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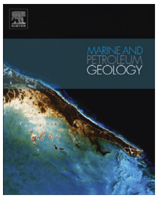

Review article

Bentheimer sandstone revisited for experimental purposes

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ABSTRACT

Bentheimer sandstone outcrop samples are ideal for laboratory studies due to their lateral continuity and block scale homogeneous nature. Over the years they have been used to investigate reservoir topics ranging from passive and active properties of oil/gas/water/rock interaction and processes to flow and transport.

This work shows an evaluation of Bentheimer sandstone properties and their characteristics to advance understanding on the mineral accessory and the physical and electrical transport properties. On the basis of the nature of depositional environments and diagenesis, we measure and characterize spatial attributes of the matrix, mainly by qualitative analysis, laboratory and stereological measurements and statistical 2D/3D reconstructions. The main contribution of this paper is the impact of mineral composition on the petrophysical quality and block scale homogeneity of the reservoir. With 3D techniques reconstructions of the new rock grain framework pore structures have been created.

Based on measurements, a review of literature data and interpretation of variation between the outcrops and flow relevant parameters, we conclude that Bentheimer sandstone is a rock that shows constant mineralogy and is largely free of paramagnetic impurities. In accordance with the results of 3D reconstructions techniques and in line with the depositional settings, they show a well sorted grain framework and a pore network that can be used to calculate the permeability and resistivity without conducting any direct laboratory measurements of either parameter. It presents a porosity with a range of 0.21–0.27 and permeabilities varying between 0.52 and 3.02 Darcy. Based on our work and literature, it is found that high permeability together with similar distribution of pore throats and bodies make the sandstone an attractive and easy obtainable candidate for comparative experimental studies. Moreover, we state by comparing various techniques that the efficiency and resolution accuracy of the applied method must be taken into consideration when planning the measurements.

1. Introduction

Bentheimer sandstone (BS) is a shallow marine formation deposited during the Lower Cretaceous. It forms a reservoir for oil and on the border between the Netherlands and Germany, outcropping in Bentheim with shallow oil reservoirs in between Enschede and Schoonenbeek (Dubelaar and Nijland, 2015; Fuchtbauer, 1963; Füchtbauer, 1955; Kemper, 1968, 1976; Knaap and Coenen, 1987). The sandstone is considered to be an ideal sedimentary rock for reservoir studies due to its lateral continuity and homogeneous block-scale nature. Both in natural appearance and thermally treated, it has a limited amount of minerals, a constant grain size distribution, porosity, permeability and dielectrical values, which makes it suitable for standard laboratory experiments and associated comparison with theory (Klein and Reuschlé, 2003; Ruedrich and Siegesmund, 2007). Therefore, Bentheimer sandstone is used to investigate a variety of reservoir topics ranging from passive and active properties of oil recovery processes to flow and transport in the groundwater zone and environmental remediation. Also, researchers often use Bentheimer sandstone in energy production studies and related processes such as geothermal energy (Jacquey et al., 2014a, 2014b; Reyer and Philipp, 2014; Smith and McKibbin, 2000) and geological storage of carbon dioxide (Al-Menhali et al., 2014; Andersson et al., 2013; Andrew et al., 2013a; Herring, 2012; Holt et al., 1995; Kvamme et al., 2006; Shojaikaveh et al., 2012).

The homogeneity and isotropy of rocks have a strong relation to the propagation of underground fluids. The major characteristics that are responsible for sandstone's homogeneity and isotropy at

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Nomenclature

A	Area, m^2
C	Constant associated with the tortuosity, [-]
D	Diameter, mm
Δn	Dissolution rate, mmol
E	Young's modulus, GPa
F	Faraday constant, C/mol
γ	Surface tension of the liquid surface, J/m^2
K	Permeability, D
K_o	Kozeny constant, [-]
L	Height, mm
L_e/L	Tortuosity, where L_e is the effective length and L the curved length, [-]
M	Mass, g
ν	Poisson's ratio, [−]
p	Pressure, Pa
P	Perimeter, mm
φ	Effective porosity, [−]
r	Radii of curvature, m
R	Ideal gas constant, J/K mol
ρ	Bulk density, kg/m^3
S	Saturation [−]
Ss	Specific surface, m/m^2
б	Charge, C/m^2
σ	Stress, MPa
T	Temperature, K
V	Volume, m^3

Subscripts

a	Area
ave	Average
b	Pore body
g	Grain
max	Maximum
m	Molar
p	Pore
rw	Residual water
s	Surface
sol	Dissolution
st	Standard
t	Tangent
v	Vapor
w	Water

Abbreviations

ASTM	American Society for Testing and Materials Standard Documents (+reference code)
BET	Brunauer–Emmett–Teller
BS	Bentheimer sandstone
CO_2	Carbon dioxide
CT	Computed tomography
FS	Fresh core samples
FSQ	Fresh core samples collected at different locations of the Romberg Quarry
GM	Gravimetric method
H^+	Hydrogen ion
H_2O	Water
HCl	Hydrogen chloride
IS	Intermediate core samples
Max	Maximum
µCT	Micro-CT scanner
N_2	Nitrogen
NaCl	Sodium chloride
NaOH	Sodium hydroxide
OS	Old core samples
PZC	Point of zero charge
SEM	Scanning Electron Microscope
STD	Standard deviation
STP	Standard Test Procedure
TS	Thin section
UP	Ultra Pycnometer
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

the small scale relate to grain size distribution, the orientation of the mineral grains/pores along a preferential direction (Wright et al., 2006), porosity and permeability – and even for samples obtained from different locations, the lack of mineral dissolution and precipitation processes that may increase the anisotropy and effectively decrease the connectivity. At field scale the homogeneity of the reservoir is predominantly determined by layering (Chandler et al., 1989), the existence of clay minerals in the zones of shear (Clavaud et al., 2008), and preferred alignment of fractures and faults.

In this study we describe the degree of block-scale homogeneity of the sample for conventional experiments and, for the more recent types of experiments (i.e., wettability and electrokinetic studies). Thus, our motivation is an unprecedented conduction, analysis and collection from the literature the prenominal Bentheimer sandstone parameters. Knowing depositional environments and diagenesis, we measure and characterize spatial attributes of the matrix, mainly by qualitative analysis, laboratory and stereological measurements and statistical 2D/3D reconstructions. In addition, we focus on overcoming the shortcomings in the literature (i.e., determination of the grain size distribution with a use of micro-CT scanner, the surface charge profile of Bentheimer sandstone with emphasis on the role of hematite and goethite).

This study was conducted at three different scales: (1) site scale (outcrop investigation); (2) laboratory scale (standard core testing); (3) microscopic scale (optical microscope, electron scanning environmental microscope), and calculated micro-scale (micro-CT and medical-CT scanner). In addition, the dielectrical behavior of the sandstone is considered as a measure for the definition of impurities in the quartz rich sandstone. This information is important for instance in wettability studies for CO_2 storage.

This research starts with the introduction of geological settings, variations on the environmental interpretations between the outcrops, and where possible, flow relevant parameters. Here primarily core measurements are considered, as they provide input data to classical reservoir evaluations and possible spread in data. The ability to predict the permeability of a porous medium and understand the impact of the pore structure is therefore imperative. Uncertainties in macroscopic reservoir characterization may originate from uncertainties in core data and consequently a more detailed microstructure characterization of Bentheimer sandstone was performed. The microstructure has a significant effect on bulk physical properties such as permeability, mechanical behavior (elastic moduli, relaxation times), electrical conductivity and heat capacity. For that reason we conducted XRD and XRF analysis and gathered the data from various studies (to make a comparison of mineral composition and amounts) (Al-Muntasheri et al., 2010;