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ORIGINAL ARTICLE

Paleozoic tectono-stratigraphic framework of the Arabian Peninsula

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Abstract Thick Paleozoic succession of siliciclastics and carbonates is well exposed and penetrated in the greater Arabian Basin. The succession included source, reservoir, and seal rocks. Though, oil and gas have been discovered in sandstone and limestone reservoirs in these rocks in several oilfields in the basin, the tectonic history of this succession has not been fully understood yet.

The Paleozoic succession of the basin is severely affected by series of major climatic and tectonic events which have caused facies change and major stratigraphic breaks. The major tectonic movements have resulted in dividing the Paleozoic succession into mega-depositional cycles. The succession is subdivided into pre- and syn-climatic and tectonic events representing well defined depositional cycles separated by regional unconformities. These mega-depositional cycles are well preserved in basinal or less tectonically affected areas where boundaries between the respective cycles are marked by possible hiatus. In more tectonically active areas, the Paleozoic succession is less preserved and boundaries between the cycles are more complicated due to longer periods of erosion by later movements and/or non-deposition. Minor stratigraphic breaks within the mega cycles subdivide them into smaller sub-cycles.

Following the deposition of the Late Caradocian Quwarah member of the Qasim Formation the area went through a gentle uplift and tilt probably related to the Taconic tectonic movements, and a drop of sea level due to glaciation. Thick succession of the Quwarah, Ra'an, Kahfah, and Hanadir members of the Qasim Formation and the Risha and Sajir members of the Saq Formation were eroded and deep paleo-valleys incised in outcrops of the two formations. Glacial and periglacial deposits of the Zarqa and/or Sarah Formations were unconformably rest on older units from Ordovician to Precambrian.

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The second main event occurred during Late Silurian where the pre-existing successions, mainly on paleo-highs, were affected by tectonic movements synchronous with the Acadian tectonic phase of the Caledonian tectonic movements. The Early Devonian Tawil Formation unconformably rests on eroded Silurian and Late Ordovician deposits of the Sharawra, Qusaiba, and Sarah Formations in the Qusayba Depression in central Arabia.

The third main event is a regional tectonic movement contemporaneous with the Hercynian tectonic movement which have reached its maximum phase in the Late Carboniferous. Earlier successions from Carboniferous to Precambrian were affected and the Permo-Carboniferous Shajara Formation unconformably rests on all underlying Paleozoic rock units in central Arabia and other paleo-highs. The Shajara rests on the Devonian Jubah, Jauf and Tawil Formations, the Silurian Sharawra, Qusaiba, and Uqlah Formations, the Ordovician Sarah, Zarqa, and Qasim Formations, the Cambro-Ordovician Saq Formation, and finally rests on Precambrian Basement complex in central Arabia.

The Paleozoic outcrops in central Arabia offer an excellent geologic window documents the influence of the three tectonic movements. The Baq'a and Buraydah quadrangles show excellent outcrops of the glacial related deposits and the merge of the sub-Zarqa/Sarah unconformity, sub-Tawil unconformity, and sub-Shajara unconformity. The three unconformities represent the Taconic, Acadian (Caledonian), and Hercynian events, respectively.

1. Introduction

Thick and well preserved succession of Paleozoic rocks is exposed and penetrated in the greater Arabian Basin. Though, oil and gas have been discovered in sandstone and limestone reservoirs in these rocks, the tectonic history of this succession is not fully understood.

Geological field work investigation related to this paper is concentrated in northwestern and central Arabia (Fig. 1). This area extends from the Tabuk area in the west to the Qusayba depression in the east and from Ash Shuwayhitiyah and Wadi Aba Aruwath (ST-8 Well) in the north to Ad Dawadimi in the south (Fig. 2). In other terms, the studied area covers the Tabuk basin in the west and the Widyan basin in the east (Fig. 3). The two basins are separated by the Hail arch. Various outcrops in this area were visited to check stratigraphic relationships of the succession under investigation.

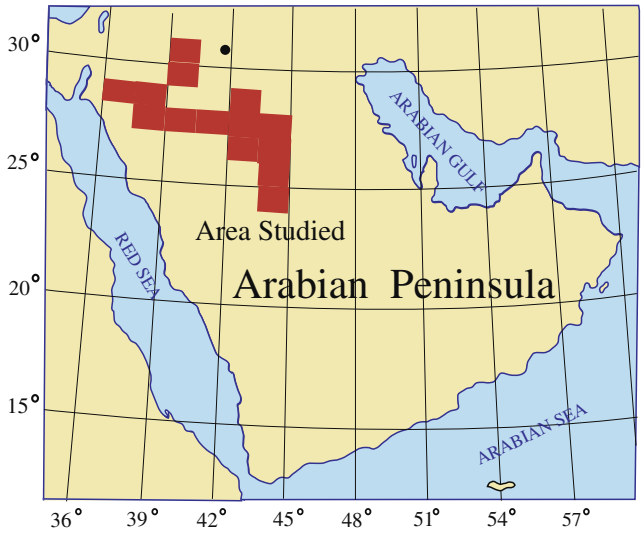

Figure 1 Index map showing the location of the studied area in northwestern and central Arabia.

Surface information and subsurface data from wells drilled in different parts of Arabia were used to demonstrate the influence of the movements in dividing the Paleozoic succession into mega-depositional cycles. The succession was subjected to climatic changes and was severely affected by series of tectonic movements.

The main objective of this paper is to document history of the three main climatic and tectonic events of the Paleozoic (Fig. 4). These events are time equivalent of global and well pronounce events of Late Ordovician Taconic movement and glaciation, Acadian, and Hercynian tectonic movements (Fig. 5).

2. Previous work

Scattered valuable information on the Paleozoic rocks in Arabia were contributed and summarized by many geologists. Among those are Powers (1968) and Laboun (1993) who compiled a great volume of data and published it in lexicons. Review of the geology of the Paleozoic is also attempted by Powers et al. (1966), Laboun (1982), and Vaslet (1987a,b). Geologic works by Janjou et al. (1996a,b, 1998), Vaslet et al. (1994, 1986), Bartlett et al. (1986), Manivit et al. (1987), Williams et al. (1987), Wallace et al. (1998), and Delfour et al. (1983) contributed valuable data and serve as handy references for detailed field works in northwestern and central Arabia.

3. Paleozoic lithostratigraphy

Paleozoic rocks are exposed in a great curved belt along the eastern margin of the Arabian Shield. Cambrian to Permian rocks are exposed in northwestern and central Arabia (Fig. 3). Nomenclature and age assignment of various Paleozoic units in Saudi Arabia are still very confusing and are subject to frequent revisions (Laboun, 1993).

The original Ordovician–Silurian Tabuk Formation of Steineke et al. (1958) was used, amended, and redefined formally and informally by many geologists; Layne and Reese (1960), Bramkamp et al. (1963a,b), Brown et al. (1963), Helal

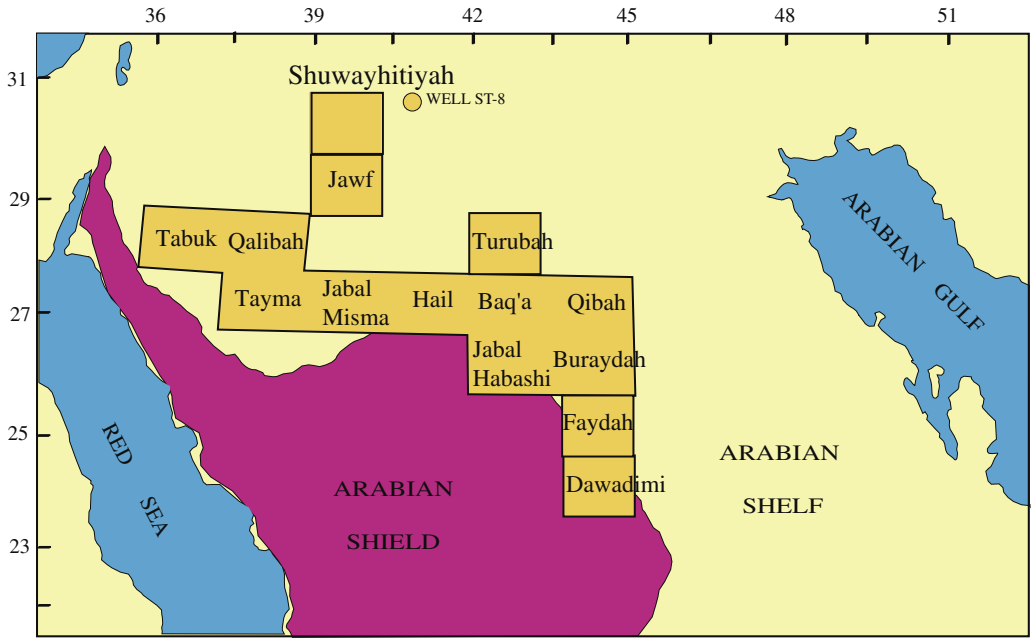

Figure 2 Location map showing the Tabuk, Al Qalibah, Tayma, Jabal Misma, Hail, Ash Shuwayhitiyah, Al-Jawf, Baq'a, Jabal Habashi, Qibah, Buraydah, Al Faydah, and Ad Dawadimi geologic quadrangles and ST- Well at Wadi Aba Arawth.

Figure 3 Generalized outcrop geologic map showing the distribution of the Paleozoic rocks exposed rocks in the Tabuk and Widyan basins in northwestern and central Arabia.

(1964), Powers et al. (1966), Powers (1968), McClure (1987), Clark-Lowes (1980), Laboun (1982, 1986), and Lozej (1983).

Recognition regional unconformities within the Tabuk Formation by McClure (1987), Clark-Lowes (1980), Laboun (1982, 1986), Laboun and Walthall (1988), Vaslet et al. (1986), Vaslet (1987a), Williams et al. (1986), Janjou et al. (1996a,b), Le Strat et al. (1985), and other geologists resulted in revising the lithostratigraphic nomenclature of the Lower Paleozoic where the term ''Tabuk Formation'' was discarded and new formations were introduced. The Tabuk Formation of Steineke et al. (1958), amended by Powers et al. (1966) is replaced by the Qasim, Zarqa, Sarah, Uqlah, Qusaiba, Sharawra, and Tawil Formations (Fig. 4).

The geologists of the Bureau de Recherches Geologiques et Minieres (BRGM) (1985) discarded the term Tabuk Formation and substituted it by seven formations: the Qasim Formation (Ordovician) (Vaslet, 1987a), Zarqa Formation (Ordovician) (Vaslet, 1987a), Sarah Formation (Ordovician–Silurian) (Williams et al., 1986), Uqlah Formation (Silurian) (Janjou et al., 1996b), Qusaiba Formation (Silurian) (redefined by Janjou et al., 1996b), and Sharawra Formation (Silurian) (redefined by Janjou et al., 1996b), and Tawil Formation (Silurian–Devonian?) (redefined Janjou et al., 1996b) (Fig. 4).

The Late Permian Khuff Formation as originally defined by Steineke et al. (1958) and redefined by Powers et al. (1966) was amended by Laboun (1982) by separating the siliciclastics at the base of the formation informally called ''basal Khuff Clastics'', ''Khuff sands'' ''Pre-Khuff Clastics'', ''Transition Zone'', and ''Incised Sand'' – from the overlying well defined carbonates and shales. Laboun (1982) introduced this

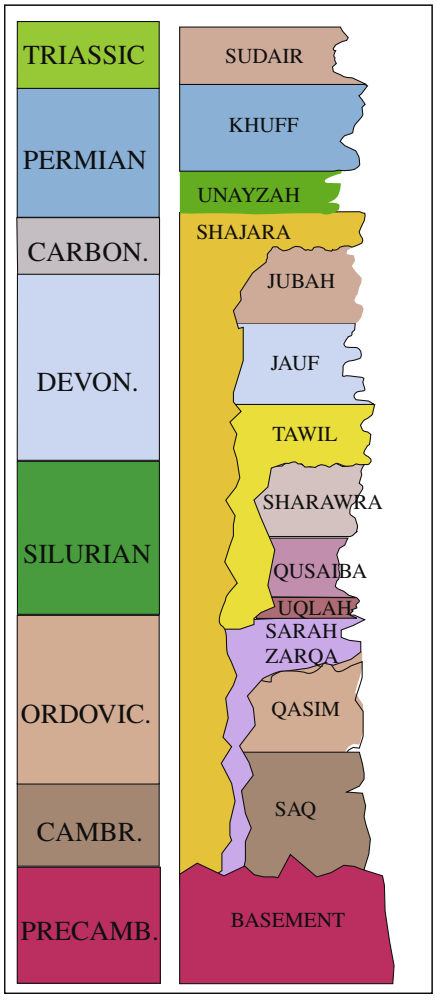

Figure 4 Composite stratigraphic section shows the nomenclature followed in this study.

section as a new lithostratigraphic unit called Unayzah Formation. The new formation, Unayzah Formation, was accepted by Saudi Aramco and have appeared in its Stratigraphic Column in March 1983. It was formally defined by Laboun (1986, 1987). A well defined sequence boundary was recognized within the Unayzah Formation. The formation was amended by Laboun (2009). The term Unayzah Formation was retained for the shallow marine sequence above the sequence boundary. The continental sandstones and shales below the boundary were introduced as the Shajara Formation. The Shajara Formation is best exposed at its type section at Wadi Ash Shajara, in the eastern side of the Qusayba depression. The basal contact of the Shajara Formation is marked by a regional unconformity where it rests unconformably on various older units from Devonian in the north to Precambrian in the south on the Central Arabian Arch.

3.1. Paleozoic Groups

The term "Tayma Group" was introduced to include all pre-glaciation succession, Saq and Qasim Formations.

The term Tabuk was reintroduced by Janjou et al. (1996a) as a group "Tabuk Group" to include "all the deposits assigned to the glacial episode that affected the continent of Gondwana during the Late Ordovician". Accordingly, the group includes the Zarqa, Sarah, and Uqlah Formations.

Janjou et al. (1996b) raised the Qalibah Formation of Mahmoud et al. (1992) to the group status "Qalibah Group" and raised the Qusaiba and Sharawra to formation ranks.

The term "Huj Group" was introduced for syn- and post-Acadian succession, comprising Tawil, Jauf and Jubah Formations.

The syn- and post-Hercynian succession, comprising Shajara, Unayzah, Khuff, Sudair, Jilh, and Minjur Formations, was included in the Buraydah Group.

The Paleozoic stratigraphic succession followed in this study is shown in Fig. 4.

3.2. Regional tectonic events

During the Paleozoic, central Arabia went through a series of epirogenic movements contemporaneous with the global tectonic movements. The Qa Hawban – Qa Qusayba – Niqrat Ablaq depression system is an excellent geological window showing the influence of the three main regional tectonic movements contemporaneous with the Taconic, Acadian (Caledonian) and Hercynian movements. The results of the three movements are represented by the sub-Zarqa/Sarah, sub-Tawil, and sub-Shajara unconformities, respectively (Fig. 5).

3.3. Taconic movement

Following the deposition of the Late Caradocian Quwarah member of the Qasim Formation the area went through a gentle uplift, tilt. This uplift is a time-equivalent to the Taconic tectonic movements. Thick section of the Quwarah, Ra'an, Kahfah, and Hanadir members of the Qasim Formation, the Rish and Sajir members of the Saq Formation, and Basement were exposed and eroded (Figs. 4 and 5). Drop of sea level and glaciation caused deep paleo-valleys incised in the outcrops of the two formations and Basement prior to the deposition of the glacial and periglacial deposits of the Zarqa and Sarah Formations (Figs. 4 and 5).

3.4. Glaciation

Late Ordovician–Early Silurian(?) global glaciation event is well documented in outcrops and represented by the glacial and periglacial deposits of the Zarqa and Sarah Formations (Fig. 4). Detailed field works by Janjou et al. (1996a,b) (Tabuk and Al Qalibah quadrangles, respectively), Vaslet et al. (1994) (Tayma quadrangle), Janjou et al. (1998) (Jabal Misma quadrangle), Bartlett et al. (1986) (Hail quadrangle), Vaslet et al. (1986) (Baqa quadrangle), Manivit et al. (1987) (Buraydah quadrangle), and Williams et al. (1987) (Jabal Habashi quadrangle) (Fig. 2) were used in this study to show the extent of the south hemisphere glaciation event into Arabia and its influence on the Lower Paleozoic succession.

3.5. Lithostratigraphy: Zarqa/Sarah Formations

The term Zarqa Formation was defined by Vaslet et al. (1986) for glacial deposits exposed at Jal (escarpment) Az Zarqa in the Baq'a quadrangle. The Zarqa Formation consists of repe-

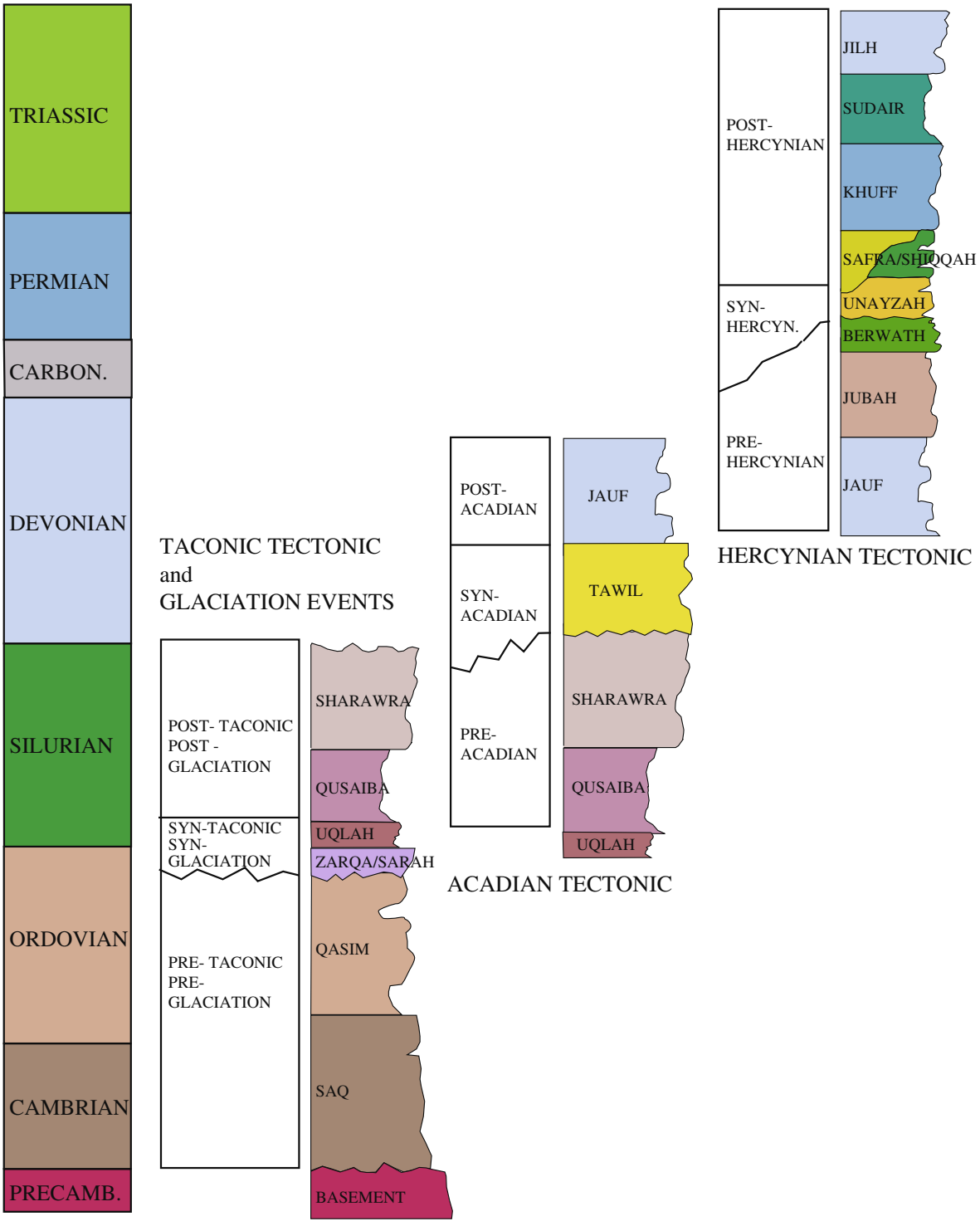

Figure 5 Generalized illustration showing the subdivisions of the Paleozoic succession into mega-depositional cycles.

tition of tillite, boulder-clay, and fine-grained, micaceous sandstone lithofacies.

The term Sarah member was first introduced by Clark-Lowes (1980, in the DGMR Open File Report, Laboun, 1993). It was introduced as a member for glacial and periglacial deposits in the Tabuk Formation. The term was raised to formational rank and formally defined by Williams et al. (1987). Vaslet et al. (1986) introduced and defined the term Hawban member for the upper section of Late Ordovician–Early Silurian(?) Sarah Formation.

The Sarah Formation cuts into the Zarqa, the Qasim and, in some places, into the Saq Sandstone (formation). Zarqa and Sarah Formation might be genetically related. Sarah Formation was deposited in more confined paleo-valleys reaching more than 300 m thick in outcrop. It consists mostly of fine- to coarse-grained, trough cross-bedded, current rippled fining

upward sandstone sequences of fluvial and or glaciofluvial origin. Glacially striated pavements occur in the lower parts of the formation, extending almost parallel to the paleo-valley axis.

The well pronounce sub-Zarqa or sub-Sarah unconformities mark the boundaries between the glacial related deposits of the Zarqa and Sarah Formations and underlying pre-glaciation Qasim and Saq Formations (Fig. 4).

The glaciation events subdivide the Cambrian–Ordovician–Silurian succession into three depositional cycles: pre-glaciation cycle (Saq and Qasim Formations), syn-glaciation cycle (Zarqa and Sarah Formations), and post-glaciation cycle (Uqlah and Qusaiba Formations) (Fig. 5).

3.6. Lithostratigraphy: Sharawra Formation

The term "Sharaura sandstone member" was first informally introduced by Roach (1951, Aramco unpublished report), (in Laboun, 1993) for 564 m thick of Silurian sandstones and shales exposed at Jabal Sharaura in Tabuk region. It was considered as a member in Tabuk Formation.

More recent work of Janjou et al. (1996b), in the Qalibah quadrangle led them to raise the member to Sharawra Formation.

The thick succession of Early Silurian Sharawra Formation of the Tabuk area (510 m thick) progressively thins eastward and is completely truncated in the Qusayba depression in central Arabia where the Tawil Formation rests directly on the Late Ordovician Sarah Formation (Figs. 6 and 7).

3.7. Acadian tectonic movements

Gentle uplift of earlier paleo-highs during Late Silurian in central Arabia is indicated by periods of erosion and/or non-deposition marked major a regional unconformity represented by a pronounced stratigraphic break where the Early Silurian Sharawra Formation was progressively eroded eastward prior to the deposition of the Early Devonian Tawil Formation (Fig. 4).

The sub-Tawil unconformity marks the boundary between the syn-tectonic sandstones of the Tawil Formation with underlying older units. This truncation is attributed to the Acadian tectonic movement which subdivide the Silurian–Devonian succession into three depositional cycles: pre-Acadian cycle (Qusaiba and Sharawra Formations), syn-Acadian cycle (Tawil Formation), and post-Acadian cycle (Jauf Formation) (Figs. 4 and 5).

Published field works by Janjou et al. (1996a) on Tabuk quadrangle, Janjou et al. (1996b) on Al Qalibah quadrangle, Vaslet et al. (1994) on Tayma quadrangle, Janjou et al. (1998) on Jabal Misma quadrangle, Bartlett et al. (1986) on Hail quadrangle, Vaslet et al. (1986) on Baqa quadrangle, Manivit et al. (1987) on Buraydah quadrangle, and Williams et al. (1987) on Jabal Habashi quadrangle (Fig. 2) were used in this study to show the influence of the Acadian tectonic movements.

3.8. Lithostratigraphy: Tawil sandstone

The term Tawil Formation was first informally introduced by Berg et al. (1944, Aramco unpublished report) (in Laboun, 1993).

The term Tawil sandstone was formally defined as a formation by Steineke et al. (1958). It was considered as the upper member of the Tabuk Formation by Powers et al. (1966).

The mainly braided fluvial and shallow marine sandstones of the Tawil Formation was subdivided by Janjou et al. (1996a,b). In the Qalibah and Tabuk regions the Tawil Forma-

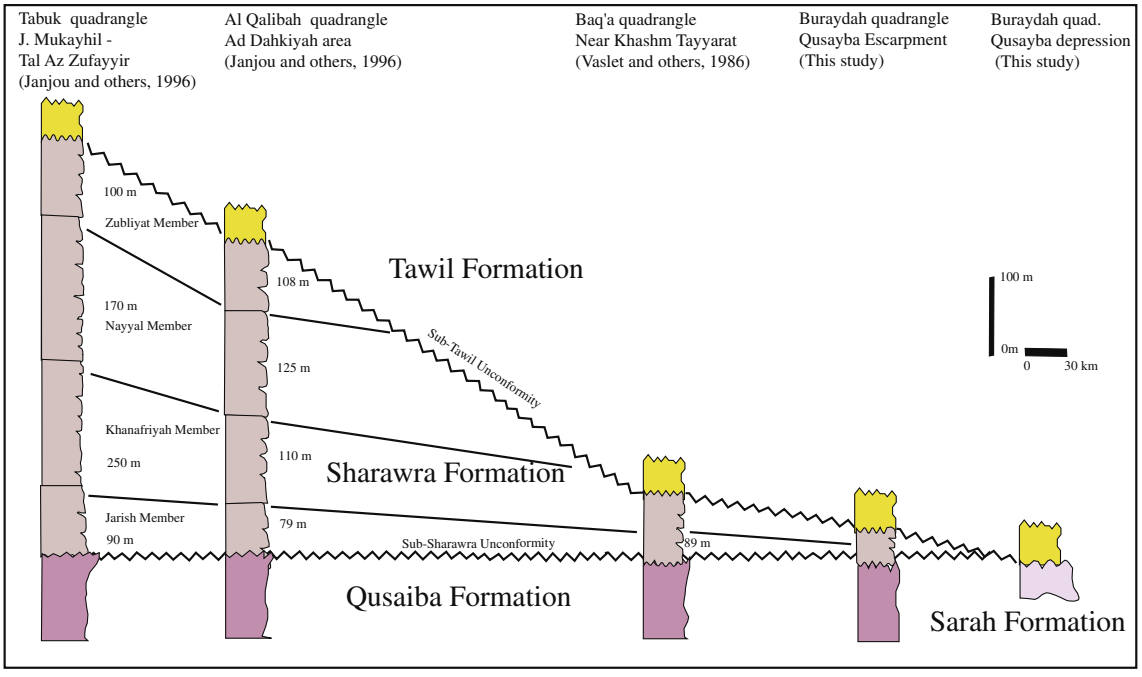

Figure 6 Stratigraphic cross section showing the influence of the sub-Tawil unconformity on the Sharawra Formation in northwestern and central Arabia. The sub-Sharawra unconformity is used as a datum for the section.

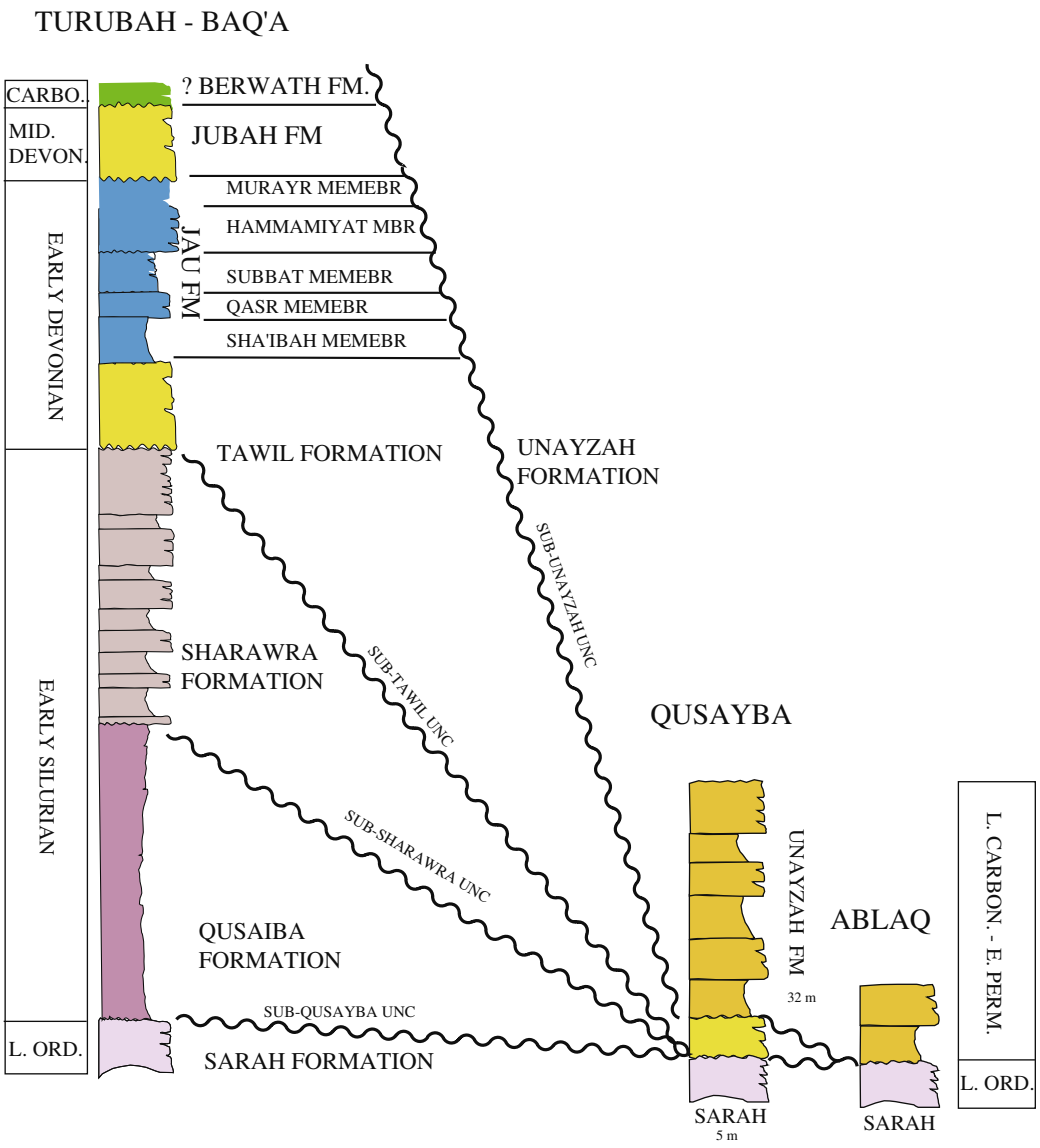

Figure 7 Stratigraphic cross section showing the influence of the sub-Unayzah unconformity on the older units, from Carboniferous Berwath in northwestern Arabia to Late Ordovician in the Qusayba depression. The sub-Qusaiba unconformity is used as a datum for the section.

tion was subdivided into four members, from bottom to top; Samra, Ghuwar, Tufayhah, and Juraniyat. Thin section of the Tawil Formation is exposed in the Qusayba depression where it is unconformably overlain by the Permo-Carboniferous Shajara Formation (Figs. 6–8). It is completely missing south of the depression.

3.9. Hercynian tectonic movements

Pulses of tectonic movements in Arabia started during Middle Devonian and reached their maximum phase during Late Carboniferous. These pulses caused stratigraphic breaks recognized below the Shajara Formation. The last phase is the most pronounced stratigraphic break in the Paleozoic succession. Earlier deposits truncated from paleo-highs prior to the deposition of the Permo-Carboniferous Shajara Formation (Figs. 4, 7 and 8).

The sub-Shajara unconformity marks the boundary between the syn-Hercynian Shajara deposits with underlying units from Carboniferous to Precambrian (Fig. 9). The thick Carboniferous–Devonian succession, the Jubah, Jauf, and Tawil Formations, well represented in northwest Arabia is truncated southeast wards and is completely missing in Niqrat Ablaq, south of Qusayba depression where the Unayzah Formation rests on the Late Ordovician Sarah Formation (Fig. 7). Exposed sections of Jubah, Jauf, and Tawil Formations in Turubah and Baq'a quadrangles were unconformably overlain by the Shajara Formation (Fig. 7). Further south, towards the central Arabian arch the Shajara Formation rests on various older units before resting directly on the Precambrian basement (Fig. 9).

The published works by Wallace et al. (1998) on Ash Shuwayhitiyah quadrangle, Wallace et al. (1997) on Al Jawf quadrangle, Vaslet et al. (1986) on Baqa quadrangle, Manivit et al.

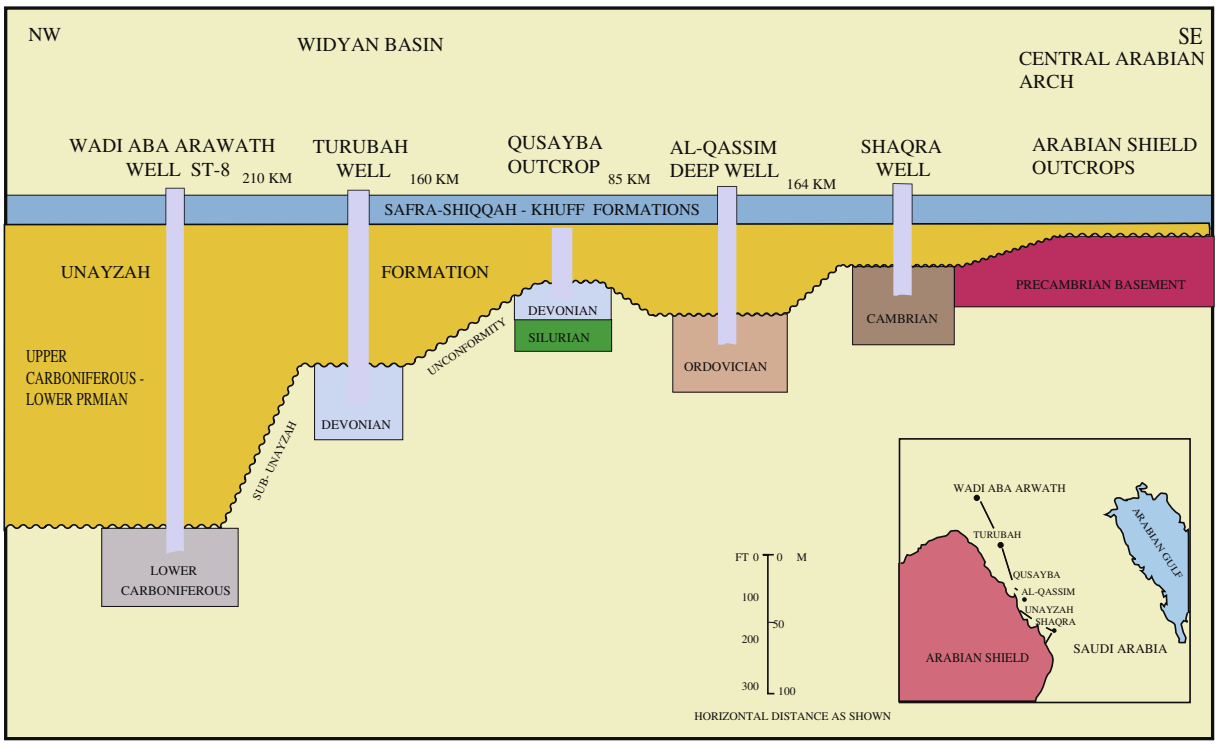

Figure 8 Generalized geologic map from Baq'a to Qusayba shows the influence of the Taconic tectonic movements and Zarqa/Sarah glacial paleo-valley and the influence of both Acadian and Hercynian tectonic movements and their merge in the Qusayba depression.

(1987) on Buraydah quadrangle, Vaslet et al. (1986) on Al Faydah quadrangle, and Delfour et al. (1983) on Ad Dawadimi quadrangle (Fig. 2) were used in this study to show the influence of the Hercynian tectonic movements.

3.10. Shajara Formation

The term Unayzah Formation was first introduced by Laboun (1982) and it was formally defined by Laboun (1986, 1987). Since then, a great amount of data were obtained from field work and deep and exploratory wells in central Arabia. Such data have resulted in the recognition of two different facies, separated by a well pronounced unconformity within the formation as originally defined by the author. The author restricted the term Unayzah Formation for the shallow marine facies above the unconformity, and introduced the term Shajara Formation for the continental deposits below the unconformity.

The Shajara Formation is best exposed at its reference section at Wadi Ash Shajara, in the eastern side of the Qusayba depression.

This regional sub-Shajara truncation is attributed to the Hercynian tectonic movements. These movements subdivide the Paleozoic succession into three mega-depositional cycles: pre-Hercynian cycle (Jubah, Jauf, Tawil, Sharawra, Qusaiba, Uqlah, Sarah/Zarqa, Qasim, and Saq Formations), syn-Hercynian cycle (Shajara Formation), and post-Hercynian cycle (Unayzah and Khuff Formations) (Fig. 5).

The Qa Ablaq is formed of the sandstones and shales of the Shajara Formation rest on the Sarah Sandstones.

The Qa Hawban–Qusayba–Ablaq depression system is an excellent geologic window shows various types of glacial rocks and structures of the Zarqa/Sarah Formation and the influence of the Taconic unconformity (sub-Zarqa/Sarah unconformity), Acadian unconformity (sub-Tawil unconformity), and Hercynian unconformity (sub-Shajara unconformity) and their merge in the Qusayba and Ablaq depressions (Fig. 8). In these depression the Shajara Formation unconformably rests on the Tawil Formation in Qusayba and on the Sarah Formation in Ablaq.

4. Conclusions

Field work investigations resulted in followings main conclusions:

1. During Late Ordovician uplift and tilt took place and thick section of Precambrian–Cambro–Ordovician succession was eroded. These movements are probably related to the Taconic tectonic movements.
2. Late Ordovician–Early Silurian(?) glacial deposits are well documented in outcrops of Zarqa and Sarah Formations. Also, paleo-valleys incised in the members of Qasim, Saq Formations, and Basement were filled with these deposits. The glaciation events subdivide the Cambrian–Ordovician–Silurian succession into three depositional cycles: pre-glaciation cycle (Saq and Qasim Formations, syn-glaciation cycle (Zarqa and Sarah Formations), and post-glaciation cycle (Uqlah and Qusaiba Formations).
3. The thick succession of Early Silurian Sharawra Formation of the Tabuk area progressively thins out eastward and is completely truncated in the Qusayba depression in central Arabia. This truncation is believed to be attributed to the Acadian tectonic period which is represented by the sub-Tawil (sandstone) unconformity. This tectonic event subdi-

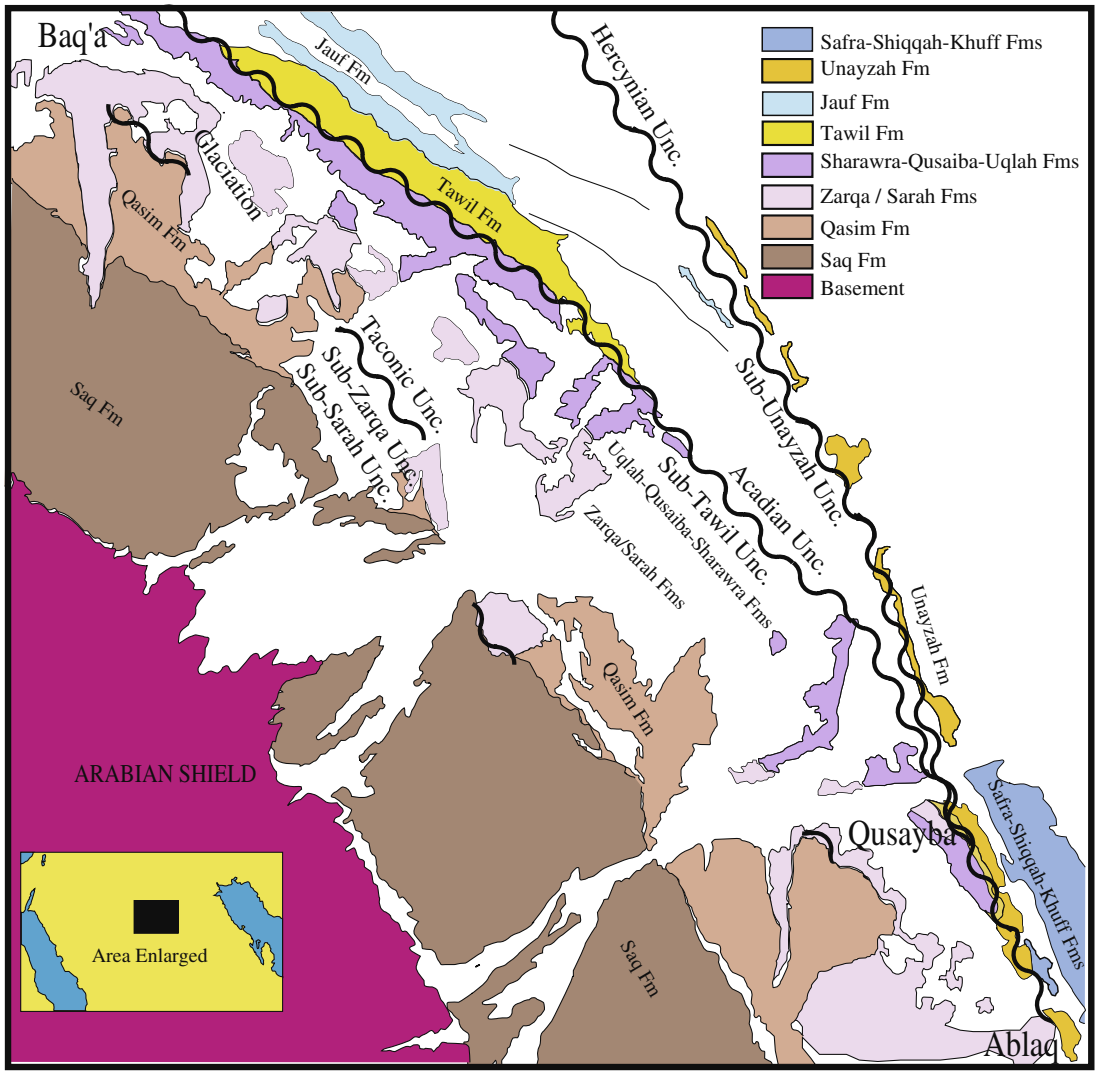

Figure 9 Stratigraphic cross section showing the influence of the sub-Unayzah unconformity on various older units, from Carboniferous Berwath in northwestern Arabia to Precambrian Basement in central Arabia. The top Unayzah Formation is used as a datum for the section.

vide the Silurian–Devonian succession into three depositional cycles: pre-Acadian cycle (Qusaiba and Sharawra Formations), syn-Acadian cycle (Tawil Formation), and post-Acadian cycle (Jauf Formation).

4. The thick Devonian succession, comprising the Jubah, Jauf, and Tawil Formations, is well represented in northwest Arabia. It is truncated southeast ward and completely missing in the Qusayba depression where the Permo-Carboniferous Shajara Formation rests on truncated sections of this succession. Further southeast the Shajara rests on truncated sections of the Qasim and Saq Formations before resting on Precambrian basements on the Central Arabian Arch. This regional sub-Shajara truncation is attributed to the maximum phase of the Hercynian tectonic movement. This movement subdivides the Paleozoic succession into three mega-depositional cycles: pre-Hercynian cycle (Jauf, Tawil, Sharawra, Qusaiba, Uqlah, Sarah/Zarqa, Qasim, and Saq Formations), syn-Hercynian cycle (Shajara Formation), and post-Hercynian cycle (Unayzah and Khuff Formations).
5. The Taconic (sub-Zarqa/Sarah unconformity), Acadian (sub-Tawil unconformity), and Hercynian (sub-Shajara unconformity) are exposed and merge in the Qa Hawban, Qusayba depression, and Niqrat Ablaq, in central Arabia.

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