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SEMA TETİKER

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Sedimentology and hydrocarbon potential of the Late Ordovician glacial deposits on the Arabian Platform and southeastern Turkey

Muhittin ŞENALP¹, Sema TETİKER²*

¹Saudi Aramco, Dhahran, Saudi Arabia
²Department of Geological Engineering, Faculty of Engineering, Batman University, Batman, Turkey

Abstract: The Late Ordovician glacial deposits are widespread and constitute a significant portion of the Early Paleozoic stratigraphic sequence of the cover rocks of the Arabian and African platforms. The glaciation lasted less than one million years between the Late Ashgillian (445 Ma) and Early Silurian (444 Ma) but it had a strong impact on the whole area. It has been proven that the glaciofluvial sandstones form important oil and gas reservoirs in Saudi Arabia and in North African and other Middle Eastern countries, including SE Turkey, but their heterogeneity and internal lithofacies characteristics have not been fully understood yet. In Saudi Arabia the hydrocarbon-producing glacial paleovalley systems forming the Sarah Formation extend 70 km in the W-E direction. In southern Turkey, similar glacial paleovalleys, defined as the Yurteri Formation, extend in a NW-SE direction. It consists of massive, well-sorted, porous reservoir sandstones of good quality and produces significant amounts of oil and sweet gas in SE Turkey. When the glaciation ceased in the Early Silurian time, the ice mass melted and released large volumes of water into the oceans. Returning waters resulted in rapid sea-level rise and onlap relations across the platforms. This widespread marine transgression deposited organic-rich, potential source-rock hot shale facies directly on the good-quality glaciofluvial reservoir sandstones. This publication is based on intensive outcrop and subsurface studies on the core samples of the reservoir sandstones and the source-rock shale facies in every part of Saudi Arabia and SE Turkey. These studies clearly indicated the hydrocarbon potentials of the Late Ordovician glaciation formed on the Gondwana plate. The aim of this paper is to demonstrate the presence of a close genetic relationship between the glaciofluvial reservoir sandstones and overlying hot shale source-rock facies and downward migration of oil and gas into the underlying porous sandstones mainly due to hydrostatic pressure.

Key words: Continental glaciation, Alpine glaciation, equilibrium line, tunnel valleys, cap carbonate, true glacial, glaciofluvial and glaciomarine deposits, clastic reservoirs, hot shale facies

1. Introduction
The late Ordovician glaciation, Late Ashgillian in age, is typically a short-lived geological event, which had a profound influence on Northern Gondwana, particularly in the Saharan regions, all of Saudi Arabia, North Africa, and SE Turkey. In terms of petroleum exploration and production, this glacial event had multiple influences on reservoir, source-rock, and trap morphology. It is well known that the prediction of the essential reservoir parameters, such as porosity, permeability, and their distribution in the subsurface, is very essential and a key challenge for successful hydrocarbon explorations. In this respect, the depositional environment, lithofacies distribution, three-dimensional geometry, lateral facies changes, source and reservoir rock relations, mineralogy of the reservoir sandstones, and hydrocarbon migration pathway must be well understood in the early phase of hydrocarbon exploration. These surface and subsurface sedimentologic studies were carried out on the hydrocarbon-producing Late Ordovician glaciogenic sandstone reservoirs and Early Silurian postglacial organic-rich source-rock shale facies and the downward hydrocarbon migration in Saudi Arabia and SE Turkey. The porosity and permeability of reservoir rocks have been shown to depend not only on the composition of framework mineralogy but also on the type of authigenic minerals and the structure, texture, and different stages of the diagenetic history of the sandstones. The aim of this paper is to review the Late Ordovician continental Gondwana glaciation and its importance for the hydrocarbon potentials in the countries located on the Arabian and African continents, including SE Turkey. This study is based mainly on long-term sedimentologic studies of the surface and subsurface of the glacial and postglacial formations in Central and NW Saudi Arabia (Vaslet,
2. Late Ordovician (Hirnantian, 445–444 Ma) Gondwana glaciation

The base of the uppermost Ashgillian deposits is an important regional erosional unconformity, which was formed during the Late Ordovician glaciation. This unconformity surface was recognized in all countries that were an integral part of Gondwanaland during this glacial period. Therefore, it is particularly useful for regional correlations and to define the amount of erosion at the base of glacial deposits. There is a general consensus among sedimentologists that the polar ice cap covered Mauritania and the size of this ice-cap was comparable to the modern Antarctic ice sheet (Figure 1).

Like all glacial episodes, the Latest Ordovician glaciation records multiple cycles of advance and retreat of the ice cap. The presence of four to five glacial cycles has been recorded in North Africa, where the ice sheet was much thinner and was affected by the seasonal climate changes. However, all the cycles are not necessarily recorded everywhere, because the glaciomarine sediments representing interglacial periods do not always overlie glacial incisions. In Libya and Mauritania all these glacial periods or phases define an overall retreating of the ice cap; however, each phase records an advance of the ice followed by a flooding and progradation of depositional systems coeval to the ice retreat (Rubino et al., 2003). At least three glacial cycles of advance and retreat were recorded in the measured section of the sand-dominated S-N-extending and well-exposed Al 'Ilb Paleovalley in Saudi Arabia. Each cycle advance is represented by polished, grooved, and striated pavements overlain by a moraine 1.5–2.0 m thick. These surfaces cover large areas in the Baqa'a (Ha'il) area (Senalp, 2006c; Senalp et al., 2018). The maximum advance of the Gondwana ice cap and the outer margin of the glacier have not been clearly established and are still matters of scientific debate. Most of the time, the outer margin of the glaciers are dominated mainly by typical glaciomarine deposits. These deposits consist of dark gray to black massive marine shales and include randomly distributed polished and striated pebbles within them. This facies represents the final stage of glaciation during the Late Hirnantian just before the Early Silurian transgression (Senalp et al., 2018).

Based on our long-term surface and subsurface studies of the several glacial paleovalleys of the Sanamah and Sarah formations in Saudi Arabia, and also the Halevikkedere and Yurteri formations in Turkey, there is no single model to explain the very heterogeneous and complex nature of glacial depositional systems (Evans et al., 1991; Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al., 2008). The sedimentation pattern along the long axis of the glacial valleys from its proximal to distal parts may show various lithofacies patterns and sedimentary structures with different reservoir quality. A type cycle starts with glacial erosion overlain by moraines or tillites showing various glacially formed sedimentary structures. This succession is overlain by the massive thickly bedded, laterally and vertically stacked channel-fill sandstones of the glaciofluvial system. In the middle parts of the valleys these glaciofluvial sandstones represent the entire valley-fill sequence. In some other valleys their depositions have been significantly influenced by rapid flooding of the rising sea level, leading to the deposition of a condensed section or immediately followed by glaciomarine silty shales. Depending on regional location, sandy prograding units infill the valleys. Some other valleys are totally filled with fluvial sandstones and display three striated pavements indicating glacial advance and retreat. The glaciofluvial sandstones pass laterally into massively to thick-bedded, wave-rippled sandstones (Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al., 2018). The top surfaces of the sandstones are burrowed and bioturbated, indicating the beginning of the Early Silurian transgression during the deglaciation period.

During the Late Ordovician, the Gondwana supercontinent became glaciated and covered deposits are common and widespread in several basins of the world. The sand-prone glacial deposits constitute a significant portion of the stratigraphic sequence of the Paleozoic successions of these countries and form very productive sandstone reservoirs for both oil and gas. The physical evidence for the presence of Late Ordovician glaciation in NW Africa (Sahara) and in the entire Arabian Peninsula is great. This glaciation is directly implicated by the common occurrence of well-defined, deeply incised U-shaped glacial valleys, filled with moraines, glaciofluvial sandstones, and glaciomarine sediments including striated dropstones. The Late Ordovician glacial deposits were first recognized in the stratigraphic succession of the Taoudeni basin (Mauritania) and the Hoggar and the Tibesti massifs of the Central Sahara. Therefore, the early and most intensive benchmark research works focused mainly on the well-defined glacial landforms and glacially formed large-scale sedimentary structures. Zimmermann (1960) provided the first suggestion regarding the Ordovician glaciation of the Sahara region. However, the first
Figure 1. (a) Schematic paleotectonic reconstruction and paleogeography of the Late Ordovician glaciation of the Gondwana supercontinent (after Vaslet, 1990). This polar projection of the southern hemisphere shows the Arabian Plate located on the margin of a polar ice cap centered on West Africa (after Vaslet, 1990). (b) The ice centers migrated from central northern Africa westward into Brazil; southward into Bolivia, South Africa, and northern Argentina; and eastward into the Arabian Plate (after Torsvik and Cocks, 2013).
description of this glacial subject was published by Sougy (1962), which was followed by several other papers listed below. The description of the Late Ordovician glacial strata from Southern Algeria was reported by Beuf et al. (1966) and Bennacef et al. (1971), followed by a magnificently illustrated paper by Beuf et al. (1971). In these studies, the polar glaciation of Gondwanaland was suggested with the South Pole located just south of the Sahara in the Guinean Gulf. Possible glacial deposits are also reported from North Africa and the Arabian Peninsula (McClure, 1978; Tucker and Reid, 1981; El Nakhal, 1990; Vaslet, 1990; Senalp and Al-Laboun, 2000; Senalp and Al-Duaiji, 2001b; Senalp, 2006a), and from Turkey (Paris et al., 2007; Ghienne et al., 2010; Senalp et al., 2018).

Deynoux (1980) reported convincing evidence of glaciation in West African in the Taoudeni basin (Mauritania). Tucker and Reid (1981) described the late Ordovician glacimarine deposits from the southern ice-sheet sector in Sierra Leone. Valley-fill sandstones are massive and present a “ruin-like” outcrop appearance. Locally, they show characteristics indicating their glaciofluvial origin. “Cordons” comprise elongated outcrops of sandstone that have been interpreted as eskers or valley-fills. Data suggest that these may be controlled by faults and tectonic lineations in the underlying basement. These deposits compare with those accumulating across extensive outwash plains along the margins of the present day Vatnajökull Ice Cap in Iceland (Deynoux and Trompette, 1981). Glaciotectonic structures, thin subglacially deposited tillites, and glacial striations characterize the base of major paleovalleys. Biju-Duval (1981) also recognized similar glacially formed paleovalleys of the same scale in the Tamadjert Formation in the central Sahara (West Africa). The paleovalleys in the Sahara and Taoudeni basin in Mauritania contain thin diamicites of less than 50 m thick, periglacial structures, and cross-bedded glaciofluvial sandstone facies. Lodgment diamicites are overlain by thick eolian sequences recording arid cold climates following glaciation (Deynoux and Trompette, 1981). Caputo and Crowell (1985) and Torsvik and Cocks (2009, 2013) suggested that the ice centers migrated from central northern Africa to southern America and eastward into the Arabian Plate. Extensive glaciofluvial outwash fans (Biju-Duval et al., 1981; Deynoux et al., 1985; Vaslet, 1990; Senalp and Al-Laboun, 2000; Senalp, 2006c) fringed the ice-sheet.

Recent estimates of the magnitude of sea-level fluctuations of the Late Ordovician–Early Silurian glaciation vary from 20 m (Bjorlykke, 1985) to 75 m (Brasier, 1989). In later studies, some of these physical glacial structures were reinterpreted. For example, the valley glacier incisions have been reexplained as tunnel valleys (Senalp and Al-Laboun, 2000; Hirst et al., 2002; Ghienne et al., 2003; Le Heron et al., 2004; Senalp, 2006c; Senalp et al., 2018). The pingo landforms reported by Vaslet (1990) in NW Saudi Arabia were reinterpreted as circular structures generated by mud diapirism (Le Heron, 2005); however, the formation of this structure has not been fully understood to date. The Late Ordovician (Hirnantian, 445 Ma) ice sheet is sand-dominated but it shows extreme lateral facies changes along the well-defined U-shaped glacial valleys. The glaciofluvial sandstone reservoirs were overlain by the organic-rich hot shale facies deposited at the base of the regional Early Silurian (Rhuddanian, 444 Ma) transgression following the melting of the ice sheet. These shales form the most prolific source-rock facies for the entire Paleozoic successions (Senalp and Al-Laboun, 2000). The Late Ordovician glaciation was a sharp but short-lived event, and it lasted less than one million years (Brenchley et al., 2003). The age of the Hirnantian glaciation is clearly recorded in the stable isotope signature of low-latitude cap carbonates. The glacial record of the Hirnantian maximum is well expressed in parts of the Gondwana supercontinent.

This economically very important Late Ordovician glaciation affected intracratic basins of North to South Africa and the Middle East. The extensive, well-preserved, laterally and vertically stacked, cross-bedded, well-sorted good-quality reservoir sandstones of glaciofluvial origin were deposited on the braid deltas in Saudi Arabia (Vaslet, 1990; Senalp and Al-Laboun, 2000; Senalp, 2006a), Jordan (Douillet et al., 2012), Algeria (Girard et al., 2012; Hirst, 2012), Libya (Moreau et al., 2005; Turner et al., 2005; Girard et al., 2012), and SE Turkey (Senalp et al., 2018). These laterally continuous ridges that are more than 50 km long allow detailed investigation of the sedimentology and lateral facies changes of the glacial successions. Excellent glacially formed sedimentary structures, such as polished shallow depressions, polished and striated pavements, thrust moraines, and lodgment tillites were reported in the Zarqa and Sarah formations of Saudi Arabia, and in the Sanamah Formation of the Wajid Outcrop Belt of southern Saudi Arabia (Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al., 2018). Large amounts of cores and well logs from the exploration and production wells in the mentioned countries have provided immense high-quality subsurface datasets on the geometry of the tunnel valleys, lateral and vertical facies changes, and reservoir quality of the mainly glaciofluvial sandstones in these areas.

2.1. Silurian transgression

The organic-rich source-rock hot shale facies deposited at the base of the regional Silurian transgression is generally accepted (Senalp and Al-Laboun, 2000; Senalp 2006a, 2006b; Senalp et al., 2018) as a postglacial transgression as a result of the melting ice mass. However, at the outcrops and in the cores and logs of the Yurteri Formation in
SE Turkey, we have already seen that the glaciomarine section, consisting of dark gray to black shale with marine fossils, includes striated chert and quartz pebbles dropped from the floating ice mass ( iceberg). This mixed facies stratigraphically occurs between the glaciofluvial sandstones and the overlying hot shale facies, defined as the base of the Silurian succession. It means that the glacial retreat was punctuated during the early phase of the transgression, which occurred during the latest Ordovician. In this respect, the Silurian transgression probably records the final phase of ice melting, but the rising of the sea level still continued. The algal dolomitic limestone on top of the hot shale below the lean shale facies represents the Maximum Flooding Surface (MFS S10, 444 Ma) of the Silurian transgression. The latest Hirnantian-earliest Silurian transgression is diachronous depending on the depositional slope of preexisting topography. The transgression started first on the ice margins and gradually moved upslope (landward) through the ice valleys or tunnel valleys. This means that, like in any transgressive sequence, the age of the marine transgression becomes gradually younger in this landward direction. The most prominent regionally very extensive but patchy hot shale source-rock facies seems to occur predominantly in regional lows, either resulting from glacial erosion or fluvial incision possibly related to the isostatic rebound. These low areas or deep depressions, in combination with late deformation, will control the migration pathways. In some regions, in addition to glaciofluvial sandstones, the lowermost Silurian transgressive sandstones are proven to be productive hydrocarbon reservoirs. These sandstones are the first reservoir sandstones, which were deposited immediately below the hot shale source-rock facies. The sandstones to be filled or at least used for the downward migration pathway are indicated by the abundance of shows in the cores. When the Late Ordovician succession is more shale-dominated or silty, deposited close to the ice margin (ice maxima), it has significantly reduced reservoir potential in the stratigraphic column.

3. Late Ordovician glaciation in Saudi Arabia

The hydrocarbon-producing Late Ordovician glacial deposits of the Gondwana supercontinent were recognized at outcrops and in the subsurface of southern (Al Wajid), central (Al Qasim), and northern (Tayma-Tabuk) regions of Saudi Arabia (Figure 2). Glacially formed deposits (moraines) and sedimentary structures were documented by McClure (1978), Senalp and Al-Laboun (2000), and Senalp (2006a).

The data regarding the direction of ice movement were based on the paleocurrent directions formed on the older sandstone units and the general trend of the U-shaped glacial paleovalleys of the Sarah Formation. McClure (1978) implied a possible genetic relationship and made correlations between these glacial deposits and the similar Late Ordovician glacial deposits, which had already been described from the Hoggar Massif of the Algerian Sahara by Beuf et al. (1966) and Bennacef et al. (1971), but he did not have enough paleontological or lithological data to make any precise correlations. Young (1981) described similar tillite accumulations from the outcrops in central Saudi Arabia and supported the idea of Late Ordovician glaciation as suggested by McClure (1978). Later field work and systematic mapping of the stratigraphic succession that includes the glacial deposits indicated the presence of two distinct formations, both bounded at their bases by strong glacial unconformities (Williams et al., 1986). Vaslet et al. (1987) proposed a lithostratigraphic revision of most of the Early Paleozoic succession of Saudi Arabia to include the two glacially formed formations into the stratigraphic column of the Early Paleozoic successes (Figure 3). Vaslet et al. (1987) recognized two distinct glacial events indicating that the Gondwana polar ice cap advanced into western Arabia in two major pulses, and they defined them as the Zarqa and Sarah formations. The Zarqa Formation is at the base and consists of repetition of tillite, boulder clay, and slumped fine-grained sandstone blocks of older formations. The Sarah Formation (Williams et al., 1986) is at the top and consists mostly of fine- to coarse-grained sandstone and, in some localities, tillites that are preserved at the base of the paleovalleys. A section of the Sarah Formation more than 300 m thick is exposed in the downstream axial portion of the Sarah Paleovalley in Al Quwarah town. The top of the paleovalley is transgressively overlain by the Early Silurian Qusaiba Member of the Qalibah Formation (Figure 3). Williams et al. (1986) stated that the Sarah Formation, at its type locality, is topographically expressed as a ridge and is interpreted to represent sediment deposited in a glacial paleovalley. Vaslet (1987, 1989, 1990) took the “valley” model, as developed by French geologists in western central Africa, and mapped several glacial paleovalleys in central and northern Saudi Arabia. The glacial paleovalleys start from the margins of the Proterozoic basement complex in the Arabian Shield and become systematically wider downstream, trending roughly northeastward or occasionally northward in direction, becoming coalescent and forming a continuous lobate outcrop belt.

McGillivray and Husseini (1992) accepted the idea of the presence of deeply incised glacial tunnel valleys in outcrops, as described by Vaslet (1987, 1989, 1990), and extended these paleovalleys eastward into the deep basin. They published a high-resolution seismic profile across a canyon-like glacial valley, which is more than 17 km wide and is filled by the undifferentiated Zarqa/Sarah Formations, several hundred meters thick. In the subsurface, there is no
indication of two glacially cut unconformities. The Sarah Formation is thin; the sandstones are fine- to very fine-grained, silica-cemented, and interbedded with dark gray shale of a marine environment. In some wells, diamictites were found in the shale.

The evidence on the Late Ordovician glaciation in every part of Saudi Arabia has increased very fast, and the glacial deposits and the glacially formed sedimentary structures were recognized regionally in various parts of the country. Senalp and Al-Laboun (2000) made intensive stratigraphic and sedimentologic studies at the outcrops between the towns of Buraydah and Ha'il to understand the depositional environment, geographic distribution, and reservoir quality and hydrocarbon potentials of these glaciogenic sandstones.

The Zarqa Formation is bounded below and above by two glacially formed unconformity surfaces (Pre-Zarqa and Pre-Sarah unconformities). The Pre-Zarqa unconformity cuts into the underlying Qasim and Saq formations and its base represents a glacially formed unconformity surface. Its upper part is also deeply incised by the second glacially formed unconformity surface at the base of the Sarah Formation (Figure 3). Therefore, the glacial deposits of the Zarqa Formation are not fully preserved anywhere in Saudi Arabia. The best outcrops are exposed at the Jal As-Saqiyah and Jal Az-Zarqa areas in NW Saudi Arabia. The formation is entirely unstratified and consists of an accumulation of tillite, thrust (pushed) moraines, boulder-clay, and lodgment tillite, which is made up of faceted, polished, and striated large granite boulders embedded in shaly, silty, and slumped fine-grained sandstone blocks. These chaotic deposits were accumulated directly by the ice after it melted during the interglacial period. The Zarqa Formation has no exploration potential.

The base of the Sarah Formation is the second glacially formed unconformity surface that deeply incised into the Zarqa, Qasim, and Saq formations (Figure 3). The upper boundary is marked by the most prolific source rock of organic-rich marine shales of the Qusaiba Member of the Qalibah Formation, deposited during the Early Silurian transgression. This second advance of the Hirnantian glaciation has direct relation with the hydrocarbon exploration on both the African and Arabian plates of Gondwana (Senalp and Al-Laboun, 2000; Senalp,
Figure 3. The Lower Paleozoic succession in central Saudi Arabia modified after Vaslet (1990) by introducing the Cruziana Shale Member (renamed as the Bukayriyah Member) as the middle member of the Saq Formation and adding the Maximum Flooding Surface (MFS) in the Qasim Formation by Senalp and Al-Laboun (2000) and Senalp and Al Duaiji (2001a).
This glaciation was short lived and lasted less than one million years but affected the intracratic basins of North Africa and the Middle East. Hydrocarbons have been produced from most of these countries and activities are still going on for deep gas explorations. Several paleovalleys extend in W-E or SW-NE directions. They are up to 300 m deep and essentially filled with sandstone. The lenses of tillite facies are preserved in the bottom parts and sides of the valleys. Senalp (2006a), based on his measured sedimentologic sections, reported that their three-dimensional geometries, internal lithofacies arrangements, vertical and lateral facies variations, stacking patterns, compositions, and reservoir qualities are significantly different from each other. There is no single model to explain their process of formation or depositional model. However, there are several lines of information suggesting that the valleys were initially cut by the ice sheet. There is almost every type of glacially formed sedimentary structure in the different stratigraphic levels of the Sarah Formation, indicating several advances and retreating stages of the ice. The most common sedimentary structures include polished and striated pavements, circular depressions, drag folds, large grooves, and chatter marks, all indicating that the ice mass was flowing on the surface of the deeply frozen ground.

The Hawban Member (Vaslet, 1990; Senalp et al., 2002) of the Sarah Formation is composed of tillite and boulder clay facies, in which the large sandstone blocks of older formations are transported by ice and mixed with the dark green silty shale facies (Figure 3). The Hawban Member, which forms the uppermost part of the Sarah Formation, represents the last stage of Late Ordovician glaciation and is preserved only in the Baq’a area (Ha’il) of central Arabia. When the Gondwana glaciation ceased in very Late Hirnantian–very Early Silurian times, the ice mass melted and released large volumes of water into the oceans. This resulted in sea-level rise and onlap relations across the platforms and shelves. During this time the incised valleys on the continental shelves were flooded by marine waters and were filled with fluvial, fluviomarine, and marine sandstones. This was followed by a widespread transgression, which deposited offshore marine shales. These postglacial shales are organic-rich and act as both seal and source. In central Saudi Arabia, the same organic-rich shale facies of the Qusaiba Member constitute the most important and regionally widespread source rock for the Paleozoic siliciclastic and carbonate rocks.

3.1. Zarqa Formation
The Zarqa Formation was formally defined and documented by Vaslet et al. (1987) from the Jal Az-Zarqa cuesta near Baq’a town (Figure 4). The outcrops of this formation are well exposed between the towns of Al-Qar’a (Buraydah) and Baq’a (Ha’il). It is confined between two strong glacially formed unconformities and consequently the formation was nowhere fully preserved. The Pre-Zarqa unconformity surface at its base cuts into the various members of the Qasim Formation. The top part is channeled everywhere by younger glacial unconformity, developed at the base of the Sarah Formation. The outcrops indicate that the deposits are preserved in the deepest parts of the large glacial paleovalleys, deeply incised into the underlying Qasim Formation. The type section of the unit, as defined by Vaslet et al. (1987), is 115 m thick and is located near the Jal Az-Zarqa cuesta on the eastern bank of Wadi U’aywij, about 10 km SW-W of Baq’a town (see Figure 2). In the type locality, the formation consists of repetition and a complex mixture of various types of predominantly basal and pushed moraines, tillite, boulder-clay, glacial dropstones, and slumped or bulldozed sandstone blocks derived from the older formations (Figure 5).

The most important feature of the unit is the presence of polished and striated granite and other igneous and metamorphic blocks (up to 1.3 m in diameter) derived from the Arabian Shield and it shows great vertical and lateral facies variations in short distances (Figure 6). This is reflected in the composition (granite or sandstone blocks of the Saq and Qasim formations), abundance, and size of the blocks within the tillite facies. The tillite and glacial dropstone facies are generally found together in the same stratigraphic interval, but they can also be interbedded with other depositional facies. In some places these two facies form almost the entire Zarqa succession (Senalp and Al-Laboun, 2000). In the Jal As-Saqiyah cuesta the tillite facies is extremely thick and comprises huge lens-shaped blocks of dislocated, well-bedded but strongly folded and fractured sandstones of the Kahfah and Quwarah members, floating in an olive gray mudstone and sandy mudstone facies (Figure 5). They were interpreted as push-moraines by Senalp and Al-Laboun (2000) and Senalp (2006a). The most interesting sedimentary structures observed at the base of the Zarqa Formation are the glacially injected diamicite dykes. These structures are common below the tillite and were reported by Vaslet (1987) at the interface between the Kahfah Member and the tillite facies of the Zarqa Formation. These complex conglomerate and diamicite dykes, which are wedge-shaped and 1.2 m long, penetrate into the underlying tigillite-burrowed sandstone facies of the Kahfah Member at the reference section of the Zarqa Formation (Figures 5 and 6).

Boulton (1997, personal communication during field trip) explained the formation of these diamicite dykes as a result of a large potential gradient between the interstitial water in the diamicite tillite facies and that in the Kahfah Member, generating hydrofracturing and hydraulic forces capable of forcing conglomerate or diamicite down into the fractures. The deeper parts of the glacially formed valleys
were filled by the tillite facies, which show no sedimentary structure in a strict sense, because all the sediments were carried in front of the moving ice mass. During this time, older sediments, mainly the sandstones and shales, were eroded from the Qasim Formation and strongly folded (Figure 5). The shales, mixed with the fresh water, have swollen and increased their volume tremendously. Swelling of the clay in this heterogeneous sediment water mixture provided extra power to the ice mass to carry huge granitic boulders in suspension. Towards the top of the Zarqa Formation, the thickness and abundance of the interbedded mudstone, shale, and laminated and wave-rippled sandstone facies increases. The section carries abundant evidence that these sediments were deposited in a shallow but standing body of water. Intense plastic deformations, as indicated by the slump structures in the wave-rippled sandstones, indicate that these subaqueous sediments were mobilized many times during deposition when the huge erratic blocks dropped into this shallow basin. There is no reservoir facies in this unit.

3.2. Sarah Formation

Clark-Lowes (1980), while mapping the Al-Qasim area, recognized a distinct unit exposed in the Khanasir Sarah (26°31'14"N, 43°11'33"E), located at the end of the Hanadir cuesta in central Saudi Arabia (Figure 7). He described conglomerates, conglomeratic sandstones, diamictites, and minor shale horizons. Clark-Lowes (1980) considered this unit as a fourth member of the Tabuk Formation and introduced it as the Sarah Member. Senalp and Al-Laboun (2000) subdivided this Sarah
Figure 5. (a) Thrust moraines (pushed moraines) form the most important part of the Zarqa Formation. (b–d) It consist of strongly folded and sheared sandstone blocks of the Kahfah and Quwarah members, embedded in the mixture of the Hanadir and Ra‘an shales (Senalp, 2006a).

Figure 6. (a) Basement-derived, polished, and striated granite boulders in the lodgment tillite (moraines) facies of the Zarqa Formation (Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al., 2018). (b) The diamicite dyke is formed at the base of the Zarqa Formation. This wedge-shaped tillite has been injected into the tigillite-burrowed sandstones of the Kahfah Member, of the Qasim Formation, due to the overly pressurized melt water under the ice mass (J. Boulton, personal communication, in Senalp, 2006a).
member into three subfacies varying with position, whether on the flanks or in the axis of the paleovalley. The hydrocarbon-producing Sarah Formation was first defined and formally introduced at the Khanasir Sarah (Sarah ridge), in the Jabal Habashi Quadrangle in central Arabia, by Williams et al. (1986), as suggested by Clark-Lowes (1980) for his Sarah Member type section. This 9-km-long topographic ridge initially trends towards the E-NE, but swings towards the north prior to resuming a more easterly trend near the town of Al Quwarah. It includes all the glacial and periglacial sediments (mainly sandstone) filling glacial valleys (Williams et al., 1986). However, McClure (1978) first suggested the glacial origin of these Late Ordovician sediments in the same area. The unit lies on the second glacial erosion surface deeply incised into the Zarqa Formation, Qasim Formation, and even the Saq Formation in its proximal parts. At the type locality, a basal diamictite facies, interpreted by Clark-Lowes (1980) to be of mudflow or tillite origin, consists of blocks and large boulders of basement rocks and locally derived sandstones of the Saq Formation, and it is overlain by fine-to coarse-grained and conglomeratic sandstone. The Sarah Formation is topographically exposed as a ridge and is interpreted to represent mainly sandstone deposited in a glacial valley (Williams et al., 1986). The subdivision of the Sarah Formation into three genetically related subfacies varying with position in the paleovalley, as suggested by Clark-Lowes (1980), was also substantiated with variations in lithology and sedimentary structures by (Williams et al., 1986). Vaslet (1989) correlated the Sarah Formation with the Sanamah Member of the Wajid sandstone of Kellogg et al. (1986) in SW Arabia. Williams et al. (1986) mapped four paleovalleys in the Jabal Habashi quadrangle. From north to south, they are the Tiraq, Tirmus, Sarah, and Hanadir paleovalleys (Figure 7). Vaslet (1989) mapped similar paleovalleys in the Baq'a area in NW Saudi Arabia. Among them, the Al 'Ilb Paleovalley is the most prominent, well exposed and laterally

Figure 7. (a) Geologic map of part of the Qasim region showing the distribution of Saq, Qasim (Hanadir, Ra'an, and Quwarah members), glaciated formed Zarqa (with tillite and boulders), and the large glacial paleovalleys of the Sarah Formation (modified after Williams et al., 1986; Senalp and Al-Laboun, 2000; Senalp, 2006a). (b) Geologic map of the Qasim area showing the distribution of outcrops of the igneous basement complex (Arabian Shield), Risha and Sajir members of the Saq Formation, and Hanadir, Kahfah, Ra'an, and Quwarah members of the Qasim Formation; glaciated formed Zarqa and Sarah formations, the Qusaiba Member of the Qalibah Formation, and the Unayzah, Ash-Shiqqah, and Khuff formations (Senalp, 2006a).
continuous. Its upper contact with the overlying hot shale facies deposited at the base of the Silurian transgression of the Qusaiba Member of the Qalibah Formation can be seen clearly. At outcrops of the Sarah Formation, the glacial paleovalleys generally extend in the W-E direction in central Saudi Arabia and the S-N direction in NW Saudi Arabia (Figure 7). They form more than 50-km-long, well-exposed, and continuous spectacular topographic ridges, providing successions to study their vertical and lateral facies changes and sedimentary structures in the direction of sediment transportation. These paleovalleys are composed predominantly of sandstone with local tillite. This locally deposited tillite at the base of the Sarah Paleovalleys is the only glacial facies observed in the Sarah Formation. This facies, when it is preserved as it was first deposited, is identical to the same facies described in the Zarqa Formation. However, this undisturbed tillite facies is very rare in the Sarah Formation.

Williams et al. (1986) and Senalp and Al-Laboun (2000) correlated the Sarah Formation with the Sanamah Member of the Wajid sandstone (Kellogg et al., 1986) in southwestern Saudi Arabia. Senalp et al. (2018) correlated the Sarah Formation with the recently defined Yurteri Formation, exposed between the Bedinan and Yurteri villages of the Mardin region. The large-scale and most convincing glacially formed sedimentary structures, such as the polished and striated pavements or deep grooves in the lower parts of the Sarah and Sanamah formations, were first discovered and superb pictures were published from different parts of Saudi Arabia by Senalp and Al-Laboun (2000) and Senalp (2006a). They also stressed the hydrocarbon potentials of the glaciogenic reservoir sandstones of the Sarah Formation. They suggested that the oil and gas in these sandstones were generated in the overlying hot shale facies and migrated downward due to the hydrostatic pressure and better reservoir facies.

3.2.1. Nature of contacts with adjacent formations

The Sarah Formation is bounded at the base by another major glacially formed unconformity surface, formed during the second advance of the Late Ordovician glaciation of the Gondwana supercontinent. This unconformity surface cuts deeply into the Zarqa, Qasim, and even the Saq Formation in its proximal parts. Because of a substantial drop in sea level, large subglacial anatomicing tunnel paleovalley systems were deeply incised by both glacial and fluvial processes to great depths exceeding 182 m in some places. Some of these valleys have a slightly meandering geometry, and in many cases widen eastward and northward in a basinward direction to form a fan-shaped braid delta. The upper boundary of the Sarah Formation is marked clearly in the Jabal Habashi, Buraydah, and southeastern part of the Baqu’a area by the organic-rich open marine shales deposited at the base of the Qusaiba Member of the Qalibah Formation during the Early Silurian regional transgression, recognized in every country located on the Gondwana supercontinent. Between the towns of Al-Ajfar and the NW of Baqu’a town, the upper part of the formation contains another glacial facies (boulder clay), called the Hawban Member, and contacting with the shallow marine beach facies of the recently defined Baqu’a Member (Senalp et al., 2002) of the Qalibah Formation. The glacially formed Hawban Member is locally developed in the upper part of the Sarah Formation and ends between Baqu’a and Ash Sharqiyyah towns. On the other hand, the overlying fully marine transgressive Baqu’a Member (Senalp et al., 2002) has much wider lateral extent and covers larger areas either on the glaciogenic Hawban Member or directly on the sandstones of the Sarah Formation where the member is missing (Senalp, 2006a). It consists mostly of fine- to coarse-grained, cross-bedded, current-rippled, laterally and vertically stacked fining-upward glacioluvial and fluvial sandstones and, in some localities, tillites are preserved at the base and on the sides of the paleovalleys. Large amounts of these tillites were reworked during the deglacial periods and redeposited in the glacioluvial sandstones. The Bukayriyah Paleovalley exposed near Al-Qar’a town cuts into the planar-bedded, shallow marine sandstones of the Qsar’a Member of the Qalibah Formation. The base of the Sarah Formation is covered with partly reworked tillites. The large-scale glacially formed sedimentary structures in the Sarah sandstones just above the tillites are located about 100 m north of this location. The thickness of the unit is also difficult to ascertain due to the preexisting paleotopography that had considerable relief in places and glaciotectonic features. The size, three-dimensional geometry, and sediment thickness of each glacial paleovalley is very different.

The glacioluvial sandstones of the Sarah Formation, deposited in the glacial valleys, are the major oil and gas reservoirs in the Middle East. The three-dimensional geometry of these unconformities were mapped in the subsurface by Senalp (2006a). He also stressed the importance of generating hand-drawn isopach maps of these sandstones and overlying organic-rich source-rock facies deposited at the base of the regional Silurian transgression to see where the source rock and reservoir rock overlie each other. Recently (Senalp et al., 2018), hydrocarbon potentials of the glaciogenic reservoir sandstones and their genetic relations with the overlying sandstones were established in the Paleozoic successions of SE Turkey. The same exercise was also carried out for the Late Ordovician glacioluvial reservoir sandstones of the Yurteri Formation and the prolific source-rock shale facies deposited at the base of the Early Silurian Dadash Formation in SE Turkey (Senalp et al., 2018). The small
village of Dadaş is located (38°16′23.099″N, 40°43′0.591″E) about 10 km NW of the town of Hazro (Diyarbakır).

3.2.2. Geometry, lithology, and thickness of the Sarah Formation

The three-dimensional geometry mapped at the many outcrops, the nature of the underlying erosional surface, and the moraine or tillite well-preserved glacially formed sedimentary structures indicate that the Sarah Formation was deposited in glacial valleys during the Late Ordovician glaciation developed on the Gondwana supercontinent. BRGM (French company) geologists mapped several paleovalleys in southern, central, and NW Saudi Arabia. Among these paleovalleys the Sarah and the Al ‘Ilb paleovalleys were extensively studied at the outcrop by Williams et al. (1986), Vaslet (1989), and Senalp and Al-Laboun (2000). The Sarah paleovalley is a more than 50-km-long U-shaped topographic ridge, initially trending towards the E-NE but swinging towards the north prior to resuming an easterly trend near Al Quwarah town, where it merges with the adjacent glacial valleys and forms a large lobate delta.

Like any other glacial valley, joint glacial, glaciofluvial, and fluvial processes formed the Sarah Paleovalley. It may be considered as a tunnel valley. This is the largest paleovalley mapped in the Jabal Habashi Quadrangle, covering the entire Qasim area of central Arabia. Its sediments are fully preserved over a length of 50 km between 13 km west of Al Khasasir (type section) and 17 km east of Al Quwarah town (Figures 2 and 7). The present-day gradient of the valley floor, from west (upstream) to east (downstream), ranges from 4 to 7 degrees. The flanks display an open U-shaped profile with slopes inclined at between 8 and 10 degrees. The outcrop pattern of the Sarah Formation suggests that the paleovalleys widen downstream and coalesce in the NE corner of the Jabal Habashi Quadrangle. The thickness of this formation varies significantly depending on the size of the paleovalley, the topography of the glacially formed unconformity surface at the base of the unit, the location within the paleovalley itself, and the amount of the sandstone preserved from later erosion. The thickest section is expected to be in the middle parts and along the long axis of each paleovalley, as it may be more than 300 m thick in the downstream axial portion of the paleovalleys.

The Sarah Formation is 37 m thick at the Khanasir Sarah type section (26°31′14″N, 43°11′33″E) and about 140 m thick in the agricultural water wells drilled at the same latitude of Al Quwarah town. Williams et al. (1986) estimated its thickness to be at least 90 m at the type locality, but only 37 m is visible at the outcrop. They also suggested that the maximum thickness in the deepest part of the Sarah Paleovalley is estimated between 250 and 300 m. In the NE corner of the Jabal Habashi Quadrangle, where the Sarah valleys coalesce and form more lobate-shaped, laterally continuous accumulations, the thickness of the Sarah Formation becomes uniform. Tracing the glacially formed Sarah Paleovalley from its most proximal parts to the eastward direction, the unconformity surface at the base of the valley cut down into sequentially younger formations (Figure 7). At the Khanasir Sarah (Sarah ridge) type section, the Sarah Formation overlies the intensely silicified, ferrugenized, and strongly bioturbated Sajir Member of the Saq Formation where the valley starts. Senalp (2006a) reported glacial striations on the sandstone beds of the Saq Formation. This glacially striated surface is visible over a distance of 25 m, displaying grooves and plucking structures that are oriented in a N75°E direction. At this location, it consists of 1.5 m of beige, medium- to coarse-grained sandstone that is locally conglomeratic and contains rounded pebbles of quartz, 1.1 to 15 cm in diameter, overlain by 8.5 m of homogeneous brown and white, fine- to medium-grained sandstone, in turn overlain by 13 m of brown, medium-grained, cross-bedded, fining-upward sandstones deposited in laterally and vertically stacked shallow channels (Senalp and Al-Laboun, 2000; Senalp, 2006a). Microconglomerate facies occurring at the base of the channels and cross-beds are inclined as much as 20°. The topmost part of the Sarah Formation is composed of 4.0 m of brown, well-bedded, medium- to fine-grained sandstone that shows slump structures where the beds are overturned. At the northern end of the Hanadir cuesta, near Jal Al Aswad, at the first major downstream bend, the Sarah Paleovalley cuts into the Hanadir and Kahfah members of the Qasim Formation (Figure 8). The graptolitic shales of the Hanadir Member have been completely eroded away, and the sharp base of the Sarah Paleovalley is perfectly exposed in a large cave. The large sandstone blocks (meter sized) of the Saq Formation, laminated shale blocks of the Hanadir Member, and granite and quartz pebbles set in a silty, sandy, or clayey matrix occur at the base of the valley. Stratigraphically and geographically, these deposits are closely associated with the glacial striations and can therefore be interpreted as tillite (Senalp and Al-Laboun, 2000; Senalp, 2006a). These sediments are conformably overlain by fining-upward channel-fill sandstones sequences. These fining-upward sequences are 3.5 to 4.0 m thick and consist of large-scale trough cross-bedded sandstones, separated by scour surfaces. The grain size ranges between large pebbles at the base and fine sand at the top. As the grain size between the pebble and fine sand is large, the fining-upward feature in grain size is perfectly developed. Towards the further east and NE, in the inferred downstream direction, the Sarah Formation becomes more fine-grained and better sorted. The pebbles and very coarse-grained sandstones have already been deposited in the proximal parts of the valley. The resulting rapid downstream decrease in grain size range makes the
vertically and laterally stacked fining-upward depositional sequences become less obvious. In the downstream directions, the red-colored Sarah sandstone outcrop in the town of Al-Quwarah (Figure 8) unconformably overlies the tillites of the Zarqa Formation, the shallow marine sandstones of the Quwarah Member, and the shales of the Ra‘an Member of the Qasim Formation in different places. The Sarah Formation consists of planar-bedded, fine-grained, and minor amounts of silty sandstone along the bedding planes. Large-scale trough cross-bedding has disappeared completely. This clearly indicates a rapid facies change in the sandstones due to change in current regime in the valley. The uppermost part of the Sarah Formation, just below the regional Early Silurian transgressive surface (MFS S10, 444Ma) of the Qusaiba Member of the Qalibah Formation, is represented by a fine-grained sandstone facies. It shows large-scale strongly bioturbated wave ripples covered with abundant marine trace fossils, identified as monolobate *Bifungites* trails. The top of the Sarah Formation is overlain by 14 m of interlaminated, brown and cream, clay-rich, fine-grained, bioturbated sandstone and silty clay. In this respect, the Sarah Formation, exposed in the town of Al-Quwarah (Figure 9), was considered as a glaciomarine facies, representing the distal end of the glacial Sarah Paleovalley at the eastern margin of the possible tunnel valley (Senalp, 2006a).

### 3.2.3. Glacial facies in the Sarah Formation

Locally deposited tillite at the base of the Sarah Paleovalleys is the only true glacial facies observed in the Sarah Formation. This facies, when it is preserved as it was first deposited, is identical to the same facies described in the Zarqa Formation. However, this undisturbed tillite
facies is very rare in the Sarah Formation. A big portion of the tillite, deposited at the base of the Sarah Formation, has been partly or completely reworked and deposited as channel lags in the lowermost part of the continuous fining-upward sequences of the genetically related glaciofluvial sandstones. Until all the large-scale glacially formed sedimentary structures were discovered and their impressive photographs were published by Senalp and Al-Laboun (2000), the sandstone-prone Sarah Formation was generally interpreted as high-energy braided stream deposits. The well-preserved tillite facies at the base of the Sarah Formation, infilling the small Ar-Rawd Al-Uyun paleovalley and similar to the Zarqa tillite facies, is well exposed on the highway from Al-Qar’a to Al-Quwarah town. The tillite facies is exposed on both sides of the highway (26°31′55″N, 43°35′48″E) immediately north of Ar-Rawd Al-Uyun town. At the outcrop, located to the east of the highway, the sharp contact between the tillite at the base of the Sarah Formation and the tigillite-bearing sandstones of the Kahfah Member of the Qasim Formation is well exposed. At this locality, the massive and unsorted tillite facies consists of polished and striated polyhedral basement cobbles derived from various sources, quartz, clay pebbles, and well-rounded, locally derived boulders of tigillite-bearing sandstone, all in a dark olive gray, rather coarse-grained siltly sandstone matrix. On the west side of the highway, on top of the small cliff just opposite the previous outcrop, the tillite facies includes red, well-rounded, slightly weathered, large polished and striated granite boulders.

Along the same highway, less than 2 km north of this location, there is another tillite facies, composed of quartz and clay pebbles, filling the base of another channel. Superposition of several layers of tillite in the lower parts of the Sarah Formation separated by more mature, well-sorted, cross-beded sandstone facies of a glaciofluvial environment clearly indicate alternation of glacial and periglacial deposition, at least in the early stages of the Sarah Formation. Higher in the section of this unit, the periglacial fluvial deposition gradually becomes more dominant over the glacial and glaciofluvial deposition (Senalp, 2006a).

3.2.4. Glacially formed sedimentary structures in the Sarah Formation

Characteristic large-scale glacial landforms (deeply incised U-shaped valleys) and well-preserved true glacial and glaciofluvial deposits (various types of moraines, tillites, and fluvial sandstones) and sedimentary structures (striated and deeply grooved polished pavements) were first recognized and documented in the Al Qasim region by Senalp and Al-Laboun (2000) and many field trips were organized to this region for oil companies.

One of the most extraordinary geological surprises of the last few years in Saudi Arabia is the discovery of new locations of most convincing large-scale glacially formed sedimentary structures in the basal parts of the Sarah Formation. Some of these structures indicate the presence of grounded ice sheets in central (Qasim and Ha’il) and NW (Tayma, Al-Qalibah, and Tabuk regions) Saudi Arabia. Senalp and Al-Laboun (2000) first found and published these sedimentary structures in three different areas. They include polished glacial pavements, striations, chatter marks, deep grooves and deep circular...
depressions on the large pavements, sediment flow (solifluction structures), and overturned drag folds in the proximal parts of the paleovalleys. These glacially formed sedimentary structures were studied in the following places.

3.2.4.1. Khashm Al-Madbā‘ah Al-Qar‘a area

The Khashm Al-Madbā‘ah area (26°23′08″N, 43°45′19″E) is situated about 2.1 km west of Al-Qar‘a town to the west of Buraydah town in the Al Qasim region. This area has a “ruin-like” outcrop appearance and is therefore easy to find. The Khashm Al-Madbā‘ah cuesta itself consists of the Ra‘an and Quwarah members of the Qasim Formation, a well-developed coarsening- and thickening-upward, progradational, tide-dominated shallow marine sequence (Senalp and Al-Laboun, 2000; Senalp and Al-Duaijji, 2001a). This sequence is cut sharply (channel margin slopes at 30°) by the Sarah Formation deposited in the northward trending Al-Bukayriyah Paleovalley (Figure 8).

The Quwarah Sandstone is red-colored, planar-bedded, fine- to medium-grained, well-sorted, burrowed, and bioturbated, and it contains small-sized tidal channels. The Sarah Formation of the incising Al-Bukayriyah Paleovalley is red, beige, or yellow to white (in many places, only red-colored), coarse- to very coarse-grained, poorly sorted, relatively massive sandstone with no evidence of bioturbation. A well-defined breccia of 0.1 to 0.25 m at the base of the channel contains small granite and quartz pebbles, and shale and sandstone pebbles reworked from the underlying Ra‘an and Quwarah members. This diamicite-breccia horizon was probably a reworked tillite deposited by a debris flow. However, a large portion of the Sarah Formation at this outcrop was deposited by high-density grain flows (Senalp and Al-Laboun, 2000).

Westward from the Khashm Al-Madbā‘ah cuesta, the base of the Sarah Formation infilling the Bukayriyah Paleovalley cuts gradually deeper into the Quwarah and then into the Ra‘an members (Figure 8). At the northern end of the Khashm Al-Madbā‘ah cuesta (26°23′08″N, 43°45′19″E) the glacially grooved, well-bedded, white to yellow, and nonbioturbated Sarah Sandstone cuts sharply into the Ra‘an Shale. This contact is strongly deformed and contains tillite at two different levels, associated with two grooved pavements. The white-colored, well-bedded sandstone is overlain by another sandstone facies of the Sarah Formation, a red-colored, massive, coarse- to very coarse-grained, poorly sorted, and nonbioturbated sandstone. The contact between these two distinctly different sandstone facies is extremely irregular, but both sandstones belong to the very heterogeneous Sarah Formation. These sedimentary structures indicating evidence of glaciation were first observed by Senalp and Al-Laboun (2000) in the lower white to yellow sandstone facies (Figure 10).

1) Glacially grooved, polished pavement covers a large area. Grooves and intervening ridges range from a few centimeters to meters in transverse sections and may continue up to 60 m and demonstrate that the pavement was created in the frozen but unlithified sediment. Their constant directions of N55°E also support these interpretations (Figure 10).

2) Striae or striations, the smaller surface markings that result from glacial abrasion, are abundant and are extremely well preserved on the exposed black polished sandstone surface, and also on the bedding planes of sandstones in various intervals 2.0 to 2.5 m below the surface (Figure 10). They vary from a few centimeters to a few tens of meters in length, and from less than 1 mm up to 5.0 cm in depth. Some striae begin and end gradually, slowly deepening or shallowing along their length, while others begin or terminate abruptly. Splitting into smaller striae is also very common. Some glacial sedimentologists claim that their bifurcation directions, when combined with data from other ice-shaped features, such as chatter marks, form one of the most useful sources of evidence on glacier flow.

3) Long and deep grooves or linear scars inscribed in the paved sandstones are the most spectacular features observed in this area. One of the U-shaped, large, straight grooves is 1.45 m deep, 3.0 to 4.0 m wide, and more than 20.5 m long. The walls are polished, and the bottom surface is covered by striations trending at N60°E. It is likely that this large, deep straight groove was formed by a grounded berg, which was deeply embedded in the soft sandstone (Figure 10).

4) Circular- to subcircular depressions form the second group of scours. These are of much larger scale than the linear grooves. Generally, these shallow depressions have a depth of 0.3 to 0.5 m and a diameter of more than 5 m. Their circular rim is black-stained, smooth, polished, and totally covered by striations trending at between N53°E and N56°E. The part of the bedding plane that forms the flank of the depression is ungrooved, but small-scale mudflows originating on the grooved surface have flowed down the flanks. The floors of these depressions are often irregular. These features were excavated by ice; however, it is possible that the ice block was anchored, and its weight had significant impact on the deepening of the circular scars. Therefore, the diameter and depth of these depressions depend on the size of the blocks. Boulton (1997) explained that this surface was one in which terminal grounded seracs have formed bergs left lying beyond the glacier margin as it retreated in a water body. They left depressions on the bedding surfaces. Glacier readvance has often grooved the higher parts of the surface (Figure 10).

5) Another type of sedimentary structure formed by glacial processes in this area includes well-developed
drag folds that occur in the sandstones just beneath the polished and striated surface. This very highly deformed horizon is 0.6 m thick. However, at least two more grooved surfaces were observed on the bedding planes 1.5 m below the main grooved surface. This observation led Boulton (1997) to think that very highly deformed drag folds were formed as a result of multiple grooved pavements.

6) Williams et al. (1986) first discovered the paleo-pingo or hydroccolith formed by the ice on the Kahfa Member, south of Wadi Al Makrim. The paleo-pingo occurs in the form of a large, eroded intumescence reaching up to 300 m in diameter. It is perfectly circular, consisting of outwardly dipping sandstone in concentric layers around a steep-flanked core that displays intense plastic deformation. The
feature appears to be a typical periglacial structure that, by analogy with present-day forms described from the polar region, originated from the uplift of sediment layers in frozen soil under pressure of a lens of ice.

3.2.4.2. Al-Luwaymi (Baq’a) area

Senalp and Al-Laboun (2000) found other suites of sedimentary structures formed by the glacial erosion in the Al-Luwaymi area (27°53'15.9"N, 42°18'15.7"E), located 8.1 km west of Baq’a town (see Figure 2). The size of the structures is rather smaller than those found in the Al-Qar’a area, but sedimentary structures were found in three successive levels of the Sarah Formation filling the Al ’Ilb Paleovalley. Most of the structures were formed directly by abrasion, which involves the rubbing, polishing, stretching, and grinding of the sandstone beds by minerals, rock particles, or boulders serving as tools held firmly at the base of the moving ice. The fully exposed glacially formed sedimentary structures occur entirely within the flat-lying, red-colored, and fine- to very fine-grained, poorly sorted, and highly micaceous glaciofluvial sandstone of the Sarah Formation (see Figure 4). The stratification was not badly disturbed. As the rate of sand deposition was high, the sedimentary structures were rapidly buried, and even delicate sedimentary structures were perfectly preserved. In the measured section, the glacially formed sedimentary structures are very common in at least four different places, located at 27°53'16"N, 42°18'28"E. These structures include large areas of polished, striated, and grooved pavements overlapped with crescentic gauges, chatter marks, crescentic fractures, fan-shaped solifluction structures, and other soft sediment deformation structures on the same polished and striated surfaces (Figure 11). Drag folds and sandstone dykes commonly occur in the underlying sandstone beds. The sandstone directly overlying the glacially grooved pavement shows wave ripples, climbing ripples, and low-angle cross-bed sets. A laterally continuous, sharp erosional surface occurs 3.0 to 4.5 m above the pavement. It is covered by a partly discontinuous layer of matrix-supported, mudstone-pebble conglomerate above which lie prograding point bar sediments and yellow-red, well-sorted, fine-grained, trough cross-bedded predominantly fluvial sandstone. The grooves on the sandstone are continuous for more than 50 m, and their width (the distance between the ridges) may be up to 10 cm. They indicate ice movement towards N29°W over the unlithified but frozen Sarah Sandstone (Figure 11). Similar well-preserved striations have also been observed in the upper parts of the Sarah Formation deposited in the Al ’Ilb Paleovalley (Senalp, 2006a).

Crescentic features, crescentic gauges, and chatter marks are formed when rock or mineral tools are not held firmly in the ice but are partly rolled along between it and the bedrock (Allen, 1970). Crescentic fractures are steadily inclined cracks or fracture surfaces, the outcrops of which are crescents concave in the direction of the ice motion. Drag folds overturned towards the north occur in the underlying sediments up to at least 0.3 m below the grooved surface. Sandstone dykes below the grooved surface trend at between N20°E and N25°E. The most interesting sedimentary structures, which also frequently occur in the Baq’a area, are fan-, tongue-, or lobe-shaped, formed by sediment flows after deglaciation. They are 2.0 to 3.0 m long, 1.5 m wide, and closely associated with other glacially formed sedimentary structures. They are interpreted to be formed by very shallow flows that have moved over a very gentle slope surface, less than 5 degrees, at right angles to the trend of grooves and intervening ridges, and dragged the ridges in the direction of flow. It indicates a sand surface near the liquid limit after deglaciation. Such a state can occur in terrestrial or subaquatic deglaciation. Boulton (1997) considers that a grounded glacier grooved the sandstone surface at a time when the sandstone was unlithified. The term “solifluction” is generally used to define this process. Movement may be confined to a few centimeters in depth; the rate of movement generally ranges between 0.5 and 5.0 cm/year, increasing towards the surface. Frost heaving soil (which has an excess of water in the form of discrete ice lenses when frozen) occurs in most solifluction features. On thawing, such soils may settle with a resultant down-slope displacement. In some temperate (wet-based) glaciers, some melting is to be expected as a consequence of the locally increased pressure. The melt water transports and deposits clay, silt, and sand-sized particles, which were incorporated into the ice, as a result of glacial abrasion of the underlying sediments (K.W. Glennie and J.D. Al-Belushi, 1996, personal communication).

3.2.4.3. Al-Zarqa (Baq’a) area

In this area, the glacially formed sedimentary structures were found on the eastern side of the Al ’Ilb Paleovalley (Senalp and Al-Laboun, 2000). They occur in the lower parts of the Sarah Formation, which cuts into the Kahfah Member of the Qasim Formation. The Al ’Ilb Sarah Paleovalley extends in the S-N direction and cuts progressively into the Saq, Qasim, and Zarqa formations. The contact between the Sarah Formation and the older sediments is very sharp and there has been significant erosion at the interface. The glacially formed surfaces occur 3.0 m above the base of the Sarah Formation. There are ploughs and chatter marks on the grooved surface demonstrating glacier movement between N5°E and N10°E. Shear folds produced by glacier movement across this surface occur in the underlying sandstones. The shear folds can extend 2.0 m below the surface. Well-defined drag folds, similar to those found in the Al-Qar’a area, also occur above the grooved surface (Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al, 2018).
3.2.4. Hawban Member of the Sarah Formation

The Hawban Member of the Sarah Formation was first introduced and defined by Vaslet et al. (1987) for the upper 54-m-thick section of the Sarah Formation below the Qusaiba Member of the Qalibah Formation in the south of Qa Hawban (Baq'a area). In this definition, the Hawban Member extends between the classical Sarah Formation at the base and the regional Early Silurian transgressive surface (MFS S10, 444 Ma) at the base of the Qusaiba Member of the Qalibah Formation at the top. The Hawban Member is locally developed between Baq'a and Ash-Sharqiyah towns, east of Ha'il. The type section defined by Vaslet et al. (1987) consists of two genetically different units, representing different depositional conditions in different environments.

Based on detailed sedimentologic studies, this definition was revised by Senalp et al. (2002). The new definition of the Hawban Member forms only the lower half of the type section and consists of tillite and boulder clay; it indicates the final advance of the Late Ordovician glaciation at the top of the Sarah Formation. However, the upper half of the section is a typical coarsening and thickening upward
progradational beach sequence deposited during the Early Silurian time and defined as the Baq’a Member of the Qalibah Formation below the Qusaiba Member. In this new definition, the Qalibah Formation includes the Baq’a, Qusaiba, and Sharawra Members. The Hawban Member is 25 m thick and consists of thick, slumped, and tectonically mixed typical boulder clay facies containing huge sandstone blocks of the older cover rocks and the Arabian Shield, ranging from 1.0 m to 5.0 m in size embedded in the silty clay matrix. The boulders consist of strongly folded and fractured sandstones eroded by ice mass from the underlying Sarah Formation (Figure 12).

The shallow marine sediments of the recently defined Baq’a Member of the Qalibah Formation transgressively overlie the tillite and boulder clay deposits. The palynological data in the offshore marine shales at the very base of the Baq’a Member indicate that the true marine conditions in NW Saudi Arabia were established during the time interval between the latest Ordovician (Late Hirnantian) and Early Silurian. This member consists of a well-developed coarsening- and thickening-upward prograding beach parasequence, which was covered by deep marine shales of the Qusaiba Member during Early Silurian time. The measured section of the Baq’a Member consists of 7.75 m of offshore marine shales, overlain by 10-m-thick lower shoreface sandstones, 11-m-thick upper shoreface sandstones, and 2-m-thick foreshore sandstones (Figure 13). Senalp et al. (2002) and Senalp (2006a) reported well-preserved, diverse, and abundant acritarchs from the olive-green offshore marine shales and silty shales (Units 1 and 2) of the Baq’a Member. Species considered as in situ forms include *Sylvandium* n. sp., *Dixallophasis remota*, *Veryhachium subglobosum* (Jardiné et al., 1974), *Veryhachium sp.*, *Leprotolypa evexa* (Colbath, 1979), and *Villosacapsula* n. sp. (quadrate shape). They concluded that the age of the Baq’a Member is restricted to the Late Ordovician (Late Hirnantian) or beginning of the very Early Silurian age (Figure 13).

### 3.2.5. Depositional environment of the Sarah Formation

The well-defined Late Ordovician glacially formed paleovalleys (tunnel valleys) and their glaciofluvial sandstones (sandur plain) forming the Sarah and Sanamah formations are continuously exposed in the large desert setting of the central and southern part of Saudi Arabia. In the absence of the locally developed Baq’a Member, the sand-prone Sarah Formation is directly overlain by the organic-rich hot shale facies at the base of the Qusaiba Member of the Qalibah Formation deposited during the Early Silurian transgression (Figure 14). This close relationship makes the Sarah Formation a very important reservoir for oil and gas accumulations and initiated new research works at outcrops and in the subsurface (Senalp, 2006a). Sedimentologic studies clearly indicated that the Sarah Formation contains the sediments of both the true glacial (glacial advance), such as various types of moraines, and the glacial retreat period, such as glaciofluvial and glaciomarine (dropstones in open marine shales).

The Hawban Member in the uppermost part of the Hirnantian succession may represent another glacial advance followed by the deposition of the offshore marine shales at the base of the Baq’a Member. The shallow marine sandstones of the Baq’a Member, overlying the offshore marine shales, were deposited in the lower shoreface, upper shoreface, and foreshore facies of the prograding beach environment. The Baq’a Member has no indication of glaciation (Senalp et al., 2002; Senalp, 2006a).

A large number of the continuous outcrops of the Sarah Formation representing different parts of the paleovalleys provide an excellent opportunity to understand the impacts of continental glaciation during its advance and retreating periods. The immense amount of data collected from outcrops helped exploration geologists to establish their depositional model deeply incised into the Zarqa, Qasim, and older formations. They had flat bottoms and gently dipping valley walls. The glacial deposits (mainly pockets of tillites), and well-preserved large- and small-scale glacial sedimentary structures are very common in the lower parts of the Sarah Formation. Based on this convincing evidence, the paleovalleys (tunnel valleys) are interpreted to be glacial in origin. Because of the strong cementation of the coarse-grained, porous sandstones at the base of the valleys, and the erosion of the shales and sandstones of the Qasim Formation, the paleovalleys are exposed now in reverse relief. In this way, the lithofacies, lithofacies stacking pattern, lateral and vertical facies changes, and reservoir quality of the Sarah Formation along the valley axis can be studied easily (Vaslet, 1990; Senalp, 1990; Evans et al., 1991; McGillivray and Husseini, 1992; Senalp and Al-Laboun, 2000; Senalp, 2006a).

The Sarah Formation, filling the paleovalleys, consists of thin glacial deposits at its base. Discontinuous layers of tillites, containing large blocks of sandstone and shale eroded from the Qasim Formation, and polished blocks of igneous rocks occur at the base of the paleovalleys. This facies is best exposed at the base of the Khanasir Sarah Paleovalley (the type locality) and at the outcrop located on the Uyun Al-Jiwa-Quwarah highway. There is every kind of large- and small-scale glacial sedimentary structure delicately preserved in the very lower parts of the formation, about 0.2 to 3 m above the Pre-Sarah unconformity. These structures were described and excellent pictures were published by Senalp and Al-Laboun (2000). They include glacially grooved and polished pavements, striations and chatter marks, long and deep grooves, circular to subcircular depressions, drag folds, paleo-pingos, and other small-scale structures.
The thick sandstone of the Sarah Formation was deposited when huge amounts of sandy material stored in the ice mass were released during the deglaciation period. The sandy material was eroded by the glacial paleovalleys cut deeply into the older sand-dominated formations, such as the Qasim (Quwarah and Kahfah members), Saq, Quweira (Al-Ula), and Siq formations. There is no single satisfactory answer to explain how the well-defined and deep Sarah Paleovalleys were formed by the glacial and glaciofluvial processes. The paleovalleys, mapped by Williams et al. (1986) and Vaslet et al. (1987, 1990) between the towns of Buraydah and Ha'il, are regularly spaced and are almost parallel to each other. Their well-defined geometry may suggest that their locations and these deep-seated and predominantly SW-NE trends have been controlled by a horst-graben system on the deep-seated Arabian Shield (Senalp, 2006a). Some of the paleovalleys coincide with the preexisting faults that crosscut the basement, but the others show no clear-cut relationship with the basement faults (Ghienne et al., 2003).

Most of the Sarah Formation, overlying the true glacial deposits, consists of thick, very uniform, coarse- to fine-grained (mainly medium-grained), and cross-bedded sandstones of glaciofluvial and glacimarine origin. They are composed of vertically and laterally stacked small-scale fining upward sequences and they show lateral facies changes along the valley axis in a predictable fashion. Some pockets of conglomeratic sandstones at the bottom of the glaciofluvial channels were probably reworked from the older glacial deposits. The flow direction of the Sarah Paleovalleys ranges from eastward to northward, but the predominant flow is in the NE direction. This flow direction is almost perpendicular to the general strike direction of the older formations. All the paleovalleys systematically broaden downstream, and after 50 to 60 km, they become coalescent and form a continuous outcrop belt. The sandstones in this continuous belt form the uppermost part of the Sarah Formation and were deposited when the paleovalleys were filled completely and the sediments overflowed the paleovalleys.

The uppermost part of the Sarah Formation is magnificently exposed at the small hill in the center of Quwarah village in the Qasim and in the Al-Luwaymi area in the Baq'a area. The sandstones are red-colored, fine- to very fine-grained, and slightly silty in the upper parts. They show horizontal parallel laminae and climbing wave ripples. In the north of the Qusaiba depression, the sandstone beds forming the top of the formation below the Silurian Qusaiba Member show large-scale wave ripples (mega-ripples) and are strongly burrowed and bioturbated. These sandstones were no longer directly glacial in origin; they were deposited in a periglacial lacustrine environment but marine conditions in this environment have gradually increased.

The Sarah Paleovalleys at the outcrops were carefully mapped in central and NW Saudi Arabia by Williams et al. (1986) in the Jabal Habashi Quadrangle of central Arabia, Vaslet et al. (1987) in the Baq'a Quadrangle of NW Saudi Arabia, and Vaslet (1990). Aoudeh and Al-Hajri (1995), using aerial photography or satellite imagery and 3D seismic reflection data lines, mapped the Sarah Paleovalleys, indicating a radiating pattern of these glacial paleovalleys around the Neoproterozoic Arabian Shield in NW Saudi Arabia (Figure 15). These paleovalleys form slightly curving ridges and merge towards the basin, then submerge under the hot shale facies of the Early Silurian Qusaiba Member of the Qalibah Formation. Almost identical paleovalleys and glacially formed deposits and
their hydrocarbon potential were also reported in Jordan
(Vaslet, 1990; Abed et al., 2005; Armstrong et al., 2005).

A large amount of intensive works at the surface and
subsurface across the Middle East and North Africa
indicated that the tunnel valleys (typically measuring
1–6 km wide and 50–65 km long) formed during the
Late Ordovician glaciation cut underneath the ice sheets
by meltwater at enhanced hydrostatic pressure (Vaslet,
1990; Senalp and Al-Laboun, 2000; Le Heron et al., 2004;
Senalp, 2006a). In central and NW Saudi Arabia, in Jordan
(Abed et al., 1993), and in the Illizi Basin of Algeria, these
incisions are observed to cut approximately 300 m into the
underlying stratigraphy (Hirst et al., 2002). The meltwater
process underneath the ice sheet is not the only process

Figure 13. The measured sedimentologic section of the Hawban Member of the Sarah Formation is 25 m thick and consists of strongly folded, slumped, and tectonically mixed typical boulder clay facies containing huge sandstone blocks of the older cover rocks and the Arabian Shield embedded in the gray silty shale. The overlying Baq'a Member is 27 m thick and consists of coarsening- and thickening-upward progradational beach sequence (Senalp et al., 2002; Senalp, 2006b).
to cut deep paleovalleys. However, there are other lines of evidence about their mode of origin. In Saudi Arabia, the Sarah Paleoavalley is about 50–60 km long, between several hundreds and several kilometers wide, and more than 300 m thick. The Bukayriyah Paleoavalley, north of Bukayriyah town, is more than 60 km wide and has no distributary, which suggests that this paleovalley is too large to have been formed through the work of a subglacial network of subglacial meltwater processes (Senalp, 2006a).

It is also suggested that these paleovalleys may have been formed as fluvial incised valleys on the exposed parts of the continental shelf during the sea-level fall, resulting from ice sheet growth. In summary, the working analogous model proposed here for the formation of up to 60-km-long and more than 300-m-thick Sarah Paleoavalley comprises the cross-shelf troughs carved by the Pleistocene ice stream, observed in the modern-day Barents Sea. However, the formation of tunnel valleys (subglacial) cannot be
ruled out and this hypothesis may still be valid for many glacial valleys. The interpreted geologic model of the Sarah Formation, deposited in Saudi Arabia during the Late Ordovician (Hirnantian, 445–444 Ma) Gondwana glaciation, is presented in Figure 16 (Senalp and Kaya, unpublished data; Senalp et al., 2018).

3.2.6. Hydrocarbon potential of the Sarah Formation
The thick and regionally deposited sandstones of the Late Ordovician glacial successions form important hydrocarbon reservoirs throughout North Africa, the Middle East, and SE Turkey. The work carried out by Senalp and Al-Laboun (2000), Senalp (2006a), and Senalp et al. (2018) on the Sarah reservoir sandstones and the overlying organic-rich Qusaiba shale of the Qalibah Formation both at the outcrop and in the subsurface indicated that the Sarah Formation has great exploration potential, particularly where the prolific hot shale facies was deposited. At present, oil and gas have been produced in many countries located on the African and Arabian plates. The exploration play is the sandstones deposited in the glacially formed incised valleys. The great thickness and presence of good reservoir sandstone facies in the Sarah Paleovalleys and their close association with the overlying hot shale facies of the transgressive Qusaiba Shale, and the gas discovery in the broadly equivalent Trebeel Formation in NW Jordan (Andrews, 1991), have significantly increased the exploration potential of the Sarah Paleovalleys in Saudi Arabia.

Understanding the close genetic relations between the glaciolfluvial and glaciomarine sandstone reservoirs and the directly overlying organic-rich (up to 14% TOC) hot shale facies deposited at the base of the Silurian transgression and the downward migration of the oil and gas was the major breakthrough for successful hydrocarbon explorations (Senalp, 2006a; Le Heron et al., 2009). In this respect, understanding the three-dimensional geometry and the lateral facies in the sedimentary successions and, in particular, the reservoir quality of the glaciogenic sandstones in the paleovalleys is very important in the early stage of hydrocarbon exploration.

The regional Silurian transgression (Rhuddanian, 444 Ma) is usually interpreted as the postglacial transgression; we have already seen that the first transgression occurs during the latest Ordovician, meaning that the glacial retreat was punctuated. In this respect, the Silurian transgression probably records the final melting of the ice mass. The transgression is diachronous depending on the preexisting topography. Source rock seems to occur predominantly in regional lows, resulting from either glacial erosion or fluvial incision possibly related to the isostatic rebound. These lows in combination with late deformation will control the migration pathways. The sandy glacial deposits or the lowermost Silurian transgressive sandstones deposited immediately below the source rock are the first reservoir rocks to be filled or at least used for the migration as indicated by the abundance of shows.

A number of exploratory wells have been drilled in central and northern Saudi Arabia targeting the periglacial sandstones of the Sarah Formation (Figure 17). Detailed sedimentologic studies of the cores from these wells have clearly indicated that the braided stream sandstone facies of the Sarah Formation deposited on the large braid delta have the best reservoir quality. These sandstones change basinward into fluvimarine sandstone, and finally into marine sandstone facies. The thickness and grain size of the sandstone facies is greatly reduced along this trend, becoming shaly, poorly sorted, and firmly cemented with very poor reservoir quality (Senalp, 2006a).

The Sarah Formation is an important gas reservoir in central Saudi Arabia. The thickness of the sandstone ranges significantly. The first author, using surface and subsurface data, generated several hand-drawn isopach maps to show these thickness variations and the reservoir quality. These maps were integrated with the gross interval isopach maps of the overlying hot shale source-rock facies of the Qusaiba Member. These source-rock shale facies were deposited in irregular and isolated depressions formed on the leftover glacial topography. These two maps were used together and continuously modified as more data became available. These confidential maps have not been published. The well logs drilled in central Saudi Arabia show the genetic relations between the sandstone reservoir facies and overlying hot shale source-rock facies (Figure 17). These logs clearly indicate that the gas generated in the hot shale facies of the Qusaiba Member can migrate easily to the underlying porous sandstones due to the pressure generated by the expansion of the gas (Senalp, 2006a). The thickness of the Sarah Formation ranges from 194 m, encountered in the deepest part of the valley, to 10 m, penetrating into the braid delta. Several wells have thickness variations between 31 m and 46 m.

3.3. Sanamah Formation
Kellogg et al. (1986) first introduced the term “Sanamah” for the second member of the Cambro-Ordovician “Wajid Sandstone” formation. The reference section of the Sanamah Member was reported from Jabal Sanamah of the “Wajid Outcrop Belt” (20°12′25″N, 44°14′55″7E), located north of Najran town in SW Saudi Arabia (Figures 3 and 18). Vaslet (1989) considered the Sanamah and Khusayyayn members of the “Wajid Sandstone” formation to be of Ordovician age and correlated them with the glacially formed Zarqa Formation of central Saudi Arabia. Senalp (1990) carried out detailed stratigraphic and sedimentologic studies of the Sanamah Member. He recognized deeply incised U-shaped glacial valleys
almost identical to the Sarah Formation of central and NW Saudi Arabia and raised the status of the Sanamah Member to the Sanamah Formation. Based on the same concept, Evans et al. (1991), Stump and Van der Eem (1995a, 1995b), and Senalp (2006a) tentatively correlated the Sanamah Formation to central and northern Arabia. This regional correlation is suggested by their position in the stratigraphic column, similar lithological composition, large-scale geometry (glacial valley), deep grooves, and large glacially formed polished and striated pavements.

3.3.1. Nature of contacts with adjacent formations

The Sanamah Formation cuts deeply into the tigillite (scolithus)-burrowed sandstones of the Dibsiyah Formation (Saq Formation in central Arabia). Its lower contact represents the base of the glacially formed valley and correlates with the Pre-Zarqa and Pre-Sarah unconformities. The Qasim Formation or its equivalent section in the Wajid Plateau Outcrop Belt was significantly removed by this regional unconformity surface, formed during the Late Ordovician glaciation (Figure 18). Senalp (1990) and Evans et al. (1991) reported the presence of the Early Silurian Qusaiba Member of the Qalibah Formation overlying the massive glaciofluvial sandstones of the Sanamah Formation in the Al Madarah area (19°36'38"N, 44°08'20"E) and Khashm Al 'Alam (18°41'0.5"N, 44°19'40"E).

3.3.2. Lithology, thickness, and depositional environment

The glaciogenic Sanamah Formation consists of a series of vertically and laterally stacked, cross-cutting, large-scale fining-upward sandstone sequences, separated by second-order channel surfaces in glacially formed paleovalleys. The formation consequently varies in thickness, lithology, and compositional and textural maturity (general sorting). Senalp (1990) measured the 153-m-thick type section of the Sanamah Formation at Bani Sanamah, Jibal Al-Wajid. The reported type section at Bani Sanamah may include only the middle and upper parts of the formation exposed at the northernmost part of the formation.

Senalp (1990) described three well-defined units in the thickest part of the measured section. The lower part of the measured section is 40.8 m thick and consists of hard, massive- to thick-bedded, cross-bedded, well-sorted sandstone overlying the granites of the Precambrian Arabian Shield. The well-exposed glacially formed deep grooves and polished and striated pavements were observed in this lower unit. The middle part of the measured section
Figure 17. (a) Suite of well logs of the massive reservoir sandstone of the Sarah Formation is directly overlain by the Early Silurian (Rhuddanian, 444 Ma) organic-rich, very prolific hot shale facies of the Qusaiba Member of the Qalibah Formation encountered in one of the exploration wells. This succession is cut deeply by the Hercynian (Permo-Carboniferous, about 305 Ma) unconformity surface (Senalp and Al Duaiji, 2001; Senalp, 2006b; Senalp et al., 2018). Thick lean shale prevents the vertical migration of the gas; therefore, the hydrocarbon generated in the hot shale facies of the Qusaiba Member migrates downward into the glaciofluvial sandstone reservoirs of the Sarah Formation, mainly by the pressure difference.

(b) Suite of well logs shows the reservoir sandstone facies of the Sarah Formation, transgressive Baq'a and Qusaiba members of the Qalibah Formation. There is a very thick hot shale reservoir facies at the base of the Qusaiba Member deposited during the Early Silurian transgression. The very thick impermeable lean shale facies prevents the vertical migration of the gas and forces the highly pressurized gas to migrate downward into the porous sandstones of the Sarah Formation (Senalp, 2006a).
Figure 17. (Continued).
Figure 18. Geologic map of the Wajid Outcrop Belt, exposed between the north of Najran in the south and Wadi Ad Dawasir in the north of southern Saudi Arabia. This is the only outcrop belt where the Late Ordovician glacial Sanamah Formation and the glacial Permo-Carboniferous successions are exposed. The map shows the locations of the measured sections from the Sanamah Formation at the Jabal Sanamah (Senalp, 1990; Evans et al., 1991).
is 10.2 m thick and consists of rather poorly sorted and cross-bedded sandstone. The upper part of the section is 102 m thick and consists of rubbly weathered, well-sorted sandstone. Senalp (1990) identified five well-defined fining-upward sequences in the measured Khashm Khatmah section. The model grain size of the sediments and the scale of sedimentary structures (bed forms) in each sequence gradually decreases, suggesting that the paleovalley was filled mainly during the deglaciation stage when the ice mass started melting. The cobble- to boulder-bearing conglomerate facies occur more commonly in the lowermost fining-upward sequence. The uppermost fining-upward sequence starts with coarse- to very coarse-grained sandstone facies.

The lower 10–25 m of the measured Khashm Khatmah section consists of a basal conglomerate facies and cuts into the tigillite (*Scolithus*)-burrowed sandstone. It contains rounded quartz pebbles and very angular sandstone cobbles reworked from the older formations. These large clasts (up to 20 cm in diameter) show well-developed imbrications. The sandstones in the upper fining-upward sequences are white to pale red and show well-developed grain size separation in the order of occurrences of sedimentary structures from higher flow regime to lower flow regime. The massive- to thick-bedded lower parts are gradually overlain by large-scale, coarse-grained, moderate- to well-sorted sandstone, followed by small-scale cross-bedded followed by current-rippled sandstone. The conglomeratic layers overlying the channel surfaces are less than 5 cm thick, and the largest clast size reaches up to only 2 to 3 cm. The fine-grained sediments (shale and siltstone) occur only in the uppermost 10-m section of the measured Sanamah Formation. The green-gray shales in the upper parts of the section may indicate the marine flooding surface into the incised valleys during Early Silurian time. Similar observations were made in the Sarah Paleovalleys by Senalp and Al-Laboun (2000) and Senalp (2006a). The sedimentary structures found in the Sanamah Formation are directly related to both glacial and glaciofluvial processes. These glacially formed structures include deep and long grooves and large polished and striated pavements, and striations along the bedding planes of the sandstones, in the lower parts of the Sanamah Formation (Figure 19). In the upper parts, the sandstones show cross-bedding and current-ripple marks. Finding more evidence of glacially formed sedimentary structures is a matter of experience in terms of where to expect these structures, the length of time scheduled for each stop during a field trip, and, of course, careful study on bedding surfaces. The other structures include large-scale, glacially formed slump structures and overturned beds. Senalp (2006a) also observed similar structures in the proximal parts of the Sarah Paleovalley in the Qasim area. Marine Figure 19. (a) Large-scale, long, and deep grooves and polished and striated glacial pavements are found commonly in the lower parts of the Sanamah Formation and indicate direct evidence for its glacial deposition. This particular outcrop is located in the Al-Qarfa area (19°58′33″N, 44°34′24″E). The striations indicate that the ice mass moved northward in direction (Senalp, 2006a). Large-scale, long, and deep grooves and polished and striated glacial pavements are found commonly in the lower part of the Juwayl Formation and indicate direct evidence for its glacial deposition. This particular outcrop is located at 19°58′33″N, 44°34′24″E in the Al-Qarfa area. The striations indicate that the ice mass moved northward in direction. (b) The glacially formed erosional unconformity surface at the base of the Sanamah Formation cuts deeply into the Late Cambrian Dibsiyah Formation (Wajid Outcrop Belt of SW Saudi Arabia). There are large-scale, polished, and striated grooves at the base of the Sanamah Formation indicating ice movement in N10°E direction (photograph by Senalp, 2005).
bionturbation was found in the shales of the uppermost part of the section in the Jibal Sanamah, indicating the eventual marine flooding of the glacially formed incised valleys (tunnel valleys).

Until recently, the environment of deposition of the Sanamah Formation was not clearly understood. First, the “Wajid Outcrop Belt” of southwest Saudi Arabia is remote; logistics and climate are not very hospitable, even harsh, for a long-term field season. It requires much preparation and commitment. Finding good evidence to interpret any depositional environment needs patience, close study, and friendship with the outcrop. The presence of the Early Paleozoic (Late Ordovician) glacial deposits in southern Saudi Arabia is less well documented than the stratigraphically correlated units in central and NW parts of the Kingdom. The paleoenvironmental interpretations of the Sanamah Formation have ascribed them to glacial (McClure, 1980; Vaslet, 1987, 1988, 1990; McClure et al., 1988; Senalp, 1990) or glacial and periglacial (Senalp, 1990; Evans et al., 1991). Kellogg et al. (1986) described the valley geometry of the Sanamah Formation and many sedimentary structures leading to the glaciogenic depositional environment; however, they did not make any interpretation about its depositional model (Figure 19). Vaslet (1989), based on his long-time experience on the glacially formed Zarqa and Sarah Formations, regarded the Sanamah Formation to be glacial in origin, and he correlated the Sanamah and Khusayyayn formations with the Zarqa Formation in central and northern Saudi Arabia. Based on recent studies, Senalp (1990) indicated that the Sanamah and Juwayl formations have many common features and suggested similar paleoenvironmental interpretations. The Permo-Carboniferous Juwayl Formation contains more tillite facies and granite boulders, and it shows abundant slumped deposits. Therefore, many researchers have correctly interpreted this formation as being a product of glacial deposition. On the other hand, the Sanamah Formation carries much evidence regarding its glacial origin, only in its lower parts. Towards the upper part of the formation the depositional facies occurs in a much more orderly manner. The pure glacial facies in the lower parts is gradually replaced by the glaciofluvial, fluvial, and eventually glaciomarine and finally open marine facies. One of the typical outcrops carrying glacial evidence is the Jibal Al-Qahr, where the above mentioned polished and striated glacial pavements and long, deep, and striated grooves were observed.

Glacial pavements with well-preserved striations trending dominantly north were also observed in many other locations. The glaciofluvial rocks unconformably overlying the Dibsiyah Formation consist of deeply channelized conglomeratic sands with interbedded cobbles and boulders of faceted, polished, and striated granite and other basement rocks. In the Jibal Al-Qahr area, the glaciofluvial sediments are in turn overlain by generally horizontal planar-bedded, medium- to coarse-grained sandstone. Senalp (1990) concluded that the stratigraphic position, type of lithofacies, lithofacies pattern, and sedimentary structures are almost identical to the same Late Ordovician Sarah Formation of the Al ’Ilb Paleovalley in the Baqa’a (Ha’il) area and the Sarah Paleovalley fully exposed in the Al Qasim area of central Arabia.

4. Late Ordovician glaciation in North Africa

Significant volumes of hydrocarbons occur in the Late Ordovician glacial deposits across North Africa (Tunisia, Algeria, western Libya, and Egypt) and the Middle East (Saudi Arabia, Iraq, and Jordan). The paleontological data from these exploration and production wells provided the most reliable chronostratigraphic markers to correlate the Paleozoic successions and glacially formed deposits of Hirnantian age across North Africa and the Arabian platform. In many respects, the overall depositional models of the Late Ordovician glacial deposits in North Africa are much more complex than those described in Saudi Arabia. Several glacial advances and retreats have been recognized in the Late Ordovician successions of North Africa. In the Sahara region production and exploration from the glacial reservoirs occur in the Hamra and Illizi basins (Algeria), in the Al Kufrah and Murzuq basins (Libya), and in the Upper Second Bani Formation (southern Morocco). In North Africa, the lower Paleozoic sandstones and especially those of Late Ordovician age give an account of reserves in more than 50 fields, many of which are categorized as giant fields (e.g., Elephant, El Sahara, Tiguentourine, Tin Fouye; Le Heron et al., 2009).

There are fundamental similarities between the Late Ordovician depositional environments of SE Turkey, Saudi Arabia, and North Africa, which allow for two principal, large-scale heterogeneities within the glaciogenic reservoirs to be defined. First, at field scale, the largest-scale control on heterogeneity in glaciogenic reservoirs (mainly the glaciofluvial sandstones deposited on the sandur plains) is connected to the place of paleoice streams or tunnel valleys. The second, at prospect-scale, are the extensive deep (up to 300 m) tunnel valley networks, which is a significant property of the reservoir system. The ice streams (tunnel valleys) are likely the most significant agent of erosion within Hirnantian ice sheets, producing tunnel valleys (Buoncristiani et al., 2007; Senalp et al., 2018). Proof for mega-scale glacial lineations gathered at the outcrops provided an excellent working model to recognize these tunnel valleys in the subsurface seismic datasets (Moreau, 2006; Senalp 2006a; Le Heron and Craig, 2008; Senalp et al., 2018).
4.1. Libya

Large volumes of recoverable hydrocarbon reserves occur in the Late Ordovician glaciogenic sandstone reservoirs in the Mamuniyat Formation in the Murzuq Basin, southwestern Libya. The hot shale facies in the lower part of the Tanezzuft Formation (Early Silurian) is proven to be the major source-rock facies in the oil and gas fields of NE African countries. The regional distribution of the hot shale facies is closely related to the underlying Late Ordovician relict glacial topographic surface (such as glacial depressions and underfilled tunnel valleys). Two major migration systems were established in the Murzuq Basin. In the first system, the oil migration is related to the existing fault system. The oil generated within the Silurian hot shale facies moved upward vertically into the younger Devonian reservoirs. In the second migration system, the oil migrated from the same Silurian hot shale source-rock facies downward into the older Cambro-Ordovician reservoirs. This migration was partly in lateral and in vertical directions due to the pressure differences (Sayılı et al., 2012). The main trapping mechanisms are structural fault-bounded simple anticlines related to complex glactoectonic events during the Late Ordovician Gondwana glaciation. Most of the preexisting fault systems were reactivated (rebound) after the melting phase of glaciation (Sayılı et al., 2012).

In the Murzuq Basin, particular attention was given to understanding the stratigraphic boundaries, sedimentology, geometry, and potential reservoir quality of the sandstones deposited in the regionally extensive tunnel valleys. Le Heron and Craig (2008) carefully mapped these tunnel valleys. This model is very similar to E-W and NE-SW trending paleovalleys of the Sarah Formation as mapped by Vaslet (1990), Aoudeh and Al Hajri (1995), and Senalp (2006a) in the Arabian Peninsula. Intensive studies by Le Heron et al. (2006) on the reservoir heterogeneity of the Late Ordovician glaciogenic sandstones in the Murzuq Basin provided valuable information on the sedimentological architecture of the tunnel valleys. They reported that the sedimentary succession deposited in the valleys consists of four well-recognized disconformity-bound units. Units 1 and 3 are mud-dominated and have no reservoir potentials. Units 2 and 4 are sand-dominated and have poor to excellent reservoir quality. Unit 2 consists of glaciofluvial and intertidal sandstones to offshore turbidites deposited during the glacial retreat. The geometry and the reservoir quality of the sandstones were determined by the paleotopography of the basin. Unit 4 represents the glacial retreat (rising sea level) and isostatic rebound. The sediments were deposited both in the shallow marine environment and also as turbidite fans in a deep marine setting. In this respect, the sedimentological architectures are variable at this level and include prograding coarse siliciclastic wedges and the infill of half-graben basins during isostatic rebound. This sedimentologic model reported by Le Heron et al. (2006) in the Murzuq Basin indicates that the sedimentation in these tunnel valleys took place in a glaciomarine environment and represents the effects of both marine and glacial processes in distal parts of the valley. In this respect, this sedimentological architecture is significantly different than the sedimentological architecture in the Sarah tunnel valleys in the Arabian Peninsula, which consist of thick successions of coarse-to medium-grained and well-sorted sandstones (Senalp and Al-Laboun, 2000; Senalp, 2006a).

4.2. Egypt

The Lower Paleozoic successions of Egypt occur in the North Western Desert and the Gulf of Suez. The Ordovician-Silurian Naqus Formation and its subsurface equivalents (the Kohla and Basur Formations) mainly consist of white-colored, medium- to coarse-grained and cross-bedded unfossiliferous sandstones, including large amounts of irregularly distributed cobbles and pebbles. Sedimentological studies indicated that these very heterogeneous deposits were accumulated in a glaciofluvial environment (Allam, 1989). Integrated stratigraphic and sedimentologic studies indicated that glacioeustatic movements determined the paleogeography of Egypt during the Late Ordovician-Silurian period (Allam, 1989). The diagnostic feature of the glaciogenic Naqus Formation is the presence of a well-defined fining-upward sequence, consisting of large-scale cross-bedded, coarse-grained pebbly sandstones, overlain by medium-grained sandstones followed by fine-grained sandstones characterized with small current ripples. There are also large amounts of poorly sorted quartz gravels, and cobbles that are irregularly distributed within the sandstones. Issawi and Jux (1982) interpreted this formation as glaciofluvial sediments, which were deposited by the great Saharan glaciers that covered large parts of NW Africa during the Late Ordovician to Early Silurian. Issawi and Jux (1982), Issawi (2000), and Issawi et al. (2002) discovered the occurrence of glacial deposits in the Late Ordovician successions in Sinai, at Wadi Qena, in the Wadi Gabgaba area, and in the southwestern part of the Western Desert. They ascribed the glaciations to the influence of northern Gondwanaland. The maximum transgression in Egypt occurred during the Early Silurian time (Rhuddanian, 444 Ma) as a result of the rising sea level during the deglaciation period.

5. Late Ordovician glaciation in Jordan

In Jordan, the Upper Ordovician glacial deposits are defined as the Ammar Formation. They were deposited in southern Jordan, forming the northern extension of the Tayma-Tabuk Basin of NW Saudi Arabia. Turner et
al. (2005) reported that the Ammar Formation comprises a lower and upper glacially incised paleovalley system, occupying a reactivated basement and Pan-African fault-controlled depressions. The lower glacial paleovalley cuts deeply into the underlying shallow marine sandstones of the Tubeiliyat Formation. This paleovalley is filled with thin glaciofluvial sandstones at the base and is overlain by about 50-m-thick shoreface sandstone facies of the shallow marine environment. The top surface of this paleovalley-fill represents glacially formed grooves and striations aligned in the east-west and northwest-southeast directions. The upper paleovalley was incised into the lower paleovalley or, in some cases, into the Tubeiliyat Formation, and it shows a similar lithofacies pattern, consisting of glaciofluvial sandstones in the lower parts and marine sandstones in the upper parts. Sedimentological studies and 3-D seismic data indicated that these glacial paleovalleys are extensions of Late Ordovician continental ice sheets that covered NW Saudi Arabia. Based on the directions of the grooves and striations at the base of the paleovalleys, occurrences of at least four stages of glacial advance-retreat were recorded (Turner et al., 2005).

Douillet et al. (2012) reported that the Upper Ordovician Ammar Formation mainly consists of glaciogenic sediments deposited in the paleovalleys, and subordinate time-transgressive fluvial to shallow marine succession overstepping both the paleovalleys and the interfluvial areas between them. The size of the paleovalleys ranges from 60 to 160 m in depth and from 1 to 3 km in width. The slopes of the valleys are estimated to be between 20° and 50°. The internal organization and depositional facies suggest their origin as tunnel valleys. The tunnel valleys are infilled by either fluvio-glacial sandstones or coarsening-upward fluviodeltaic successions including fine-grained clayey sediments. Reoccupation of previous valleys is evident in many places. At least three generations of tunnel valleys are inferred from cross-cutting relationships, although they most probably only reflect temporary standstills and minor readvances related to the overall recession following the main glacial advance recorded in Saudi Arabia (Douillet et al., 2012). Petrophysical studies indicated that higher permeabilities (1.5–3 darcy) are found in the glaciofluvial sandstones. Their porosities range between 22% and 28% and they contain high amounts of diagenetic clay. The lateral and vertical stacking patterns of fining-upward fluvio-glacial channel-fill sandstones increase their reservoir quality (Douillet et al., 2012).

The upper paleovalley-fill of the Upper Ammar Formation is directly overlain by the hot shale facies at the base of the Batra Formation. This potential source rock was deposited during the Early Silurian (Llandovery, 444 Ma) transgression, which correlates with the Qusaiba hot shale facies of Saudi Arabia and the hot shale facies at the base of the Dadaş Formation in SE Turkey (Senalp et al., 2018). Senalp (2006b) suggested that the paleovalleys and their ages, general trends, and related infilling sediments comprising the Ammar Formation are essentially correlative to the Sarah Formation of Saudi Arabia and also the Yurteri Formation, which was recently discovered in the Bedinan area of SE Turkey (Senalp et al., 2018).

6. Late Ordovician glaciation in Iraq

The Lower Paleozoic successions of Iraq, particularly in the Western Desert, close to Jordan, have significant amounts of hydrocarbon potentials because there are several organic-rich hot shale facies within the successions. Of course, the regionally widespread Akkas hot shale facies, deposited at the base of the Early Silurian transgression, has the highest source rock potential. In the Akkas-1 well, two hot shale units have a combined thickness of 61 m and total organic carbon (TOC) values that reach 16.6% (Al-Hadidy, 2007). Several reservoirs and seals present exploration targets in the Western Desert of Iraq. In the Akkas field, light oil (specific gravity of 42 API), sweet oil, and gas (no H₂S) were discovered in 1993 in the Akkas and Khabour formations, respectively. The Khabour reservoir occurs in the Late Ordovician K1–K4 members and consists of sandstones with a fracture porosity of up to 7.6% and permeability 0.13 mD. Very recent studies indicated that the base of the K1 Member of the Khabour Formation represents the glacially formed unconformity surface. The oil and gas occur in the glaciofluvial sandstone reservoirs of Hirnantian age. The Akkas reservoir occurs in the upper Qaim Member of the Silurian Akkas Formation and consists of sandstones that have porosity of 6.5% and permeability of 0.2 mD (Al-Hadidy, 2007).

7. Late Ordovician glaciation in Turkey

Evidence for the Late Ordovician glaciation successions is provided by deeply incised glacial valleys, filled by the polished and striated granite boulders, striated glacial pavements, and dropstones in the glaciomarine sediments. The syn-glacial and post-glacial deposits are fully represented and they were defined as the Halevikdere and Yurteri Formations (Ghienne et al., 2001; Monod et al., 2003; Ghienne et al., 2010; Senalp et al., 2018). The Halevikdere Formation represents a fining-upward depositional model and shows an ice-marginal signature. The lower part of the glacial succession consists of channelized sandstones deposited in an ice proximal setting. These sediments are conformably overlain by the interbedded sandstone, siltstone, and shale with some dropstones representing a glaciomarine facies (Monod et al., 2003; Ghienne et al., 2010).
The distinctly different Yurteri Formation was first recognized and defined by Senalp et al. (2018) between the Bedinan (Gürmeşe) and Yurteri villages located between the towns of Kızıltepe and Derik west of Mardin (Figure 20). The Yurteri Formation (37°28.651′N, 40°48.399′E) is a 530-m-thick, steep-sided U-shaped glacial valley incised into the shallow marine sediments of the Bedinan Formation. This thick-bedded, coarse- to fine-grained sandstone, including a few granite boulders, forms three well-defined fining-upward successions indicating three cycles of glacial advance-retreats. In the NW direction, the glacial valleys gradually widen and form glaciofluvial broad deltas. These glaciofluvial sandstones produce significant amounts of oil and gas between the towns of Diyarbakır and Batman. The dark gray shales, including striate pebbles and slumped sandstones of glaciomarine deposits, were also reported on top of the glaciofluvial sandstones (Senalp et al., 2018). The regional depositional model of the glaciogenic Yurteri Formation is based on the sedimentologic studies of the glacial valleys at the surface and their correlation between the logs in the subsurface. Recent sedimentologic studies at outcrops and in exploration wells clearly indicated that the Late Ordovician ice sheet has extended into the Mardin region, which forms the northernmost part of the Arabian Platform. This study also highlighted the hydrocarbon potential of SE Turkey, SE Turkey, Egypt, Jordan, Iraq, Syria, and Iran together formed the integral part of this supercontinent and were deposited by a continental ice sheet (Senalp et al., 2018).

7.1. Halevikdere Formation

In Turkey, the presence of Late Ordovician glacial deposits was clearly demonstrated by Ghienne et al. (2001, 2010) and Monod et al. (2003). They carried out intensive field work on the Lower Paleozoic sections in many different parts of the Central and Eastern Taurus, and in the Border Folds region (Derik, Mardin area). The following information was taken from their publications. These studies have provided very clear evidence of ice-related deposits and meaningful sound sedimentologic interpretations on the Late Ashgillian sediments, between the Şorta Tepe and Pusçutepe Shales. Monod et al. (2003) also reinterpreted the Ordovician-Silurian relationships. Previously, the conglomerates at the base of the Silurian succession (Pusçutepe Shales; Dean et al., 1981) in Turkey were reinterpreted as glacial diamicrites. These coarse-grained sediments were dated as Late Ashgillian, reflecting the proximity of an ice sheet. In order to separate the genetically different ice-rafted deposits from nonglacial marine Ordovician and Silurian successions, Ghienne et al. (2001) introduced the new name Halevikdere Formation. The stratotype of this new formation is defined along the Halevikdere stream in the eastern Taurus Mountains, about 2.5 km E-SE of Değirmentaş village of Sarız town (on the Kayseri-Kahramanmaraş highway), where the glacial record is best represented.

The new Halevikdere Formation rests upon the 100-m-thick, periglacial, shallow marine Şorta Tepe Formation (correlates with the Qasim Formation of Saudi Arabia and Bedinan Formation of SE Turkey), which consists of finely laminated siltstones and sandstones that grade upwards into red or green silty shales. At the type section, the contact between the Şorta Tepe and Halevikdere Formation is transitional. In the uppermost 5 m of the Şorta Tepe Formation, thin manganese-rich horizons are

Figure 20. Schematic map, part of southeastern Turkey, showing the location of the towns mentioned in this study.
interstratified with green silty shales and are followed by thin (less than 5 cm) levels of sandy diamictite, containing isolated quartz gravels.

7.2. Eastern Taurus region
Monod et al. (2003) measured eight stratigraphic and sedimentologic sections between the Sarız and Saimbeyli areas, near Kayseri in the Eastern Taurus Mountains. These eight sections show only minor lateral facies changes. The ice-related deposits are subdivided into lower, middle, and upper sedimentary units.

7.2.1. Lower unit
This glaciogenic unit has an erosional contact with the underlying muddy sandstones of the Şort Tepe Formation and consists of a chaotic succession of massive-bedded, fine- to coarse-grained, poorly sorted sandstones, which were deposited in laterally and vertically stacked channels of various sizes, indicated by the erosional lower surfaces. The bases of the larger channels within the upper part of this unit are overlain by well-sorted, quartz-gravel conglomerate lenses. They are 0.5 m to 10 m thick, 3 m to 50 m wide, and oriented in E-W directions (Monod et al., 2003). The presence of polished and striated pebbles (mainly vein quartz, granite, and metamorphic rocks) indicates their derivation from nearby glacially formed deposits. The upper part of this unit is composed of better-sorted sandstones deposited in wider but shallow channels, suggesting the effects of winnowing by waves and reflecting more ice-distal conditions (maybe a glaciomarine setting).

7.2.2. Middle unit
This unit lies above the grooved and striated surface oriented in the N31°E direction. This striated glacial pavement is directly overlain by a muddy sandstone facies about 10 cm thick. The upper part of this unit consists of dark-colored and massive- to thick-bedded sandstones, which pass upward into the better stratified, laterally discontinuous, and 1- to 3-m-thick coarsening- and thickening-upward parasequences. Each parasequence has poorly laminated sandy siltstones in the lower parts grading upward into the interbedded sandstone (1–5 cm thick) and mica-rich siltstone layers ranging between 1 mm and 2 cm in thickness. The sandstones are horizontally bedded and wave-rippled and also show hummocky cross-stratification. These sedimentary structures indicate deposition in a storm-dominated lower shoreface part of a beach environment. In some places, polished and striated exotic dropstones are very common and show deformed laminae at their base, indicating their origin from a floating ice mass (iceberg). Monod et al. (2003) reported that these polished and striated surfaces indicate the presence of subglacial pavements, upon which abrasions by hard debris (like quartz pebbles) trapped in the basal parts of the glaciers have grooved, cemented, but unlithified sandstones and striated the embedded pebbles. The overlying thin horizons were interpreted as subglacial tillites or diamictites. Coarsening-upward parasequences reflect the progradation of sandy lobes, incised by hummocky cross-stratified sandstones of storm deposits. Of course, the fall-out of ice-rafted dropstones indicates drifting icebergs (Senalp and Al-Laboun, 2000; Senalp and Al Duaiji, 2001b; Senalp, 2006a).

7.2.3. Upper unit
In the type section there is a rapid transition between the middle and upper units of the Halevikdere Formation. The upper unit consists of interbedded wave-rippled, very fine-grained sandstone, black siltstone, and shale succession and also includes rare granule- to cobble-sized dropstones, suggesting distal glaciomarine depositional conditions. The stratigraphic succession of the upper unit is transgressively overlain by black open marine shales. The lower 2 m of these shales yielded index graptolites of the lowermost Llandovery (Kozlu et al., 2002). This regional marine flooding surface at the base of the Silurian correlates with the base of the Qusaiba Member of the Qalibah Formation of Saudi Arabia and organic-rich shale facies at the base of the Dadaş Formation (Senalp et al., 2018). This organic-rich shale facies is called hot shale and is the most prolific source rock for both the oil and gas of the Paleozoic reservoirs (Senalp, 2006a; Senalp et al., 2018). Monod et al. (2003) and Ghienne et al. (2010) reported that the onset of Late Ordovician glaciation appeared in the highest beds of the Şort Tepe Formation. This contact is defined as MFS S10 (444 Ma) by Senalp (2006a) and Senalp et al. (2018).

In conclusion, all the data provided by Monod et al. (2003) and Ghienne et al. (2010) indicate that the type section of the Halevikdere Formation is located on the northern margin of the Gondwana ice sheet. The ice mass was thin and affected by short cycles of climatic changes. The ice mass frequently advanced towards the sea during the cold period and retreated during the warm periods. This setting is totally different than the measured section of the Yurteri Formation. The Yurteri Formation is a more than 330-m-deep tunnel valley and filled fully by coarse-grained sandstone and pebbly sandstone. It was far distant from the sea; therefore, there was no shale deposition (Senalp et al., 2018).

7.3. Southern and southeastern Turkey
Monod et al. (2003) and Ghienne et al. (2010) recognized the same three glaciogenic deposits at numerous places in the Taurus range, between the towns of Anamur (between Alanya and Silifke, to the east of Antalya) and Sarız (between Pınarbaşı and Tufanbeyli, to the south of Kayseri). They measured detailed sedimentologic sections north of Kozan, near Akkaya village, west of Ovacık village, and in Bedinan village. To the west of Ovacık village,
the lower unit rests upon sandstones and shales of the Seydişehir Formation, containing graptolites and trilobites indicating Arenig age (Dean and Monod, 1990). This observation provides a very critical piece of information and supports the magnitude of the glacially formed regional unconformity surface during the Hirnantian. In the west of Ovacık village, this glacially formed unconformity surface cuts very deep into the underlying succession. The Şort Tepe Formation has been completely eroded and removed by this 445 Ma unconformity surface and the glacial deposits of the Halevikdere Formation rest directly on the Seydişehir Formation. The lower part of the Halevikdere Formation consists of muddy sandstones with some pebbles, which are overlain by coarse-grained, cross-bedded, and well-sorted sandstones and finally by fine-grained and wave-rippled sandstones suggesting the reworking of glaciomarine sediments by wave processes. This lower unit is overlain by the middle unit, which contains abundant dropstones. The uppermost unit is a sandstone facies 0.4–2 m thick, marked with an erosion surface. It is overlain by the hot shale facies representing the regional Silurian transgression.

7.4. Border folds of SE Turkey (Mardin area)

The presence of ice-related sediments was first reported by Biju-Duval et al. (1974) in Paleozoic inliers, about 15 km west of Mardin (Figure 20). The glacial deposits were observed in the upper part of the type section of the Bedinan Formation. They reported that discontinuous patches of coarse-grained sandstones, with extensional step fractures of glacial origin and probable subglacial bedforms, directly overlie the shales and storm-dominated sandstones of the Bedinan Formation. As in other places, there are coarsening- and thickening-upward parasequences above the conglomeratic facies. The fine- to coarse-grained silty sandstones in the lower parts of the parasequence contain abundant faceted and striated pebbles of quartz, rhyolite, and granite. They are overlain by fining-upward parasequences ranging from silty sandstones to silty shales with some slumped sandstone blocks. Monod et al. (2003) reported that the glacial deposits in the Halevikdere Formation in the Mardin area (SE Turkey) were different from the same succession exposed in the Eastern Taurus Mountains.

Tetiker et al. (2015) and Senalp et al. (2018) studied the same section, located to the east of Bedinan (new name is Gürmeşe) village. This section is slightly different than the Halevikdere type section. Monod et al. (2003) did not observe the impressive glacial valleys in the same region. The glacial valley is narrow and deep and stratigraphically below the Halevikdere facies. Senalp et al. (2018) measured the complete section of the glacial deposits exposed between the upper part of the Bedinan Formation and the Cretaceous unconformity below the carbonates of the Mardin Group. They defined the entire section as the Yurteri Formation, which consists of the most impressive sandstone-filled deep glacial valley and glaciomarine sediments of the deglaciation period. The lithofacies, geometry, and trend of the sand-filled tunnel valley of the Yurteri Formation is almost identical to the Late Ordovician glacial valleys of the oil- and gas-producing Sarah Formation of Saudi Arabia (Senalp et al., 2018).

7.5. Yurteri Formation of southeastern Turkey

The Yurteri Formation was first recognized and defined by Senalp et al. (2018) at the outcrop, to describe the glacially formed sedimentary successions exposed between Bedinan (Gürmeşe), Yurteri, and Konur villages (Figure 20). In previous studies, based on lithofacies characteristics and the presence of polished and striated pebbles in the sediments of this unit, they were interpreted as glaciofluvial and glaciomarine in origin. However, the thick sandstone and conglomeratic sandstone facies filling, and the glacial valley (tunnel valley), have not been recognized. In many respects the Yurteri Formation is almost identical to the glacially formed hydrocarbon-producing Sarah Formation of Saudi Arabia (Senalp and Al-Laboun, 2000; Senalp, 2006a; Senalp et al., 2018). In this respect, the Yurteri Formation has great hydrocarbon potential and deserves to be recognized as a separate formation to evaluate its geometry, reservoir quality, and relationship with the directly overlying hot shale facies at the base of the Dadaş Formation deposited during the Early Silurian transgression. The Yurteri Formation was recognized in many expiration wells, drilled in the Diyarbakır and Batman regions and producing significant amounts of oil and gas in the Bismil region. Previously, this distinctly different thick sandstone with sharp basal contact was included between the shale-dominated upper part of the Bedinan Formation and the hot shale facies of the Dadaş Formation and was considered as part of the Bedinan Formation.

Sedimentologic studies indicated that the base of the Yurteri Formation is deeply incised into the Bedinan Formation and represents the narrow U-shaped glacially formed unconformity surface formed at the beginning of the Hirnantian time (445 Ma). At the outcrop, the previously described three units (glacially formed tunnel valley deposits, glaciofluvial braided delta deposits, and glaciomarine deposits) of the Yurteri Formation are overlain by a marked regional unconformity surface at the base of the Mardin Group. However, in the subsurface, depending on their location in the depositional system, the glaciofluvial braided delta and glaciomarine deposits are overlain by the hot shale facies of the Dadaş Formation.

The type sections of the glacial tunnel valley-fill and the glaciomarine or glaciolacustrine deposits of the
Yurteri Formation were measured between the Bedinan (Gürmeşe) and Yurteri villages in the Derik area of the Mardin region (Figure 21). The type section of the glacial paleovalley facies was measured at the same location as the continuation of the Bedinan Formation. The top of the formation is overlain directly by the Cretaceous unconformity surface at the base of the Mardin Group; therefore, the glaciomarine or glaciolacustrine facies of the Yurteri Formation is not present in this section. This upper unit was measured in the east of the paleovalley and west of Yurteri village.

7.5.1. Lithology, thickness, and depositional environment
The Yurteri Formation consists of three genetically related glacial facies, which are defined as three units in this study and are described in detail in the following sections. These are: 1) the glacially formed tunnel valley deposits, 2) the glaciofluvial braided delta deposits, and 3) glaciomarine deposits (Figure 21).

7.5.1.1. Unit 1
This unit represents the most significant glacial deposits and carries all the physical and sedimentologic characteristics of the Late Ordovician glaciation. They were deposited in a tunnel valley, which is more than 330 m thick, U-shaped, but a narrow valley, trending in the N45°E direction. This U-shaped glacial paleovalley is deeply incised into the interbedded shale and sandstone facies of the shallow marine Bedinan. This valley-fill sandstone unit is eroded at its top by the Cretaceous unconformity at the base of the Mardin Group, suggesting that its true thickness is more than the measured value. This NE trend is consistent with the trends of other glacial valleys exposed in Jordan and NW Saudi Arabia.

In the measured section, this tunnel valley is filled with massive- to very thick-bedded, coarse-grained, and pebbly deposits, and includes a few granite boulders. The facies analysis of these coarse-grained deposits indicates the presence of three fining- and thinning-upward sequences, indicating two distinct depositional processes. The base of each fining- and thickening-upward sequence represents an erosional surface and consists of massive- to very thick-bedded, very coarse-grained, poorly sorted sandstone, containing randomly distributed, polished, faceted, and striated quartz and chert pebbles and a few granite blocks (Figure 22).

The lower part of the glacial valley was deposited directly by the ice mass during its advance and indicates very minor reworking by the melt water of the ice mass. The upper half of the fining- and thinning-upward sequence is markedly different and consists of horizontal planar-bedded, gently cross-bedded, coarse- to fine-grained (but mainly medium-grained), moderate- to well-sorted sandstone, with excellent reservoir quality. This sandstone facies was deposited by the fluvial system when the ice mass melted during the interglacial period (glacial retreat). The glacial valley forms a glaciofluvial braided delta (Unit 2), which is located about 50 km to the north of Yurteri village (Figure 23). The presence of deep glacial paleovalleys and other ice-related deposits (glaciofluvial sandstones and the overlying genetically related organic-rich hot shale facies in the northernmost part of the Arabian Platform (Mardin region)) clearly indicates the further extension and much wider distribution of the Late Ordovician ice sheet than was previously believed and strongly increases the hydrocarbon potential (Senalp et al., 2018).

Similar glacial valleys are also encountered in the subsurface and they occur in SE Turkey close to the Syrian border. They also extend in a NE-SW direction and are incised into the Bedinan Formation, as observed in the Yurteri area (Mardin region). The well-established valleys were recorded in the Akçakale-1 (270 m), Ceylanpınar-1 (290 m), Ambarcık-1 (110 m), Siverek-2 (96 m), Gercüş-1 (82 m), Kaldırım (53 m), and Girmeli-1 (80 m) wells. It is established that the glacial valley observed in the Ceylanpınar-1 well connects to the measured outcrop section in the Yurteri area.

Within the literature, there is a continuous debate regarding the origin and formation of these late Ashgillian paleovalleys. Their maximum depth observed at outcrops is 650 m, but it can be deeper depending on the amount of glacioeustatic fall in sea level. In large parts of the world a maximum fall of c. 100 m can be reasonably expected. A mechanism for the formation of deeper paleovalleys or channels is thus required to explain incisions of c. 550 m into the underlying stratigraphy (i.e. 100 m of incision following the eustatic fall, plus 550 m of extra incision, giving a total of 650 m). The following model is proposed for the incision of the glacial valleys of the Yurteri Formation, but it can also be applied for the formation of the Zarqa and Sarah formations. This model signifies the importance of subglacial erosion below sea level. In this proposed model, subglacial scouring and erosion by high-velocity meltwater streams is interpreted to have been responsible for cutting the observed valleys and channels on the Arabian Plate. Subglacial processes are a major mechanism to produce erosion below sea level and grounded ice sheets below sea level are also present today in Antarctica. High-velocity subglacial meltwater valleys (tunnel valleys) below sea level are present today in Antarctica (Bentley, 1964). High-velocity subglacial meltwater valleys below sea level act as fast-flowing ‘gutters’, carrying large volumes of water and sediment that debouch at the front of ice margin. If they are above sea level, these sediments flow out onto the outwash plain.

The meltwater systems are under high pressure as a result of their great length, large hydraulic head, nature of the underlying sediments (impermeable clay vs. porous
sandstone), and load of the overlying and very thick ice sheet itself. Similar submarine and subglacial processes have been proposed as the mechanism for similar channel systems observed in North Africa (Sutcliffe et al., 2000a, 2000b). In addition, glaciers have a strong erosive capability, and where a significant substrate angle exists to provide velocity, they are known to produce 'over-deepened' glacial valleys (Senalp et al., 2018).

7.5.1.2. Unit 2
The type section of the Yurteri Formation is located about 30–35 km north of the type locality of Unit 1. The sandstones are well exposed on the Derik-Mazıdağı highway near Konur village. The lower surface cuts into the youngest section of the Bedinan Formation, but it is unconformably overlain by the Cretaceous carbonates of the Mardin Group. The measured section is 20 m thick; it consists of 3 vertically and laterally stacked, medium- to fine-grained, gently cross-bedded, well-sorted channel-fill sandstones and covers large areas (Senalp et al., 2018). The thickness, geometry, and lithofacies characteristics are very similar to the Yurteri Formation encountered in the wells drilled in the Diyarbakır, Bismil, and Batman regions. These sandstones were deposited on the braid plain in front of the tunnel valleys by the fluvial system during the melting phase of the ice mass; therefore, they carry less evidence of their glacial origin. The braided systems are likely to have multiple but shallow channels such that the melt water flow diverges many times around bedforms or

Figure 21. (a) Type locality of the Yurteri Formation, located NE of Bedinan (Gürmeşe village, Figure 19). The 330-m-thick U-shaped glacial tunnel valley cuts deeply into the Bedinan Formation. It extends in the N45°E direction. Sharp and erosional surface represents the glacially formed unconformity surface at the base of the Yurteri Formation, incised into the open marine shales of the Bedinan Formation. (b) Contact between west side of the paleovalley and the Bedinan Formation. (c) East side of the erosional base of the Yurteri Formation into the offshore marine shales of the Bedinan Formation. (d) Medium-grained and well-sorted good-quality reservoir sandstone facies, deposited during the partial melting of the ice. These glaciofluvial sandstones are the significant oil and gas reservoirs in large areas between Diyarbakır and Batman (Senalp et al., 2018).
islands and reconnects. Eventually the bar becomes large enough that the channel width is insufficient to remain stable, and the channel widens by cutting laterally against the banks and the bar. As the channel widens, flow depth decreases and the bar begins to emerge above the water surface. They were deposited in a large braided delta formed in front of the deep glacial paleovalley during glacial retreat (Senalp et al., 2018).

7.5.1.3. Unit 3
In the type locality, some parts of Unit 1 are overlain by Unit 3, which was previously defined as the Halevikdere Formation (Monod et al., 2003; Ghienne et al., 2010). The section is exposed on the east side of the tunnel valley deposits. The very coarse- to coarse-grained, pebbly sandstone facies of Unit 1 are overlain by the 75 m thick section of Unit 3, consisting of two genetically related depositional facies. The lower depositional facies rests on top of the glacially formed erosional surface. It is 22 m thick and composed of massively to crudely bedded conglomeratic sandstones. The pebbles mainly comprise quartz pebbles of 1–10 cm with striated faces, rare boulders, and clasts of granites, aplites, and rhyolites. This lower unit was interpreted as glaciomarine outwash deposits. The upper depositional facies is about 60 m thick and represents a perfect fining- and thinning-upwards succession from silty medium-grained sandstone to sandy siltstone (fine diamictite) and dark gray laminated shale. At the base of the section, there are numerous quartz granules and some dropstone pebbles and highly distorted and folded large sandstone blocks ranging from 1 to 4 m in diameter, slumped from the valley walls and completely isolated in the shale. The uppermost part of the section consists mainly of dark gray massive- to laminated-shale with small pebble-sized diamictites. The sediments of Unit 3 represent a typical glaciomarine or glaciolacustrine lithofacies, which were deposited during the sea-level rise in the deglaciation period. The genetic relations among the deep, narrow glacial valleys (tunnel valleys), glaciofluvial sandstones deposited on the braid delta, and glaciomarine sediments are represented in Senalp et al. (2018). The predicted depositional model for the formation of the Yurteri Formation is presented in Figure 24 (Senalp et al., 2018).

7.5.2. Hydrocarbon potential of the Yurteri Formation
In light of current stratigraphic and sedimentologic studies, it is understood that the Paleozoic successions in SE Turkey are hydrocarbon-prospective. It is already proven that the sandstones deposited in the glacially formed paleovalleys and their genetically related glaciofluvial sandstones of the newly defined Yurteri Formation constitute one of the most important successions for hydrocarbon explorations (Senalp et al., 2018). This formation correlates with the Sarah Formation of Saudi Arabia. These high-quality reservoir sandstones (19–38 m thick) are directly overlain by the organic-rich hot shale facies deposited at the base of the Dadaş Formation. There are many fields in Diyarbakır and Batman regions producing significant amounts of both oil and gas from the Yurteri Formation. It is certain that understanding the geometry and the trend of the glacial paleovalleys and the patchy distribution of the hot shale facies will significantly improve and facilitate the exploration and producing potentials of these glaciogenic sandstone reservoirs. Understanding the migration pathway of the oil and gas and the trapping mechanism is very crucial for successful exploration. In the early phase of hydrocarbon exploration, hand-drawn isopach maps were prepared for the glaciogenic sandstone reservoirs and the overlying hot shale source rocks to understand their regional distribution and the potential areas where they overlie each other. The genetic relationship between

Figure 22. (a) Polished and striated quartz and chert pebbles in the glacial paleovalley of the Yurteri Formation. (b) Large granite boulders are found in the glacial paleovalley sandstones of the Yurteri Formation. Close-up view of the granite boulder, transported from the Neoproterozoic Telbesmi Formation, part of the Arabian Shield (Senalp et al., 2018).
Figure 23. (a) Sequence stratigraphy and sedimentology of the Bedinan Formation, glacially formed, 330-m-thick sandstone succession of the Yurteri Paleovalley and the glaciomarine facies, in the measured type section between the towns of Bedinan (Gürmeşe) and Yurteri. (b) Measured section of the glaciofluvial braid delta deposits of the Yurteri Formation, located about 30 km north of Gürmeşe village. C-U: Coarsening-upward sequence, F-U: fining-upward sequence (Senalp et al., 2018).
<table>
<thead>
<tr>
<th>AGE</th>
<th>UNIT</th>
<th>THICKNESS (m)</th>
<th>LITHOLOGY</th>
<th>EXPLANATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARDIN GROUP</td>
<td>LATE ORDOVICIAN HIRANIAN</td>
<td></td>
<td>Limestone, dolomitic limestone</td>
<td>CRETACEOUS EROSIONAL SURFACE</td>
</tr>
<tr>
<td></td>
<td>YURTERI FORMATION</td>
<td>18</td>
<td>SANDSTONE: fine-medium bedded, fine-very fine grained and crumbling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>SANDSTONE: yellowish gray, light gray, low carbonated well cemented</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>SANDSTONE: well bedded, (fine-medium thickness) very fine grained</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>SANDSTONE: (channel fill) light yellow, plenty of mica, shale conglomerates, underdeveloped cross layer, medium fine-very fine grained</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>SANDSTONE: horizontal stratification (2-10 cm), very fine grained, crumbling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>SANDSTONE: wedge shaped channel fill, 80-90 m lateral width, yellowish, very sorted, crumbling</td>
<td>EROSIONAL SURFACE WITH GLACIAL ORIGIN (445 Ma)</td>
</tr>
<tr>
<td>MIDDLE ORDOVICIAN</td>
<td>BEDINAN FM.</td>
<td></td>
<td>Sandstone and shale intercalated, upwards grain size and increased thickness of the layer</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 23.** (Continued).
8. Discussion and conclusions

It has been proven that the regionally deposited glaciofluvial sandstones of the Late Ordovician glacial successions form important oil and gas reservoirs in Saudi Arabia, North Africa (Libya, Algeria, and Egypt), the Middle East (Jordan, Iraq), and SE Turkey, but their heterogeneity and internal lithofacies complexities have not been fully understood yet. There is no single depositional model to explain their genetically related depositional lithofacies, lateral facies changes, and vertical and lateral stacking patterns. The sedimentary structures of glacially related depositional systems are very complicated, because the ice sheets carved the existing topography through deep glacial valleys into the shelf, transporting and depositing large amounts of sediment into the deeper parts of the basin and releasing strong water flow during the deglaciation period.

Surface and subsurface studies demonstrated that the organization of the glacial sedimentary record is controlled by the geometry of the basin, duration of the glacial period (Hirnantian, 445–444 Ma), and location of the deep U-shaped glacial tunnel valleys (Senalp et al., 2018). The glacial erosion by the fast-flowing ice streams
was intensive during glacial maxima. However, glacial sediment transportation and deposition was most effective by the melt water released during glacial recession (Senalp, 2006a). The tunnel valleys, such as the Sarah and Sanamah formations of Saudi Arabia, were filled up in two well-defined stages. The first or initial stage is characterized by moraine or tillite facies deposited in the proximal parts of the valleys. The second stage is represented by the deposition of laterally and vertically stacked, fining-upward channel-fill sandstones of a glaciofluvial environment. These sandstones have been proven to be great reservoirs. They are overlain by the glaciomarine sandstones and shales including dropstones near the ice margin. In Saudi Arabia, the geometry of the basin, the trends and three-dimensional geometries of these glacial paleovalleys, and the types of lithofacies in the valleys have also been influenced by local tectonic uplift initiated in the Neoproterozoic igneous basement, known as the Arabian Shield (Senalp, 2006a; Senalp et al., 2018).

During the deglaciation period, immense amounts of fresh water returned to the sea and caused sea-level rise. The rising sea level during very Early Silurian time (444 Ma) was very fast and marine waters flooded over the glaciogenic deposits. Initially, the marine
waters flooded into isolated depressions (mainly the unfilled paleovalleys and the depressions formed under the thick and heavy ice sheet) on the glacially formed topographic surfaces. The organic-rich hot shale facies were deposited in these depressions under anaerobic conditions; therefore, all the organic matter was preserved and generated hydrocarbons. Eventually, the entire glaciogenic succession was covered by the coarsening- and thickening-upward progradational deltaic sequences during Middle-Late Silurian time (Senalp, 2006a). The hydrocarbons generated at the base of the Silurian transgression migrated downward into the Late Ordovician glaciofluvial sandstone reservoirs (Senalp, 2006b; Senalp et al., 2018). Large amounts of cores and well logs from the exploration and production wells in the above mentioned countries have provided immense quantities of high-quality subsurface datasets on the geometry of the tunnel valleys, lateral and vertical facies changes, and reservoir qualities of the mainly glaciofluvial sandstones in these areas. Understanding the close genetic relations between the glaciofluvial and glaciomarine sandstone reservoirs and the directly overlying organic-rich (up to 14% TOC) hot shale facies deposited at the base of the Silurian transgression and the downward migration of the oil and gas was a major breakthrough in successful hydrocarbon explorations (Senalp, 2006a).

Finally, the authors of this publication would like to stress the importance of generating hand-drawn isopach maps of the glaciogenic reservoir sandstones and the overlying organic-rich source rock facies deposited at the base of the regional Silurian transgression to predict the best potential areas where the source rock and reservoir rock are thick and overlie each other.

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References


Sutcliffe OE, Dowdeswell JA, Whittington RJ, Theron JN, Craig J (2000a). Calibrating the Late Ordovician glaciation and mass extinction by the eccentricity cycles of Earth’s orbit. Geology 28: 967-970.


