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Sequence stratigraphy and hydrocarbon potential of the Paleozoic successions on the Arabian Platform and southeast Türkiye

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Abstract: In 1989, the first prolific hydrocarbon reservoirs were discovered by Saudi Aramco in the highly porous and permeable friable continental sandstones (Unayzah reservoirs) and shallow marine carbonates (Khuff reservoirs) of the Paleozoic successions in the south of Riyadh, central Arabia. Since 1989, Saudi Aramco has discovered new oil and gas fields in various stratigraphically and genetically different units of the Permo-Carboniferous and Permian successions. These successions were strongly affected by tectonic movements (Caledonian and Hercynian orogenesis) and Early and Late Paleozoic Gondwana glaciations. Therefore, the thickness of some sections was fully eroded or significantly reduced. The sequence stratigraphic interpretation of the Paleozoic successions allowed us to understand the depositional environments and regional distribution of the source, reservoir, and cap rock facies in improved palynologic studies. Hydrocarbons were discovered with the Late Permian continental sandstones of the Unayzah Formation, the glaciogenic sandstones of the Late Ordovician Sarah Formation in Saudi Arabia, Late Silurian Hazro reservoir in southeast Türkiye, and the cold desert eolian sandstones of the Permo-Carboniferous Haradh Formation. Potential source rock facies of the Qusaiba Shale Member in Saudi Arabia and the hot shale facies of the Dadaş Formation in southeast Türkiye were deposited at the base of the Early Silurian regional transgression (444 Ma) during the melting phase of the huge Gondwana ice mass. The hydrocarbons migrated downward into the glaciogenic reservoir sandstones due to the hydrostatic pressure provided a useful depositional environment model. The hydrocarbon discoveries have provided core and well log data for regional correlations. Every aspect of the sequence stratigraphy was investigated and various types of unconformities, sequence boundaries, glaciation periods, and maximum flooding surfaces were recognized and correlated between Middle East countries. The relationship between the sea-level fluctuations and sediment supply into the basin was established by the regressive (progradational) and transgressive parasequences and parasequence sets. This genetic sequence stratigraphic approach has significantly increased the hydrocarbon explorations and production in the entire Arabian Platform.

Key words: Sequence boundary, maximum flooding surfaces, source rocks, reservoir rocks, hydrocarbon migration, system tract

1. Introduction

The Arabian Plate includes the Arabian Peninsula together with southeast Türkiye, Syria, Jordan, Iraq, and the Zagros Mountains of southwest Iran. It is bordered by the African Plate in the west, Sudan and Indian Plates in the south, Eurasian Plate in the west and northwest, and Anatolian Plate in the north. The geological map of the Arabian Plate illustrates that the present-day Arabian Plate is bounded by a variety of complex tectonic regimes. The Dead Sea transform strike-slip fault zone, which borders the Arabian Plate in the west, has undergone right-lateral displacement of about 107 km since the Middle Miocene. This displacement corresponds to a slip rate of about 6–10 mm/year (Stern and Johnson, 2010). The present study followed the results of more than 30-year-long sequence stratigraphic and sedimentologic field studies of the Paleozoic successions, mainly in Saudi Arabia and southeast Türkiye. The main purpose of this study was to stress the importance of the application of sequence stratigraphic parameters in hydrocarbon exploration.

The thick Paleozoic successions in Saudi Arabia extend between the Early Cambrian (541 Ma) fluvial sediments of the Siq Formation and the Late Permian (260.4 Ma) Khuff carbonates and contain a significant amount of oil and sweet gas reserves. The first Paleozoic well was discovered in 1988 in Hawtah-1 well, South of Riyadh. Since then, many new fields have been discovered in Late Ordovician and Permo-Carboniferous glacio-fluvial sandstones, Middle-Late Permian red-colored fluvial and eolian sandstones, and Late Permian incised-valley fill sandstones. Since the first discovery well until 2019 (retirement), the stratigraphy, sedimentology, and reservoir geology of

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these Paleozoic successions have been studied by Şenalp and the results have been provided regularly as informal company reports and in official publications (Şenalp, 1995; Şenalp and Al'Duaiji, 2001b; Şenalp, 2006a, 2006b; Senalp and Tetiker, 2022; Şenalp and Tetiker, 2020, 2021, 2023, 2024). These successions are more than 5500 m thick and are mainly composed of siliciclastic rocks, carbonate rocks, and evaporites. These sedimentary successions become systematically younger from the Arabian Shield in the west toward the Arabian Gulf in the east. In general, the wedge-shaped continental and shallow marine sand-dominated sedimentary sections surround the Arabian Shield, but eastward (basin ward), the red-colored continental siliciclastic sections intertongue with the shallow marine sediments, and finally, open marine shales become dominant and thicker in the deep basin. Every day, these rocks are becoming a primary target for hydrocarbon exploration in almost in every part of Saudi Arabia and neighboring Middle East countries (Oman, Jordan, Iraq, and southeast Türkiye). The thick Paleozoic successions of southeast Türkiye, located on the northern margin of the Arabian Plate, extend from the Early Cambrian (541 Ma) sandstones and algal dolomitic limestones of the Sadan Formation to the Late Permian (260.4 Ma) shallow marine carbonates of the Gomanibrik Formation. The silisiclastic succession consists of continental (glacial, desert, and fluvial), marine (prograding delta and shoreface) sandstones and transgressive open marine and prodelta shales. The productive Khuff carbonate rocks (algal limestones and dolomites) and genetically related evaporites were deposited in a tidally influenced shallow marine environment and coastal lagoons. Based on the measured sedimentologic sections at outcrops, intensive core studies, and well log analysis, various unconformities, correlative conformities, marine flooding surfaces (mfs) and maximum flooding surfaces (MFS) were recorded. Eventually, new formations and genetically related members were recognized and the entire sequence stratigraphy of the Paleozoic successions was established.

The important information gathered from the outcrops and subsurface of Saudi Arabia and southeast Türkiye indicated that deep erosional unconformity surfaces were formed during the Late Ordovician (defined as the Yurteri Formation) and Permo-Carboniferous Gondwana glaciation and during the tectonically driven Caledonian and Hercynian orogenesis. Regional MFS resulted during the deglaciation periods and led to the deposition of the organic rich hot shale facies [17% total organic carbon (TOC)] directly on the glaciogenic reservoir sandstones. However, mfs separating the parasequences were formed during the eustatic sea-level fluctuations (Şenalp et al., 2018; Senalp and Tetiker, 2022; Şenalp and Tetiker, 2020, 2021, 2023, 2024).

2. Materials and methods

This study was carried out in the Wajid outcrop belt, Al Qasim and Haîl, and Tayma-Tabuk regions of Saudi Arabia and Zabuk valley (Derik, Mardin) and the Hazro-Dadaş regions (Diyarbakır) of southeast Türkiye (Şenalp, 2006a, 2006b; Şenalp et al., 2018; Şenalp and Tetiker, 2020; Şenalp et al., 2021; Senalp and Tetiker, 2022; Şenalp and Tetiker, 2023, 2024). Sequence stratigraphic studies of the Paleozoic successions in these regions have been based on a large number of outcrops measured in stratigraphic and sedimentologic sections and regional correlations. Various unconformity surfaces were generated by the tectonic movements during Caledonian and Hercynian Orogeny and the Late Ordovician and Permo-Carboniferous continental Gondwana glaciation when the sea level dropped about 130 m in many places. MFS following the deglaciation period, nondepositional surfaces (diastems), lateral and vertical facies, changes in the stacking patterns of genetically related sedimentary facies (coarsening- and thickening-upward regressive sequence or fining upward transgressive sequence), and primary sedimentary structures were recorded, and their depositional conditions were interpreted. These large amounts of valuable data were integrated and used to construct parasequences, parasequence sets, systems tracts, and finally, to interpret their depositional systems and hydrocarbon potential. The subsurface studies were carried out mainly on the cores, cutting samples, palynologic data, and well logs of the exploration and producing wells. These data were adjusted to the well logs and integrated with measured outcrop sections and palynologic data. On the Arabian Plate, a number of regional stratigraphic cross-sections were built in between the exploration wells of several regions (Şenalp and Al-Laboun, 2000; Şenalp and Al-Duaiji, 2001a, 2001b; Şenalp, 2006a, 2006b). These stratigraphic cross-sections emphasized the importance of the tectonically driven Caledonian and Hercynian unconformities and the glacially formed unconformities at the base of the Late Ordovician and Permo-Carboniferous continental Gondwana glaciation.

Thirty-two representative and extensively cored exploration and producing wells were chosen from eastern central Saudi Arabian areas (Abu Jifan, Dilam, Ghinah, Haradh, Hazmiyah, Hawtah, Jawb, Layla, Niban, Nuayyim, Qirdi, Shamah, Tinat, and Umm Jurf) to study the sequence stratigraphy of the entire Paleozoic succession. This comprehensive study (locations of various erosional unconformity and flooding surfaces, stratigraphic architecture, lateral facies variations, depositional origin, and hydrocarbon potential) of all the siliciclastic and carbonates were published by Şenalp and Al-Duaiji (2001a, 2001b), Şenalp (2006a, 2006b), and Şenalp et al. (2018). The hand-drawn gross interval isopach maps of each formation were greatly aided by the regional cross-sections (Şenalp, 2006a, 2006b; Şenalp et al., 2018).

3. Late Precambrian (Neoproterozoic System, 720–541 Ma)

3.1. Arabian-Nubian shield in Saudi Arabia

The Precambrian Basement Complex is known as the Arabian-Nubian Shield in Saudi Arabia and Bitlis Massive (or Telbesmi Formation) in southeast Türkiye (Figure 1). The Arabian Shield is a series of basement terranes and consist predominantly of the Late Precambrian (720–541 Ma) metamorphosed volcanic and volcano-sedimentary rocks intruded by igneous rocks, principally diorite and granite. Terranes are large three-dimensional chunks of earth crust bounded by major strike-slip faults. The orientation of sutures separating the mosaic of terranes and basement blocks is believed to be of fundamental importance to the subsequent development of the sedimentary cover (Şenalp and Al-Laboun, 2000; Şenalp and Al-Duaiji, 2001b; Şenalp, 2006a).

3.2. Telbesmi Formation in southeast Türkiye

The Neoproterozoic basement of the Telbesmi Formation was defined by Moses (1936). It is located 3–5 km south of the town of Derik (Mardin) and is the oldest formation in Türkiye. It is also exposed at the bottom of the Kaplan Deresi (Tiger River) near Penbeğli village (Tut, Adıyaman). This Late Neoproterozoic igneous basement complex is overlain by the continental fluvial sandstones of the Early Cambrian (540 Ma) Sadan Formation (correlated with the Siq Formation from Saudi Arabia). The Telbesmi Formation consists of agglomerate and various volcanic rocks, mainly black syphilitic basalt, red augite andesite, and white rhyolite. The high hill, located to the east of Telbesmi village, has some glacially formed, polished, and striated surfaces. These surfaces and the presence of carbonates (most likely to be cap carbonate), associated with the volcanic rocks, are thought to be related to the Marinoan glaciation (630 Ma), which covered the entire Earth (Snowball Earth). In this model, the limestones were deposited during the melting phase of this glaciation. In this case, the age of the Telbesmi Formation is older than 630 Ma.

Figure 1. Outcrop of the Late Neoproterozoic igneous basement complex in the Midyan region, west of Saudi Arabia.[1]

[1]Şenalp M (2009). Aramco field trip to Midyan region.

4. Sequence stratigraphy of the Paleozoic successions on the Arabian Platform

The consequences of multiple variations in the sea level and tectonic movements were documented in the Paleozoic sedimentary successions covering the whole Arabian Plate. Over the Arabian Plate, eustatic fluctuations in the sea level caused transgressions, regressions, and the creation of several local and regional maximum flooding surfaces as well as unconformity surfaces, which can be recognized by their missing sections, erosional sequence borders, and nondeposition. Caledonian and Hercynian tectonic orogenies were also responsible for eustatic sea-level changes. Furthermore, specific evidence of Early Paleozoic (Late Ordovician) and Late Paleozoic (Carboniferous–Early Permian) continental Gondwana glacial eustasy was observed in the sedimentary sections. This evidence includes the presence of moraines, polished and striated surfaces, dropstones, and deeply incised glacial paleovalleys and associated braid deltas formed on the sandur plain.

The Late Neoproterozoic (635–541 Ma) and Paleozoic (541–260 Ma) sequence stratigraphic history of the Arabian Platform, including southeast Türkiye and Middle East countries, are discussed in this study. The entire Paleozoic succession was subdivided into genetically related depositional facies, parasequences, parasequence sets, and system tracts to interpret their depositional environments, sequence stratigraphy and eventually their hydrocarbon potential. For this purpose, using sedimentary facies analysis, the sedimentary structure lateral facies variations were studied to define the type of parasequences through MFS on the subsurface and surface of southeastern Türkiye and Saudi Arabia. In the second stage, the vertical stacking patterns of these parasequences were used to establish the transgressive, regressive, and aggradational parasequence sets to predict the sea-level changes and rate of sediment supply. The concept of systems tract is based on the recognition of various unconformity surfaces of glacial and tectonic origin and MFS, formed at the base of the regional marine transgression during the deglaciation period. These data in connection with eustatic global sea-level changes, were used to establish and define the sequence stratigraphy of the Paleozoic successions in Saudi Arabia and were correlated with southeastern Türkiye and other neighboring countries (Şenalp and Al-Duaiji, 1995; Şenalp and Al-Laboun, 2000; Şenalp and Al-Duaiji, 2001b; Şenalp 2006a, 2006b; Şenalp et al., 2018; Şenalp and Tetiker, 2020, 2021; Şenalp et al., 2021; Senalp and Tetiker, 2022). In the following sections, the sequence stratigraphy of the Paleozoic succession extending from the Early Cambrian (541 Ma) to Early Permian (MFS P20, 260 Ma) will be discussed.

5. Cambrian System (541–485 Ma)

In the Sultanate of Oman, the Pre-Cambrian (Neoproterozoic) System (720–541 Ma) overlies the Crystalline basement (850–800 Ma). During the Neoproterozoic, two well-defined glaciations were recorded in Oman. These are defined as the Sturtian (730–700 Ma) and Marinoan (665–635 Ma) glaciations. The Late Neoproterozoic (Ediacaran, 635 Ma) to Early Cambrian (541Ma) successions are defined as the Nafun Group in Oman, the Jubayla Group in northwest Saudi Arabia, and the Telbesmi Formation in southeast Türkiye (Şenalp, 2006a; Şenalp et al., 2018).

Thick and continuous continental and marine siliciclastic successions and shallow-marine carbonates of the Cambrian System are well preserved and best exposed at the outcrops of southern Jordan (400 m thick), northern Saudi Arabia and southeast Türkiye (more than 2000 m thick). In Saudi Arabia, the continuous Cambrian successions are preserved between Khaybar in the south and Tayma in the north (Figure 2). In southeast Türkiye, the Cambrian successions are preserved along the Zabuk Valley extending in the area between the towns of Derik and Kızıltepe (Mardin) (Figure 3). The sand concentration of the Cambrian strata diminishes with thickness northward, indicating a growing separation from the source region. Based on the well-defined sequence boundaries (unconformities and correlative conformities), mfs and MFS, and age dating, the Cambrian System was subdivided into the four subsystems (Şenalp et al., 2018, 2021). These are Early Early Cambrian (541–529 Ma), Late Early Cambrian (529–514 Ma), Middle Cambrian (514–497 Ma), and Late Early Cambrian (497–485 Ma).

5.1. Early Early Cambrian (541–529 Ma)

5.1.1. Saudi Arabia

The Early Early Cambrian Siq Formation (Powers et al., 1966) is observed in the Tabuk-Tayma outcrop belt of northwest Saudi Arabia. The type section is located in a steep cliff next to a gas station in the town of Shakri (Figure 4). This succession nonconformably overlies the Pre-Cambrian basement complex (Arabian Shield). This highly irregular unconformity surface (Figure 4) is defined as the Pre-Siq Unconformity (Şenalp, 2006a; Şenalp et al., 2018) and is dated at about 541 Ma. At the outcrops, the Siq Formation is a red-colored, large-scale, fining and thinning upward sequence. The lower parts of the formation generally consist of dark red-colored, massive to horizontal planar-bedded, coarse- to very coarse-grained (partly conglomeratic) poorly sorted alluvial sandstone facies. It is conformably overlain by coarse- to medium-grained, trough cross-bedded and well-sorted fluvial sandstone facies. This fluvial sandstone is conformably overlain by the well-bedded, medium-grained, well-sorted, and bioturbated sandstones with abundant and well-

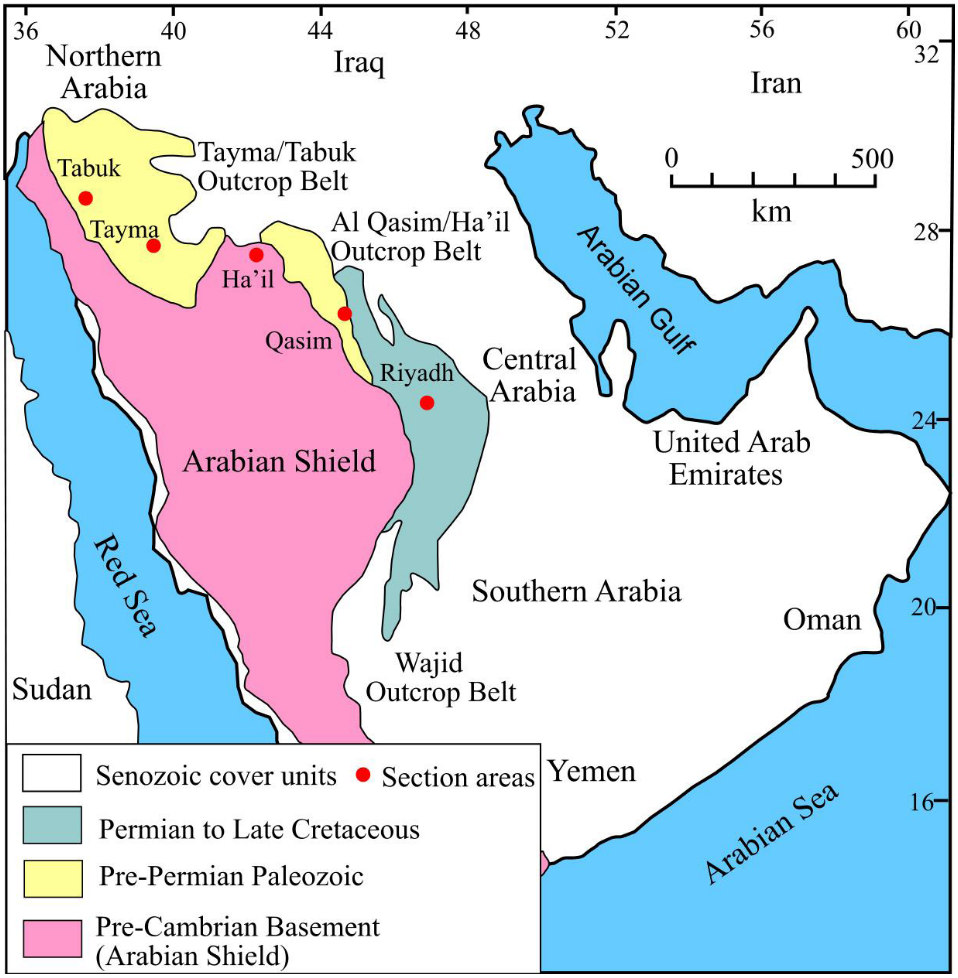

Figure 2. Map indicating the locations of Saudi Arabia's Paleozoic outcrops (Şenalp, 2006a).

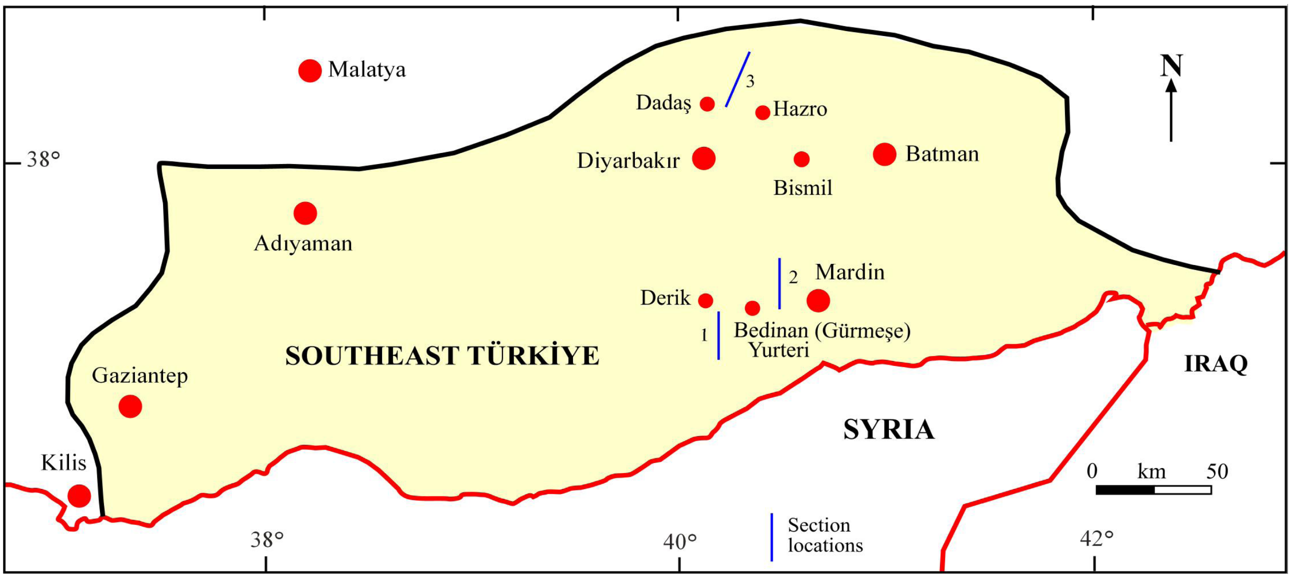

Figure 3. Geological map showing the locations of the measured sections and Paleozoic outcrops in southeast Türkiye (Şenalp et al., 2021).

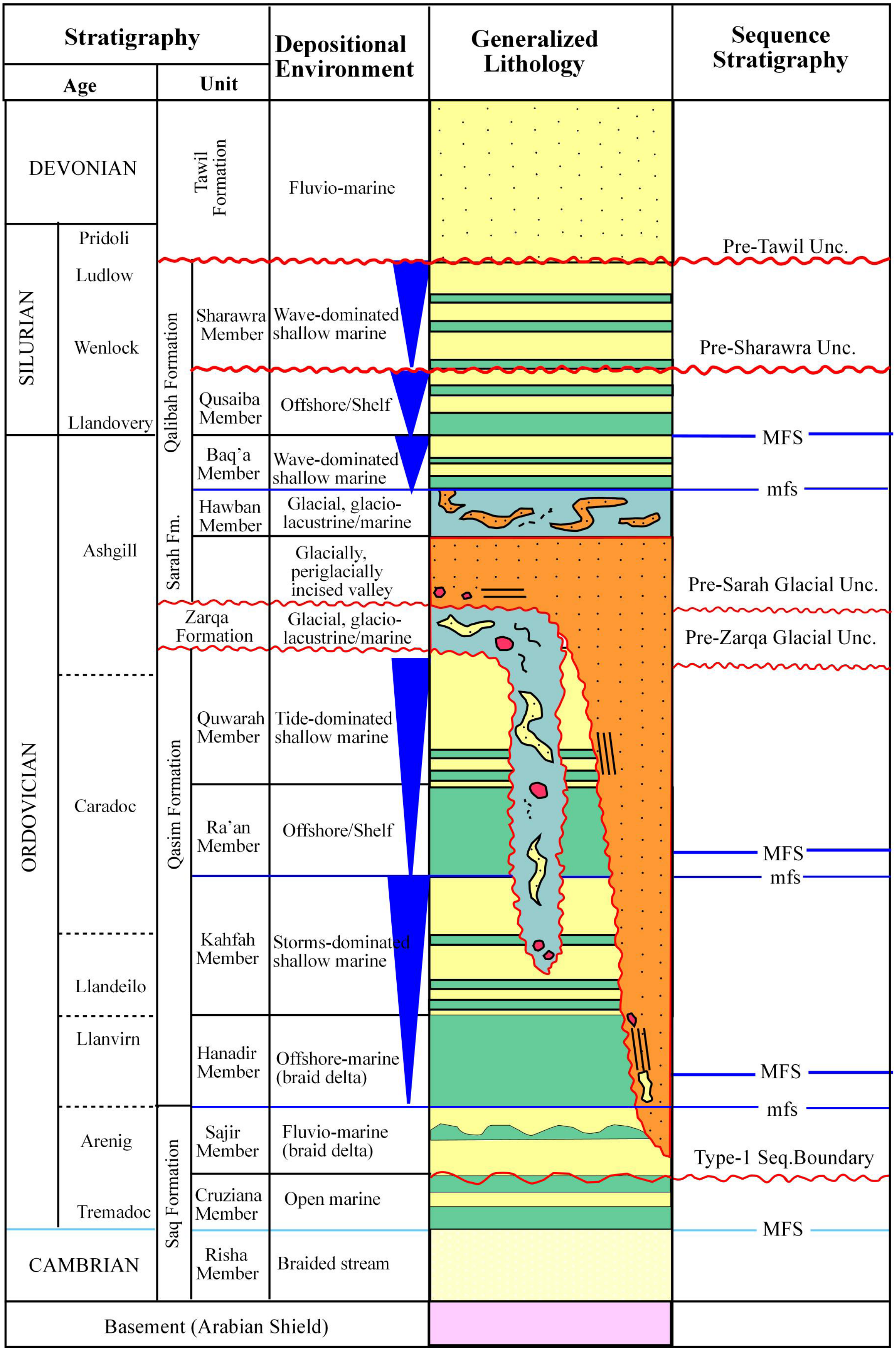

Figure 4. Stratigraphy and definitions of the Lower Paleozoic Successions from Saudi Arabia (Şenalp and Tetiker, 2020).

developed sigmoidal tidal bundles indicating the strong tidal currents. The uppermost part of the Siq Formation is represented by thin-bedded, wave-rippled sandstone and bioturbated siltstone, indicating deposition in a shallow marine (upper shoreface, and foreshore) environment. In some places, these shallow marine sediments are overlain by medium- to fine-grained, well-sorted, large-scale, high-angle, cross-bedded coastal eolian sandstones. In the reference section, Khursaniyah-81, the Siq Formation is more than 302 m thick, and consists of interstratified brick red siltstone, hematitic shale, and light gray to reddish-brown, very fine- to fine-grained, micaceous sandstones (Şenalp, 2006a). The Early Cambrian age was assigned to the formation, from the stratigraphic position just below the marine Middle Cambrian Burj Formation.

5.1.2. Southeast Türkiye

The Early Early Cambrian Sadan Formation (Ketin, 1966) is located near the town of Derik (Mardin) and the section was measured along the north–south trending Zabuk Valley (Figure 3). The Sadan Formation overlies the Proterozoic Telbesmi Formation (about 635–541 Ma), which was a topographic high as a horst block and provided siliciclastic sediments to the entire Cambrian succession (Figure 5). The top of the Sadan Formation with the Zabuk Formation has a sharp and very irregular erosional surface (Pre-Zabuk Unconformity) and represents a sequence boundary (Şenalp et al., 2018). The Sadan Formation is 186 m thick and consists of red-colored sandstone, conglomerate, massive mudstone, and algal dolomitic limestone facies. The sandstone bodies are wedge shaped and show fining upward depositional model. Trough crossbedding and lateral accretion surfaces at the base of the section indicate their deposition as point bars in a meandering fluvial system. In some cases, these sandstone bodies are laterally and vertically stacked. These point bar sandstones are surrounded completely by the red mudstones of the flood plain environment (Figure 6).

The primary characteristic of the Sadan Formation is the presence of 14-m-thick algal dominated dolomitic limestone, interbedded with red flood plain mudstone in middle of the section. Based on the regional correlation with Iran and Saudi Arabia, this shallow marine carbonate facies indicates an Early Cambrian regional marine transgression and represent the MFS (MFS Cm10, 540 Ma). The algal dolomitic limestones are also overlain by the same red massive mudstones indicating that the carbonates were deposited in an arid coastal plain environment (Şenalp et al., 2018). Ketin (1966) correlated these marine algal carbonate facies with the carbonate facies of the same age, exposed in the area between Kerman and Sagand in eastern Iran (Şenalp et al., 2018). In the Zagros Basin (southwestern Iran), the lower Cambrian is primarily composed of detrital shale, sandstone, and conglomerate with intercalations of limestone.

5.2. Late Early Cambrian (529–514 Ma)

5.2.1. Saudi Arabia

The Late Early Cambrian successions were defined by Şenalp (2006a) and Şenalp et al. (2018) as the Al ʻUla Formation (previously called the Quweira Sandstone) in northwest Saudi Arabia). It is exposed only in the Tayma-Tabuk Basin, in the famous historical place, Petra, in southern Jordan, and the Zabuk Formation in southeast Türkiye. The outcrops of the Late Early Al ʻUla Formation are best observed in the tombs of the old settlement area in Madain Saleh (Figure 7). In the town of Al ʻUla, the thick, pale brown sandstones sit on an irregular regional unconformity surface cutting into the dark red-colored Siq Formation and represent a very important sequence boundary separating the two markedly different depositional systems (Şenalp, 2006a; Şenalp et al., 2018). The Al ʻUla Formation in the town of Al ʻUla and close to Madain Saleh consists of thick, pale brown, medium- to coarse-grained, even partly conglomeratic, large-scale, high-angle, both planar and trough cross-bedded sandstone facies. The conglomeratic intervals contain pebbles of milky quartz, granite, and other igneous and metamorphic basement rocks. The sedimentary features of the formation indicate that this formation was deposited by a sand-dominated, high-energy braid stream system when the source area was tectonically uplifted. The large-scale, high-angle cross-stratification and the uniform grain size distribution in the sandstones, forming mainly in the upper part of the formation may indicate that some parts of the formation might have been deposited as eolian sand dunes (Şenalp, 2006a; Şenalp et al., 2018). The Al ʻUla Formation in western Saudi Arabia correlates with the Quweira Formation in Jordan and the Zabuk Formation in southeast Türkiye.

5.2.2. Southeast Türkiye

The Zabuk Formation stratigraphically extends between the MFS Cm10 (540 Ma) and MFS Cm20 (about 514 Ma). Based on these well-defined MFS, the age of the formation was accepted as the Late Early Cambrian (Late Terreneuvian and Early Epoch 2). The Zabuk Formation, exposed along the Zabuk Valley is a very impressive outcrop with its very high topography and the strong erosional unconformity of its surface (Pre-Zabuk Unconformity) at its base cutting into the massive mudstones of the Sadan Formation, defining a sequence boundary. Its upper boundary, with the thick carbonate sequence of the Middle Cambrian Koruk Formation, is conformable. The Zabuk Formation is 300 m thick and consists of five different but conformable and genetically related depositional units. These units are arranged in a fining- and thinning-upward transgressive sequence, indicating the gradual rise of the base line (sea level). These units in the stratigraphic order (from older to younger) are: 1) braided stream unit (Figure 8), 2)

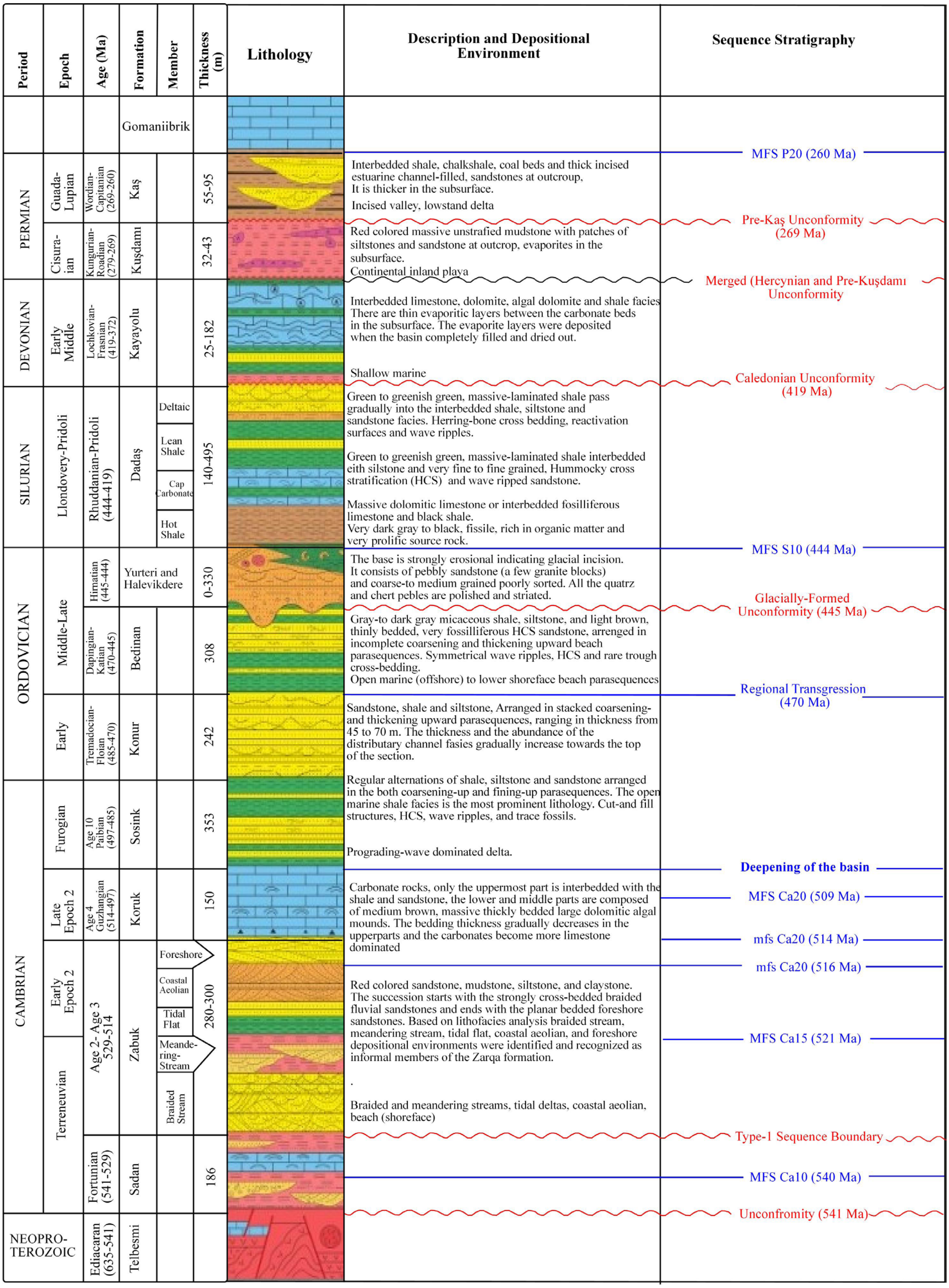

Figure 5. Sequence stratigraphy of the Paleozoic successions in southeast Türkiye. The regional erosional surfaces, MFS, mfs, and type-1 sequence boundaries were defined by Şenalp et al. (2018, 2021).

Figure 6. The lowermost part of the Sadan Formation consists of interstratified point bar sandstones and flood plain mudstones of the meandering fluvial system surrounded by the red playa mudstones.

Figure 7. Madain Saleh, the tombs in this old settlement area were cut in the Al 'Ula Formation.

meandering stream unit, 3) tidal flat unit, 4) coastal eolian unit, and 5) foreshore unit. The nature of the contacts and different lithofacies between these five different units reflects the tectonic evolution of the region, sea-level fluctuations (simply transgression and regression), and the amount of sediment supply to the basin. The interpreted depositional model and lateral facies changes of the genetically related depositional units are presented in Figure 9.

The thick and well-sorted, braided stream sandstones of the Zabuk Formation have good reservoir potential for hydrocarbon accumulation. There is no potential source rock facies in the section, but the overlying algal stromatolitic carbonates of the Koruk Formation may have some organic matter. In this case, the hydrocarbons generated in the Koruk Formation can migrate downward into porous and permeable, braided stream sandstones. Şenalp (2006a, 2006b), based on his regional studies on various parts of the Arabian Plate, correlated the Zarqa Formation with the Al ʻUla Formation in Saudi Arabia and Quweira Formation in Jordan (Şenalp et al., 2018).

5.3. Middle Cambrian (514–497 Ma)

During the Middle Cambrian, northwestern Saudi Arabia, Syria, Jordan, and Türkiye were covered by regional marine transgression and carbonate and siliciclastic rocks (Burj and Konur formations) were deposited on the large continental shelves of these countries.

5.3.1. Saudi Arabia

The Middle Cambrian Burj Formation has no outcrop in Saudi Arabia, but it was encountered in the Zalma-1 well in northwest Saudi Arabia and in the Khursaniyah-81 well in eastern Saudi Arabia. In the fully covered cores, the Burj Formation sits directly on the Early Cambrian Siq Formation and consists of interbedded marine algal dolomite, dolomitic limestone, limestone, siltstone, and shale. The core samples in the Khursaniyah-81-well yielded Early–Middle Cambrian acritarch assemblage where the MFS Cm20 (about 510 Ma) were identified (Şenalp, 2006a; Şenalp et al., 2018).

5.3.2. Southeast Türkiye

In southeast Türkiye, the 150-m-thick and well-preserved carbonates of the Koruk Formation occur along the north–south trending Zabuk Valley near the town of Derik. Thick-bedded algal dolomitic limestones deposited during the Middle Cambrian, form the main part of the Koruk Formation (Şenalp et al., 2018, 2021). The shallow marine carbonates are transgressive on the foreshore sandstones

Figure 8. Braided stream facies forming the lowermost part of the Zabuk Formation, exposed at its type locality along the Zabuk Valley, in the Derik area of the Mardin region. These troughs cross-bedded, well-sorted sandstones were deposited in the vertically and laterally stacked shallow channels and various midchannel bars by the sand-dominated, high energy, braided stream system in the lowstand systems tract (Şenalp et al., 2018, 2021).

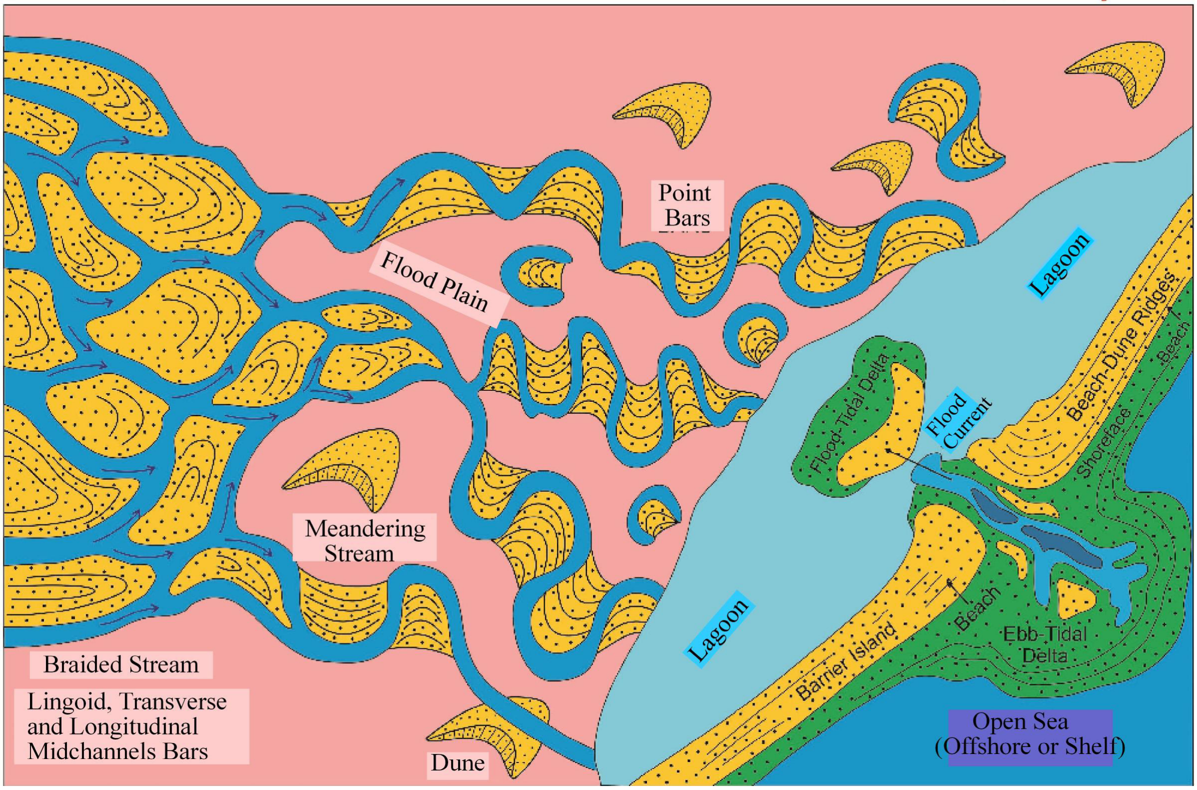

Figure 9. Interpreted depositional model of the five genetically related units of the Zabuk Formation, in the Derik area (Mardin region) of southeast Türkiye (Şenalp et al., 2018).

of the Zabuk Formation. Its upper part is conformably overlain by the open marine pelagic shales of the Sosink Formation. The lower part of the measured section consists of dolomite and dolomitic limestone characterized by large-scale algal mounds. The uppermost part of the measured section is composed of thin-bedded micritic limestone, interbedded with shale, marl, and very fine-grained, wave-rippled sandstone. The entire succession represents gradual deepening of the wide continental shelf environment (Şenalp et al., 2018). Based on intensive palynologic studies, the age of the Koruk carbonates were dated as Middle Cambrian (middle Menevian).

Sediment from the Early to Middle Cambrian era was deposited in Iran's maritime Arabian Plate margin. An example of how these conditions were set earlier and persisted longer is the finding of Redlichia trilobites from the Early–Middle Cambrian in the region northwest of Tehran, Iran. The Middle Cambrian in the Zagros Basin (southwestern Iran), generally consists of limestone, shale, and trilobite-bearing marl (Setudehnia, 1978). The MFS Cm20 (510 Ma) is placed in middle of the formation. The age and lithofacies characteristics of the Koruk Formation are very similar to those of the Burj Formation outcropping in the south of Aqaba in Jordan (Şenalp et al., 2018). The algal laminae in the large algal stromatolites have good potential to be good source rock to generate hydrocarbon. Similar algal limestones in the Huqf Supergroup of Oman during the Neoproterozoic have been proven to be very productive source rock facies for oil.

5.4. Late Cambrian (497–485 Ma)

In the Late Cambrian, the Middle Cambrian carbonate deposition was gradually terminated, and the siliciclastic sequences were deposited on Saudi Arabia, Jordan, Syria, and southeast Türkiye. As result of deepening of the basin, there was a significant increase in the amount of clastic sediment from the source area.

5.4.1. Saudi Arabia

The thick and fully exposed Late Cambrian succession is described as the Saq Formation in central Saudi Arabia. The type locality is the Jabal Saq, located about 17 km north of the town of Bukayriyah (Figure 10). Stratigraphically, it extends between the crystalline basement complex of the Arabian Shield and the Hanadir Member of the Qasim Formation. The Saq Formation is separated into the Risha Member (Late Cambrian), and the Sajir and Bukayriyah members (Early Ordovician). The Risha Member is transgressively overlain by the marine sediments of the Bukayriyah Member. The type section is 190 m thick and consists of light gray to light brown, thick-bedded, coarse-

Figure 10. The type section of the Saq Formation is located in the Qasim area, approximately 17 km north of Bukayriyah town (Şenalp, 2006a; Şenalp et al., 2018).

to very coarse-grained (sometimes pebbly), high-angle, cross-bedded micaceous sandstones. The slumped and overturned cross-bedded sandstones are very common in the section, indicating that the sandstones of the Risha Member were deposited by the high-energy, sand-dominated braided fluvial system.

5.4.2. Southeast Türkiye

In the Mardin region of southeast Türkiye, the Late Cambrian succession is presented by the Sosink Formation in the Zabuk Valley (Şenalp et al., 2018). It is a 353-m-thick coarsening- and thickening-upward progradational sequence. Its lower boundary with the Koruk carbonates is transitional and indicates gradually subsiding and deepening of the basin. The contact was placed where the interbedded shale and wave-rippled sandstone facies started. However, the upper contact with the Konur Formation is sharp and indicates a significant rotation of the Arabian Plate (Şenalp et al., 2018). The Sosink Formation consists of regular alternations of shale, siltstone, and sandstone, which are arranged as complete and incomplete beach parasequences, forming a progradational parasequence set. The open marine shales dominate the lower part of the formation. The most common sedimentary structures in the beach sandstones are the cut and fill structures, hummocky cross-stratified (HCS) wave ripples, and various trace fossils, all indicating that the Sosink Formation was deposited in a strongly wave-dominated deltaic sequence on a large continental shelf (Şenalp et al., 2018).

6. Ordovician System (485–444 Ma)

The succession of sedimentary rocks representing the Ordovician System on the Arabian and African Plates extends from the regional mfs (mfs O10, 485 Ma) defined at the base of the Bukayriyah Member of the Saq Formation to the regional marine transgressive surface (MFS S10 444 Ma). In Saudi Arabia, this surface is defined at the base of the Silurian Qusaiba Member of the Qalibah Formation (Figure 4). The succession of the Ordovician System includes the Sajir and Bukayriyah members of the Saq Formation, the Qasim Formation, and the glacially formed Sarah and Zarqa formations. Similar Ordovician successions in southeast Türkiye (Figure 5) consist of the Konur Formation (Şenalp et al., 2018), Bedinan Formation, and the glacially formed Yurteri Formation (Şenalp, 2006a; Şenalp et al., 2018; Şenalp and Tetiker, 2020, 2021). Based on the palaeontologic and palynologic data, the presence of sequence boundaries, and MFS, the

Ordovician System is subdivided into time-stratigraphic successions in the following way. They were carefully distinguished and separated from the rework palynoforms carried from reworking of the older formations.

1. Early Early Ordovician System (485–478 Ma)
2. Late Early Ordovician System (478–470 Ma)
3. Middle-to-Late Ordovician System (470–445 Ma)
4. Late Ordovician System (445–444 Ma)

6.1. Early Early Ordovician System (485–478 Ma)

6.1.1. Saudi Arabia

The Early Early Ordovician successions in Saudi Arabia consist of the Bukayriyah Member of the Saq Formation. The open marine sediments (predominantly of pelagic shales with abundant *Cruziana* trace fossils) of the Bukayriyah Member are transgressive on the Late Cambrian fluvial sandstones of the Risha Member of the Saq Formation and represent the Early Ordovician (Tremadoc) regional marine transgression (MFS O10, 485 Ma). Its upper part is deeply cut and eroded by the Sajir Member of the Saq Formation, representing a well-defined type-1 sequence boundary as a result of the dropping sea level. This erosional surface is laterally extensive and can be observed in every part of Saudi Arabia. The Bukayriyah member is approximately 20–22 m thick and consists of interbedded white, light bluish-gray, purple, dark red- to brown-colored, very fine-grained wave-rippled, micaceous sandstone of the offshore marine sediments. The sediments, including the same type of *Cruziana* trace fossils (*Cruziana* vilanovae), have been observed in the Ram Sandstone in Jordan and Konur Formation in southeast Türkiye (Şenalp et al., 2018).

6.2. Late Early Ordovician (478–470 Ma)

6.2.1. Saudi Arabia

In Saudi Arabia, the Late Early Ordovician (Arenig) Sajir Member (Vaslet et al., 1987; Şenalp and Al-Duaiji, 2001b) is the uppermost member of the Saq Formation. The base of the Sajir Member (Pre-Sajir Unconformity) cuts deeply into the Bukayriyah Member and removed a significant portion of the marine sediments. Its upper contact with the Middle Ordovician (Dapingian) Hanadir Member of the Qasim Formation is a sharp lithological break. This surface provides an easily recognizable landmark representing a regional marine transgression, which was designated as MFS O20 (470 Ma) by Senalp and Al-Duaiji (2001a). The sandstones in the lower parts are coarse to very coarse grained and show both trough and planar crossbedding, indicating different depositional processes. The upper parts of the member consist mainly of sandstone, which is interbedded with thinly bedded, red to brown siltstone layers. Upward in the section, the siltstone layers become thicker and laterally more continuous. The lower parts of the Sajir Member were deposited by the fluvial system. The uppermost 10 m of the section shows sigmoidal crossbedding, indicating the presence of tidal processes operating in the lower reaches of the fluvial channels close to shoreline. The Sajir Member is correlated with the middle and upper parts of the Konur Formation in the Mardin region and Seydişehir Formation in the Konya region.

6.2.2. Southeast Türkiye

In southeast Türkiye, the Konur Formation, exposed along the Zabuk Valley (Derik, Mardin area), represents the sedimentary succession deposited during the Late Early Ordovician (478–470 Ma). It is conformable with the underlying Sosink Formation but there is a major difference in their depositional systems, sand/shale ratio, and the reservoir quality of the sandstones (Figure 11). Its upper part is overlain by the open marine shales of the Bedinan Formation and indicates a regional marine transgression. The Konur Formation is 242 m thick and consists predominantly of sandstone and minor amounts of shale and siltstone in the lower parts. The type section is arranged in stacked coarsening-and thickening-upward prograding parasequence sets. The thickness of each parasequence ranges from 45 to 70 m. The thickness and abundance of the distributary channel facies gradually increase toward the top of the section (Figure 11). The inner mouth bar and subaqueous distributary channel fills of the Konur Formation are composed of thick-bedded, medium- to coarse-grained sandstone facies, which have significant reservoir potential. The lack of source rock facies beneath this portion is the primary issue. The Konur Formation correlates with the Bukayriyah and Sajir members of the Saq Formation in Saudi Arabia, the Khanaser Formation in Syria, and the Umm Sahm Formation in Jordan (Şenalp and Al-Duaiji, 2001a; Şenalp, 2006a, 2006b). This stratigraphic interval has not been penetrated yet in Iraq (Al-Hadidy, 2007).

6.3. Middle-to-Late Ordovician System (470–445 Ma)

The Middle-to-Late Ordovician successions include the Qasim Formation in Saudi Arabia, the Khabour Formation in Iraq, and the Bedinan Formation in southeast Türkiye. These formations are located on a broad, stable marine shelf that dips gently and borders the Paleo-Tethys Ocean. In order to make room for the deposition of a siliciclastic wedge that was more than 1220 m thick on the border of the Gondwana continent, the shelf was inclined toward the northeast of today.

6.3.1. Saudi Arabia

The Qasim Formation is well exposed in Saudi Arabia and is also recognized in every part of the Arabian and African platforms. The successions are well exposed in the Al Qasim and Ha'il region of central Saudi Arabia and in the Tayma-Tabuk Basin of northwest Saudi Arabia, and are also recognized in many exploration wells (Figure

Figure 11. Coarsening- and thickening-upward deltaic parasequence of the Konur Formation consisting of the thin to medium planar outer mouth bar sandstones, cut by the thick-bedded, distributary, channel-fill sandstones of the inner mouth bar environment (Şenalp et al., 2018, 2021).

4). The Qasim Formation consists of shallow marine and shelf siliciclastic sequences of the Quwarah, Kahfah, Ra'an, and Hanadir members, which are organized in two coarsening-upward progradational parasequences and have a total thickness of about 200 m in the outcrop area. Two stratigraphic and sedimentologic sections were measured from each progradational sequence by Senalp and Al-Duaiji (2001a). These four members of the Qasim Formation were placed in a sequence stratigraphic context and are given below.

1. Hanadir Member

The silt and shale-dominated Hanadir Member and the conformably overlying sand-dominated Kahfah Member (Williams et al., 1986) are best exposed at the Al-Hanadir cuesta between the towns of Buraydah and Qusaiba, in central Saudi Arabia. These two members form a lower coarsening- and thickening-upward, progradational sequence set of a storm-dominated beach environment of the Qasim Formation (Şenalp and Al-Duaiji, 2001a). The member is transgressive over the Sajir Member of the Saq Formation. It is 22 to 25 m thick but in some places, it is deeply truncated by the glacially formed Sarah Formation and its thickness is significantly decreased. The lower 15-m-thick unit consists of interbedded dark gray, black homogeneous shale, silty claystone, and wave-rippled very fine-grained sandstone facies. The upper 7-m-thick unit consists of regularly alternating shale and fine-grained, graded-bedded sandstone. The abundant pelagic fauna indicate the age of this regional marine transgression as early Middle Ordovician (Early Late Llanvirn).

2. Kahfah Member

The 110-m-thick Kahfah Member (Vaslet et al., 1987) forms the upper part of the lower coarsening- and thickening-upward storm-dominated progradational beach parasequence of the Qasim Formation (Şenalp and Al-Duaiji, 2001b). It is transgressively overlain by the black homogeneous offshore marine shale facies of the Ra'an Member. The succession consists of many vertically stacked thickening- and coarsening-upward, complete and incomplete beach parasequences. One complete beach parasequence is 21.50 m thick and begins at the base with greenish-gray or medium-gray, homogeneous or laminated, fissile, bioturbated shale and thin laminae of graded-bedded siltstone deposited in an offshore marine environment, below the storm wave base. It is overlain by the interbedded shale and sandstone facies. Sandstone is grayish yellow- to green-colored, well-bedded, fine- to very fine-grained and show excellent examples of HCS overlain by symmetrical wave ripples. This interval represents a storm-dominated transition zone or lower shoreface beach facies. The HCS sandstone's initial appearance suggests that the depositional location has gotten shallower above the base of the storm waves. This section is overlain by a light brown, medium- to thickly bedded, strongly trough cross-bedded, medium-grained, well-sorted, burrowed (Tigillites or *Skolithos*) sandstone unit deposited in the upper shoreface beach environment. The topmost segment of the beach parasequence is made up of fine- to medium-grained, reddish-brown, well-sorted, planar-tabular-bedded (upper flow regime) consisting of gently dipping (seaward direction) laminae, and strongly *Skolithos*-burrowed sandstone, deposited in a foreshore beach environment (Şenalp and Al-Duaiji, 2001b).

3. Ra'an Member

The dark gray fissile offshore marine shales at the base the Ra'an Member (Williams et al., 1986) transgressively overlies the foreshore sandstones of the Kahfah Member (Şenalp and Al-Duaiji, 2001b). Its upper contact with the Quwarah Member is gradational and both members together form the upper coarsening-upward tide-dominated progradational parasequence of the Qasim Formation. The 40-m-thick Ra'an Member at its type locality starts with 3.5-m-thick, dark gray to blackish organic rich fissile offshore shales of potential source rock facies. They are overlain by the 36.3-m-thick, cliff-forming dark gray fissile shales, graptolitic micaceous siltstone and laterally continuous burrowed sandy siltstone facies. This MFS occurs in the shales at the base of the Tubeiliyat Formation in Iraq, the Afendi Formation in Syria, and the Bedinan Formation in southeast Türkiye (Şenalp et al., 2018).

4. Quwarah Member

The Quwarah Member (Williams et al., 1986) crops out near the town of Al-Quwarah in the Al Qasim region and forms the upper half of the upper coarsening- and thickening-upward, tide-dominated progradational sequence of the Qasim Formation (Şenalp and Al-Duaiji, 2001a). The regularly interbedded siltstone, shale and thin-bedded sandstone facies occurs only in the lower parts of the section and conformably overlies the Ra'an Member. In contrast, its upper boundary is deeply incised and eroded by the glacially formed paleovalleys at the base of the Zarqa and Sarah formations**.** The Al Qar'a measured section is 29 m thick, of which 17 m overlays the Ra'an Member and 12 m conformably overlays the Quwarah Member. The base of the section is covered by recent sabkha salts, but its upper boundary is cut by the Sarah Formation. The contact between the Ra'an and Quwarah members is sharp, indicated by the occurrence of well-bedded sandstones with many sedimentary structures.

The lower 3 m of the 12-m-thick Quwarah Member consists of pale greenish, yellow- or white-colored, very fine- to fine-grained (coarsening-upward), well-sorted sandstone. Flaser bedding (Reineck and Wunderlich, 1998), wave-modified current ripples, tidal bundles (Nio and Yang, 1991), and burrows are the most common sedimentary structures. The upper 1.5-m part of this unit consists entirely of light-colored, fine- to medium-grained, well-sorted, large-scale, cross-stratified and imbricated lens-shaped sigmoidal sand bodies containing tidal bundles. The uppermost part of the measured section is 9.2 m thick and forms a small steep cuesta. Its upper contact is shortened by the Sarah Formation, although its lower contact with the underlying unit is gradational. Strong evidence for a tidal method of deposition can be seen in this light-colored, fine- to medium-grained, well-sorted sandstone block, which has a wide range of sedimentary features. However, the large-scale, lens-shaped, cross-bedded sandstone (tidal sand waves) that predominates in the lower unit gradually disappears, and is replaced by sandstone bodies up to 30 cm thick that have horizontal planar bedding, well-developed reactivation surfaces, and large-scale crossbedding with tidal bundles. *Skolithos* and *Asterosoma*, two typical vertical burrows that feed on suspension and are coated with iron oxide, aid in differentiating the Quwarah Member from the Sarah Formation. The physical components of this depositional system are understood as barrier islands subject to tidal influence, tidal inlets, and related ebb-tidal deltas in a mesotidal (tidal range of 2–4 m) coastal environment (Prothero, 1990; Şenalp and Al-Duaiji, 2001a). Al-Hajri (1995) allocated a Late Caradocian to Middle Ashgillian age for the Quwarah Member.

6.3.2. Southeast Türkiye

The well-defined Qasim Formation in Saudi Arabia is correlated with the Middle-to-Late Ordovician Bedinan Formation (Cobb, 1957) in southeast Türkiye. The successions are exposed near the Bedinan vilage (new name is Gürmeşe) located 20 km south–southeast of the town of Derik (Mardin). The dark gray open marine graptolitic shales of the Bedinan Formation are transgressive on the deltaic (inner mouth bar) sandstones of the Konur Formation (Şenalp et al., 2018). Its upper part is deeply incised by the glacially formed Yurteri Formation, which correlates with the Sarah Formation in Saudi Arabia. The Bedinan Formation is 308 m thick and consists mainly of gray to dark gray micaceous shale, siltstone, and light brown, thinly bedded, very fossiliferous sandstone. These siliciclastic rocks are arranged in one incomplete coarsening- and thickening-upward beach (offshore and lower shoreface) prograding parasequence. They were deposited in a shallow marine environment of a wide continental shelf. The offshore marine shale and siltstone facies are more abundant in the lower parts, but the bedding thickness, sedimentary structures, and grain size of the sandstones increase upward. The most common sedimentary structures in the sandstones include symmetrical wave ripples, HCS, and very rare trough crossbedding. The Qasim and Bedinan formations are correlated with the Khabour Formation in Iraq and are subdivided into the seven K1 (younger) to K7 (older) members (Al-Hadidy, 2007).

6.4. Late Ordovician Glacial System (445–444 Ma)

The base of the uppermost Ashgill deposits is a well-defined erosional unconformity surface that was formed during the Late Ordovician (Hirnantian, dated at 445 Ma) continental Gondwana glaciation, representing a significant sequence boundary (Şenalp and Al-Laboun, 2000). The Late Ashgill (445–444 Ma) was characterized by the expanding polar glaciers across Gondwanaland, which had a very significant contribution to the hydrocarbon explorations. The deeply incised glacial paleovalleys and glacio-fluvial sandstones are widespread in several basins in South America, North America, Europe, and in African and Arabian Plates, including large parts of Saudi Arabia, Jordan, Iraq, and Türkiye (Figure 4). They make up a sizable component of the geological sequence of the cover rocks in these countries and provide very productive sandstone reservoirs that can hold both gas and oil. There is a general consensus among sedimentologists that the polar icecap covered sub-Sahara Africa (present-day Mauritania) and the size of this icecap was equivalent to that of the current Atlantic ice sheet. The initial theory on the Sahara region's Ordovician glacier (Mauritania) was provided by geologist Zimmermann (1960) in a report to the International Geological Congress in Copenhagen. Deynoux (1985) reported convincing evidence of glaciation in West Africa in the Taoudenni Basin. The overall sand content of the sediments deposited by this ice sheet is high. Despite having a high overall sand content, the sediments left behind by this ice sheet are prone to drastic lateral facies changes and are closely related to the most significant and prolific source rock that was left behind at the base of the Early Silurian regional transgression (444 Ma) after the ice sheet melted (Şenalp and Al-Laboun, 2000; Şenalp et al., 2018; Şenalp and Tetiker, 2020).

6.4.1. Saudi Arabia

The presence of glacially striated, rounded, grooved, polished, sandstone faceted, and granite boulders and tillite deposits was first documented in the Paleozoic outcrop section along Jal as-Saqiyah cuesta in the Qasim region by McClure (1978). These field observations were used as convincing evidence for the Late Ordovician (Hirnantian) Gondwana glaciation in central Saudi Arabia. This short-lived glaciation provided two genetically related but significantly distinct glacial deposits, called the Zarqa and Sarah formations (Vaslet et al., 1987; Şenalp and Al-Laboun, 2000; Şenalp et al., 2018; Şenalp and Tetiker, 2020).

6.4.1.1. Zarqa Formation

The Jal Az-Zarqa cuesta in the Baq'a Quadrangle in the Ha'il region is the source of the Zarqa Formation, which was formally identified and recorded by Vaslet et al. (1987). The outcrops are easily spotted between the cities of Baq'a (Ha'il) and Al-Qar'a (Buraydah). Its basis is the Pre-Zarqa Unconformity surface, which cuts into the various Qasim Formation components. The top of the Zarqa Formation is incised all around by the younger glacial unconformity developed at the base of the Sarah Formation. The type section of the Zarqa Formation is 115 m thick and consists of a recurrence and complex mixture of different types of moraines (predominantly pushed and basal moraines), tillite, and boulder-clay. There are abundant glacial dropstones and chunks of sandstone that have slumped or been bulldozed, which are the remnants of earlier formations. Among the most significant characteristics of this glaciogenic formation are the polished and striated granite together with other metamorphic and igneous blocks (diameters up to 1.3 m) that came from the Arabian Shield (Şenalp and Al-Laboun, 2000). The tillite facies in the Jal As-Saqiyah cuesta is incredibly thick and consists of large, lens-shaped blocks of dislocated, well-bedded, but severely folded and cracked sandstones from the Kahfah and Quwarah members floating in an olive gray, sandy mudstone and mudstone facies. They are thought to be push-moraines (Şenalp and Al-Laboun, 2000; Şenalp et al., 2018; Şenalp and Tetiker, 2020).

6.4.1.2. Sarah Formation

The Sarah Formation was first described by Williams et al. (1986) at the Khanasir Sarah near the town of Al Quwarah, in central Saudi Arabia. This formation is a typical glacial paleovalley, bounded at the base by a major erosional surface that cuts deeply into the Qasim, Zarqa, and even into the Saq Formation in its proximal parts (Figure 4). It consists of all the periglacial and glacial sediments filling the paleovalleys. Several Sarah paleovalleys have been mapped at the surface, and they have been traced into the subsurface of northern Saudi Arabia with three-dimensional seismic data (Şenalp and Al-Laboun, 2000; Şenalp, 2006a; Şenalp et al., 2018; Şenalp and Tetiker, 2020). The Sarah Formation is overlain by the organic rich hot shale facies deposited at the base of the Early Silurian regional marine transgression (MFS S10, 444 Ma) as a result of the rising sea level during the deglaciation period.

The fine- to coarse-grained, current-rippled, cross-bedded, horizontally and vertically piled, fining-upward, fluvial and glaciofluvial sandstones make up the majority of the Sarah Formation. Primary tillites can be found in several locations at the sides and base of the paleovalleys.

The thickness of the Sarah Formation depends on the size of the paleovalley and its position within the paleovalley, as it may be more than 300 m thick in the downstream axial section of the paleovalleys. Various sedimentary structures were described and reported by Şenalp and Al-Laboun (2000) and Şenalp and Tetiker (2020) from the Wajid, Al-Qasim, and Ha'il regions of Saudi Arabia. They are generally found at approximately 0.3 to 1.2 m above the Pre-Sarah Unconformity surface. The glacially formed sedimentary structures include long and deep grooves, deep circular to subcircular depressions on the pavements, polished and striated pavements, chatter marks, sediment gravity flow (fan-shaped solifluction structures), and overturned drag folds. Şenalp and Al-Laboun (2000) carried out petrologic studies on the hydrocarbon potential of the glaciofluvial reservoir sandstones of the Sarah Formation and the source rock potential of the directly overlying hot shale facies of the Qasim Member of the Qalibah Formation. The oil and gas produced in the hot shale facies migrated downward into the glaciofluvial sandstones due to the hydrostatic pressure difference.

6.4.2. Southeast Türkiye

Comprehensive studies of the Late Ordovician glaciation in every division of Saudi Arabia provided an immense amount of information on the surface and subsurface geology of the Arabian and African plates including, Iraq, Jordan, Syria, and southeast Türkiye, and will be discussed in the following sections.

6.4.2.1. Yurteri Formation

The Yurteri Formation in southeast Türkiye was initially identified and formally characterized by Şenalp et al. (2018) to characterize the glacially produced sedimentary successions exposed between the communities of Bedinan (Gürmeşe), Konur, and Yurteri (Derik, Mardin). Previous research[2] concluded that the sediments in this unit were glaciofluvial and glacio-marine in origin based on lithofacies features and the existence of polished and striated pebbles. The tunnel valley's (glacial valley's) thick and conglomeratic sandstone facies, on the other hand, have not been identified. The Sarah Formation in Saudi Arabia, which produces hydrocarbons, and the Yurteri Formation are nearly similar in many ways, with both having been created by glaciers (Şenalp and Al-Laboun, 2000). Given its high potential for hydrocarbons, the Yurteri Formation merits further investigation into its geometry, reservoir quality, and link to the hot shale facies just above it at the base of the Dadaş Formation, which was deposited throughout the Early Silurian (444 Ma) regional transgression.

The narrow U-shaped, glacially formed unconformity surface is represented by the base of the Yurteri Formation, which is deeply carved into the Bedinan Formation (Figure 12). In the subsurface, based on their location on the depositional system, the glacio-fluvial braid delta and glacio-marine deposits are overlain by the Silurian (Rhuddanian 444 Ma) hot shale facies of the Dadaş Formation. Three glacial facies that are genetically related make up the Yurteri Formation. These are: a) tunnel valley deposits, b) glacio-fluvial braid delta deposits, and c) glacio-marine deposits. Comprehension of the trend and the geometry of the glacial paleovalleys and the distribution of the overlying hot shale facies will significantly facilitate the exploration and production potential of this glaciogenic sandstone reservoir. Comprehending the migration pathway (along the fault plane or downward migration due to the pressure difference) of the gas and oil as well as the trapping system is essential to the exploration's success.

7. Silurian System (444–419 Ma)

On the Arabian and African Platforms, the Early Silurian (Llandovery) represents the most significant regional marine transgression (MFS S10, 444 Ma) following the deglaciation (melting) phase of the Late Ordovician (Hirnantian, 445 Ma) Gondwana ice mass. The sea level started rising fast when the ice mass gradually melted, and huge amounts of fresh water returned into the sea. The Silurian System extends between this worldwide mfs (mfs S10 444 Ma) and the regional unconformity surface formed by the Caledonian Orogeny (423 Ma). The Silurian System is defined as the Qalibah Formation in Saudi Arabia, the Dadaş Formation in Türkiye, the Akkaş Formation (Hoseiba and Qaim members) in Iraq, the Mudawwara and Kisha formations in Jordan, and the Batra (or Ratiya) Formations in Syria (Turner et al., 2005; Şenalp, 2006a). The general characteristics of the Silurian successions in these different regions are very similar to each other, and they show a well-defined overall coarsening- and thickening-upward progradational sequence. The organic rich hot shale facies was deposited at the base of the succession during the very early Silurian transgression. This hot shale facies is 20–70 m thick and contains 7%–15% TOC (Figure 13). This hot shale facies is thought to be the main source of the light oil with low sulfur found in the Paleozoic sandstone reservoirs (Devonian, Permo-Carboniferous, Late Ordovician, and Permian) of all the countries on the African and Arabian plates, based on data from biomarkers and carbon isotope analyses. They are also the main target for unconventional hydrocarbon exploration.

7.1. Saudi Arabia

The stratigraphy, sedimentology, and palynology of the Silurian successions are best developed and intensively

[2] Şenalp M (2012). Field trip guide book to the Midyan Area, NW Saudi Arabia. Dhahran, Saudi Arabia: King Fahd University of Petroleum and Minerals (KFUPM).

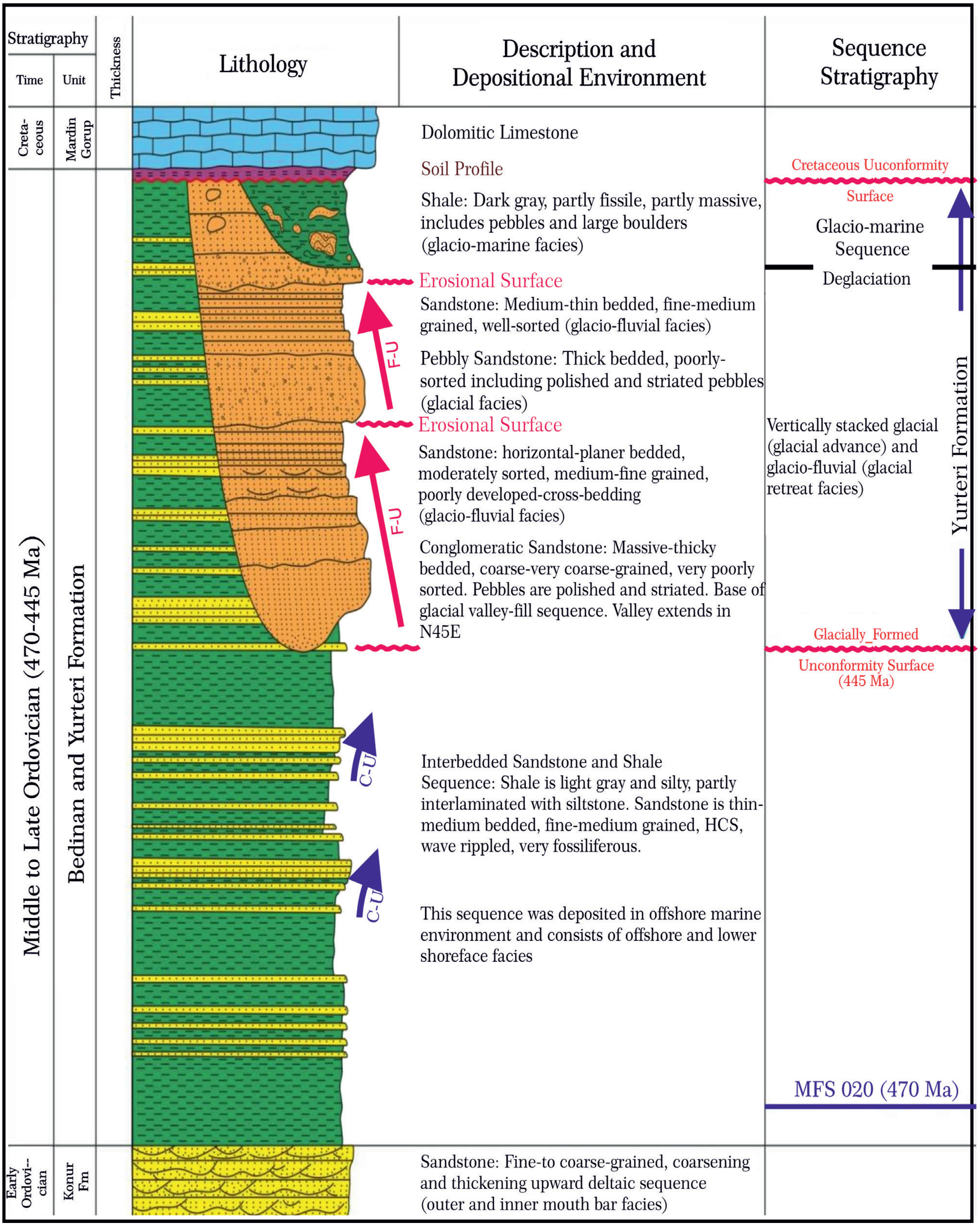

Figure 12. Sequence stratigraphy and sedimentology of the Bedinan Formation are found in the measured type section that extends between the villages of Bedinan (Gürmeşe) and Yurteri, as well as the glacio-marine facies and the glacially formed Yurteri paleovalley (Şenalp et al., 2018; Şenalp and Tetiker, 2020).

Figure 13. The Qusaiba hot shale facies forms the lowermost part of the Qusaiba Member. It was deposited during the regional Silurian transgression (444 Ma) following the deglaciation of the Late Ordovician glaciation (445 Ma).

studied at outcrop and exploration wells in every part of Saudi Arabia. These valuable data have provided a best exploration and production model for other countries.

7.1.1. Qalibah Formation

The Silurian Qalibah Formation was defined by Mahmoud et al. (1992) for the stratigraphic succession extending between the Sarah and Tawil formations in the Al-Qalibah-Tayma area, northwest Saudi Arabia. In this definition, the Qalibah Formation was subdivided into the lower shale-dominated Qusaiba Member and the upper sandstone-dominated Sharawra Member. Şenalp et al. (2002) revised the Qalibah Formation by introducing the new Baq'a Member at the base of the formation (Figure 4). The Qalibah Formation disconformably overlies the Sarah Formation, and in most places, it starts directly by the Qusaiba hot shale facies. Its upper contact with the Devonian (Lochkovian) Tawil Formation is sharp and represents a regionally formed erosional surface (Devonian Caledonian Orogeny). This Pre-Tawil Unconformity surface occurs between the interbedded marine shale and HCS sandstone facies of the Sharawra Member and the medium- to coarse-grained, trough cross-bedded, unfossiliferous, braided fluvial sandstone facies of the Tawil Formation. In the Qasim region, the Qalibah Formation is exposed only in the Qusaiba depression. The surface reference section of the Qalibah Formation is located between the towns of Al-Qalibah and Tayma. The measured 499-m-thick section represents a well-defined coarsening- and thickening-upward marine progradational parasequence sets (Şenalp and Al-Duaiji, 2001a). The composite subsurface reference section was constructed from the Udaynan-1 and ST-39 wells drilled in the south of Riyadh.

7.1.1.1. Baq'a Member

The Baq'a Member is a 27-m-thick coarsening- and thickening-upward, prograding beach parasequence and consists of 7-m-thick offshore marine shale facies at the base, overlain by 20-m-thick shoreface and foreshore sandstones at the top. The top surface is black-stained, ferruginous, silica-cemented, wave-rippled, and strongly burrowed and bioturbated. This significant surface represents a hard ground (diastem or nondepositional surface). Palynologic studies of the shales indicated a Late Ashgill (Late Ordovician) to Early Silurian age for the Baq'a Member shale (Figure 4).

7.1.1.2. Qusaiba Member

In the surface reference section of the Qalibah Formation, the Qusaiba Member is 256 m thick and directly overlies the light brown, medium- to coarse-grained, and well-sorted sandstones of the glaciofluvial Sarah Formation. The uniformly black, euxinic organic-rich, hot shale facies at the base is 70 m and contains abundant graptolites (Şenalp and Al-Duaiji, 2001b; Şenalp et al., 2002). This shale facies was deposited at the base of the Early Silurian (Rhuddanian, 444 Ma) transgression during the short-lived Late Ordovician (Hirnantian, 445 Ma) when the Gondwana ice mass melted (Figure 14). Upward, the section gradually becomes shallower and consists dominantly of laminated, medium gray shale, very fine-grained, wave-rippled sandstone, gradually overlain by medium-grained, well-sorted, HCS sandstone, with thin laminae of mica-rich siltstone in the upper part (Şenalp and Tetiker, 2020). The hot shale facies (up to 17% TOC) at the lowermost part of the Qusaiba Member was proven to be the most prolific source rock facies for the entire Paleozoic reservoir in Saudi Arabia and other Middle East countries (Figure 13).

7.1.1.3. Sharawra Member

The Sharawra Member in the measured reference section is 243 m thick, but in many places, its upper part is cut and partly eroded by the Pre-Tawil Unconformity formed by the Caledonian Orogeny. It is made up of fine-grained sandstone alternating with silty micaceous shale. Toward the top of the member, the strongly burrowed and bioturbated HCS sandstone facies become more dominant, indicating deposition in a shallow marine environment. Şenalp (2006a) reported that the Sharawra Member is characterized by the numerous occurrences of black-stained, ferruginous surfaces, which indicate breaks in the sedimentation. Bioclastic and phosphatic conglomeratic sandstone layers occur in the lower parts of the section.

7.2. Southeast Türkiye

The 135-m-thick Silurian section, extending between the underlying glaciogenic Yurteri Formation (Late Ordovician) and the overlying Kayayolu Formation (Devonian) is defined as the Dadaş Formation, exposed in the Hazro area (Diyarbakır). The type section consists of shale, siltstone, sandstone, and a minor amount of limestone in the lowermost part of the section. These siliciclastic rocks are arranged in a continuous coarsening- and thickening-upward, wave, and tide-dominated deltaic progradational parasequence set. The succession consists of typical hot shale facies at the bottom, overlain by interbedded shale and limestone, hot shale facies, and is capped by the deltaic sandstone facies forming the prolific Hazro Reservoir for both gas and oil (Şenalp et al., 2018; Şenalp and Tetiker, 2020; Şenalp et al., 2021; Şenalp and Tetiker, 2023, 2024). The highly organic-rich shale facies directly overlies the glacio-marine sandstones of the Yurteri Formation. In the subsurface, it is encountered in almost every well drilled in the Diyarbakır region. Its high radioactive character is easily recognized on the gamma ray logs. The thickness of this unit is quite variable, determined by the underlying irregular glaciogenic relict topographic surface. The hot shale was deposited during the earliest Silurian (Rhuddanian, 444 Ma) regional transgression.

The hot shale facies have gradational contacts and forms the thickest portion of the formation. The lower part of the section is more shale dominated but its upper part consists of interbedded sandstone and shale facies. The shale is light to medium gray, silty, and interbedded with thin-bedded limestone and, very fine- to fine-grained sandstone forming short and incomplete parasequences. The top of each parasequence represents a significant break in the sedimentation (diastem). The surface is cemented and covered with mollusk shells. At the shoreline, the prograded-seaward, shale-dominated Dadaş-1 and Dadaş-2 Members were conformably overlain by the inner mouth bar reservoirs sandstones, which were deposited by the delta distributary channels (Şenalp et al., 2018, 2021; Şenalp and Tetiker, 2023, 2024).

The deltaic sandstone facies forms the progradational parasequence set of the Dadaş Formation. In some cases, there are two distinct delta lobes consisting of the outer and inner mouth bar sandstones, which are separated by the offshore marine shales. The top of the deltaic sequence is eroded by the Pre-Kuşdamı Unconformity surface, indicating the impact of the Caledonian (Devonian, 420 Ma) tectonic event. The lowermost part consists of the interbedded sandstone and shale and displays wave ripples and abundant horizontal burrows and bioturbation. This facies is cut periodically by the high-angle, cross-bedded, medium- to coarse-grained, well-sorted, porous, weekly cemented, channel-fill sandstones, representing the inner mouth bar facies of the deltaic environment. The sandstones were deposited under a fluvial, wave- and tide-dominated environment (Figure 15). Both the outer and inner mouth bar sandstones have excellent reservoir quality and produce hydrocarbon in many wells in the Diyarbakır region.

8. Devonian System (419–359 Ma)

8.1. Saudi Arabia

The Late Silurian Sharawra Member of the Qalibah Formation and the Carboniferous Berwath Formation are the boundaries of Saudi Arabia's Devonian System, which is best exposed in the Sakaka (Al-Jawf) and Ha'il regions. It is represented by the Tawil, Jauf, and Jubah formations. In

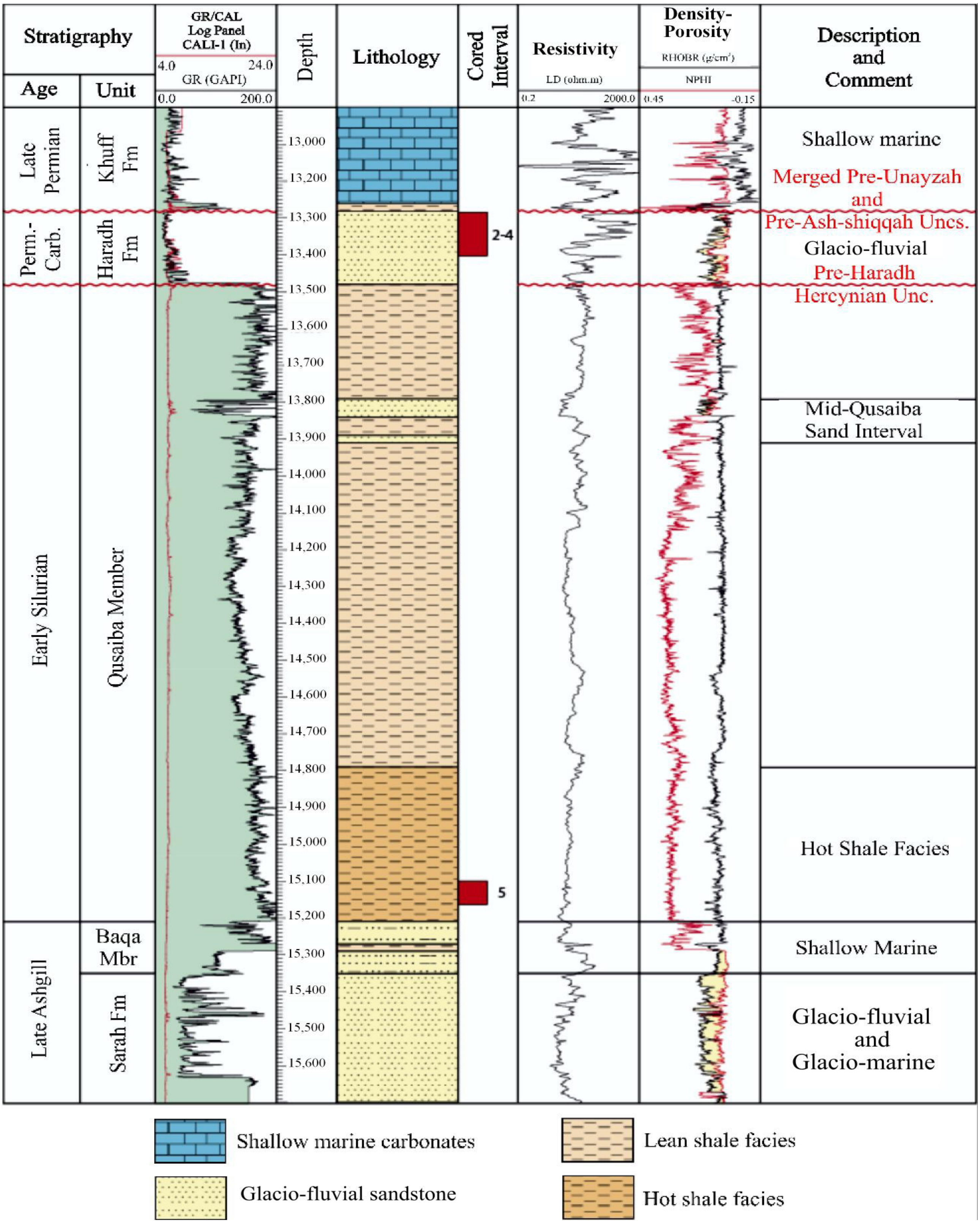

Figure 14. Suite of well logs of the Qusaiba and Baq'a members of the Qalibah Formation in the Mazalij well. The rest of the Paleozoic successions were cut and eroded by the regional unconformities during the Hercynian orogenesis (305 Ma) and Permo-Carboniferous glaciation (300 Ma). There is a thick hot shale facies directly overlying the Baq'a Member (Şenalp, 2006a; Şenalp and Tetiker, 2020).

Figure 15. Strongly cross-bedded, medium- to coarse-grained, well-sorted, inner mouth bar sandstones of the delta environment, forming the uppermost part of the Dadaş Formation. The sandstone produces hydrocarbon and is defined as the Hazro Reservoir (Şenalp et al., 2018).

every part of Saudi Arabia and southeast Türkiye, the base of the Devonian successions is characterized by a regional unconformity surface representing the Acadian phase (?) of the Caledonian Orogeny during the Late Silurian to Early Devonian.

8.1.1. Tawil Formation

The Early Devonian Tawil Formation was formally described by Steineke et al. (1958) from the north-facing escarpment at Jabal At-Tawil, located 50 km southwest of the town of Dawmat Al-Jandal in the Al-Jawf region. The well-exposed section consists of more than 300-m-thick, red- to black-colored, strongly cross-bedded, medium- to coarse-grained, partly conglomeratic, iron-stained sandstone. The Tawil Formation was also encountered in many wells drilled in northern and central Saudi Arabia for deep gas exploration in the Devonian Jauf Reservoir overlying the Qalibah Formation. Şenalp (2006b) and Şenalp et al. (2018) divided the section into five fining- and thinning-upward units (parasequences). Each unit shows a similar lithofacies stacking pattern and starts with an irregular erosion surface (type-1 sequence boundary), formed at the base of the fluvial sandstones, and capped by strongly tigillite (*Skolithos*)-burrowed marine sandstones. The section just above the erosional surface is a very thick-bedded, massive to large-scale, cross-stratified, coarse- to very coarse-grained, conglomeratic sandstone deposited by high-energy, sand-dominated fluvial system. This middle section is deposited in a fluvio-marine environment. The upper parts of the unit consist of fine- to very fine-grained, strongly tigillite-burrowed sandstones. This upper unit also contains well-developed tidal channels, and tidal flood deltas. Stratigraphically, the potential reservoir sandstones are close to the prolific source rock shale facies of the Qusaiba Member. However, thus far, there have been no hydrocarbon discoveries made in this formation.

8.1.2. Jauf Formation

The Jauf Formation, consisting of a 283-m-thick sequence of sandstone, shale, and limestone exposed in the typical area, 15 km northwest of the town of Dumat al-Jandal, was introduced by Berg et al.[3] The Jauf Formation was subdivided into five formally defined conformable members. These are from top to bottom: the Murayr, Hammamiyat, Subbat, Qasr, and Sha'iba members (Şenalp, 2006b; Şenalp et al., 2018).

[3] Berg ELB, Beverly Jr, Northrup, Steinekem M, Bramkamp, RA (1944). In: Al-Laboun AA (editor). Lexicon of the Paleozoic and lower Mesozoic of Saudi Arabia. Saudi Arabia: Al-Hudhud Publishers.

The shale-dominated marine Sha'iba Member is conformable with the underlying large-scale, cross-bedded fluvial sandstones of the Tawil Formation and represents the MFS Devonian 10 (MFS D10). The Pre-Islamic Fort Qasr Marid in Dawmat Al-Jandal was built on the type section of the Qasr Member. The most distinctive feature of the Qasr Member in the Al Jawf area is the occurrence of large algal mounds in the massive limestones of the upper half of the section. The Subbat Member consists of a coarsening- and thickening-upward, lowstand, deltaic parasequence set. The regularly interbedded sandstone and shale facies of the outer distributary mouth bar is cut deeply by the overlying distributary channel facies. The channel-fill sandstone section is capped directly by the limestone (rim rock) of the Hammamiyat Member. The uppermost coarsening- and thickening-upward, deltaic parasequence is also exposed in the Al-Huj area, in northern Saudi Arabia (Şenalp, 2006b; Şenalp et al., 2018). The Hammamiyat Member gradually overlies the thin limestone layers of the Subbat Member and itself is conformably overlain by the Murayr Member of the Jauf Formation. The 118-m-thick continuous section of the Hammamiyat Member consists of alternations of light gray, thin- to thick-bedded, very-fine, crystalline limestone and coarse crystalline dolomite (Şenalp, 2006b; Şenalp et al., 2018). The lower surface of the Murayr Member is conformable with the Hammamiyat Member, but its upper part is eroded by the erosional surface at the base of the Jubah Formation. The Murayr Member is a mixed siliciclastic and carbonate facies, consisting of sandstone, siltstone, shale, sandy dolomite, and limestone. This member contains abundant fish debris and fragments of *Prototaxities* (terrestrial fossil fungi) (Şenalp, 2006a, 2006b).

8.1.3. Jubah Formation

The Jubah Formation was first introduced by Şenalp (2006b) to define the upper part of the siliciclastic section exposed in the Al Jubah area, near the town of Sakaka, in the northeastern part of Saudi Arabia. He reported the presence of a sharp erosional unconformity surface at the base of the Jubah Formation (Pre-Jubah Unc.). It cuts deeply into the lower part of the Murayr Member, or even about 20 to 23 m into the Hammamiyat Member. The Jubah Formation is unconformably overlain by the Cretaceous Aruma or Biyadh formations. However, in many places, its upper part is usually cut by the Hercynian Unconformity (Permo-Carboniferous) surface. Only in the Abu Safah-29 and ST-8 wells, the Jubah Formation is conformably overlain by the Carboniferous Berwath Formation. In the type locality, the Jubah Formation is 220 m thick and consists of red- to brown-colored, thin- to thick-bedded, fine- to medium-grained, moderate to poorly sorted, friable- to weakly cemented sandstone. Sedimentologic studies of this formation in the Al-Jawf and Al-Huj areas indicated that the sediments were deposited by a braided stream system (Şenalp, 2006b; Şenalp et al., 2018). The sandstone units form vertically and laterally stacked, fining-upward, channel-fill sequences. All the evidence (siltstone, shale or mudstone facies) observed at various outcrops and in the measured sections indicates that a high-energy hydrodynamic system prevailed during the deposition of the upper part of the Jubah Formation. They might represent type-1 sequence boundaries (erosional unconformities) due to a periodic drop in the sea level.

8.2. Southeast Türkiye

The Kayayolu Formation, which is found in the Hazro area of Diyarbakır, is the name given to the Devonian succession found in southeast Türkiye (Bozdoğan et al., 1987). Due to the continuous tectonic activity in this area during the Paleozoic era, the Devonian succession was severely affected by these numerous tectonic events, with just the lowest portion of the succession remaining preserved. The type section of the formation was determined in the exploration wells. The Kayayolu Formation directly overlies the deltaic sandstones of the uppermost member of the Dadaş Formation. The boundary between these two formations is a regional unconformity surface, formed during the Caledonian Orogeny. The impacts of the regional Hercynian orogeny (305 Ma) and following glacial unconformities of the Permo-Carboniferous age (300 Ma) were recognized in the cores and logs of the exploration wells in subsurface. The strong regional unconformity at the base of the Middle-Late Permian continental Kuşdamı Formation cuts directly into the Kayayolu Formation and greatly reducing its thickness. This Pre-Kuşdamı Unconformity is confidently linked with the Pre-Unayzah Unconformity in Saudi Arabia.

The Kayayolu Formation in the measured outcrop section in the Hazro area is 182 m thick and overlies the red paleosol surface developed on the Caledonian Unconformity surface. Shale of a greenish-gray color covers the interbedded sandstone and shale facies at the bottom of the section. The upper part is represented by the thickly bedded, algal, dolomitic limestone. In the Kayayolu-2 and Kayayolu-4 wells, drilled in the Diyarbakır region, the 188-m-thick section consists of limestone, dolomitic limestone, and dolomite. The algal carbonates of the Kayayolu Formation are lithologically similar to the Qasr Member of the Jauf Formation in Saudi Arabia.

9. Early Carboniferous System (359–323 Ma)

In Saudi Arabia, and other countries of the Arabian Platform, Carboniferous successions are severely eroded and removed by both the overlying tectonically driven Hercynian Unconformity (305 Ma), and the deeply incised erosional surface of the Permo-Carboniferous Gondwana continental glaciation (300 Ma). In Saudi Arabia, only the

Early Carboniferous Berwath Formation was reported in a few exploration and production wells. In southeast Türkiye (Diyarbakır region), the Carboniferous System is completely missing, and the Late Permian siliciclastic continental Kuşdamı Formation directly overlies the Early Devonian algal carbonates of the Kayayolu Formation.

9.1 Saudi Arabia

9.1.1. Berwath Formation

The continental red bed Jubah Formation (Late Devonian) is transgressively overlain by the Carboniferous Berwath Formation. The full section of the Berwath Formation was identified in Stratigraphic wells ST-8 (110-m-thick type section), ST-7, and Abu Safah-29 (reference section). Şenalp (2006a) reported that stratigraphically, the Berwath Formation extends between the Jubah Formation and the Pre-Haradh Unconformity (Hercynian). Based on the cores and cutting samples, the stratigraphic section consists of sandstone, shale, organic-rich coaly shale, and dolomite, which were deposited in a warm shallow marine to large coastal plain environment in a highstand system tract. The reference well, Abu Safah-29, is located in the Arabian Gulf, about 530 km northeast of Riyadh. This well has penetrated into the Haradh (Permo-Carboniferous), Berwath (Carboniferous), and Devonian-aged Jubah, Jauf, and Tawil formations. Therefore, the 124.97-m-thick section of the Berwath Formation is more complete and better defined than the ST-8 well. The age of the Berwath Formation was defined as Early Carboniferous (Mississippian), representing the time span extending from Tournaisian to Serpukhovian (359–323 Ma). No reservoir facies developed in the Berwath Formation, but organic-rich shales may be considered as a rather poor-quality source rock facies compared to the hydrocarbon accumulation in the glaciogenic sandstone reservoirs of the Haradh Formation that lie above.

10. Permo-Carboniferous System (305–290 Ma)

The time interval between 305 to 290 Ma, which includes the Late Carboniferous and Early Permian, is referred to as the Permo-Carboniferous epoch. In locations where there is no obvious stratigraphic break and where transitional fossils are present, permo-carboniferous rocks can be found. During the Permo-Carboniferous (about 300 Ma), there was a period of great Gondwana continental glaciation. The sequence stratigraphy of the Permo-Carboniferous and Permian successions in Saudi Arabia and southeast Türkiye is characterized by the occurrence of a number of unconformities and the MFS. This interval extends between the top of the Berwath Formation (Hercynian Unconformity, 323 Ma), and the MFS P20 (260 Ma) at the base of the Khuff D carbonate. It is known as the Unayzah Reservoir and includes stratigraphically and sedimentologically different formations separated by the regional unconformity surfaces. These regional unconformities were formed by worldwide orogenic events, Gondwana glaciation, and sea-level fluctuations.

In Saudi Arabia, the thick stratigraphic sequence, deposited during the Permo-Carboniferous System, extends between the Pre-Haradh (Hercynian) Unconformity (305 Ma) at the base, and the Pre-Unayzah Unconformity (290 Ma) at the top. It is underlain by the Berwath Formation and overlain by the Late Permian red bed Unayzah Formation. This thick succession includes the Ruhaiya and Juwayl formations in the Wajid Outcrop Belt (southwestern Saudi Arabia), and the Jawb and Haradh formations in the subsurface of central Arabia (Şenalp and Al-Duaiji, 2001b; Şenalp et al., 2018; Senalp and Tetiker, 2022).

10.1. Southern Saudi Arabia

10.1.1. Juwayl Formation

The two well-defined, northwest–southeast trending, U-shaped glacial paleovalleys of the Juwayl Formation are located in the Wajid Outcrop Belt's northeastern section. They are covered in the algal cap carbonates of the Ruhaiya Formation and cut deeply into the strongly cross-bedded sandstones of the Khusayyayn Formation (Şenalp, 2006b; Senalp and Tetiker, 2022). The Neoproterozoic Arabian Shield is just beneath the paleovalleys in several locations. While the easterly paleovalley system is 160 m deep, 10 km wide, and extends in a south–north direction, the part that is visible of the westerly paleovalley system is at least 152 m thick, up to 8.2 km wide, and extends approximately 50 km in a southeast–northwest direction. In the measured section, the Juwayl Formation is 130 m thick and consists of large, polished and striated, granitic erratic boulders deposited as lodgment tillites directly on the large-scale, long and deep grooves, polished and striated glacial pavements (Figure 16). The erratics, which originated from metamorphic and granitic basement and range from less than 0.38 to 1.7 m in diameter, occur in two zones. The lower zone is 30 m above the base and the upper zone is 70 m above the base. Gray-green to red silty shale predominates in the first 50 m, with sandstone interbedded with fine-grained, tan to purple sandstone that includes a significant quantity of white striated quartz and chert pebbles.

10.1.2. Ruhaiya Formation (MFS P10)

Situated directly on the tillite facies of the Juwayl Formation, the measured Ruhaiya type section is roughly 20 m thick and situated on a small hill known as Bani Ruhaiya (Şenalp, 2006b; Şenalp et al., 2018; Senalp and Tetiker, 2022). Ferruginous crusts measuring a few centimeters thick indicate the interface between these two formations. Faded to light gray marl, shale, and siltstone facies are interbedded at the beginning of the Ruhaiya Formation.

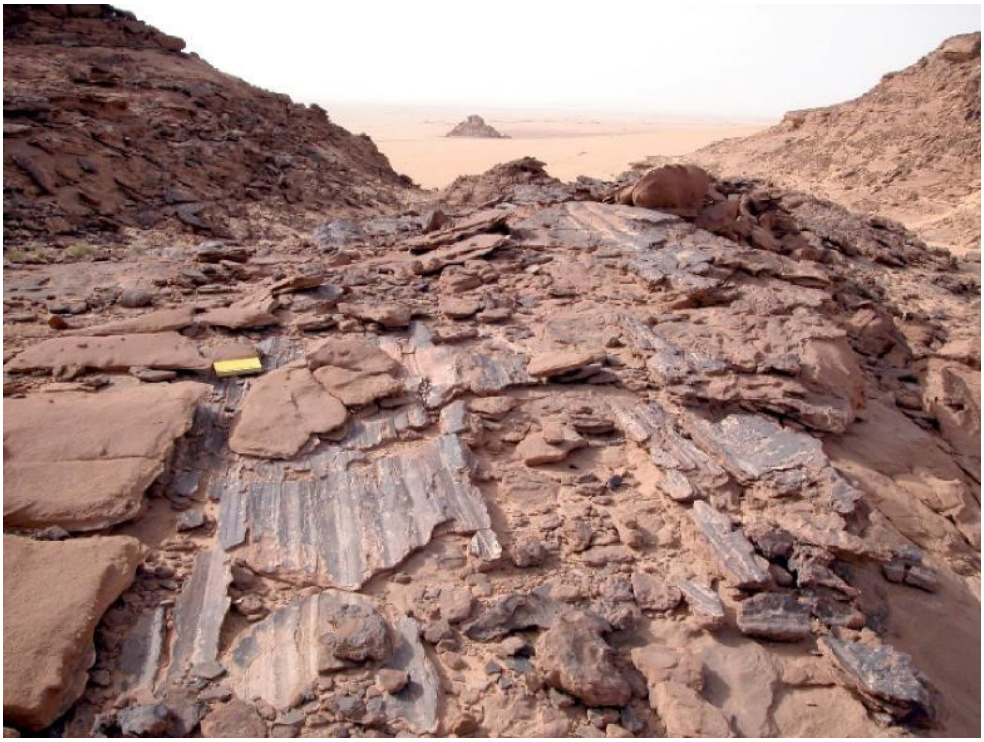

Figure 16. The bottom part of the Juwayl Formation is frequently home to large-scale, long, deep grooves as well as striated, polished glacial pavements, which provide concrete proof of the formation's glacial deposition. This specific outcrop can be found in the Al-Qarfa area (19°58′33″N, 44°34′24″E). The ice mass drifted toward the north, as indicated by the striates (Şenalp, 2006b; Şenalp and Tetiker, 2020).

Algal dolomitic limestone facies and light bluish-gray, sandy, silicified limestone are conformably layered above this. Dome-shaped algal laminations distinguish the limestone and algal dolomitic limestones. The beds of dolomitic and limestone are silicified, thick, and full of chert nodules. They also have thin layers of pinkish fine-grained sandstone interspersed throughout; however, there is clear evidence of algal laminations in these beds. According to Şenalp (2006b), the Ruhaiya Formation represents the MFS Permian10 (MFS P10, 290 Mabp) and was formed as a cap carbonate facies during the end of the deglaciation period. It shares genetic affinities with the Permo-Carboniferous glaciations. Similar lithofacies assemblage also occurs in the same stratigraphic interval, known as Lusaba Limestone in Oman.

10.1.3. Late Palaeozoic glaciation in the subsurface of central Arabia

The Haradh and Jawb formations of the Unayzah Reservoir were glacially deposited, and Senalp and Al-Duaiji (2001b) introduced them and connected them with the Juwayl and overlying Ruhaiya formations after oil and sweet gas were discovered in the glaciofluvial sandstones in various areas in central Saudi Arabia. Additionally, they established a correlation between the Juwayl Formation and the boulder beds of the Al Khlata Formation in Oman's Haushi Group (Penney et al., 2011).

The Unayzah Reservoir, extending between the Late Permian (259.1 Mabp, base Wuchiapingian) Khuff D carbonate at the top and the Hercynian (pre-Haradh) Unconformity (307 Mabp, base Kosimovian) at the bottom, is an informal definition of the Permo-Carboniferous successions in central Saudi Arabi. Four formations constitute this broad stratigraphic succession that produces hydrocarbons; they reflect the marine (Ash-Shiqqah Formation), continental (Unayzah Formation), and glacial (Haradh and Jawb formations) environments. The mfs and regional (pre-Ash-Shiqqah and pre-Unayzah) unconformity surfaces divided these formations (Senalp and Al-Duaiji 1995, 2001b; Şenalp et al., 2018; Senalp and Tetiker, 2022). Following these findings, extensive drilling was conducted, yielding an extensive amount of new subsurface lithologic and palynologic data that have been used to determine the genetic stratigraphy and sedimentology of the Carboniferous, Permo-Carboniferous, and Permian systems. Between the Hercynian (pre-Haradh) and pre-Unayzah unconformities lies the lower stratigraphic layer (Late Carboniferous to

Early Permian), which contains the genetically linked and conformable formally designated glaciogenic Haradh and Jawb formations (Figure 17).

10.1.3.1. Haradh Formation

The Permo-Carboniferous glaciogenic deposits were initially identified by Şenalp (1997, unpub. company rep.) in the cores of the deep exploration well, Haradah-601, discovered in the central Saudi Arabian Haradh field. The same successions, commonly referred to as the Haradh Formation, were found in numerous other fields in the same region, including Wudayhi, Waqr, Tinat, Niban, and Jaw (Şenalp and Al-Duaiji, 2001b). They suggested that the deep and narrow proximal glacial paleovalleys of the Juwayl Formation, exposed in the Wajid Outcrop Belt

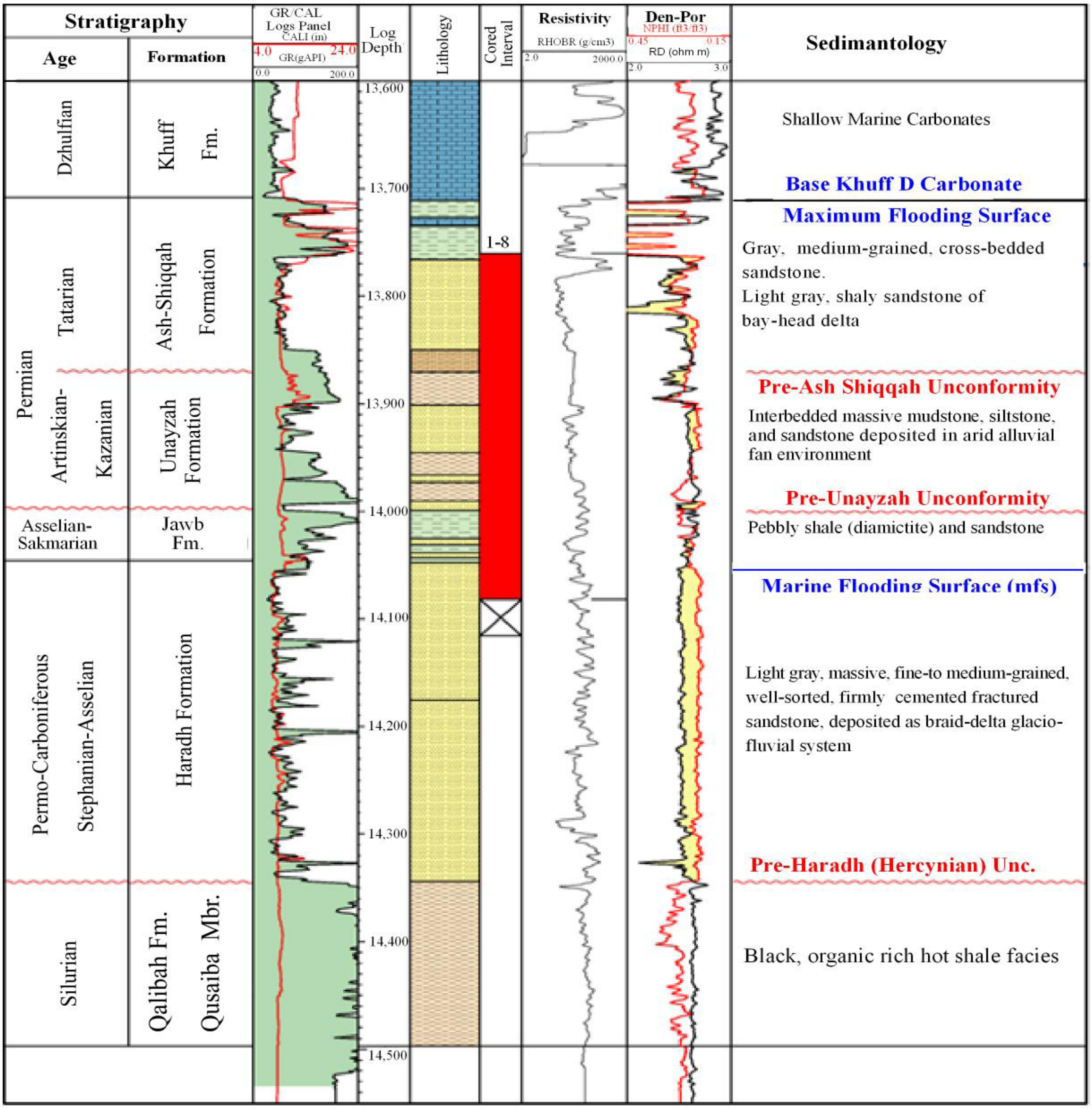

Figure 17. Sequence stratigraphy of the Permo-Carboniferous successions (Unayzah Reservoir), consisting of the Juwayl (Haradh), Jawb, Ruhaiya, Unayzah, and Ash-Shiqqah formations, encountered in the Wudayhi-2 well, drilled in central Saudi Arabia. The major stratigraphic difference between the Wudayhi-1 and Wudayhi-2 wells indicates the erosional importance of the various unconformity surfaces in the Paleozoic successions (Şenalp, 2006b; Şenalp et al., 2018).

(southwestern Saudi Arabia), expanded from the south to a north direction. They deposited hydrocarbon-producing glaciofluvial and cold desert eolian sandstones of the 350-m-thick Haradh Formation in the subsurface in central Saudi Arabia. The Hercynian Unconformity and the Early Silurian Qusaiba Member of the Qalibah Formation are both cut by the unconformity surface at the base of the deep glacier valleys. If the reservoir fractures, the Haradh formation, which is composed of fine- to coarse-grained, well-sorted, silica-cemented, and occasionally high-angled, cross-bedded sandstone, will release gas. The diamictite facies, sandstone, and interbedded, interlaminated, dark gray shale make up the conformably underlying Jawb formation. These two formations were formed as a glaciolake or glaciomarine facies, huge glaciofluvial braided stream, and cold-climate eolian sand dune during the Permo-Carboniferous Gondwana glaciation and the deglaciation eras that followed. The most abundant source rock potential for the glaciogenic sandstone reservoirs of the Haradh Formation, which are immediately above it, is found in the organic-rich hot shale facies of the Early Silurian (Rhuddanian, 444 Mabp) Qusaiba Member, which extends deeper by the Hercynian Unconformity surface in many wells drilled in central Arabia.

10.1.3.2. Jawb Formation

The Jawb Formation was first recognized and formally introduced to the Permo-Carboniferous stratigraphy by Senalp and Al-Duaiji (2001b), during core studies in the Jawb-1 well, drilled in central Saudi Arabia. The type section in this well is 43.6 m thick and of that, a 13.6-m-interval was cored. The Jawb Formation conformably overlies the thick sandstones of the genetically related Haradh Formation. It is nonconformably overlain by the homogeneous red siltstone and playa mudstone facies of the continental Unayzah Formation. The Jawb Formation in the cores consists of regularly interbedded, shallow marine, lacustrine, and glaciogenic sediments. Shallow marine sediments are represented by dark gray to black homogeneous shale, laminated shale, siltstone, and sandstone. However, the top portions of the sandstone have well-developed wave ripples. These sediments were deposited in the offshore and distant regions of the lower shoreface environments. The glaciogenic sediments are made up of thick beds of massive-looking, pebbly mudstone (diamictite) facies, which are irregularly distributed throughout the silty shale matrix. There is significant disruption in the connections between the big stones and the shale laminae. During the deglaciation eras, the floating ice mass (iceberg) released pebbles into the shallow sea environment.

11. Permian System (289–260 Ma)

11.1. Saudi Arabia

Between the Pre-Unayzah Unconformity (289 Ma) at the base and the MFS P20 (260 Ma) that developed at the base of the Khuff D carbonate, lie the stratigraphic succession deposited during the Permian System. This succession includes the continental Unayzah and the marine Ash-Shiqqah formations, separated by the Pre-Ash-Shiqqah Unconformity. The Ash-Shiqqah Formation consists of the Lower Ash-Shiqqah and Upper Ash-Shiqqah members separated by the type-1 sequence boundary developed at the base of the incised valley and its associated lowstand delta. In some cases, this unconformity surface cuts through the underlying Unayzah Formation and the progradational lowstand delta parasequence sits directly on the Permo-Carboniferous glaciogenic Haradh Formation. However, it is also true that in many cases, the Pre-Unayzah Unconformity cuts into the deeper parts of the Permo-Carboniferous successions and Pre-Unayzah and the Pre-Haradh unconformities merge together (Şenalp and Al-Duaiji, 2001b; Şenalp et al., 2018).

11.1.1. Unayzah Formation

Forming the middle section of the most productive sandstone of the Unayzah Reservoir, the Middle Permian Unayzah Formation occurs between the Pre-Unayzah and Pre-Ash-Shiqqah unconformities. The type section of the Unayzah Formation is only 8.5 m thick, and located in downtown Unayzah, where the small outcrop of the formation is exposed among houses. Recently, this location was completely destroyed and turned into a recreation area. The 36.3-m-thick reference section of the formation is located in Wadi Al-Shajarah in the Qusaiba depression, and it is thicker and better exposed than at the type locality. In the subsurface, the Unayzah Formation was first encountered in the Hawtah-1 discovery well. Senalp and Al-Duaiji (1995, 2001b) reported the Hawtah-6 well as the subsurface reference well of the Unayzah Formation.

The Upper Unayzah Formation sits differentially on the previous layers and is composed of reddish-colored, cross-bedded sandstone, well-sorted mudstone, siltstone, sandstone, caliche, and a minor nodular anhydrite. The most significant and most dominant reservoir facies is the medium- to fine-grained, high-angle, cross-bedded eolian sandstones (Figure 18). In many intervals, fine- and medium-grained sandstones alternate regularly as well-defined laminae and display color banding in the foreset beds. The medium-grained sandstone is well-sorted to very well-sorted, except for those grains that have quartz overgrowth around them.

In the Late Artinskian to Kazanian era, the Unayzah Formation was deposited in a continental setting as merging alluvial fans predominated by braided streams and an eolian system. These conditions graded into a meandering stream and playa lakes (Şenalp and Al-Duaiji, 2001b). In central Arabian fields, the Pre-Unayzah Unconformity cuts deeply into the Qasim Formation and good-quality reservoir sandstones sit directly on the most prolific hot shale source

Figure 18. Core photos of the Unayzah Formation's fine-to medium-grained, well-sorted, high-angle, planar-tabular, hot-desert eolian dune sandstone facies found in the Shamah-1 well in central Arabia. The thick caliche facies covers this thick dune sandstone facies (Şenalp, 2006b; Şenalp et al., 2018).

rock facies (e.g., Hawtah-1 well). Hydrocarbons produced in the hot shale facies migrate directly into the porous and permeable fluvial and eolian sandstones (Şenalp and Al-Duaiji, 2001b). The Upper and Middle members of the Gharif Formation in Oman are correlated with the Unayzah Formation (Şenalp, 2006b; Şenalp et al., 2018).

11.1.2. Ash-Shiqqah Formation

The Late Permian (Roadian-Capitanian) marine siliciclastic Ash-Shiqqah Formation creates the uppermost part of the Unayzah Reservoir (Şenalp and Al-Duaiji, 2001b). Stratigraphically, it extends among the Pre-Ash-Shiqqah Unconformity surface on top of the Unayzah Formation at the base, and the Khuff D Carbonate MFS (259.1 Mabp) at the top (Figure 15). It is informally separated into the Lower and Upper Ash-Shiqqah members through a type-1 sequence boundary.

The Lower Ash-Shiqqah Member extends between the Pre-Ash-Shiqqah Unconformity surface at the base and the type-1 sequence boundary at the top. It is a transgressive sequence consisting of basal transgressive sandstone overlain by the offshore marine shales, interbedded shale, and sandstone. The lower contact of the Upper Member of the Ash-Shiqqah Formation is a type-1 sequence boundary that developed at the base of the incised valley, indicating a substantial drop in the sea level (Figures 19a and 19b). The shallow marine carbonates of the Khuff Formation, which represent the MFS P20, conformably cover the top of the section (260 Ma).

The Upper Member consists of genetically related incised valleys and lowstand deltaic sequences (Figure 19). They form very thick and productive oil and gas reservoirs. This valley-fill sequence in subsurface ranges in thickness between 27 and 33 m in the Hazmiyah field. They formed more than 150-m-thick lowstand deltas in the Abu Shidad, Haradh, Wudayhi, and Waqr fields in central Saudi Arabia. In some wells, there is organic-rich, dark gray, early shale at the base of the lowstand delta sequence. This shale has source rock potential for generating oil and gas in the

Figure 19. (a–b) Fluvial-dominated incised valley-fill sequence consisting of coarse-to very coarse-grained, strongly cross-bedded sandstone. There are large, silicified logs at the base of the incised valley, oriented parallel to the paleocurrent direction (Şenalp, 2006b; Şenalp et al., 2018).

overlying incised valley-fill sandstones and the lowstand deltaic sequences.

11.2. Southeast Türkiye

The stratigraphic succession of the Permo-Carboniferous System is entirely missing in southeast Türkiye. In the Hazro area of the Diyarbakır region, the Permian System spreads from the base of the thick carbonate succession of the Gomanibrik Formation to the MFS P20 (260 Ma), which developed at the base of the Pre-Kuşdamı Unconformity (290 Ma). The Kuşdamı Formation's red bed continental series is a part of this succession and the shallow marine Kaş Formation (correlated with the Ash-Shiqqah Formation). The Kaş Formation is conformably overlain by the thick carbonates of the Gomanibrik Formation (correlated with the Khuff Formation) and represents MFS P20 (260 Ma).

11.2.1. Kuşdamı Formation

The Kuşdamı Formation was formally identified by Şenalp et al. (2018) in Kuşdamı village, near the town of Hazro. It was also found in the cores removed from the exploration wells in the Diyarbakır region. The lower and upper boundaries of the Kuşdamı Formation represent the most important regional unconformity surfaces of the Arabian Platform. The lower erosional boundary cuts into the Devonian Kayayolu Formation. The upper erosional boundary occurs at the base of the Kaş Formation and cuts into the Kuşdamı Formation. The type section consists of red-colored, massive mudstone, siltstone, evaporitic mudstone, and local lenses of fresh water limestone in the red mudstones. In the exploration wells, there are evaporates measuring 2 to 4–5 m thick (mainly anhydrite) interbedded with the red mudstones. The Kuşdamı Formation was deposited in a playa environment under arid climatic conditions.

11.2.2. Kaş Formation

The 41.5-m-thick, shallow marine, and coastal plain sediments of the Kaş Formation, near the town of Hazro, transgressively overlie the continental red bed mudstones of the Kuşdamı Formation. (Şenalp et al., 2018). Between these two formations, there is a thick layer of paleosol created by caliche, which suggests a large rift in the age of the section. The delta distributary channel-fill sandstones, shales and coal beds of the shallow marine and coastal plain sediments are conformably overlain by the thick carbonate section of the Gomanibrik Formation.

12. Conclusion

In this study, the importance of glacial depositional environment in forming potential reservoir sandstone facies was clearly established. The regional significance of substantial and recurring uplift on Saudi Arabia's central Arabian Arch was also highlighted by this study.

In Oman, in the southeastern part of the Arabian Platform, the Late Precambrian (Neoproterozoic) successions are conformably overlain by the Early Cambrian section and this transition is well documented in the deep exploration wells. In the remaining Infracambrian basins of Oman, Mauritania, and Mali, two separate periods of Cryogenian (720–635 Ma) glaciations are recognized throughout the Neoproterozoic; however, these two stages of glaciation are only recognized from Oman.

The igneous Proterozoic Basement is directly beneath the Paleozoic successions in Saudi Arabia and other Middle East countries, including southeast Türkiye. The sedimentary series was continually deposited from the early Cambrian to the late Permian eras. The sandstone and carbonate rocks of the Paleozoic successions in Saudi Arabia and other nations on the Arabian Platform have recently been found to contain unassociated gas, condensate, and Arabian super light oil. A vast quantity of information on the subsurface geology of both reservoir and nonreservoir formations has been obtained from stratigraphic and sedimentologic investigations of outcrop sections as well as the exploration and production wells from these numerous reservoirs.

The Arabian Platform's thick Paleozoic siliciclastic successions offer good prospects for a thorough sedimentary facies investigation and the creation of a sequence stratigraphic framework. In this study the entire Paleozoic succession extending between the Early Cambrian (MFS Cm10, 540 Ma) Sadan Formation and the Late Permian (MFS P20, 260.4 Ma) Khuff Carbonates were subdivided into the several formations and members based on the sequence stratigraphic principals (Figure 20). The MFS, mfs, and unconformities (sequence boundaries) produced by glaciers and tectonic activity. The MFS Ca20 (510 Ma) is represented by the thick carbonate Koruk Formation (early Middle Cambrian), which connects with the Burj Formation, which is defined in Jordan.

Special emphasis was given to the Late Ordovician (445 and 444 Ma) and Perrno-Carboniferous (350 and 240 Ma) continental Gondwana Glaciations. Their genetic relations with the overlying organic rich hot shale facies deposited at the base of the regional marine transgression following the deglaciation period highlighted the hydrocarbon potential of the glaciofluvial sandstone reservoirs. The Late Ordovician glaciofluvial sandstones (Zarqa and Sarah formations) produce oil and gas in almost every part of Saudi Arabia and Middle East countries. The Permo-Carboniferous (Haradh Formation) glaciofluvial and cold desert eolian sandstone reservoirs are represented only in central Saudi Arabia. The Caledonian (419 Ma) and Hercynian (305 Ma) orogenies are the cause of the tectonically generated unconformities. A number of

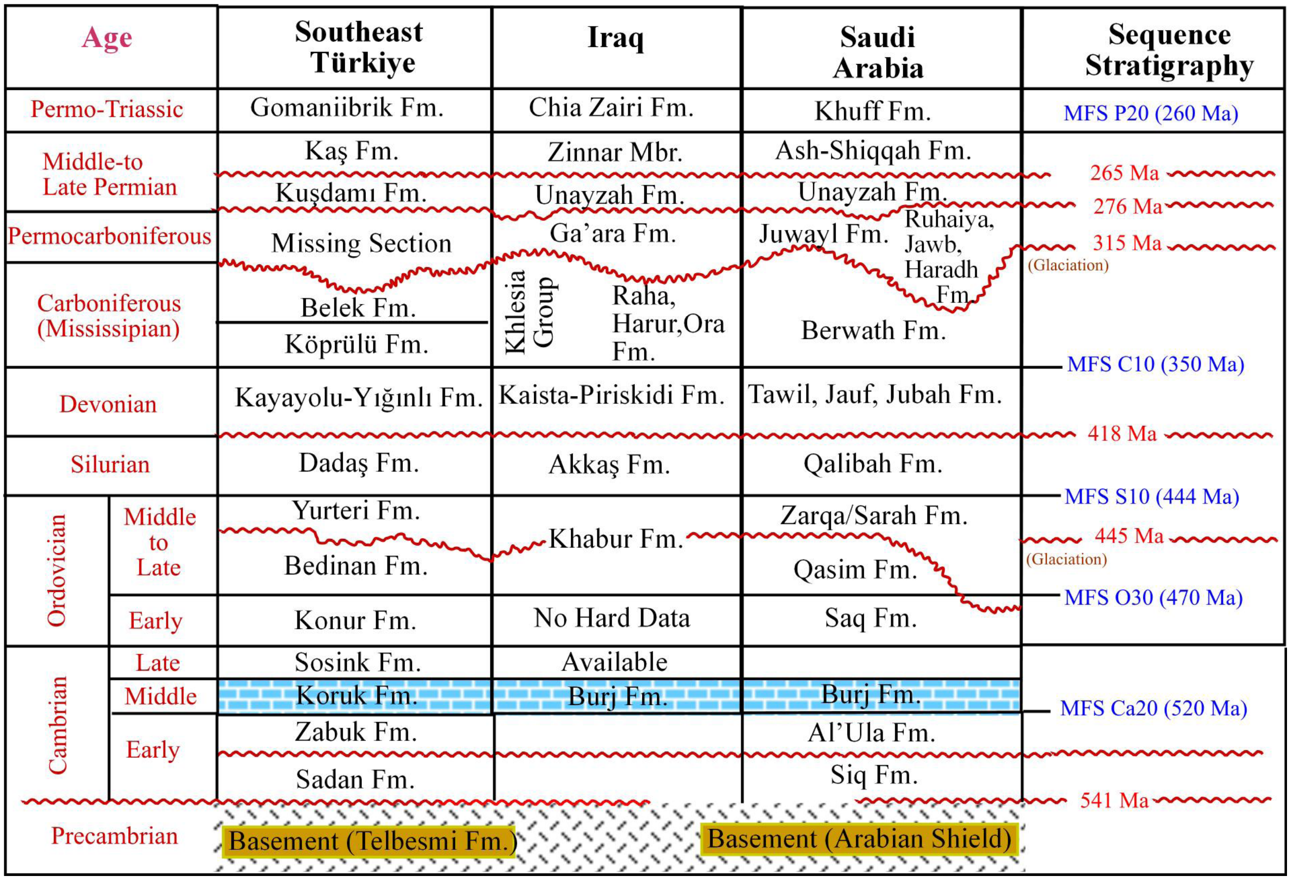

Figure 20. Regional sequence stratigraphic correlation of the Paleozoic successions (Şenalp, 2006b).

stratigraphic discontinuities, which include significant nonconformities and different sequence boundary orders, were also identified in the successions.

The well-developed parasequences and typical coarsening- and thickening-upward progradational parasequence sets were best defined in the Middle Ordovician, Silurian, and Devonian successions. The thick, massive, and organic-rich shales at the base are conformably overlain by oil-producing reservoir sandstones, which were deposited as distributary mouth bars and distributary channels in a fluvial-dominated deltaic environment. The hydrocarbons migrated upward from the underlying transgressive marine shales into the shallow marine sandstones. The Saudi Arabia Carboniferous sequence is poorly preserved since the Pre-Haradh (Hercynian) Unconformity surface destroyed the deposits. The glacier valleys in the Arabian Platform severely cut the tectonically created Hercynian Unconformity surface, creating a highly uneven surface that the glacial sediments were deposited on.

The Permian succession in Saudi Arabia stretches from the base of the Khuff Formation to the Permo-Triassic boundary at the Pre-Unayzah Unconformity. A significant rifting that produced several isolated intermountain basins where the deep red continental sediments were present is represented by the Pre-Unayzah Unconformity surface (alluvial fan, braided stream, meandering stream, eolian sand dunes, and playa mudstones) were deposited under arid climatic conditions during the Artinskian, Kungurian, and Roadian (290–269 Ma).

The marine Ash-Shiqqah Formation extends between the continental red bed Unayzah Formation and the carbonates of the Khuff Carbonates (269–260 Ma). It is divided into the Upper and Lower members, separated by a type-1 sequence boundary. The Lower Member of the Ash-Shiqqah Formation is transgressive on the continental red mudstones of the Unayzah Formation. The unconformity surface is indicated by a thick paleosol (caliche) that developed on the continental (playa) mudstones of the Unayzah Formation. The Upper Member of the Ash-Shiqqah Formation is transitional with the carbonates of the Khuff Formation. The MFS P20 (260.4 Ma), near the base of the carbonates, marks the long-term termination of siliciclastic deposition. Subsequently, the Arabian Platform evolved into a shallow carbonate shelf, often becoming so shallow that it gave rise to heavy layers of gypsum, anhydrite, and occasionally halite, forming an evaporitic pan. The excellent caprock of the Khuff Reservoirs was formed by these evaporite beds.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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