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The Role of Outcrop Analogue Studies for the Characterization of Aquifer Properties

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Abstract: Aquifers are large (sedimentary) bodies, which contain significant amounts of water that can be economically exploited as drinking water or for agricultural purposes. Aquifers are subsurface reservoirs and hence, their properties cannot be directly determined through visual examination. The petrophysical characteristics of the sediments, however, are most important for the assessment of the quality of the reservoir and for modeling of the fluid flow. Geophysical logging of the wells is one methodology that provides basic information on lithological and hydrogeological properties of a reservoir. In recent years, outcrop analogue studies have become a powerful tool in sedimentology for the assessment of reservoirs, both in hydrocarbon and aquifer studies. Data from exploratory drilling campaigns can significantly be augmented by observations on the outcrop of the corresponding stratigraphical interval with the objective to validate the borehole information through direct observation. In addition, through the physical separation of the outcrop area and the subsurface, the increased spatial coverage of a reservoir and its equivalents provides additional information about facies and their changes and thus on reservoir properties. In the study of Saudi Arabian aquifers, we have conducted outcrop analogue studies on the Wajid Group and on the Wasia-Biyadh aquifers. A typical workflow in these siliciclastic strata starts with the detailed lithologic logging of a section and the subsequent mapping of the facies across the outcrop. Together with bedding and bed forms, these are the basic elements of a 3-dimensional architectural framework of the depositional environment. In addition, the spectral gamma ray emissions are logged at the same interval (usually 30 cm) as in the boreholes. In a subsequent step, samples are taken for the measurement of porosity and permeability and for the detailed lithologic description of the sediment under the microscope. Finally, the structural inventory along the outcrop is documented. The orientation (strike, dip) of the fracture system is determined and the opening of individual fractures is measured together with the width between individual joints or fractures. In addition, the total number of fractures within a predefined outcrop surface is determined. After acquisition of all data, these are combined with those from the wells and incorporated into a 3-dimensional model of the facies architecture of the corresponding aquifer. This model will then serve as a basis for the large-scale hydrogeological modeling of the entire reservoir.

Key words: Outcrop analogue study · Poroperm · Facies analysis · Fracture analysis · Wajid · Wasia

INTRODUCTION

Aquifers are large (sedimentary) bodies, which contain significant amounts of water that can be economically exploited as drinking water or for agricultural purposes. Aquifers are subsurface reservoirs and hence, their properties cannot be directly determined through visual examination. Groundwater management strongly depends on models of the hydrogeological situation which describe and predict groundwater flow. Hence, the characterization of the aquifer system is a prerequisite for any groundwater management plan [1, 2], especially in areas that mainly depend on fossil groundwater reserves.

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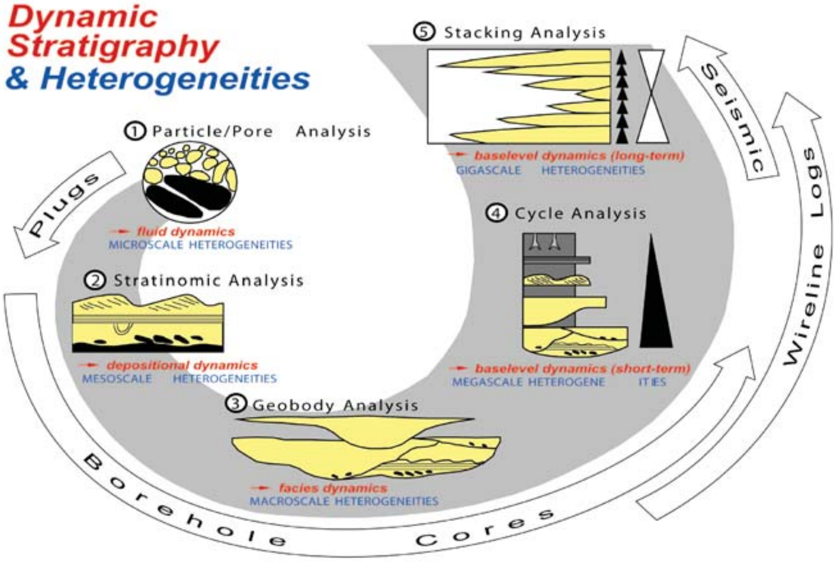

Fig. 1: Workflow for outcrop analogue studies

Aquifer characterization includes the structuring of the model area in hydrostratigraphical units [3]. A hydrostratigraphical unit possesses homogeneous hydraulic properties with respect to its capability to transmit and to store groundwater. Aquifer characterization mainly depends on point information, e.g. well data and the quality of these point data control the quality of the model. Most important for the assessment of the quality of the reservoir and for modeling of the fluid flow are the petrophysical characteristics of the rocks. Geophysical logging of the wells is one methodology that provides basic information on lithological and hydrogeological properties of a reservoir.

In recent years, outcrop analogue studies have become a powerful tool in sedimentology for the assessment of reservoirs, both in hydrocarbon and aquifer studies. Data from exploratory drilling campaigns can significantly be augmented by observations on the outcrop of the corresponding stratigraphical interval with the objective to validate the borehole information through direct observation. In addition, through the physical separation of the outcrop area and the subsurface, the increased spatial coverage of a reservoir and its equivalents provides additional information about facies and their changes and thus on reservoir properties.

In the study of Saudi Arabian aquifers, we have conducted outcrop analogue studies on the Wajid Group and on the Wasia-Biyadh aquifers. A typical workflow in these siliciclastic strata starts with the detailed lithologic logging of a section and the subsequent mapping of the facies across the outcrop (Figure 1). Together with bedding and bed forms, these are the basic elements of a 3-dimensional architectural framework of the depositional environment. In addition, the spectral gamma ray emissions are logged at the same interval (usually 30 cm) as in the boreholes. In a subsequent step, samples are taken for the measurement of porosity and permeability and for the detailed lithologic description of the sediment under the microscope. Finally, the structural inventory along the outcrop is documented. The orientation (strike, dip) of the fractures system is determined and the opening of individual fractures is measured together with the width between individual joints or fractures. In addition, the total number of fractures within a predefined outcrop surface is determined.

The permeability and storage capacity for groundwater in sedimentary rocks are linked to the porosity of the rock and to a network of openings corresponding to bedding planes, joints, faults and other fractures. Shape, spacing, number and distribution of these are often controlled by the sedimentary facies and architecture [4-6]. Both small-scale and large-scale variations in sedimentary facies and architecture are of importance for the definition and zonation of hydrofacies units. This is shown by an example from the Paleozoic Wajid Sandstone, located in the south of the Kingdom of Saudi Arabia.

Sandstones with planar cross bedding alternate with bioturbated layers. The permeability of the planar bedded sandstone is in the range from 50 to 400 mD, its distribution is isotropic. In contrast, the bioturbated layers show permeabilities of up to 1,000 mD (Figure 2).

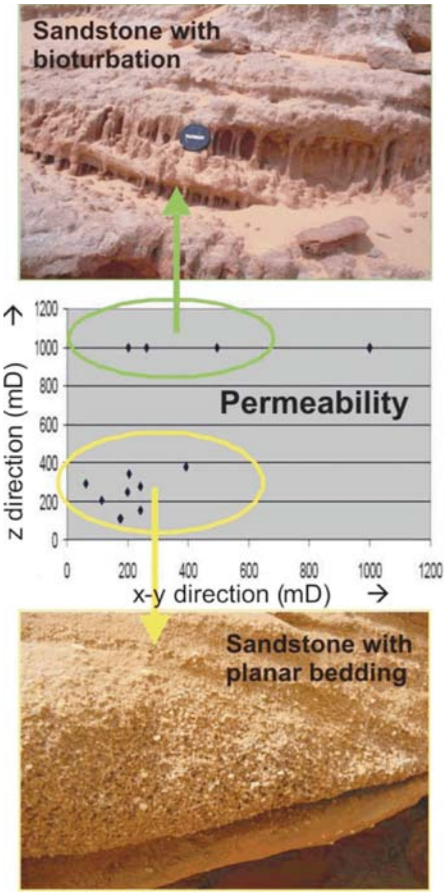

Fig. 2: Examples for small-scale hydrofacies units from the Lower Wajid Sandstone in Saudi Arabia (Dibsiyah Formation, Jabal Dibsiyah). The permeability distribution of the planar bedded sandstone (lower picture) is isotropic. The difference between horizontal and vertical permeability is small. The "*Skolithos*" sandstone (upper picture) is extremely anisotropic. Its vertical permeability is 5 times higher than its horizontal permeability. The vertical *Skolithos* burrows are produced by worms living in the sediment

The permeability distribution is anisotropic: vertical permeabilities are up to 5 times higher than horizontal permeabilities. The bioturbation is made by Skolithos sp.; this worm species penetrated the seafloor and left behind vertical burrows, which account for the anisotropy in permeability. The difference in permeability, especially the greatly enhanced vertical permeability in the bioturbated layers, influence the groundwater flow and hence lead to different hydrofacies units within a few meters of rock. Note that the lithology – medium- to coarse-grained sandstone – remains the same.

On the large scale, 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 formations, 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.* [7] 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 [8] and Filomena [9] 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 [10] 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 Formation and the lower Sanamah Formation. The lower aquifer (lower sandstone sequence) is effectively separated from the upper one by the siltstones and shales of the Qusaiba Shale equivalent. The upper aquifer (upper sandstone sequence) comprises the Khusayyayn Formation and the Juwayl Formation.

The distribution of the sedimentary successions of the Wajid Sandstone in the outcrop belt shows a different picture. The Dibsiyah Formation crops out extensively in the western part of the study area where it is overlain by the lower Sanamah Formation. As the lower Sanamah fills an erosional relief and as its maximum thickness is attained in the center of the erosional valleys, the combined thickness of the Dibsiyah plus the lower Sanamah Formations 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 sandstone sequence in the subsurface). The Khusayyayn is the most widespread unit in the study area and has excellent porosities and permeabilities. The Juwayl Formation is present in two NW-SE trending outcrops that represent the former erosional relief [11]. 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

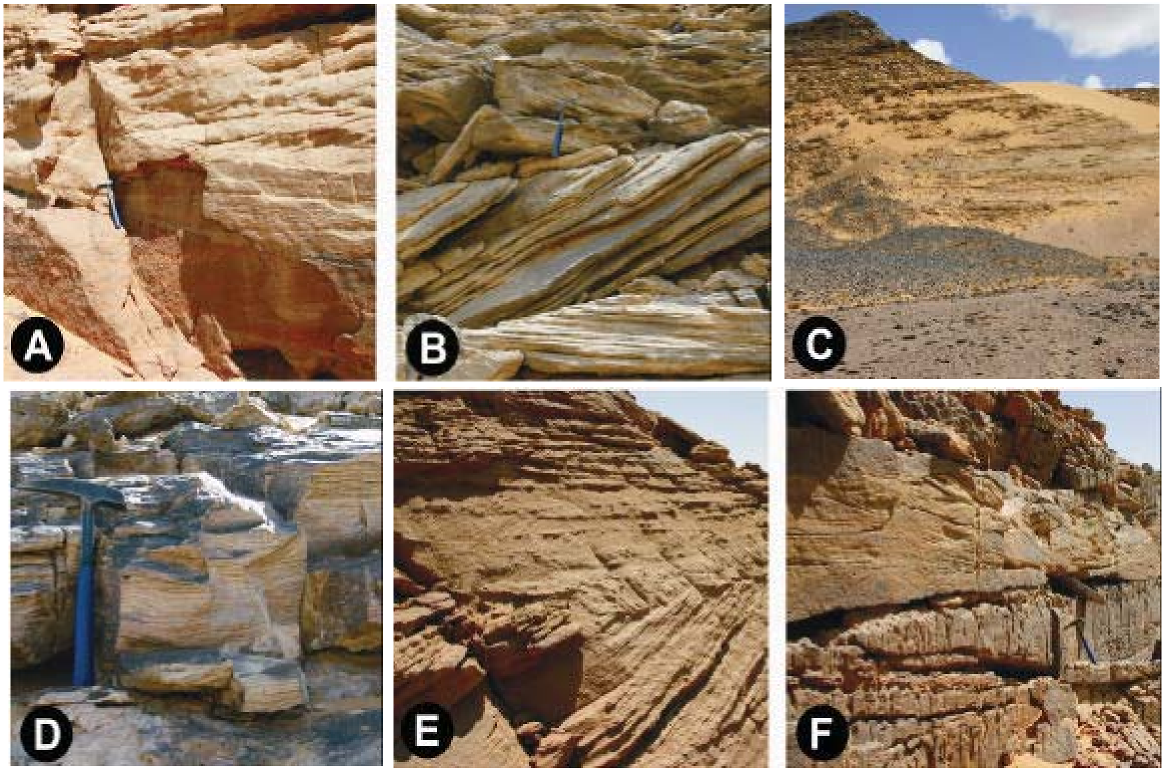

Plate 1: Sedimentary aspects of Wajid Sandstone. A: Migrating submarine dune overlain by tidal channel facies; lower unit, Dibsiyah Formation. B: Herring-bone cross stratification in coarse-grained sandstones; Khusayyayn Formation. C: Silty-shaly, thin-bedded deposits of the Qusaiba Shale equivalent. These horizons act as aquitard in the subsurface. D: Laminated warve sediments in the Juwayl Formation. E: Tidal-channel facies in the lower part of the Dibsiyah Formation. F: Alternation of submarine burrowed Skolithos-sandstones and tidal-channel facies of the Dibsiyah Formation. The interpretation of the aquifer characteristics of these horizons is given in Figure 2.

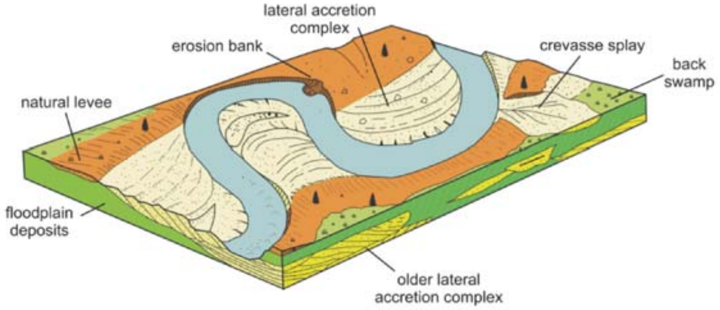

Fig. 3: Basic sedimentologic architectural elements of a meandering river system as exemplified by the Wasia Group in Central Saudi Arabia [13]

shales equivalent to the upper Sanamah Formation. The lithology and the patchy distribution of the sediments, caused by cut-out of strata beneath the Khusayyayn unconformity, make the upper Sanamah Formation 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.

Another example presents a large-scale approach to the zonation of hydrogeological units on the basis of a regional basin facies model. This approach is shown for the Cretaceous Wasia Group. The Wasia Group represents the complex facies architecture of a meandering river system with main channels, floodplains and lakes (Figure 3).

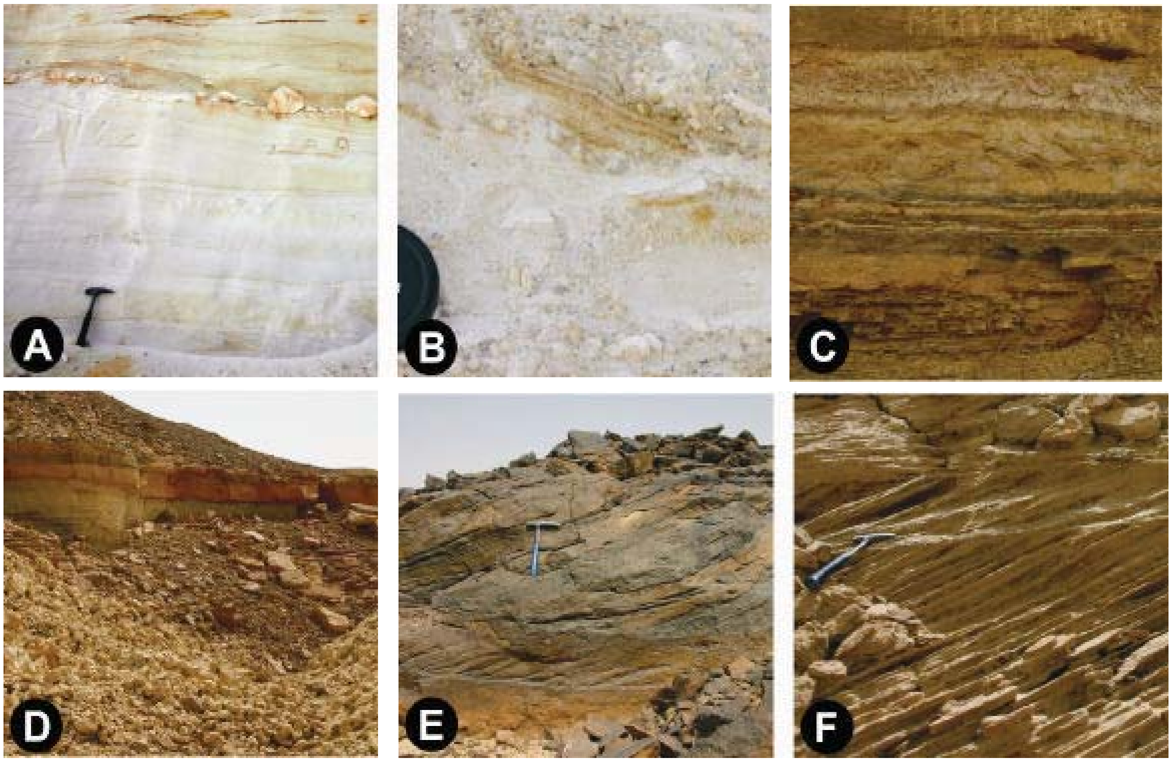

Plate 2: A: Fluvial facies with channel-lag deposits of the Majma Formation, Wasia Group. B: Conglomeratic channel fill with reworking in fluvial facies of Majma Formation. C: Variegated claystones of the Qibah Formation represent floodplain deposits. Uppermost layer is marine dolomite at the boundary to the Malihah Formation. D: Claystones and red siltstones of the Qibah Formation are interpreted as almost 9 m thick paleosol. E: Conglomeratic fluvial channel in sandstones and silt stones of the Malihah Formation. F: Fluvial sandstones of the Majma Formation. These facies of the Wasia Group document the laterally rapidly shifting environments with the corresponding effects on permeability and porosity.

The Majma Formation of the Wasia Group consists of a succession of variegated claystones and siltstones and fine- to medium-grained sandstones. These sediments laterally grade into conglomeratic and coarse- grained sandstones. Diagenetic features are prominent within the Majma Formation and include limonitic crusts, hardgrounds, concretions and evaporite nodules.

Near Ath Thamama, two kaolinite horizons are present that are interpreted as fossil soils formed during intensive chemical weathering under tropical conditions. The Majma Formation represents overall transgression [12]. It was deposited in coastal environments in which fluvial, deltaic and tidal sediments were formed. The repeated pulses of transgression and regression are much better reflected in the subsurface where accommodation was higher.

The Qibah Formation is a succession of variegated claystone, siltstone and some sandstone. Two limestone beds are present in the Qibah Quadrangle; they possibly correspond to dolomitic horizons in the Riyadh quadrangle. Marine fossils have been found in this unit; the fauna includes echinoderms, lamellibranches, foraminifers and sponges.

The Malihah Formation is an irregular succession of variegated claystones, siltstones and sandstones. Locally, conglomerates are developed. Wood fragments are common in the deposits. The Qibah and Malihah formations form a regressive sequence, starting with marine limestones and siliciclastic sediments and passing upward into nearshore marine and terrestrial deposits. Several paleosols have been observed within this succession, among which is a prominent horizon with roots in life position. In general, there is a clear change in facies from the areas north of Riyadh, where sandstones prevail, to the area of Al Kharj SE of Riyadh, where shales and siltstones dominate. Nevertheless, conglomeratic sandstone bodies are common in this southern area. The upper part of the Wasia outcrop belt there is expected to act as an aquitard, whereas in the sandstone-dominated north, the Wasia Group is a major reservoir unit.

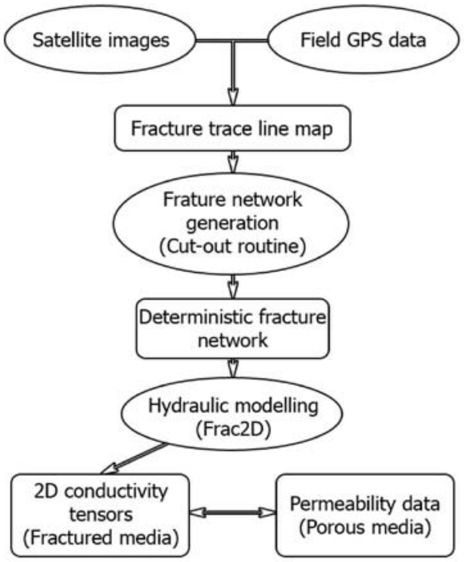

Fig. 4: Methodology for the assessment of fracture flow in aquifers (Zeeb *et al*., in press)

Consequently, rapid lateral facies changes within the Wasia Group hamper the prediction of permeability and storage capacity even over short distances. Only a careful sedimentologic analysis and a mapping of architectural elements can provide basic data for the groundwater model.

Finally, an additional, new approach is used to estimate the influence of voids and fractures on fluid flow in the aquifers. This method (Figure 4) was developed by Zeeb *et al.* [14] for studies of the Paleozoic Wajid Sandstone and is based on basic studies by Blum *et al.* [15-17]. This method evaluates two-dimensional conductivity tensors to determine the direction of the maximum flow in the fractures aquifers. This is based on evaluations of satellite images and field GPS data, from which fracture trace line maps are produced. From these maps, deterministic discrete fracture networks are established which are the basic input into hydraulic modeling. Combined with permeability and porosity studies, the modeling indicates that fracture flow is an important component in the Wajid aquifer.

CONCLUSIONS

Hydrogeological models generally have to deal with a lack of data. This is due to the nature of the studied object, the aquifer: it is mostly inaccessible for direct investigation, only penetrated by few punctual drillings and heterogeneous in its composition. Indirect methods, such as geophysical investigations, can amend the punctual field data. However, using geological ‘a priori’ knowledge of sedimentology, tectonics or aquifer development contributes significantly to the quality of the hydrogeological model.

The examples from the Kingdom of Saudi Arabia show the many parameters that influence the spatial distribution of aquifer characteristics. The need and importance of geological expertise is often underestimated. This results in an incomplete or even wrong aquifer characterization, although numerous and good-quality field data are available. Main contributions of geological expertise – or so called geological ‘a priori’ knowledge – to aquifer characterization are the assessment of:

- Hydrogeological heterogeneities in homogeneous lithology (lateral, vertical, linear),
- Local features with a regional impact on groundwater flow,
- Regional scale lithological variations within the aquifer,
- Genesis and state of aquifer development.

For aquifer characterization and the development of a hydrogeological model on a regional scale geological expertise is a must.

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