high TOC content. The later sea level fall and transgression of delta gradually resulted in deposition of shallower facies so that first delta front shale-sandy shale facies deposited and later deposition of sandstone-shaley sandstone and red mudstone of delta plain facies followed. Deposition of red mudstone represents subaerial exposure of sediments and prevalence of oxidizing condition supported by occurrence of anhydrite grains. All these evidence indicate that the Sarchahan Formation was deposited in different sub-environments of a delta which was greatly affected by sea level fluctuations. The Late Silurian sea level fall could result in erosion of later deposited sediments and even the whole formation in some parts of the Zagros Mountains as previously discussed.

Conclusions

Based on petrographic studies, five petrofacies and three facies associations were identified in the Sarchahan Formation. The lithology of the Sarchahan Formation changes from shale to sandy shale, sandstone and red mudstone. The lower part of the formation has a high amount of black shale which is the result of deposition in the deeper parts of the basin, and has higher TOC values. Meanwhile, the upper part is composed of sandstone and red mudstone which are the result of the deposition in the shallower part of the delta environment. Variations in facies association in combination with palynological studies indicate deposition in different parts of a delta environment from prodelta to delta plain from bottom to the top. Cementation, compaction and dissolution are the main diagenetic features which affected the Sarchahan Formation. Silica cement is the most abundant cement type which resulted in porosity reduction and increase in brittleness of sandstone facies. Based on correlation chart of the formation, it is concluded that the ratio of the shale/sand increases towards the Arabian Basin and decreases towards the Zagros Basin in Iran.

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References

Abu-Ali, M.A., Franz, U.A., Shen, J., Monnier, F., Mahmoud, M.D., Chambers, T.M., 1991. Hydrocarbon generation and migration in the Paleozoic sequence of Saudi Arabia. In Middle East Oil Show. OnePetro, Bahrain, pp. 345-356.

Al-Husseini, M.I., 2000. Origin of the Arabian Plate structures: Amar collision and Najd rift. GeoArabia, 5(4): 527-542.

Al-Saad, H., Sadooni, F.N., 2016. Stratigraphy and Petroleum systems of the Palaeozoic (Pre-Khuff)

Succession, Qatar. Journal of Petroleum Geology, 39(4): 357-373.

Beydoun, Z.R., Clarke, M.H., Stoneley, R., 1992. Petroleum in the Zagros Basin: a late tertiary foreland basin overprinted onto the outer edge of a vast hydrocarbon-rich paleozoic-mesozoic passive-margin shelf: chapter 11: 309-339.

Bordenave, M.L., 2008. The origin of the Permo-Triassic gas accumulations in the Iranian Zagros foldbelt and contiguous offshore areas: a review of the Palaeozoic petroleum system. Journal of Petroleum Geology, 31(1): 3-42.

Bordenave, M.L., 2014. Petroleum systems and distribution of the oil and gas fields in the Iranian part of the Tethyan Region, AAPG Memoir #106, Petroleum Systems of the Tethyan Region: 505-540.

Ghavidel-Syooki, M., 1986. Palynological study and age determination of Faraghan Formation in Kuh-e-Gahkum region at southeast of Iran. Iranian Journal of Science and Technology, 12: 11-28.

Ghavidel-Syooki, M., 1990. The encountered Acritarches and Chitinizoans from Mila, ILebek, and Zard-Kuh Formations in Tang-e-Ilebek at Zard-Kuh and their correlation with Paleozoic sequence at Chal-i-Sheh area. Symposium on Diapirism with special reference to Iran, 1: 140-218.

Ghavidel-syooki, M., 1993. Palynological Study of Paleozoic Sediments of the Chal-I-Sheh area Southwestern Iran, Journal of Sciences, Islamic Republic of Iran, 4(1): 19-93.

Ghavidel-syooki, M., 1995. Palynostratigraphy and palaeogeography of a Palaeozoic sequence in the Hassanakdar area, central Alborz Range, northern Iran. - Review of Palaeobotany and Palynology, 86: 91-109.

Ghavidel-syooki, M., 1996. Acritarch Biostratigraphy of the Palaeozoic Rock units in the ZagrosBasin, Southern Iran. Acta Universitatis Carolinae Geologica, 40: 358-411.

Ghavidel-Syooki, M., 1997. Acritarch biostratigraphy of the Paleozoic rock units in the Zagros Basin, southern Iran. Acta Universitatis Carolinae Geologica, 40: 385-411.

Ghavidel-syooki, M., Winchester-Seeto, T., 2004. Chitinozoan biostratigraphy and palaeogeography of Lower Silurian strata (Sarchahan Formation) in the Zagros Basin of Southern Iran. Memoris of the Association of Australasian Palaeontologysts, 29: 161-182.

Halawani, A. H., Al-Duaiji A., Bahabri, H.B., Basyoni, H., Al-Dabbagh E.A., Al-Ramadan, K., Al-Ajmi, F.H., Al- Mahri, K.A., 2013. Phanerozoic stratigraphy of Saudi Arabia Part 1-Paleozoic Successions of Arabian Shelf Saudi stratigraphic committee members (Cover Rock): 62.

Jones, P.J., Stump, T.E., 1999. Depositional and tectonic setting of the Lower Silurian hydrocarbon source rock facies, central Saudi Arabia: American Association of Petroleum Geologists Bulletin, 83(2): 314-332.

Kashfi, M.S., 2000. Greater Persian Gulf Permian-Triassic stratigraphic nomenclature requires study. Oil & Gas Journal, 98(45): 36-36.

Konert, G., Afifi, A.M., Al-Hajri, S.A., Droste, H.J., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate: GeoArabia, 6: 407-442.

Le Heron, D.P., Dowdeswell, J.A., 2009. Calculating ice volumes and ice flux to constrain the dimensions of a 440 Ma North African ice sheet. Journal of the Geological Society, 166(2): 277-281.

Luning, S., Craig, J., Loydell, D.K., Storch, P., Fitches, B., 2000. Lower Silurian 'hot shales' in North Africa and Arabia: regional distribution and depositional model, Earth-Science Reviews, 49: 121-200

Luning, S., Loydell, D.K., Sutcliffe, O., Salem, A.A., Zanella, E., Craig, J., Harpel, D.A.T., 2000. Silurian-lower Devonian black shales in Morocco: which are the organically richest horizons?. Journal of Petroleum Geology, 23(3): 293-311.

Luning, S., Shahin, Y.M., Loydell, D., Al-Rabi, H.T., Masri, A., Tarawneh, B., Kolonic, S., 2005. Anatomy of a world-class source rock: Distribution and depositional model of Silurian organic-rich shales in Jordan and implications for hydrocarbon potential. AAPG bulletin, 89(10): 1397-1427.

Mahmoud, M.D., Vaslet, D., Husseini, M.I., 1992. The lower silurian Qalibah formation of Saudi Arabia: an important hydrocarbon source rock (1). AAPG Bulletin, 76(10): 1491-1506.

Morad, S., Ketzer, J.M., DE Ros, L.F., 2000. Spatial and Temporal Distribution of Diagenetic Alterations in Siliciclastic Rocks: Implications for Mass Transfer in Sedimentary Basins: Sedimentology, 47: 95-120.

Motiei, H., 1993. Stratigraphy of Zagros. Geological Survey of Iran, Tehran, 536pp, (in Persian).

Owen, A. W., Robertson, D. B. R., 1995. Ecological changes during the end-Ordovician extinction: Modern Geology, 20: 21-39.

Paris, F., Owens, B., Miller, M.A., 2007. Palaeozoic palynology of the Arabian Plate and adjacent areas. Revue de micropaléontologie, 1(50): 1-13.
Pars Oil and Gas Company, 2017. Sedimentology and Geochemistry of Paleozoic in south of Iran. Internal report.
Pettijohn, F.J., 1975. Sedimentary Rocks, 3rd ed. Harper and Row, New York, 628 pp.
Pettijohn, F.J., Potter, P.E., Siever, R., 1987. Sand and Sandstone. Springer-Verlag, New York, 553 pp.
Rabani, a.r., Afshari, n., Khaleghi, m., 2007. Geochemical studies of Faraghun, Sarchahan and Siahu Formation and evaluation their role in gas generation in Fars and Bandar-Abbas regions, 17(65): 53-61.
Rong, J.-Y., Harper, D.A.T., 1988. A global synthesis of the latest Ordovician Hirnantian brachiopod faunas: Transactions of the Royal Society of Edinburgh Earth, 79: 383-402.
Saberi, M.H., Rabbani, A.R., Ghavidel-syooki, M., 2016. Hydrocarbon potential and palynological study of the Latest Ordovician-Earliest Silurian source rock (Sarchahan Formation) in the Zagros Mountains, southern Iran. Marine and Petroleum Geology, 71: 12-25.
Senalp, M., Al-Duaiji, A.A., 2001. Qasim Formation: Ordovician storm-and tide-dominated shallow-marine siliciclastic sequences, Central Saudi Arabia. GeoArabia, 6(2): 233-268.
Tucker, M.E., 2001. Sedimentary Petrology-An Introduction to the Origin of Sedimentary Rocks. Blackwell. Scientific publication, London, 257 pp.
Tyson, R.V., 1995. Sedimentary Organic Matter. Chapman & Hall, 615pp.
Van der Zwan, C.J., 1990. Palynostratigraphy and palynofacies reconstruction of the Draugen Field Offshore Mid Norway. Review of Palaeobotany and Palynology, 62: 157-186.
Vieira, M.M., De Ros, L.F., 2006. Cementation patterns and genetic implications of Holocene beachrocks from northeastern Brazil. Sedimentary Geology, 192(3-4): 207-230.
Worden, R.H., Burley, S.D., 2003. Sandstone diagenesis: the evolution of sand to stone. Sandstone Diagenesis: Recent and Ancient, 4: 3-44.
Zamanzadeh, S.M., 2008. Sedimentary petrology/environment and sequence stratigraphy of Zakeen and Faraghan Formations in their type section (Bandar-Abbas area). Ph.D. thesis. University of Tehran.