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Impacts of pore- and petro-fabrics, mineral composition and diagenetic history on the bulk thermal conductivity of sandstones

Bassem S. Nabawy [a, *], Yves Géraud [b]

[a] Department of Geophysical Sciences, National Research Centre, Cairo, Egypt
[b] Ecole Nationale Supérieure de Géologie, Université de Lorraine, Nancy, France

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A B S T R A C T

The present study aims to model the bulk thermal fabric of the highly porous ($26.5 \leq øHe \leq 39.0\%$) siliceous Nubia sandstones in south Egypt, as well as their pore- and petro-anisotropy. The thermal fabric concept is used in the present study to describe the magnitude and direction of the thermal foliation 'F', lineation 'L' and anisotropy 'λ'.

Cementation, pressure solution, compaction and the authigenic clay content are the main pore volume-controlling factors, whereas the cement dissolution and fracturing are the most important porosity-enhancing factors.

The bulk thermal fabric of the Nubia sandstone is raised mostly from the contribution of the mineral composition and the pore volume. The kaolinite content and pore volume are the main reducing factors for the measured bulk thermal conductivity 'k', whereas the quartz content is the most important enhancing factors.

The optical scanning technique, which is one of the most accurate and precise techniques, was applied for measuring the bulk thermal conductivity 'k' of the studied samples. For the dry state, the average thermal condutivity 'k_{av}' in the NE–SW, NW–SE and vertical directions, varies from 1.53 to 2.40, 1.54 to 2.36 and from 1.31 to 2.20 W/(mK), respectively. On other hand, 'k_{av}' for the saline water-saturated state for the NE–SW, NW–SE and vertical directions varies between 2.94 & 4.42, 2.90 & 4.31 and between 2.39 & 3.65 W/(mK), respectively.

The present thermal pore fabric is slightly anisotropic, 'λ' varies from 1.10 to 1.41, refers mostly to the NW–SE direction (k_{max} direction, elongation direction), whereas the petro-fabric refers to NE–SW direction (k_{max} direction, elongation direction). This gives rise to a conclusion that the pore- and petro-fabrics have two different origins.

Therefore, studying the thermal conductivity of the Nubia sandstone in 3-D indicates a pore fabric elongation fluctuating around the N–S direction.

1. Introduction

To achieve a better understanding for the thermal flow mechanism in porous rocks and materials, the bulk thermal conductivity 'k' has been studied theoretically and experimentally since many decades (e.g. Muskat, 1937; Blackwell, 1954, 1956). Recently, more attention has been paid for measuring 'k' due to its new applications in geothermal energy production and storage. It is of great importance for predicting the heat flow from geothermal reservoirs and for the thermal conductivity studies on rock materials.

A large set of techniques is available to measure the bulk thermal conductivity 'k' parameter but it is a long time consuming to make a measurement.

The contactless tool for measuring 'k', which applied to the present study, provides a good quality of the experimental data and modelling of the geothermal reservoirs (Popov et al., 2012). Measuring the bulk thermal conductivity using the optical scanning method can be run in a high speed, and has the advantage of measuring directly on the rock samples and its applications for the thermal anisotropy 'λ' estimation (Popov et al., 1999).

The bulk thermal conductivity 'k', is defined as "the quantity of heat 'Q' transmitted through a thickness 'L' in a direction normal to

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* Corresponding author.
E-mail address: bsnabawy@yahoo.co.uk (B.S. Nabawy).

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a surface of area ‘A’ due to a temperature gradient ‘Δt’, under steady state conditions”. Assuming that the heat flow is dependent only on the temperature gradient, k could be calculates as follows:

$$k = \frac{Q}{A} * \frac{L}{\Delta t} \tag{1}$$

It is also defined as “the ability of rock to conduct heat, measured in W/(mK), it could be calculated simply as follows.

Thermal properties of rocks are controlled by two sets of parameters, external parameters like pore fluid saturation, temperature and pressure, and internal parameters like mineral composition, pore volume and structures. In addition, density is present in the formulation of all the thermal parameters, and it is mostly controlled by two parameters, the mineral composition and the pore volume (McKenna et al., 1996; Maqsood and Kamran, 2005).

The authigenic clay content, as a common mineral composition, plays a main role in reducing the pore volume and closing the pore apertures (Bjørlykke et al., 1989). Pribnow and Umsonst (1993) calculated the bulk thermal conductivity of some crystalline rocks and indicated that the obtained values are mostly controlled by the quartz content.

Since porosity is a diagnostic property of sedimentary rocks, the pore volume and geometry are the key-control of the different physical properties, e.g. the bulk thermal conductivity (Lo et al., 1986; Tiab and Donaldson, 1996; Jones and Meredith, 1998; Rasolofosaon and Zinszner, 2002; Benson et al., 2005; Louis et al., 2005; etc…).

Porosity is mostly enhanced by some porosity-enhancing diagenetic factors, e.g. dissolution and leaching out of cement and grains, fracturing, weathering, and increasing or decreasing the rock volume, as well as some primary factors, e.g. grain sorting, sphericity and roundness (Nabawy and Kassab, 2014). On the other side, pore volume is reduced by cementation and precipitation from invasion by later solutions, re-crystallization, packing and compaction with depth and metamorphism (Bjørlykke, 1993, 1994; Bjorkum, 1996; Bjørlykke and Høeg, 1997). Porosity of the Nubia sandstone in south Egypt has been evolved as the net result of these enhancing and reducing factors which led to a complex pore fabric (Nabawy, 2013, 2014).

Taking into consideration the pore volume of a given rock, numerous theoretical & empirical correlations and models have been introduced to estimate the thermal conductivity of its matrix from its bulk thermal conductivity (Progelhof et al., 1976; Fuchs et al., 2013).

A careful review of these models; however, indicates that no one correlation or technique accurately predicts the bulk thermal conductivity of all types of mixtures. So, the main target of the present study is to declare and model the impacts of the pore volume and mineral composition on the average bulk thermal conductivity ‘k’ of the Nubia sandstone.

2. Geologic setting and lithostratigraphy

Nubia sandstone (Jurassic to Late Cretaceous) in SW Egypt are mainly composed of quartz arenite suffered from a long dry weather history. Their deposition was always topped by oolitic ironstone beds at the end of each depositional cycle. Therefore, the studied Nubia sandstone formations are characterized by intercalation of horizontal bedded thin oolitic ironstone beds (5–15 cm thickness); sometimes found as laminas filling vertical and inclined fractures.

The arid weather that prevailed for a long time, fracturing, dissolution and leaching out of some of the ironstone beds may be the source of invasion of much iron-bearing solutions. This invasion offered some ferruginous quartz arenite beds in alternation with the quartz arenite in the Nubia sandstone sections.

Lithostratigraphy and classification of the Nubia sandstone (250 m) is still a matter of controversy; it is bare of fossils and similar in the mineral composition. It has been studied in its type sections by many workers, e.g. Said (1962), Issawi (1973), Klitzsch (1979), Hendriks (1988), Issawi and Osman (1993), etc.

The Nubia sandstone has been studied in the area located between Lat. 22°15′ – 22°45′ N and Long. 31°00′ – 31°45′ E (Fig. 1) and can be summed up into four formations.

2.1. *Adindan formation (52.0 m, Jurassic-Valanginian)*

Its base is composed of 24 m of friable sandstone of greyish white to pale yellow highly fractured sandstone. Upwards, the Adindan Formation is composed of greyish white friable sandstone intercalated with highly fractured oolitic dark brown ironstone thin beds.

2.2. *Abu Simbel formation (120 m, Valanginian-Barremian)*

It conformably overlies the Adindan Formation. Its lower parts are composed of varicoloured mudstones intercalated with some friable sandstone beds followed upward by yellowish white friable sandstone. Upwards, its middle and top parts are composed of planar and tabular cross-bedded yellowish white to varicoloured friable sandstone.

2.3. *Abu Ballas formation (52.0 m, Aptian-Albian)*

Abu Ballas Formation is separated from the underlying Abu Simbel Formation by a regional thrust faulting. Its lower part (23.0 m) consists of reddish yellow, highly fractured, friable and blocky sandstone cross bedded at the base and pebbly upwards, intercalated with greyish coloured blocky mudstone and shales. Upwards, Abu Ballas Formation is composed of yellowish white cross bedded, coarse grained and conglomeratic sandstone intercalated and topped with thin beds of oolitic ironstone (5–15 cm).

The Abu Ballas Formation have been controlled by a long history of tectonism which mostly increased the fracture porosity and the friability of the Nubia sandstone. This intensive tectonism has also greatly affected the oolitic ironstone beds in this area causing bending, lamination and mostly fracturing.

2.4. *Kesiena formation (26.0 m, Campanian-Maastrichtian)*

It unconformably overlies the Abu Ballas Formation and disconformably overlain by the Paleocene Kurkur Formation. It is composed of greyish white to yellowish white, well bedded and friable sandstone. The middle part of Kesiena Formation is characterized by a greyish white phosphatic bed.

3. Sampling, materials and methods

A total of nineteen rock samples (fresh and not weathered) were selected representatively for the studied rock facies, and oriented horizontally to the magnetic north and vertically to the bedding plane.

To reveal the mineral composition, a number of thin sections were prepared and examined under the polarized microscope. Nomenclature and classification of the studied samples were done following Pettijohn et al.'s, 1973 classification for sandstones. The studied thin sections were impregnated using blue dye for estimating the pore volume under the microscope using the point