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Pore space characterization in carbonate rocks — Approach to combine nuclear magnetic resonance and elastic wave velocity measurements

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ABSTRACT

Pore space features influence petrophysical parameters such as porosity, permeability, elastic wave velocity or nuclear magnetic resonance (NMR). Therefore they are essential to describe the spatial distribution of petrophysical parameters in the subsurface, which is crucial for efficient reservoir characterization especially in carbonate rocks. While elastic wave velocity measurements respond to the properties of the solid rock matrix including pores or fractures, NMR measurements are sensitive to the distribution of pore-filling fluids controlled by rock properties such as the pore-surface-to-pore-volume ratio. Therefore a combination of both measurement principles helps to investigate carbonate pore space using complementary information.

In this study, a workflow is presented that delivers a representative average semi-axis length of ellipsoidal pores in carbonate rocks based on the pore aspect ratio received from velocity interpretation and the pore-surface-to-pore-volume ratio S_{por} as input parameters combined with theoretical calculations for ellipsoidal inclusions. A novel method to calculate S_{por} from NMR data based on the ratio of capillary-bound to movable fluids and the thickness of the capillary-bound water film is used. To test the workflow, a comprehensive petrophysical database was compiled using micritic and oomoldic Lower Muschelkalk carbonates from Germany. The experimental data indicate that both mud-dominated and grain-dominated carbonates possess distinct ranges of petrophysical parameters. The agreement between the predicted and measured surface-to-volume ratio is satisfying for oomoldic and most micritic samples, while pyrite or significant sample heterogeneity may lead to deviations. Selected photo-micrographs and scanning electron microscope images support the validity of the estimated representative pore dimensions.

1. Introduction

Reservoir characterization aims at describing the spatial distribution of petrophysical parameters such as porosity, permeability or water saturation (Lucia, 1995, 2007); these parameters in turn are controlled by pore space characteristics (Mavko et al., 1998; Schön, 2011, 2015). The influence of pore space features on reservoir producibility and storativity cannot be reduced on a purely volumetric effect (i.e. porosity); pore size, shape, and interface effects control the relationships. Carbonate rocks are of specific interest because they serve as reservoirs for water, geothermal resources, and hydrocarbons, but also as potential storage reservoirs. Carbonates are, however, characterized by a huge diversity of fabrics, pore geometries and complex pore structures (different scales, shapes and types of connection) due to their partly biogenic origin and various chemical and diagenetic processes (e.g. Choquette and Pray (1970)).

Sonic or acoustic logs are conventionally part of every logging program measuring the transit time of elastic waves traveling through the formation (e.g. Asquith and Krygowski (2004)). The elastic properties of rocks are dominated by the properties of the solid rock matrix including voids (e.g. pores or fractures; Schön, 2011). According to Anselmetti and Eberli (1993), pore type is equally important as the absolute amount of porosity for the resultant velocity in carbonates. Eberli et al. (2003) found relationships between velocity and grain size and shape, sorting, and the content of grains and carbonate mud in unconsolidated carbonate sediments, as well as cement and pore type in consolidated carbonate rocks.

In contrast, nuclear magnetic resonance (NMR) logs are sensitive to the pore-filling fluid rather than lithology and provide information on a reservoir's porosity, fluid state and type (movable/producible fluids, bound fluids) and permeability, based on the investigation of relaxation processes of hydrogen nuclei in the pore fluids. While NMR measurements are successfully used in sandstone reservoirs (e.g. Allen et al. (2000, 2001) and Amabeoku et al. (2001)), in carbonate rocks the low surface relaxivity of the carbonate matrix, very long relaxation times caused by large pores, and dispersed T_2 distributions due to a wide range of pore sizes still result in challenges for reservoir evaluation (Logan et al., 1998; Westphal et al., 2005; Di Rosa et al., 2006; Chen et al., 2008).

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So far, both sonic and NMR methods are mostly used individually to determine similar petrophysical information on carbonate rocks; both methods seem to be sensitive to the same pore space features (carbonate fabric, pore size and type). Anselmetti and Eberli (1999) presented a velocity-deviation log for carbonate rocks indicating zones with frame-forming pore types, fractured zones/borehole break-outs, or zones with high interparticle or micro porosity. A permeability prediction method for carbonate rocks based on porosity, the ratio of compressional wave to shear wave velocity and specific surface was introduced by Fabricius et al. (2007), which works well for mud-dominated fabrics (i.e. mudstones, wackestones, packstones, floatstones), but fails in mud-poor fabric types with fracture or vuggy porosity. Kumar and Han (2005) presented a method to estimate the aspect ratio of different carbonate pore types and their volume fractions based on bulk porosity and water-saturated compressional wave velocities. Fournier et al. (2011) introduced an equivalent pore aspect ratio to relate diagenetic history and pore space evolution to elastic properties. Fournier et al. (2014) and Brigaud et al. (2010) studied the impact of pore type and diagenetic processes on velocities. Lima Neto et al. (2014) predicted the amount of microporosity, a representative pore aspect ratio and shear wave velocity in microporous grainstones and other fabric types based on differential effective medium theory using digital image analysis, porosity and dry compressional wave velocity and presented polynomial curves for different carbonate texture types for velocity prediction based on effective pressure and bulk porosity (Lima Neto et al., 2015). Knackstedt et al. (2009); Derzhi et al. (2011); Kalam et al. (2011), and Kalam (2012) derived petrophysical properties of carbonate rocks using digital rock physics based on digitized 3D core computer tomography. Parra et al. (2001) and Ramakrishnan et al. (2001) found that a combination of NMR and acoustic logs can identify vuggy pores and the degree of connectivity in carbonates, based on compressional wave attenuation, phase velocity or shear modulus, while NMR logs are sensitive to matrix porosity (inter- and intragranular porosity). Chen et al. (2008) described an NMR permeability model for carbonate rocks accounting for pore connectivity and facies types, while Westphal et al. (2005) suggested cutoffs related to pore types for permeability estimation. Frank et al. (2005) and Mardani et al. (2013) identified NMR facies groups with distinct reservoir quality based on surface relaxivity, specific surface, permeability, and diffusion studies which mainly depend on pore geometry and fabric.

In consideration of these findings and keeping in mind that both methods assess formations using different measurement principles, it seems likely that they deliver complementary information. The purpose of this study is to assess if a combination of compressional wave velocity and NMR transverse relaxation (T_2) data can enhance our knowledge about a formation's representative pore space features on a quick-look basis. We present a new joint interpretation workflow for NMR and velocity information to derive representative pore dimensions in carbonate rocks. NMR data are used to derive pore-surface-to-pore-volume ratio S_{por} using a novel approach based on the ratio of capillary-bound to movable fluids and the average thickness of the capillary-bound water film. The average pore aspect ratio α is determined using the Budiansky and O'Connell (1976) method for ellipsoidal cracks located in a non-porous host material. Both pieces of information are combined to derive a representative characteristic pore semi-axis length using an evaluation grid established for ellipsoidal pores. It is important to note that the derived aspect ratio and semi-axis lengths need to be regarded as fitting parameters and do not represent an estimate of the actual pore shape of certain pore size groups. To verify the validity of our assumptions, directly measured specific surface data, selected photo-micrographs and scanning electron microscope (SEM) images are used. This new workflow may be relevant for extending the information gained from NMR and acoustic logging to enhance reservoir characterization with regard to storativity and predictions of fluid flow in carbonate rocks.

2. Material and methods

A set of Lower Muschelkalk samples (Middle Triassic, Germany) was selected for petrophysical investigations. During the Anisian (Middle Triassic), large parts of Central Europe were covered by the Triassic Germanic Basin (sometimes also called Central European Basin; see Fig. 1). Its associated Lower Muschelkalk carbonates reflect the evolution of a mud-dominated ramp system bordering the north-western Tethyan shelf (Götz and Lenhardt, 2011). Three seaways in the south and south-east (i.e. the East Carpathian, Silesian–Moravian, and Western Gates) connected this epeiric sea to the open Tethys Ocean. The semi-enclosure of the basin led to distinctive facies differentiation between its western and eastern parts (Götz and Gast, 2010). The eastern part of the Germanic Basin was dominated by fully marine conditions during almost the entire Anisian, while in the western part evaporitic conditions of an enclosed basin with restricted circulation prevailed. When the eastern marine gateways opened, marine incursions gradually advanced westwards. In the Lower Muschelkalk succession four transgressive events could be distinguished (Feist-Burkhardt et al., 2008).

At the sampling site Rüdersdorf near Berlin located in the central part of the Germanic Basin, the Lower Muschelkalk is typically composed of two facies types (see Fig. 2). Wellenkalk which is composed of successions of dark gray, biogenic/peloidal limestones alternating with marly peloidal/micritic limestones and the yellowish oomoldic limestones of the Schaumkalk (Bodzioch and Kowal, 2001; Noack and Schroeder, 2003). These facies represent different energetic conditions on a carbonate ramp. Wellenkalk was formed in positions both above and below fair-weather wave base and storm wave base and comprises fine-grained micritic limestones and marl of stillwater environments as well as shell limestones or tempestites. Characteristic features are undulating compaction structures which developed where sediments of different densities were deposited on top of each other (Zwenger, 1993). The oomoldic Schaumkalk was formed in shallow marine environments (water depths of a few meters) under high energetic conditions. It is characterized by its partly cemented, but mostly open spherical to ellipsoidal pores which were formed by dissolution of ooids. A peculiar lithological feature occurring in the Schaumkalk succession is a layer with about 15% dolomite content which likely formed in the supratidal zone of a sabkha environment. Apart from that, hardgrounds with signs of bioerosion and occasional micritic limestone layers with undulating compaction structures similar to those of the Wellenkalk may also be present in the Schaumkalk succession (Zwenger and Koszinski, 2009).

Compressional wave velocity v_p and magnetic resonance properties were measured on cylindrical plugs of 5.5 cm length and 3.5 cm diameter (Fig. 3). Since all rock samples were taken at an open pit mine, their original orientation was not preserved. Plugs were drilled with a water-cooled diamond coring drill perpendicular to bedding, where visible, and sample ends were trimmed and paralleled to within 0.05 mm. Afterwards, the samples were dried until a constant mass was measured and equilibrated to room temperature before the measurements were conducted. The measurement setup for the transmission velocity experiments consisted of an ultrasonic transmitter–receiver pair with piezoelectric transducers, a signal generator, a signal amplifier (all Geotron Elektronik), a storage oscilloscope, and a computer with the measurement software.

The transducers were pressed against the plug faces with a pressure of about 1 bar and an 80 kHz impulse was used to generate the compressional wave signal. Since the transducers' pointed tips ensure appropriate coupling, no contact agent was needed. The velocities were calculated from the one-way traveltime of the acoustic wave along the sample axis divided by the sample length. Uncertainty in velocity measurements is within approximately 1%.

The samples' dry mass was determined and used along with the measured cylinder volume to calculate dry bulk density. Grain density ρ_g was determined with a helium pycnometer employing the gas displacement method (AccuPyc 1330, Micromeritics) and used along with the dry