Advances in understanding the relation between reservoir properties and facies distribution in the Paleozoic Wajid Sandstone, Saudi Arabia

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Abstract The Wajid Sandstone is one of the most important groundwater reservoirs in the Kingdom of Saudi Arabia. The knowledge of the dimensions and the distribution of its sedimentary facies are essential for high quality reservoir interpretation. Hitherto, the facies and their dimensions are only roughly known from extrapolation of subcrop data and geophysical surveys.

Sedimentological logging and correlation of the sections led to an interpretation of the depositional processes and a more detailed facies model. Based on systematic lithofacies and architectural element analysis, the so far established and published facies characteristics derived from subcrop information of the depocenter in the West of the Kingdom and also from the outcrop area have to be modified.

These data have important implications on reservoir properties of the Wajid sandstone. The sandy deposits guarantee a high primary porosity and permeability up to 1 D. Bioturbation leads to pronounced anisotropy in some horizons. Of major importance, however, are late diagenetic cementation effects which focus on faults, fractures and horizontal to subhorizontal discontinuities. Most widespread is iron cementation which makes up almost impermeable seals and separates reservoirs horizontally and vertically. The primary control on reservoir quality is due to a gradual facies change from W to E. Fine-grained silty layers are increasingly intercalated towards the E but are almost completely absent in the W. Consequently, in the western area, the Wajid Group forms a combined reservoir but in the subsurface is separated into two layers.

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Introduction

In Saudi Arabia, the Paleozoic Wajid Sandstone is an important groundwater reservoir and in the subsurface, several individual aquifers have been distinguished (GTZ-DCo 2007). The properties of the individual aquifers and their correlation to facies and depositional environment, however, are only poorly known. We present preliminary results of a detailed investigation on facies, lithology, and depositional environment in the Wajid Sandstone (Fig.1). It is subdivided into five formations, the Dibsiyah, Sanamah, Qalibah, Khusayyayn, and Juwayl formations (Kellogg et al. 1986).

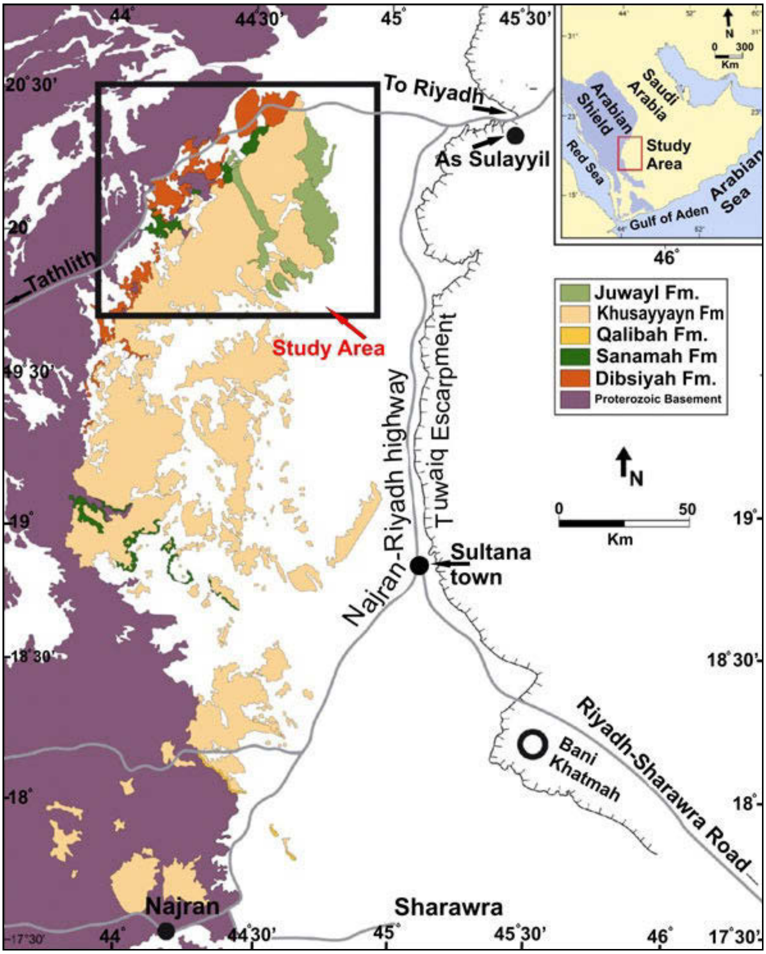

Fig. 1. Outcrops of the Wajid Sandstone and its members (modified from Al Husseini, 2004) in SW Saudi Arabia.

In general, biostratigraphic control on the deposits of the Wajid Sandstone is very poor. It has been dated mainly indirectly through correlation of geophysical data to the subsurface (Evans et al. 1991). Following this correlation, the Dibsiyah is of Cambrian or Ordovician age; the Sanamah corresponds to the latest Ordovician. The Qalibah is interpreted to correspond to the Early Silurian, while the Khusayyayn was deposited during Devonian and Early Carboniferous time. The Juwayl comprises glacigenic deposits and their formation is attributed to the Upper Carboniferous and Lower Permian glaciation.

Dibsiyah Formation

The Dibsiyah is a succession of medium-grained to conglomeratic sandstones with few intercalations of finer siliciclastic horizons. The Dibsiyah is subdivided into a lower and an upper part. The lower unit has a minimum thickness of about 60 m at Jabal Dibsiyah, the upper part a minimum thickness of 130 m.

The lower Dibsiyah consists of a succession of cross-bedded medium to coarse-grained sandstones and fine conglomerates. The dominant color of the sediments is gray, many of the horizons, however, have a red color. Sedimentary structures include lateral accretion complexes and low-angle, 2D-trough cross bedding. In the 3rd dimension, these structures continue in very persistent cross-bedding with near planar lower and upper bounding surfaces. Bioturbation is present from the lowest exposed horizons to the top of the unit. Horizontal burrows have been observed on few bedding planes. Vertical burrows of *Skolithos* sp. are locally abundant in the sandstones of all lithologies, including conglomeratic sandstones. Very scarce *Cruziana sp.* has also been observed.

The upper Dibsiyah is composed of medium to coarse-grained sandstones. Locally, lenses or thin layers of red siltstone to fine-grained sandstone are intercalated. The dominant sedimentary structure is low-angle, 2D-trough cross bedding of the same type observed in the lower unit. They are laterally very persistent and individual units can be traced over several hundred meters. Herringbone cross stratification is present locally and always associated with the large 2D bedforms. Lateral accretion complexes are also present in this upper part of the Dibsiyah; individual complexes may show foresets up to 2 m high and several centimeters thick. They often show a sigmoidal geometry. Many of them are traceable across entire outcrops.

Bioturbation is much more important than in the lower unit. One of the main elements is *Skolithos sp.* that is present widely scattered within individual horizons, somewhat crowded to almost “frame-building” in some horizons. These “pipe rocks”, common in many Cambrian and Ordovician siliciclastic successions, are also known as “Tigillites”. In the upper Dibsiyah, thickness of *Skolithos* pipe rocks varies between some 10 centimeters to several meters. Simple *Skolithos* burrows are often associated with larger burrows attributed to *“Bergaueria” sp*. The almost “reef-like” horizons of *Skolithos* and/or *Bergaueria* are up to 13 meters thick. Most of the internal sedimentary structures have been destroyed by burrowing; however, the primary cross-bedding is often faintly visible.

The presence of a variety of burrowing organisms and *Cruziana sp.* in both units testifies to deposition of the entire Dibsiyah in a marine environment. In their majority, the low-angle, 2D through cross-bedded horizons represent tidal channels. The lateral accretion complexes are interpreted as large submarine megaripples or dunes typical of meso- to macrotidal environments (Einsele 2000).

The lower unit received coarser detritus than the upper unit. This might indicate that the rivers delivering the detritus had higher transport capacity than during deposition of the upper unit or that the coast was close by, in turn indicating a relatively low sea level. Towards the upper part of the Dibsiyah, sea-level was relatively rising so that after deposition of large submarine dunes, these dunes or megarippels were burrowed by *Skolithos* and *Bergaueria*. The depth of burrowing (up to 50 cm) indicates that the animals had abundant time during which no additional sediment was supplied that would have forced the organisms to try to evade. This is in agreement with models that suggest that *Skolithos* burrows are dominantly formed during times of transgression or maximum flooding (e.g., Hamon et al. 2005). Depositional environments were shifting rapidly so that there is a repeated succession of burrowed and non-burrowed sediments.

Sanamah Formation / Qusaiba Shale

The Sanamah is a succession of coarse-grained sandstones and conglomerates in its lower part and fine-grained sandstones, siltstones, and some shales in its upper part.

The lower Sanamah rests unconformably on the Dibsiyah and fills an erosional relief up to several 10s of meters deep. In many sections outside the actual channels, and beneath the upper Sanamah, there is just a thin veneer (6 – 10 m) of lower Sanamah preserved. The basal part of the upper unit was deposited across the post-lower Sanamah topography and has a similar distribution as the sediments of the lower unit. The upper part of the succession is only exposed in the Jibal al Qahr. Although genetically related to the Sanamah Formation, these deposits might represent the subsurface Qusaiba Shale of the Qalibah Formation in this part of Saudi Arabia.

In the Jabal Atheer section, the lower Sanamah is 92 m thick. There is no continuous section of the Qusaiba in the study area but in the Jibal al Qahr about 50 m are exposed beneath the unconformity with the Khusayyayn.

The lower Sanamah consists of a succession of conglomerates, conglomeratic sandstones, and medium- to coarse grained sandstones. The conglomerates fill large channels and in most cases are the basal fill of the pre-existing topography. They are composed individual lobes, each several 10 of centimeters thick and graded, from pebble size at the base to medium or coarse sand in the upper part. Where the basal conglomerate layers had filled up the relief, subsequent layers and channels are locally laterally amalgamating, forming more widespread deposits (on outcrop scale). Conglomerates are not only present as channel fills but also form part of migrating bars. They mainly show an overall fining-upward or show a lateral decrease in grain size. Above this succession there is a package of gray to yellowish medium to coarse-grained sandstones. In many outcrops, these sandstones are massive and lack apparent internal structures. Locally, these massive sandstones eroded into the underlying sediment producing overhanging walls. Outside the main valleys, the thin veneer of lower Sanamah consists of channelized conglomerates and conglomeratic sandstones with well-developed high-angle, 3D trough cross bedding.

Clast- and matrix-supported conglomerates and coarse conglomeratic sandstones represent the basal channel-fill facies association (Keller et al. 2011). They are interpreted as coarse glacial outwash sediment near melt water outlets. A facies association of massive to cross-bedded sandstones, arranged in clinoforms, fills up the upper part of the valleys. These sediments are interpreted as Gilbert-type deltas prograding from sandur plains into the water-filled valleys during glacier retreat. Together with glacial striations, striated clasts, and similar corresponding features, these sediments indicate a glacial origin of this part of the Wajid Sandstone (Keller et al. 2011).

The upper Sanamah starts with an iron-cemented horizon, up to 20 cm which is overlain by some shales and siltstones. Locally sandstones were deposited that indicate large-scale slumping. Up section, white fine- to medium-grained sandstones alternate with shales. In its upper part, the upper Sanamah or Qusaiba consists of a succession of light colored fine sandstones, siltstones, and shales. The sediments are thinly bedded and locally show some burrows. Close to the preserved top of the succession, mud cracks have been observed.

The basal deposits were laid down rather rapidly, so that the sands were subject to slumping. The lateral variability of the sedimentary successions (Stump and Van der Eem 1996) and the mud cracks indicate that they were probably not deposited on an open shelf but either in marginal marine environments (deltas) or in a lake setting.

Khusayyayn Formation

The Khusayyayn Formation (> 52m) is a monotonous succession of medium to coarse-grained sandstones and unconformably rests on older strata. The Khusayyayn consists of a stacked succession of giant cross-bedded sandstones; individual complexes locally are up to 2 meters high. The foresets are several centimeters thick and are often graded. Grain size mainly decreases from coarse sand to medium sand, but locally pebbles have been found in the basal layer of individual foresets. These thick cross-bedded units are associated with herringbone cross stratification and small low-angle, 2D trough-bedded structures. Discrete packages within the succession were found, which seem to occur in all sections. At Jabal Khusayyayn, the succession starts with mainly coarse-grained, large-scale cross-bedded units. This is followed by small-scale bed forms in which medium to coarse sand dominates. Higher up, a massive sandstone unit was found which shows evidence of slumping and dewatering (flame structures). This unit in turn is followed by some 10 meters of fine to coarse-grained sandstones in small-scale bed forms with abundant channels. The uppermost unit again is dominated by large-scale bed forms and coarse-grained, often pebbly sandstones.

We interpret the Khusayyayn to have been deposited on a high-energy open shelf. This is indicated by the lateral continuity of the large cross-bedded units. They represent submarine megaripples or dunes and testify to strong unidirectional currents of tidal origin. The low-angle-trough cross-bedded units represent tidal channels. A tidal environment is also indicated by herringbone cross stratification repeatedly observed in the sections.

Juwayl Formation

The Juwayl Formation (> 100 m) shows the highest lithologic variability among the Paleozoic sandstones. It was deposited across an erosional surface that deeply cuts into the underlying strata. The Juwayl is present in two outcrop belts trending NW - SE corresponding to two major glacial valleys (Kellogg et al. 1986).

Thick, massively bedded fine to coarse-grained sandstones are a major constituent of the Juwayl. In places, they lack apparent sedimentary structures; in other places, these sandstones consist of stacked channels, often with lateral accretion phenomena. Locally, these sandstones cut vertically into the underlying sandstones and formed positive morphologic forms. Up section, these sandstones are overlain by reddish sandstones with high-angle, 3D through cross bedding and some ripple-drift cross bedding.

Another succession starts with thin conglomeratic sandstones with few pebbles. Up section, finely laminated shales are present. The alternation of mm-thick sandstone and clay laminae indicates a varve origin of these sediments. Large basement boulders and conglomerate clasts are present within these shales.

The varve sediments and the associated boulders and clasts leave little doubt that these sediments were deposited in a proglacial lake. The big boulders represent dropstones indicating the presence of icebergs. Consequently, the accompanying sediments also should be of periglacial origin. The 3D trough cross-bedded sediments were deposited by braided rivers and possibly partly represent braid delta deposits that formed in one the glacial lakes. The massive sandstones without apparent internal structure may represent eskers or drumlins deposited beneath or in front of the moving ice. The steep walls of the channels indicate that the sediment may have been frozen during erosion.

Implications for aquifer properties

The sedimentary succession of the Wajid Sandstone is dominated by medium- to coarse-grained sandstones. Fine sandstones, pebbly sandstones, and conglomerates are present but of less importance. Siltstones and shales are rare. Almost the entire stratigraphic succession is characterized by very weak cementation and the near total absence of matrix, i.e., of silt and clay in the sediments. This fact has consequences for the reservoir potential of the Wajid Sandstone. In all members, there is a primary visible porosity which has been estimated to vary between 20% and 30% of the rock. This is in agreement with studies by Evans et al. (1991) who report average porosities of 20% for the Dibsiyah, 21% - 25% for the Sanamah, 23% for the Khusayyayn, and locally 30% for the Juwayl. Similarly, Dirner (2007) and Filomena (2007) report porosities between 18% and 31% for the Wajid Sandstone. Together with high effective permeabilities of 1 to 8 darcies, this makes the Wajid Sandstone principally an important reservoir rock.

A recent study (GTZ-DCo 2007) has shown that in the subsurface, the Wajid Sandstone succession represents two individual fractured bedrock aquifers separated by an aquitard. The lower aquifer is represented by the Dibsiyah and the Sanamah, effectively separated from the upper one by the siltstones and shales of the Qusaiba. The upper aquifer comprises the Khusayyayn and the Juwayl.

The distribution of the sedimentary successions of the Wajid Sandstone in the outcrop belt shows a different picture. The Dibsiyah crops extensively in the western part of the study area where it is overlain by the Sanamah. The combined thickness of the Dibsiyah plus the unconformable Sanamah rarely exceeds 200 m. As porosities and permeabilities are on the order of the same magnitude, they should form a homogenous reservoir (equivalent to the lower aquifer in the subsurface). The Khusayyayn is the most widespread unit in the study area and has excellent porosities and permeabilities. The Juwayl is present in two NW - SE trending outcrops that represent the former erosional relief (Kellogg et al. 1986). The petrophysical properties are close to the underlying Khusayyayn, so that these two units together form another combined reservoir (the upper sandstone sequence in the subsurface). The major difference to the subsurface is the absence of an effective aquiclude or aquitard, which in the subsurface is represented by thick shales of the Qusaiba. The lithology and the patchy distribution of the sediments, caused by cut-out of strata beneath the Khusayyayn unconformity; make the Qusaiba an ineffective aquitard. Consequently, as there is no separator between the lower and the upper sandstone sequence, in the Wajid outcrop belt, there is only one major reservoir.

Conclusions

In the study area, the Wajid Sandstone consists of 5 distinct lithologic units: The Dibsiyah, the Sanamah, the Qusaiba, the Khusayyayn, and the Juwayl formations.

The Dibsiyah Formation is a marine succession dominated by tidal deposits which up section grade into open shelf deposits. After deposition of the Dibsiyah, a pronounced relief was developed and filled with glacial sediments of the Sanamah. The Qusaiba is a predominantly fine-grained succession of patchy distribution. The depositional environment may have been a marginal marine setting or even a palustrine environment. It is overlain by the Khusayyayn Formation, which is a very uniform succession and which has the widest distribution of the units. It is composed of an alternation of submarine dunes and tidal sediments. Two large valleys were carved into these deposits prior to the deposition of the glacigenic Juwayl Formation. The latter shows a variety of sedimentary facies; however, the spatial and temporal relations between these deposits are not yet clear.

Except for the Qusaiba, all rocks show well developed porosities and permeabilities between 20% and 30% and 1000 md to 8000 md. In the absence of an effective aquitard, these rocks form one major reservoir.

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